The surveyors in the longest tunnel of the world

Special Edition English

Ingenieur-Geometer Schweiz (IGS)
Ingénieurs-Géomètres Suisses (IGS)
Ingegneri-Geometri Svizzeri (IGS)

Bild: AlpTransit Gotthard AG

Dear reader,

There are very few moments in life providing us with a reason to be proud for the work that has been accomplished. Participating in the construction of the longest tunnel in the world is certainly one of those reasons. The surveyors are too often perceived as minor actors in the big construction projects. Without them, however, a major work such as the construction of a big tunnel couldn't be realized. The surveying specialist meets many challenges and resolves numerous problems and we hope that the lecture of this booklet will help you to better understand the nature of those challenges.

IGS is proud to present you the articles written by the actors of the «construction site of the century» and wishes you much pleasure and interest while reading them.

Maurice Barbieri
IGS President (Ingénieurs Géomètres Suisses)

Since the citizens of the canton of Schwyz brought the letter of rights they had obtained from Italy over the Gotthard home in 1240, the pass has again and again been of fateful importance for the Confederation. In the dangerous years of World War II, General Henri Guisan set up our armed forces in such a way that the two historic trans-Alpine railway lines Gotthard und Lötschberg-Simplon would have been interrupted if Hitler and Mussolini had ordered an attack. Even today Switzerland sees itself as an *independent* country in accordance with Article 2 of its Federal Constitution. But Switzerland is not an island of egoists. Therefore, our country has decided to carry out its enormous «new trans-alpine railway» or NEAT project through the Lötschberg and the Gotthard mountains on its own. Europe and the world, however will obviously benefit more from this double digit billion investment than we ourselves. The achievement, however – the reduction in travelling distance and time between Zurich and Milan from four to two hours and 40 minutes – is predominantly a Swiss one.

Achievements such as these are never in vain: Let us recall in silence those workers who, despite modern safety precautions, this time too, like others more than a century ago, died for the sake of duty. But let us also remember the effort and the ingenuity that went into this venture. It includes the triumph of Swiss geomatics. We recall: When the main breakthrough of the tunnel was accomplished on 15 October 2010, the deviation of the two tunnels was only 8 centimetres laterally and 1 centimetre in height. How did the engineers and surveyors manage to achieve such results? Well, parallel to construction mapping and monitoring tasks, instrumental engineering was also promoted so that the precision requirements could be met. Thus, atmospheric effects that have an influence on measurements had to be minimised or directional transmission achieved via the 800 metre deep vertical shaft of Sedrun.

Also the major transition had to be made from the good old triangulation method to the global satellite navigation system and laser scanning.

Once again, the cadastral survey agency in my department, the DDPS, delivered an outstanding performance that fills me with pride. May this booklet provoke similar feelings in many readers and may it provide valuable services to the specialists as a technical reference, but also bear witness to us all of that what we know, at least since Pestalozzi:

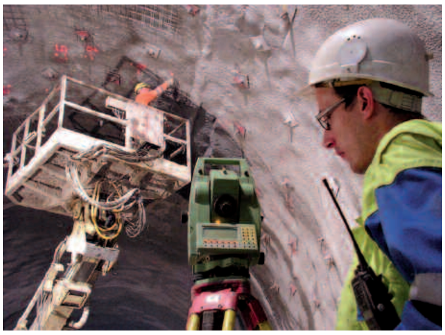
Humans have unlimited capabilities if they really set their minds to something!

Best regards

Federal Councillor Ueli Maurer

Contents




Contents

Gotthard and Ceneri Base Tunnels
The New Gotthard Rail Link takes shape

AlpTransit Gotthard is creating a future-oriented flat rail link through the Alps which will bring marked improvements to rail travel and transportation systems in the heart of Europe. At the centre of the new rail link is the Gotthard Base Tunnel – at 57 km the world's longest, and with a rock overburden of up to 2500 m the world's deepest, tunnel. Adjoining it to the south in the Canton of Ticino as continuation and extension is the 15.4-km-long Ceneri Base Tunnel. Together, the tunnels form the new Gotthard Rail Link: a continuous flat route through the Alps.

R. Simoni

In several referendums, Swiss voters decided clearly in favour of protecting the sensitive Alpine regions and a corresponding transport policy: as far as possible goods traffic should be transferred from the roads to the railways. The New Gotthard Rail Link provides the central infrastructure to implement this transfer policy. In view of their extent and the long planning and construction time, the base tunnels under the Gotthard and Ceneri can be regarded as construction projects of the century. Several generations of engineers, planners and surveying specialists, as well as several thousand miners, are contributing to their realisation.

Continuous flat route through the Alps

With the AlpTransit Gotthard, a flat rail link through the Alps is being constructed. The highest point of the railway route, at 550 m above sea level, is no higher than the city of Berne, The maximum gradual gradient of the flat rail link is 12.5 per thousand on the aboveground sections and 8.0 per thousand in the base tunnels. Since there are also no curves with tight radii, long, heavy trains can travel efficiently. The transport offerings for passengers and freight can be substantially improved.

For goods traffic, the new route allows freight trains to be twice as long and heavy as today. Transporting the same quantity of goods will require fewer locomotives and personnel. Freight trains with a pulled weight of more than 2000 metric tons can cross Switzerland without stopping and without mid-train or pushing locomotives. The daily number of freight trains on the new Gotthard route will increase from around 140 trains today to 220 trains per day. The transfer policy brings not only economic but also ecological benefits.

AlpTransit Gotthard integrates Switzerland into the European high-speed network for passenger traffic. The passenger trains of the future will travel the new route at speeds of up to 250 km per hour. The Gotthard and Ceneri base tunnels will reduce passenger travelling time between Zurich and Milan from just under four hours today to two hours and forty minutes. There will also be optimal connections between the Swiss and Italian timetable systems in Zurich and Milan.

Gotthard Base Tunnel

Construction concept and route

The 57-km-long Gotthard Base Tunnel consists of two parallel single-track tubes. The two rail tunnels run about 40 m apart and are joined at approximately 325-m intervals by connecting galleries. Situated one third and two thirds of the way through the tunnel at Sedrun and Faido are multifunction stations containing track crossovers, components of the ventilation systems, and technical areas with

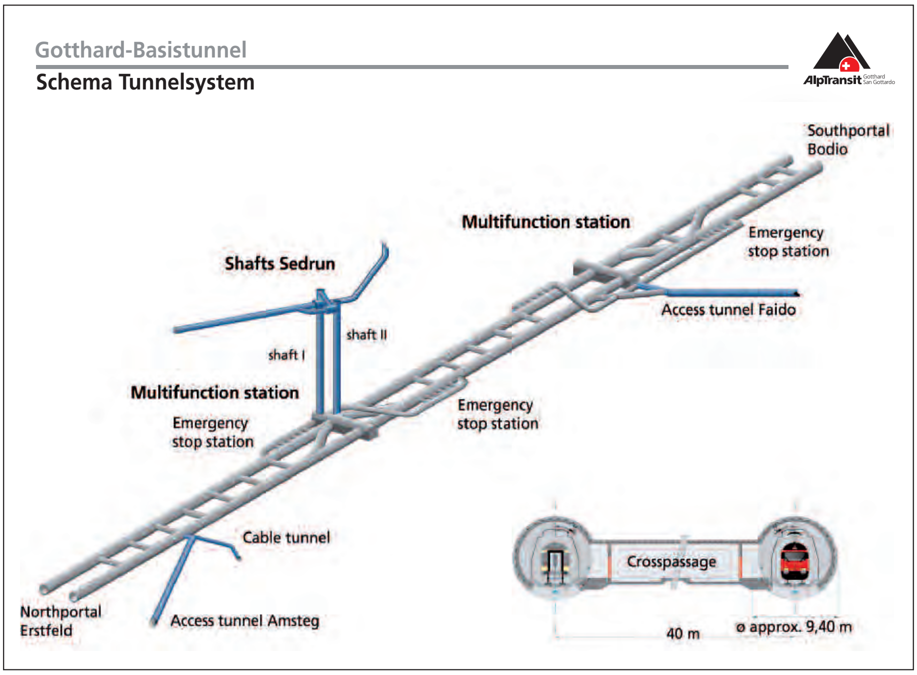


Fig. 1: The tunnel system of the Gotthard Base Tunnel.

Fig. 2: To stabilise the rock in the Sedrun section, flexible steel rings were installed.

safety and switching systems, as well as two emergency-stop stations, which are directly linked by separate access tunnels. Because of the geology between the north portal at Erstfeld and the south portal at Bodio, the route of the Gotthard Base Tunnel forms a large letter S. This allows the route to pass through the structurally most favourable rock formations and avoid even greater depths of overlying rock. Further factors affecting the choice of route were the locations of the portals and optimisation of the lengths and positions of the intermediate headings. When deciding where to locate the intermediate headings, the most important criteria were ease of access, risk of avalanches, floods, rock falls and landslides, as well as ground water.

Constructing five sections simultaneously

To optimise construction time and costs, drilling took place simultaneously from the portals at Erstfeld and Bodio, as well as from three intermediate headings at Amsteg, Sedrun and Faido. The intermediate headings simplified construction logistics as well as the supply of fresh air. In the Erstfeld, Amsteg, Faido and Bodio sections, open hard-rock tunnel-boring machines (TBMs) with cutting diameters of between 8.8 and 9.58 m were used. For geological reasons, the main tubes in the Sedrun section were excavated by conventional drilling and blasting.

Support was provided directly from the tunnel-boring machine by means of systematic anchoring and shotcrete. The machines can also insert steel supports in the form of partial or complete rings. At the rear end of the TBM, the tunnel invert is produced from cast-in-place concrete. The sealing for the tunnel tubes is installed from back-up construction sites. Where large-scale water ingress or corrosive water is encountered, full sealing is implemented. The normal cross-section of the inner vault is not steel-reinforced. It is normally 30 to 35 cm thick. In confined rock conditions, inner linings with a wall thickness of up to 120 cm are used. In a subsequent work operation, side benches, ground-water pipelines and cable systems are installed. The completed single-track tubes have a minimum free cross section of 41 m^2 (usable diameter 8.4 m).

Present state of work on the Gotthard

As of mid-October 2010, of the total of 151.8 km of tunnels, galleries and passages of the Gotthard Base Tunnel, only 2.4 km, or 1.6%, remain to be excavated. Concrete work is in progress in both tubes. Of the total of 114.6 km of tunnel lining work, at the beginning of October,

Fig. 3: World record under the Gotthard: on October 15, 2010, the miners celebrated the final breakthrough in the east tube of the Gotthard Base Tunnel.

104.9 km of the invert (92%) and 67.8 km of the vault (59%) had been concreted. On October 15, 2010, the first final breakthrough of the Gotthard Base Tunnel took place in the east tube between Sedrun and Faido. In April 2010 the final section of rock in the west tube between Faido and Sedrun is scheduled to be cut. At the point of breakthrough, the depth of covering rock is 2500 m. The breakthrough took place with great accuracy: the measured deviations were 8 cm horizontally and 1 cm vertically.
Work in the various construction sections is at different stages. In the northern aboveground approach section (Altdorf-Rynächt), work is in progress on the railway track bed and the various built structures. Temporary relocation of roads and railway tracks was necessary. In the Erstfeld section, excavation of the tunnel tubes was completed in mid-2009. Work on the two cut-and-cover tunnels, which when completed will form the most northerly section of the Gotthard Base Tunnel, is also progressing rapidly. The Amsteg section has been ready for installation of the railway infrastructure since December 2009. In the Faido and Sedrun sections, the main focus of the work in addition to the conclusion of drilling is installation of the infrastructure systems in the multifunction stations and lining of the tunnel tubes. In the west tube of the Bodio section, installation of the railway infrastructure has already begun. The east tunnel continues to be used to store supplies for the tunnel construction sites at Faido. Construction of the southern aboveground approach section is complete. Construction of the new Swiss Federal Railways (SFR) operations control centre (CEP) is in progress. In the future, all railway traffic between Arth-Goldau and Chiasso will be controlled from this CEP at Polleggio.

Installation of railway infrastructure

In the three sections of Amsteg, Sedrun North and Bodio West, the single-track tubes are already fully concreted along a length of more than 40 km and ready for installation of the railway infrastructure. In May 2010, installation of the railway systems began at the south portal of the Gotthard Base Tunnel in the Faido-Bodio West section, in parallel with completion of the concrete shell in other sections of the tunnel.
In the Faido-Bodio West section, a total of more than 14 km of railway track, catenary and electric power supply systems are being installed as well as telecommunication and train control systems and crosscut infrastructure systems. Extensive test runs will subsequently be performed in the section. The main installation of the railway systems in the north will take place starting in 2013. Commercial operation of the Gotthard Base Tunnel with scheduled train services is planned to start in 2017.
The permanent railway infrastructure systems comprise the concreted track bed, the catenaries, the electric power supply, the 16.7 Hz tractive power supply, and telecommunications installations for landline, wireless and safety systems. In addition, for the duration of the construction, temporary systems are required, such as construction-plant power supply, construction telecommunications and construction-site ventilation. These systems will be installed first.
The greatest challenge for installation of the railway systems is the confined space of the Gotthard Base Tunnel. All materials are brought entirely by rail into the tunnel through the two portals.. Access for tired vehicles, and particularly turning space in the 57-km-long tunnel, are very limited. Two installation sites at Biasca in the south and Altdorf/Rynächt in the north provide the logistical facilities for installation of the railway infrastructure. More than 1000 technical interfaces must be coordinated to make trouble-free rail traffic in the Gotthard Base Tunnel possible. The material required includes 31 000 cubic metres of concrete for the track bed, 308 km of rails, 3200 k of copper cable for the power supply, 417 emergency call columns, and 120 km of antenna cable for wireless communication.

Fig. 4: In May 2010, installation of the railway infrastructure began in the west tunnel in the Bodio section.

Ceneri Base Tunnel

Construction concept

The Ceneri Base Tunnel also consists of two parallel single-track tunnels, which are linked at intervals of approximately 325 m by connecting galleries. With a length of 15.4 km, the Ceneri Base Tunnel will have no track crossovers or multifunction stations. At the beginning of October 2010, a total of 39.78 km had been excavated representing almost 24%

Fig. 5: Drilling holes for blasting by the north portal of the Ceneri Base Tunnel.

of tunnels and galleries of the Ceneri Base Tunnel. The Ceneri Base Tunnel is being dug entirely by conventional drilling and blasting.
The main tunnelling is proceeding from Sigirino, where the miners are working towards the north and south in both tubes. Inward drilling is also proceeding from the portals in the north (Vigana) and south (Vezia, near Lugano). All excavation should be completed in 2015, after which the railway infrastructure also will be installed in the Ceneri Base Tunnel. Commissioning is scheduled for 2019.

Present state of work on the Ceneri Base Tunnel

At Camorino, the area north of the north portal of the future Ceneri Base Tunnel, various undertakings have been carried out on built structures and subprojects such as canals, bridges and underpasses. These will form part of the link between the Ceneri Base Tunnel and the existing Swiss Federal Railways line. Tunnelling work in the area of the north portal at Vigana began in 2009. Because of the short vertical distance to the overhead A2 motorway, this work had to be carried out with special caution. The first blast for the main northward and southward tubes took place at the Sigirino intermediate heading in March 2010. In April 2010 at the south portal in Vezia, the first blast took place for the first approximately 300 m of tunnelling to the north. Also at the south portal, because of the close proximity to residential and commercial infrastructure, including the late seventeenth-century Villa Negroni, drilling must be executed with special care.

Summary

AlpTransit Gotthard is creating a future-oriented flat rail link for travel through the Alps. Its central infrastructures are the two base tunnels under the Gotthard and Ceneri mountains. They will reduce the time to travel by train from Milan to Zurich to less than three hours. There will also be a marked improvement for rail-based freight traffic through the Alps.
The Gotthard Base Tunnel, with a length of 57 km between the north portal at Erstfeld and the south portal at Bodio, and with a rock overburden of up to 2500 m, is the world's longest and deepest tunnel. The final breakthrough in the east tunnel took place on October 15, 2010. Scheduled train services are planned to start at the end of 2017. The Ceneri Base Tunnel, with a length of 15.4 km, connects Vigana in the north with Vezia, near Lugano, in the south. The first train should be able to travel through the Ceneri in 2019.

Dr. Renzo Simoni
Chief Executive Officer
AlpTransit Gotthard Ltd.
Zentralstrasse 5
CH-6003 Lucerne/Switzerland
renzo.simoni@alptransit.ch

AlpTransit: A European link through the Swiss Alps

Railway lines through mountainous areas are unique: Their main purpose is not to provide access to the regions they traverse, but to link the regions that are divided by mountains. If the regions lie in the same country, the railway line is a means to improve national cohesion. If the regions are located in different countries, however, the line becomes of international interest. A combination of the two cases leads to challenges that result in unconventional decision making processes. At the Gotthard Railway, this decision-making took place at a time when Swiss foreign relations were in a delicate state. The transport flows transiting the Alps through Switzerland do not naturally follow a predetermined path, but three competing corridors exist: in the west, center and the east of the country. As the resources and demand would not justify the development of three parallel railway corridors, a choice had to be made. This choice was heavily influenced by the cantons and hampered by their disagreements.

Prof. Dr. Ulrich Weidmann

1845–1882: The realization of the Gotthard Railway

With the Schöllenen gorge bridged, the Gotthard pass became a significant trade route and strategically important point, although transport volumes at that time may seem negligible by today's standards. Since 1845, even before the first railway in the country was in operation, railway lines through the Alps have been studied. There were many doubts, however, and the pioneers Stephenson and Swinbune, referred to as federal consultants, discouraged the implementation of alpine railways in 1850. They may have been caught up in the British design philosophy, which favored rather straightforward alignments. At the time it had yet to be proven that building such railway lines was possible.
Three fundamental innovations paved the way: First the Semmering railway of 1854 proved that inclinations of 25 ‰ and 190 m radii were indeed manageable. Second, in 1871 the Blackforest railway pioneered deviations from topography and artificial elongations of the railway line to keep inclinations at acceptable levels. Finally, during the construction of the Mont Cenis railway, opened in the same year, decisive advancements in tunneling techniques were achieved.
In 1869, in a conflict-laden process, the politician and entrepreneur Alfred Escher led a new assessment of the Gotthard railway, enabling political support after having first favored a transit route to the east of the Alps. Strategic interests of Italy and Germany helped in this process, as they contributed CHF 45 million and CHF 20 million, respectively, to the estimated overall project cost of CHF 187 million. Options studied for the alignment included a visionary base tunnel at 800 m above sea level, as well as the use of very steep ramps with cable cars. When the line opened in 1882, contemporary design approaches similar to those applied in other great alpine railways of the time prevailed.

1946–1983: Gotthard Base Tunnel projects without results

Despite technological advances, operating the Gotthard railway remained costly. As a consequence, in 1946 the idea of a base tunnel was revived. A commission to study a road link across the Gotthard that could be kept open in winter recommended a highway line as well as a Gotthard railway base tunnel line. This focus on the Gotthard passage, however, provoked competing proposals further east and west. Still, in 1970 the Gotthard line was confirmed by the transalpine railway tunnel commission (KEA). The then department of transport and energy (EVED) published a concept in 1973 that called for double tracking the Lötschberg line and, as a long-term plan, a Gotthard Base Tunnel.
While the double tracking was completed between 1977 and 1992, interregional disagreement continued, especially between Gotthard and Splügen, as the «east alpine railway promise» made by the Bundesrat in 1878 kept being cited. A joint group was not able to deliver a clear recommendation. In the meantime, the transit volume collapsed and, as a result, pressure to act was lifted. Consequently, the Bundesrat put the issue on hold in 1983.
With the opening of the Gotthard A2 highway in 1981, the success of the Gotthard railway was diminished: Passenger numbers fell from 7 million per year in 1979 to only 3 million in 2009. In freight transport, the rail modal share fell from 90% to 65%. In 1999 rail freight was liberalized, and the Lötschberg-Simplon line gained more and more market share, further reducing the Gotthard market share in Swiss transalpine rail freight from 75% to only 55%.

1985–1994: Alpine transit decisions and the alpine protection clause

When parliament discussed the Bahn 2000 infrastructure investment package in 1986, the alpine transit railway was still omitted. This left the cantons of Ticino and Valais without a viable perspective for an unknown length of time. Soon, political motions called for a new transalpine route – and this time, the timing was right: The increasing number of trucks disproved the claim that the Gotthard high-

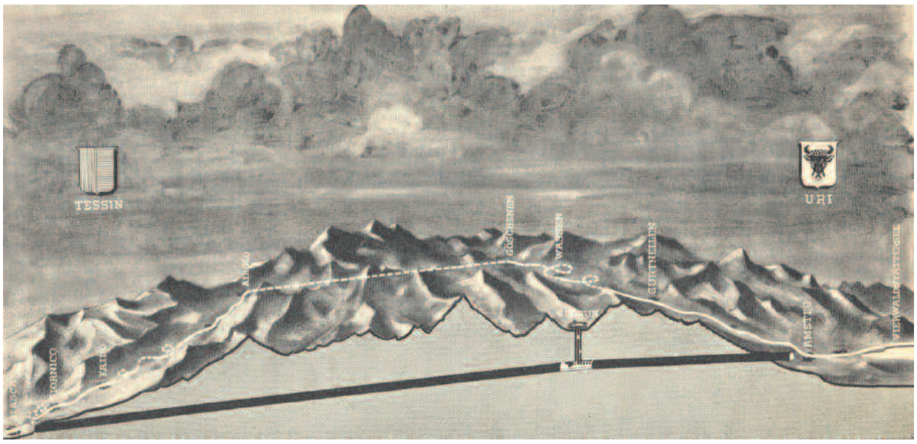


Fig. 1: Sketch of an idea for the Gotthard Base Tunnel from Eduard Gruner, published in 1947 (Collection of the author).

way would serve mainly passenger traffic. At the same time, the destruction of the protective forests took place, which was attributed to a general forest decay resulting from road traffic. During this situation, a call for unrestricted transit for trucks up to 40 tons was made by the EU. During these conflicting issues, new alpine railways became a political issue. The Bundesrat quickly had the proposed lines re-evaluated. Thirteen of the cantons favored the Gotthard, seven the Lötschberg, and six the Splügen. Under the perceived pressure to act, the simultaneous construction of two transit railways, Gotthard and Lötschberg, was then announced in the 1990 alp transit dispatch and approved by the citizens in 1992.

With this decision made, Switzerland was able to obtain EU-agreement to raise the freight road tolls to their maximum level upon the opening of the Lötschberg Base Tunnel and to keep the night and Sunday travel prohibitions for road freight transport. However, an increase in the maximum weight to 40 tons, commencing in 2005, had to be agreed upon. As a quick measure, the Lötschberg line was upgraded to 4 m corner height in order to accommodate intermodal transports by 2001.

For the regions directly affected, however, this was not enough. In 1989, the «alpine initiative for the protection of the alps region from transit traffic» launched its campaign, demanding that all transit traffic should be by rail, from each end of the Swiss border. After a heated controversy preceding the vote, this initiative was approved with a 51.9% majority in 1994 and is now article 84 of the federal constitution.

1995–2010: Redimensioning and the law to shift freight transport

In 1992, freight transport profitability was at its peak; however, by 1996 it had decreased by 25%. From 1994 on, doubts about profitability grew. In 1995, a redimensioning was commissioned: The Lötschberg Base Tunnel was to be double tracked only in its southern third and on the Gotthard line; the second Zimmerberg tunnel, a new line from Arth-Goldau to Erstfeld (including Urmiberg and Axen tunnels) and the Bellinzona bypass were omitted.

At that time, opening estimates were still 2006 for the Lötschberg Base Tunnel and 2008 for the Gotthard Base Tunnel, justifying the capacity reduction of the former. The completion dates slipped, however, and while full operations in the Lötschberg base tunnel commenced in 2007, the Gotthard base tunnel will not be in operation until 2016 or 2017, and the Ceneri Base Tunnel will take until 2019 to complete. Consequently, the single-track at the Lötschberg now constitutes a significant bottleneck.

The law pertaining to alpine protection was also delayed and became active only in 2001. A modal shift goal was set, calling for a reduction in the number of trucks crossing the Alps to no more than 650,000 by 2009. While slight success was recorded in the beginning, the number of trucks increased again beginning in 2007, and the 2010 estimate was 1.3 million trips. Realizing that the goal of 650,000 is nearly impossible to achieve, the target year has been extended to 2019.

The Gotthard Base Tunnel and passenger transport

For rail passenger traffic, the Gotthard Base Tunnel will reduce travel times from the German part of Switzerland by an hour, thus creating a new landscape and putting most of the Ticino within reach for day trips from most of German

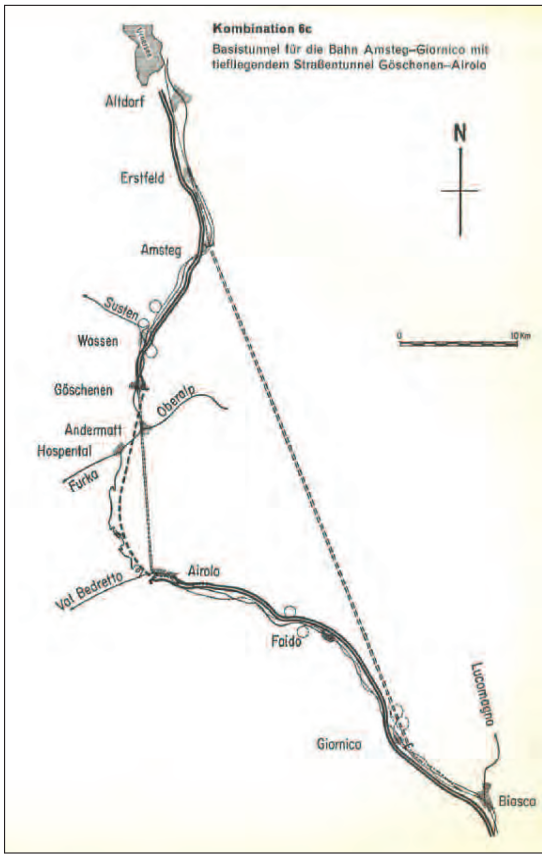


Fig. 2: Proposal 6c of the Commission «Safe winter road link though the Gotthard» from 1963 (Collection of the author).

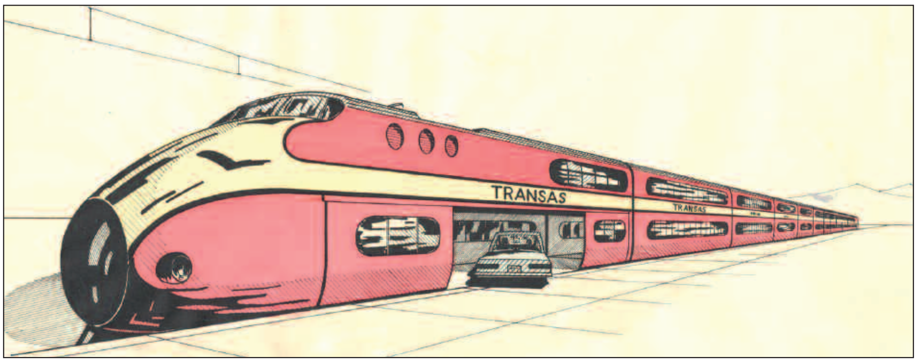


Fig. 3: The slightly different base tunnel project: TRANSAS study from the Federal Office of Transport (1972), car shuttle train with a top speed of 210 km/h (Collection of the author).

Switzerland. This will immediately improve the competitiveness of rail compared to road traffic. Already the demand for the Lötschberg Base Tunnel has increased by a third, and an even stronger effect is expected at the Gotthard. In the long term, 18 000 to 19 000 passengers per day are expected; about the same volume as before the highway was opened. Most of this volume will come from domestic leisure and business travel, and to a smaller extent from international travel between Switzerland and Italy. However, a significant volume of traffic is not expected as the major population centers north and south of the Alps are too far from each other. A major change is expected in the settlement patterns of southern Switzerland. Already an increase in investment activity has been observed in the vicinity of the major railway stations. Around the Lötschberg line, an increasing number of people living south of but working north of the Alps has been observed. Similar development is expected with the completion of the Gotthard Base Tunnel, albeit to a smaller extent, as the main centers of Lucerne, Zug and Zurich are still significantly more than an hour away. However, a major increase in events such as conventions and seminars is expected.

The Gotthard Base Tunnel and freight transport

In the freight sector, the prospects are controversial: The Gotthard Base Tunnel by itself is unlikely to achieve the modal shift goal. While travel times and operational complexity for long freight trains decrease significantly, these improvements are not as large, seen in context with the long running times of those trains. Consequently, a market share gain of no more than 2.5% is expected. More important for today's just-in-time logistics concepts are on-time performance and the degree of flexibility of train paths, requiring the railway infrastructure to provide this flexibility. However, the previously mentioned redimensioning measures create a series of bottlenecks on the lines leading to the Gotthard that can hardly be remedied, even with the next step in infrastructure development, namely, «future development of the railway infrastructure» (ZEB).
There are further issues complicating the matter: About half a million trucks per year bypass Switzerland, primarily using the Brenner. Moreover, neighboring countries have little understanding of the unique path Switzerland is taking with re-

Line	Continuous operation	Highest inclination [‰]	Minimaler Radius [m]	Apex height [m above sea level]	Apex length [m]
Semmering	1854	25.0	190	898	1430
Brenner	1867	25.0	285	1371	–
Mont-Cenis	1871	30.2	345	1298	13 657
Schwarzwald	1871	20.0	300	832	1698
Gotthard	1882	27.0	280	1155	15 003
Arlberg	1884	31.0	250	1311	10 250
Simplon	1906	25.0	300	705	19 803
Tauern	1909	27.0	250	1226	8551
Karwendel	1912	36.5	200	1185	–
Ausserfern	1913	32.0	190	1128	512
Lötschberg	1913	27.0	300	1240	14 612
Tenda	1928	25.0	300	1073	8099

Table 1: Parameters of European mountain railways of the 1st Generation.

Fig. 4: Combined freight train on the Gotthard south ramp at Lavorgo (Photo SBB AG).

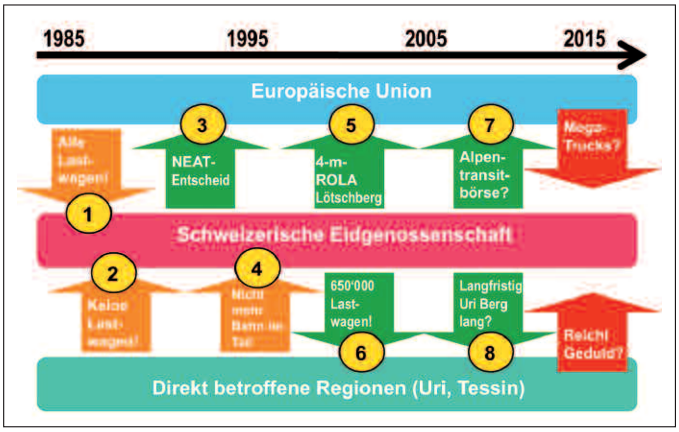


Fig. 5: NEAT as a key element for equalizing interests among Switzerland, Europe and the affected regions (own Figure).

gard to traffic in the alpine region. A converging of social and safety standards between rail and road freight is not observed. Also, the introduction of 25 m trucks with a maximum weight of 60 tons lobbied for by a number of European countries would deal a blow to the ecologically oriented transport policy of Switzerland. There is hope regarding this issue, however, as in some European countries these longer vehicles are also the topic of public debates, and the EU accepts the strategic importance of the Swiss alpine transit railways. Thus the railway corridor A, from Rotterdam to Genoa, has been selected to be the first one to be fully inter-operational by 2015.

Conclusion

Is the Gotthard Base Tunnel a European transportation artery? It is, considering the history of its formation and its importance in freight transport: It is part of one of the most important freight transport corridors on the continent. It is being financed by Switzerland entirely, however, and at the current train path fees, its usage by foreign transports will be highly unprofitable. Its importance as a national passenger corridor prevails and, with respect to the spatial developments, the Gotthard Base Tunnel will even have a strong regional component.

In this light, the new European alpine transversal (NEAT) is best viewed as a linking element: It is the key element of the ongoing negotiations between Switzerland and the European Union and the regions directly affected. Within this uncommon situation in foreign affairs, Switzerland has found a very specific Swiss answer. The success of this answer, however, can hardly be controlled by Switzerland. It is possible that the NEAT might be more of a touchstone for the EU's transportation and environmental goals than it might currently realize.

information on the sources available by the author

Prof. Dr. Ulrich Weidmann
Institut für Verkehrsplanung/
Transportsysteme
ETH Zürich
Wolfgang-Pauli-Strasse 15
CH-8093 Zürich
weidmann@ivt.baug.ethz.ch

Mode of transport / axis	2000	2001	2002	2003	2004	2005	2006	2007	2008
Road	8.9	10.4	10.6	11.6	12.5	12.9	12.9	14.2	14.6
Total rail	20.6	20.8	19.3	20.5	23.0	23.7	25.2	25.3	25.5
thereof Gotthard	*16.8*				*16.0*		*16.2*	*15.5*	*15.5*
thereof Simplon	*3.8*				*7.0*		*9.0*	*9.8*	*10.0*
Overall total	29.5	31.2	29.9	32.1	35.5	36.6	38.1	39.5	40.1

Table 2: Transported freight volumes over the Swiss Alps in million net tons (UVEK: Relocation Report January 2007 - June 2009).

Modern technologies and concepts solving the geodetic challenges of AlpTransit

With construction of the Gotthard Base Tunnel, the surveying experts were faced with new requirements in geodetic metrology. These could be achieved with innovative ideas and the development of new surveying methods. Simultaneously to the staking out and monitoring tasks, in particular in the 1990s, revolutionary developments took place in the field of geodetic instrumentation that allowed achievements in accuracy and reliability otherwise unattainable.

H. Ingensand

Newly developed technologies for the metrology tasks of the Gotthard Base Tunnel project

The former triangulation and trilateration methods for establishing a reference network (Elmiger et al., 1993) were replaced completely by GPS and then by GNSS (Fig. 1). In 2005, the ETH set a world record with simultaneous measurements using 28 GNSS receivers to check the existing reference network (Ryf, 2006). Precision digital levels, which have been produced since 1995 by all major manufacturers, are indispensable in today's high precision measurements. The minor height differences at the final breakthroughs of the tunnels speak for the accuracy of this new technique based on image processing. Especially for the height measurements in tunnels, homogeneous illuminations for levelling staffs had to be developed. With the use of digital levels it also became possible to detect any settlement above the Gotthard road tunnel (swisstopo, 1998). The settlement monitoring systems of the dams of Nalps, Cunera, St. Maria and the surrounding surface would have been unthinkable without a new generation of motorized and automatically pointing tacheometers. With these instruments, in combination with GPS and geotechnical sensors, submillimetre movements of the dams and the slopes of the valleys could be determined. Due to these monitoring systems, further settlements during the tunnelling could be stopped and counteractions immediately taken. With the new millennium laser-scanning technology mastered the tunnel measurements. In 2002, the first experiments using laser scanners to determine the tunnel geometry and deformations were carried out. Meanwhile, laser scanning became a standard method in tunnel monitoring and documentation (Zogg, 2007). In addition to these technologies a so-called Tubemeter was developed at the ETH in 1997 in the course of a study on risk minimization (Fig. 2). This instrument determines the geometrical deviation in a test drilling before the breakthrough. Technologically the Tubemeter can be regarded as a «gliding» polygon. The height differences are continuously determined by inclination measurements.

Solving the refraction and turbulence effects in tunnelling

With the use of today's high precision optical instruments come detrimental systematic and stochastic effects on the measurements caused by external atmospheric influences in the form of refraction and turbulence. In particular, in tunnels and the optical monitoring of dams these influences are to be carefully taken into account and modelled. Research activities into refraction in tunnels, especially in the portal areas, have been carried out since 1997 using a mobile temperature gradient measurement system developed at the ETH (Fig. 3) (Hennes et al., 1999).
During the period 1997–2001 a so-called dispersometer was constructed at the ETH Zurich that allows refraction-free direction measurements. The refraction free direction is computed from the difference of the angles of arrival of the red and blue laser beam free of hypotheses (Fig. 4). The technical challenges, however, in generating the two laser beams and the submicron detection of the offset of the blue and red laserspot are very high. Thus, this technology has not been implemented in geodetic instruments up to now but the functionality of a dispersometer has been demonstrated in a PhD thesis (Böckem, 2001).

The direction transfer in the vertical shaft of Sedrun

Another challenge of the Gotthard Base Tunnel was the direction transfer in the 800 m vertical shaft at Sedrun. Alternative solutions such as direction transfer using polarized light, double plumbing, or a spatial trilateration network along the wall of the vertical shaft had to be rejected for reasons of accuracy and. cost. Hence, only the transfer using north finding gyroscopes, as they were originally developed for measurement in mines, was left. But it has to be taken into account that gyroscopic measurements are systematically affected by external influences such as temperature and deflections of the vertical that are in turn derived from gravity models. Thus, since 1997 measurements using an inertial navigation system have been considered as an independent direction transfer method (Fig. 5). The efforts of the Technical University of Munich to perform the direction transfer using an inertial system in the Olympic Tower confirmed the expectations of experts that an inertial system can provide the same accuracy as the gyroscope (Neuhierl et al., 2006).

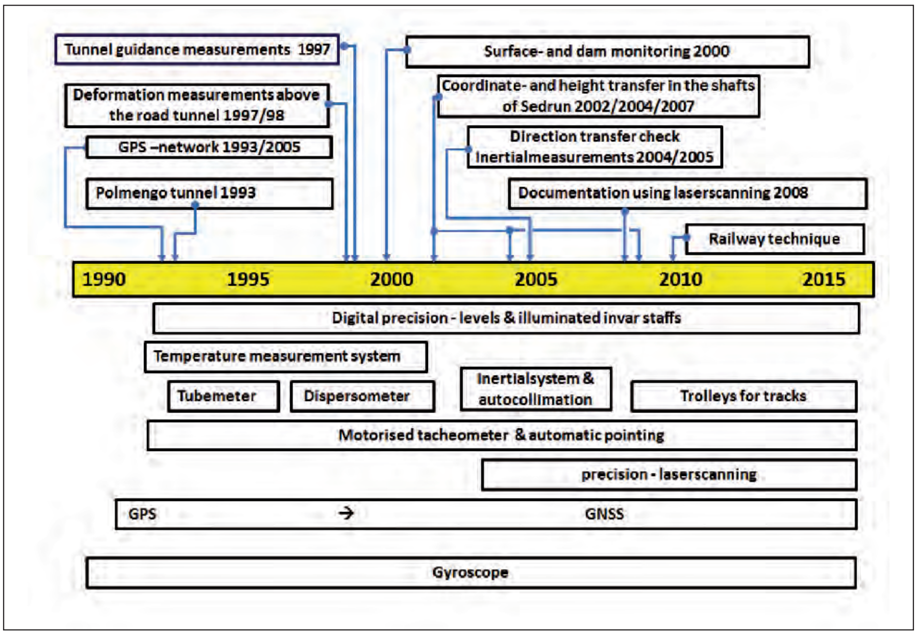


Fig. 1: Progress in metrology technologies vs. the construction phases of the Gotthard Base Tunnel.

The comparison of these measurements carried out in 2004 and 2005, resulted in a difference of 2.2 mgon compared to the gyroscopic measurements.

Kinematic track surveying technology

For the installation of the rail tracks, Swisstrolley™ (a track measurement trolley (Fig. 6)) was developed within the terms of a project financed by the Commission for Technology and Innovation (CTI) (Glaus, 2006). SwisstrolleyTM has been successfully used in the Thalwil Tunnel, being part of the feeder route to the Gotthard Base Tunnel. In the so-called slab track technique, a submillimetre accuracy for the staking out procedure is required. This accuracy is achievable using this track trolley in connection with precision tacheometers. For the track measurements in the Lötschberg Tunnel, the UniBw München kinematically measuring RACER system was used and is used in the Gotthard Base Tunnel now.

Summary

The AlpTransit project with its requirements for high accuracy and reliability initiated an important progress in the de-

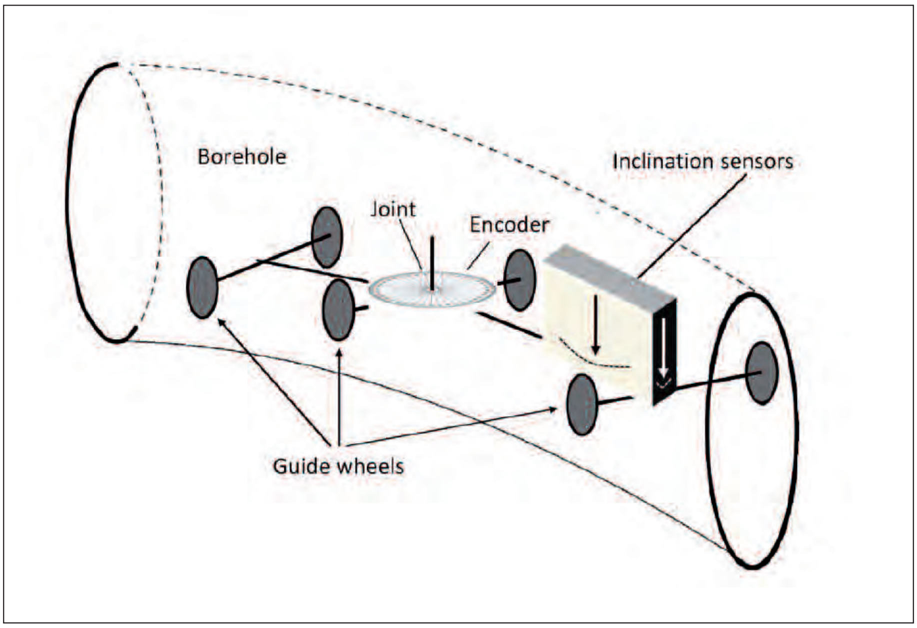


Fig. 2: Design of the ETH Tubemeter (1997).

Fig. 3: Temperature gradient measurement system.

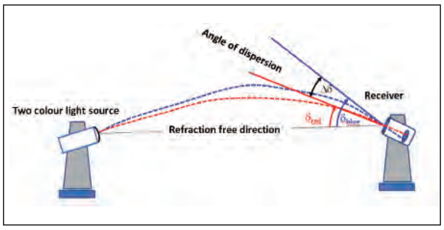


Fig. 4: Principle of the ETH dispersometer.

Fig. 5: Direction transfer using IMAR inertial navigation system.

Fig. 6: Swisstrolley™ (terra) and RACER (UniBw).

velopment of instruments and the computation of measurements. In addition, the permanent monitoring systems for dam and terrain observations led to improved scientific knowledge and new theories. With the successful tunnel breakthrough, the performance of geodetic measuring techniques and the modelling of particular factors in tunnels has been demonstrated.

References:

Neuhierl, T., Ryf, A., Wunderlich, T., Ingensand, H. (2006): AlpTransit Sedrun: Weltpremiere mit inertialer Messtechnik. Geomatik Schweiz, 6/2006.

Ryf, A. (2006): Gotthardtunnel: Weltrekord. Reporter 55: Das Magazin der Leica Geosystems. Heerbrugg, Oktober 2006.

Hennes, M., Dönicke, R., Christ, H. (1999): Zur Bestimmung der temperaturgradienteninduzierten Richtungsverschwenkung beim Tunnelvortrieb. VPK, 8/99, S. 418–-426.

Glaus, R. (2006): The Swiss Trolley – A Modular System for Track Surveying. Geodätisch-geophysikalische Arbeiten in der Schweiz (SGK), Band 70.

Zogg, H.-M. (2007): Terrestrisches Laserscanning zur Aufnahme von technischen Bauwerken am Beispiel von Schachtkammern. In: Beiträge zum 74. DVW-Seminar «Terrestrisches Laserscanning – Ein Messverfahren erobert den Raum» (Red.: Barth/Foppe/Schäfer), Fulda.

Elmiger, A., Köchle, R., Ryf, A., Chaperon, F. (1993): Geodätische Alpentraverse Gotthard. Geodätisch-geophysikalische Arbeiten in der Schweiz, Nr. 50.

Böckem, B. (2001): Development of a dispersometer for the implementation into geodetic high-accuracy measurement systems. Diss. ETH No 14252.

Swiss Federal Office of Topography Swisstopo (1998): Bodensenkungen über dem Gotthardstrassentunnel. Presse Mitteilung 22.1.1998.

Prof. Hilmar Ingesand
Geodätische Messtechnik und Ingenieurgeodäsie
Institut für Geodäsie und Photogrammetrie
ETH Zürich
Wolfgang-Pauli-Strasse 15
CH-8093 Zürich
ingensand@geod.baug.ethz.ch

Geodetic Basis and Main Control Surveys in the Gotthard Base Tunnel

This article summarizes the surveying work of the Gotthard Base Tunnel Surveys Consortium from 1995 to 2010. Beginning with the contractual requirements, the geodetic basis and the establishment of the reference frameworks NetzGBT_Lage and NetzGBT_Höhe are described. The concept of tunnel surveying, the performance and processing of tunnel controls and the survey of the 800 m Sedrun vertical shaft are presented. The analysis of survey data and the appraisal of accuracy and reliability are explained. The theoretically expected breakthrough accuracies (breakthrough prognosis) of the four main breakthroughs in the Gotthard Base Tunnel and the actually achieved breakthrough results are compared and assessed in a historic context.

R. Stengele, I. Schätti-Stählin

1. Tasks and Responsibilities of the Consortium Gotthard Base Tunnel Surveys (VI-GBT)

The Gotthard Base Tunnel Surveys Consortium

In 1995, the Gotthard Base Tunnel Surveys (VI-GBT) Consortium applied for the planning and performance of the geodetic works in the NEAT lot «Gotthard Base Tunnel». This Consortium brings together the know-how of four Swiss engineering and surveying companies with a total of 120 employees:

- Grünenfelder und Partner AG in Domat/Ems
- BSF Swissphoto AG in Regensdorf
- Studio Meier SA in Minusio
- Studio Gisi SA in Lugano

Tasks and Responsibilities

Having won an international bidding competition in 1995, the Consortium was entrusted with the responsibility for the following tasks by the AlpTransit Gotthard AG:

1. Geodetic basis
2. Aboveground control network for position and height
3. Densification of the control network in 5 portal areas
4. Measuring concept for tunnel surveying
5. Periodic heading controls and main control surveys as a basis for the steering control in position and height
6. Verticality measurements in the 800 m Sedrun shaft
7. Choice of breakthrough zones optimized for surveying
8. Permanent monitoring surveys (subsidences, shifts) underground and above ground
9. Control surveys of the completed construction: profiles, shoulders, shafts, blanket-coverage laser scanning, track beds and railway systems.

In conjunction with additional publications, this article provides an overview of tasks 1 to 6. In a project with a time frame of 20 years, concepts and technologies need to be continuously adjusted to new developments. This requires innovation, process orientation and meticulous knowledge management at all levels. Project and quality management are a key competency and pose – apart from the purely technical requirements – a huge challenge for the project managers in charge.

Accuracy and Tolerance

The main task and responsibility is steering the drive (tunnel-boring machine and blasting) at a transverse and longitudinal accuracy of 10 cm and 5 cm in height. As customary in surveying, this accuracy requirement is defined as one standard deviation (1 σ) in a statistical sense. The contract stipulated a maximum acceptable error (tolerance, worst case) of 2.5 σ and confidence intervals of 95% for position and 99% for height. This results in a maximum acceptable transverse and longitudinal surveying error of 25 cm and 12.5 cm in height. In other words: «In order to meet the accuracy requirements in more than 20 km long tunnel sections, the transverse and longitudinal error per 100 m must not exceed 1 mm, and the height error may even amount to 0.5 mm only.»

2. Control Network (Position): *NetzGBT_Lage*

The aboveground control network is comprised of 28 main survey points spread over the portal areas. They were permanently marked on geologically stable rock and were measured with GPS for the first time in 1995 in accordance with the state of the art at that time. To increase both accuracy and reliability, one point of the National Survey LV95 was included in the vicinity of each of the five portals. A Helmert transformation of the high-precision, free GPS network to the connection points in the area of the main portals in Erstfeld and Bodio minimized the positional differences to existing networks (cadastral surveying, Swiss Federal Railway networks) without diminishing the inner accuracy of the GPS control network. Based on the adjustment of all measurements, the accuracy of the «NetzGBT_Lage» was estimated at 1 $\sigma_{y,x}$ < 7 mm and 1 σ position < 10 mm, respectively. The relative accuracy between two random points is < 10^{-6} in all cases. Backup markings at all points of the basic and portal networks allowed for the monitoring of local shifts over the project duration of 20 years.

In summer 2005 – that is 10 years after the establishment of the control network and one year after the first main breakthrough in Bodio-Faido – a complete repeat measurement of the GPS control network took place. With the co-operation of VI-GBT and ETH Zürich, the entire network was measured «in one go» with 28 GPS receivers. Except for one point, the positional differences between the measurements of 1995 and 2005 fell within the 95% confidence interval.

Also in summer 2005, the Swiss Gravity Field Consortium (SKS), in co-operation with ETH Zürich and the Institute of Geodesy of the University of Hannover, carried out astro-geodetic measurements checking the orientation of each portal network. Direct comparisons of azimuths measured astronomically and reduced into the projection plane with azimuths of NetzGBT_Lage showed an orientation difference of approx. 1 mgon between Erstfeld und Bodio. The orientation differences between the «neighbouring» portals were < 0.3 mgon. Furthermore, astro-geodetically determined vertical directions were compared to those of the CHGeo98 geoid model (Fig. 1). Based on these results, one could safely assume that the gaug-ing/calibration/reduction of the geographic gyro azimuths could be done without systematic errors.

3. Control Network (Height): *NetzGBT_Höhe*

It was clear to VI-GBT, even in the proposal phase, that complete precision levellings across several alpine passes as a direct connection between all five portals was out of the question for economic reasons. It was equally clear that the existing national levelling network was unsuitable as a height reference system for the stake out of the Gotthard Base Tunnel for several reasons: «working heights», no heights strictly reduced in accordance with potential theory, no overall adjustment of levelling loops, no consideration of recent crustal movements, and known inconsistencies (between Amsteg-Sedrun, 8 cm height gap in Ticino).

The Federal Office of Topography (swisstopo) was already working on the elimination of these weaknesses in the course of the renewal of the national levelling and the establishment of the new height reference framework LHN95. Work on LHN95 in the geographic area of NEAT was therefore prioritized and closely co-ordinated between swisstopo and VI-GBT. All national levellings carried out in the last decades were digitised, gravimetrically reduced and strictly adjusted using a kinematic model for the uplift of the Alps. By applying this method, the complex precision levellings could be limited to approximately 30 km of connection levellings from the portals to the national levelling network. An excellent synergy developed through synchronization of the interests of the National Survey with those of the Gotthard Base Tunnel project!

With the definition of the height reference framework for the Gotthard Base Tunnel (NetzGBT_Höhe), it followed that the effect of the gravity field on all underground measurements had to be taken into account in the form of orthometric corrections. Orthometric corrections and the resulting theoretical loop closing errors (non-parallelism of equipotential surfaces → path dependence of levellings) were calculated by swisstopo for each tunnel section along the tunnel axis and in the 800 m deep vertical Sedrun shaft by means of mass, density and gravity models (Fig. 2). The various model based corrections in the height system added up to more than 10 cm in certain tunnel sections. They clearly exceeded the required height accuracy and even the accuracy at which height differences can be levelled in the first place. The model of uplift of the Alps alone (vertical speed = 1.2 mm/y in Ticino, 0.8 mm/y in Sedrun) results in a height difference of 7 mm in the Faido-Sedrun tunnel section over a time frame of 15 years, which represents more than 10% of the required height accuracy.

Of course, the numerous height corrections (orthometric correction, uplift of Alps extrapolated to the time of breakthrough, network embedding deficiencies) were not suited for practical implementation on the construction site. This is why linear overall corrections were calculated for each tunnel section and applied by VI-GBT to the underground height measurements. This way, all other parties involved in the project were spared the problem of height correction.

In summer 1995, the (not hypothesis free) gravity model used by swisstopo was reviewed by gravimeter measurements performed by ETH Lausanne in the already

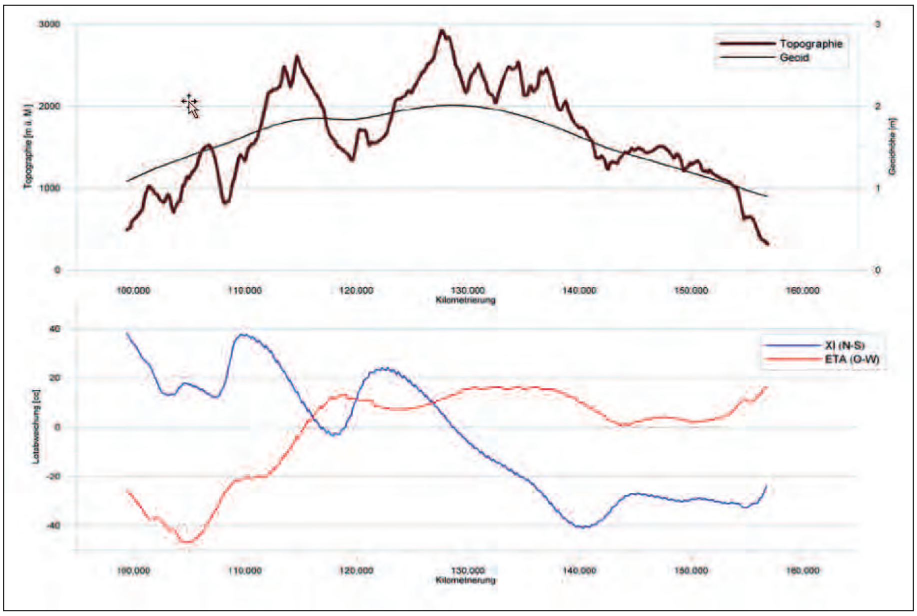


Fig. 1: Topgraphy, geoid and components of deflection of the vertical on the Gotthard Base Tunnel axis

completed tunnel sections in Bodio and Sedrun. Differences between model based and measured gravities of < 3 mGal with an (theoretical) effect on the breakthrough error of < 1 mm were determined in the Bodio section. In particular the very good coincidence in the vertical Sedrun shaft was acknowledged very favourably at that time.
In view of the complexity of height determination based on geophysical and geometric measurements in Europe's geographically and topographically most challenging region, the excellent breakthrough results in height are highly remarkable, and they constitute a real performance record for everybody involved in the conceptual design and implementation of the height reference framework NetzGBT_Höhe.

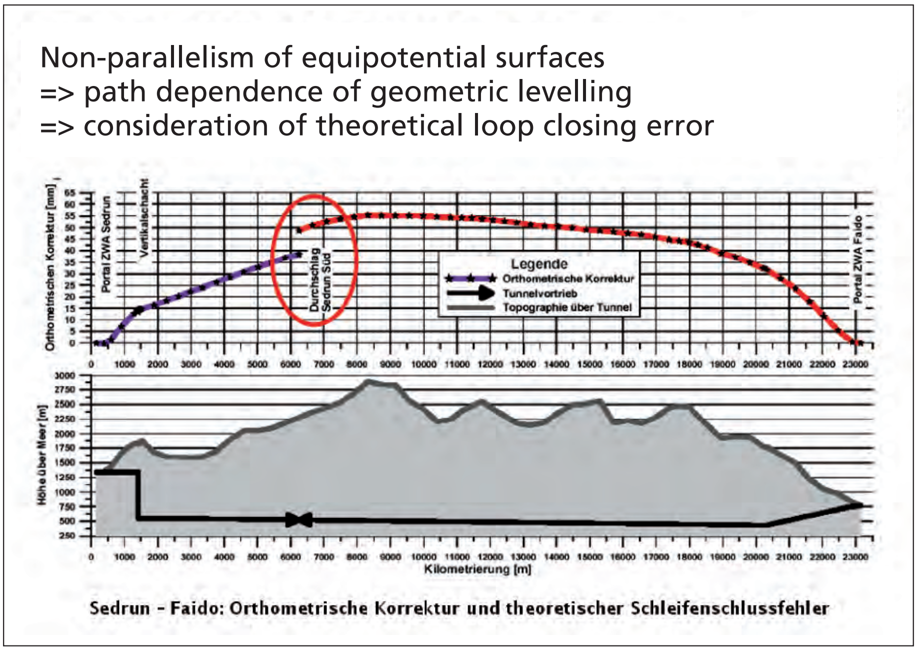


Fig. 2: Model based orthometric corrections and loop closing errors of levelling.

4. Underground Control Network: Tunnel Surveying

The reference frameworks «NetzGBT_Lage» (position) and «NetzGBT_Höhe» (height) provided the basis for the underground tunnel network and, with that, for the stake out of the tunnel axis and the control of the TBM and blasting headings.

Importance of Portal Networks

Both in the literature and during practical work on the construction site, great importance is attached to maximizing the accuracy and increasing the reliability of control networks and tunnel networks. The interface between aboveground and underground surveying in the portal area, however, is neglected all too often, in theory as well as in practice. The accuracy potential can only be fully exploited if scale and orientation of the control network is transferred underground via the portal area without any significant loss of accuracy. This challenge is frequently underestimated, and unfavourable conditions in the portal area are more often the rule rather than the exception: challenging topographic settings, ever-changing site installations, ventilation equipment, site traffic, local deformations, limited visibility and narrow curve radii in the access tunnels complicate this task considerably. The special refraction problem due to the substantial temperature gradient at the portal is alleviated by additional measurements of temporary support points in the immediate vicinity of the portal (few metres outside and inside).
The initial situation for the tunnel survey in the entry area of the tunnel is as follows:
Coordinate accuracy: 1 σ (y, x, H) < 10 mm, azimuth accuracy: 1 σ (azimuth) < 0.5 mgon. With that, the acceptable transversal deviation would be reached with a (theoretical) sighting length of 11.4 km.

Underground Surveying Concept

There are numerous concepts and methods for the design and implementation of polygon networks. All of them aim at minimizing the unfavourable error propagation in elongated traverses and the systematic effects of dangerous horizontal refraction. However, a generally accepted scientific consensus – that is, the optimal solution - doesn't exist. The VI-GBT opted for the following surveying concept (Fig. 3) in 1995 and has adhered to it consistently over the course of 15 years:

- Parallel precision traverses in both single-track tunnels, with connection measurements between every 3rd or 4th traverse point
- Strict placement of traverse points in the middle of the tunnel at intervals of 400 to 450 m.
- Overlapping sightings, i.e., measurements to the nearest two traverse points in both directions, sighting distances not more than 900 m.
- Gyro support of the traverse after every 5th to 7th traverse point (every 2 to 3 km). Multiple determinations of mutual gyro azimuths on the same traverse sections in different measurement campaigns.
- Height transfers by precision levelling (to/from); control by trigonometric levelling of the traverse.
- In curves: shifting of the traverse points by max. 1 m outwards, reduction of distance between points down to 300 m, compliance with >1.5 m sighting distance from tunnel wall, no overlapping sightings.
- Alternating deployment of staff and equipment (particularly gyro instruments) in order to minimize systematic effects.

Pre-analysis

By means of a network simulation (pre-analysis) it was verified a priori that the surveying concept would meet the required accuracies in position and height. The essential parameters of the stochastic model were defined as follows:

- Directions 3 cc
- Distances 0.5 mm + 1 ppm
- Gyro azimuths (single measurements) 15 cc
- Centering 0.5 mm
- Leveled height differences 1.0 mm/km
- Coordinate transfer in the 800 m deep Sedrun shaft 24 mm *(«3 mm per 100 m»)*

It is very important to make rather conservative assumptions in simulations in order to make allowances for the below par underground measurement conditions.

Scope of Tunnel Controls

As soon as two (max. three) new traverse points had been marked out in the concrete floor – that is after tunnelling 1300 m at the maximum – the coordinates were determined by VI-GBT in the course of a «small tunnel control». The new points were linked to at least three of the nearest existing traverse points, which resulted in a traverse measurement of 2 to 2.5 km. After every 3 km of tunnel drive a «large tunnel control» was performed with a traverse measurement spanning 8 to 10 points, which is over a length of 3.5 to 4.5 km.

In every tunnel section, an additional «half time control» was performed after reaching approx. 50% of the total drive length. Additionally, an overall control was carried out approx. 1.5 km before reaching the boundary of the lot. Half time and overall controls included measurements in the portal network and the entire underground tunnel network.

This scenario ensured that measurements stemming from at least four different tunnel controls and performed at very different points of time were available at every traverse point.

Usually, an independent azimuth control with the precision gyro Gyromat-2000 was carried out In the course of the «large tunnel controls». Mutual azimuths of two to three traverse sides were measured underground on each mission. In order to ensure that controls of gyro measurements were as independent as possible, three different gyros were used alternately: DTM Essen, Bundeswehr University of Munich and ETH Zürich. For the same reason, measurement campaigns were strictly separated from data analysis and processing.

Underground measurements always take place under tough conditions. Apart from permanent time pressure, unfavorable conditions (visibility, light, noise, temperature, humidity, ventilation, traffic…) as well as logistic and safety-related restraints are common. A time window of only 12 h was available for the small tunnel controls. Large tunnel controls were usually carried out during scheduled construction breaks (Christmas/New Year, Easter, summer vacation).

5. Surveys in the 800 m Vertical Sedrun Shaft

At the intermediate access point Sedrun, tunnelling to both north and south started at the bottom of an 800 m deep shaft. The position transfer from the cavern at the head of the shaft down to the level of the tunnel was realized in 2002 using two different methods: one optical and one mechanical. With the construction of the second shaft in 2004, an opportunity emerged to perform an additional optical plumbing 39 km south of the first shaft. In January 2007, barely one year before the Amsteg-Sedrun breakthrough, an additional optical control plumbing took place. With that, three optical and one mechanical plumbing were available for the point transfer.

Optical Plumbings

The optical plumbing from the top to the bottom was done with a Leica nadir plummet (resolution 1:200 000 = 0.5 mm per 100 m), see Figs. 4 and 5. Three plummet corridors were measured in order to improve accuracy and reliability. Their arrangement was determined by the existing shaft installations. Prisms with centric light-emitting diodes, staked out with approximate coordinates at the bottom of the shaft, served as targets. The precision positioning on the tripods was done with cross slides (two axis slide tables).

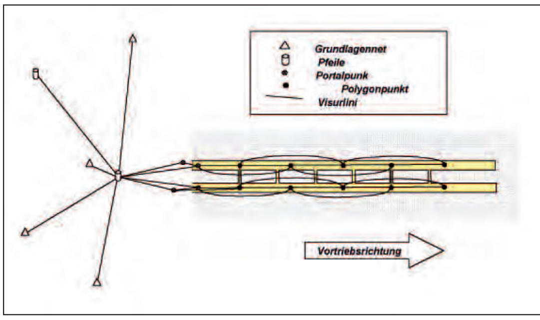


Fig. 3: Underground surveying concept.

Mechanical Plumbings

The mechanical plumbing was conducted through three corridors as well. The installations of the winches, the deflection pulleys and the insertion of the 800 m long plumb wires used up an entire working day (Figs. 6 and 7). Loading each wire with discs weighing 390 kg completed the installation. After letting the plumb bobs rest for 12 hours, measurements were initiated the next morning. Using two theodolites on two stations, 10 reversal points of the three oscillating plumb bobs were measured in both telescope positions. The second measurement series was acquired after reducing the weights to 192 kg, and the third again with the full load of 390 kg.

Model for the Correction of Deflection of the Vertical

During the point transfer, the deflection of the vertical directly affects the accuracy of the coordinates; its consideration is therefore absolutely essential. Furthermore, the plumb line is curved, and the correction values at the top and the bottom of the shaft differ (Figs. 8 and 9). The

Fig. 4: Nadir plummet at head of shaft.

deflection of the vertical was determined at an accuracy of 0.3 mgon using the software CHGeo98. Deflections of the vertical and plumb line curvature resulted in correction values for the coordinate transfer of up to 34 mm.

Results of Plumbing Measurements

The immediate comparison of all plumbing measurements showed a variation of < 20 mm. The inner accuracy of a plumbing campaign was determined by comparing the congruence of the two triangles formed by the three plumbing corridors at the top and at the bottom of the shaft. For the overall adjustment, the mechanical plumbings were introduced at an accuracy of 1 $\sigma_{\Delta y \Delta x}$ = 5 mm, and the optical plumbings at 1 $\sigma_{\Delta y \Delta x}$ = 10 mm. Thus the plumbing methods achieved a much better accuracy than anticipated. Here, too, it is worth mentioning that the model-based corrections from deflection of the vertical and plumb line curvature exceeded the actual accuracy of the plumbing several times.
The accuracy of the height transfer through the 800 m shaft is 1 $\sigma_{\Delta H}$ = 3 mm. An azimuth for a 39 m basis differing only by 0.2 mgon from the gyro azimuth (mean value from several campaigns) was the result of the plumbings in both shafts.

6. Adjustment of Tunnel Networks and Breakthrough Prognosis

Accuracy of Observations

All adjustments of tunnel networks were done for position and height with the LTOP software from swisstopo. After the preparation of the raw data (set mean values, meteo reduction, etc.), the quality of the observations in each tunnel control was assessed by virtue of a free adjustment.
It turned out that the frequency distributions of the normalised corrections applied to the observations came very close to the theoretical normal distribution in all tunnel sections (Fig. 10).
Also, the general comparison of variances «a posteriori vs. a priori» of all observations (global test according to Baarda) confirmed that the choice of the stochastic model was right and appropriate.

Fig. 5: Positioning of tripods at bottom of shaft.

As an average of all tunnel controls in all sections, the following a posteriori observation accuracies were found for the main variance components:

- 12,406 direction measurements 2.7 cc
- 2809 gyro azimuths (single measurements, not averaged) 10.8 cc
- 11 600 distance measurements 1.6 mm/km

Calculation of Coordinates

Each coordinate calculation was made by virtue of an overall adjustment, thus seamlessly adjusting all measurements of all relevant tunnel controls. Measurements in deformation areas were excluded in advance from the overall adjustment. A slight decline of the inner accu-

Fig. 6: Deflection pulley with plumb wire.

Fig. 7: Plumb bobs with 192 kg loads.

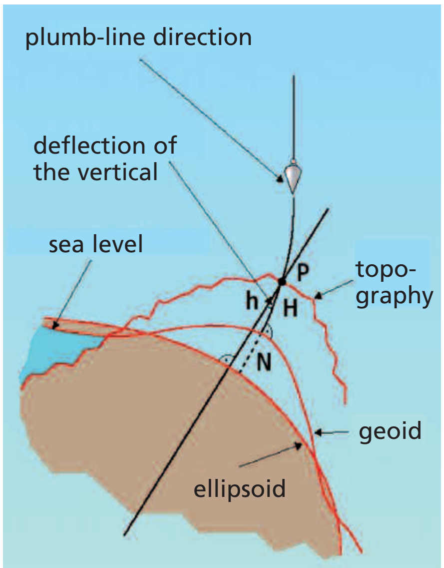


Fig. 8: Plumb-line direction and plumb-line curvature.

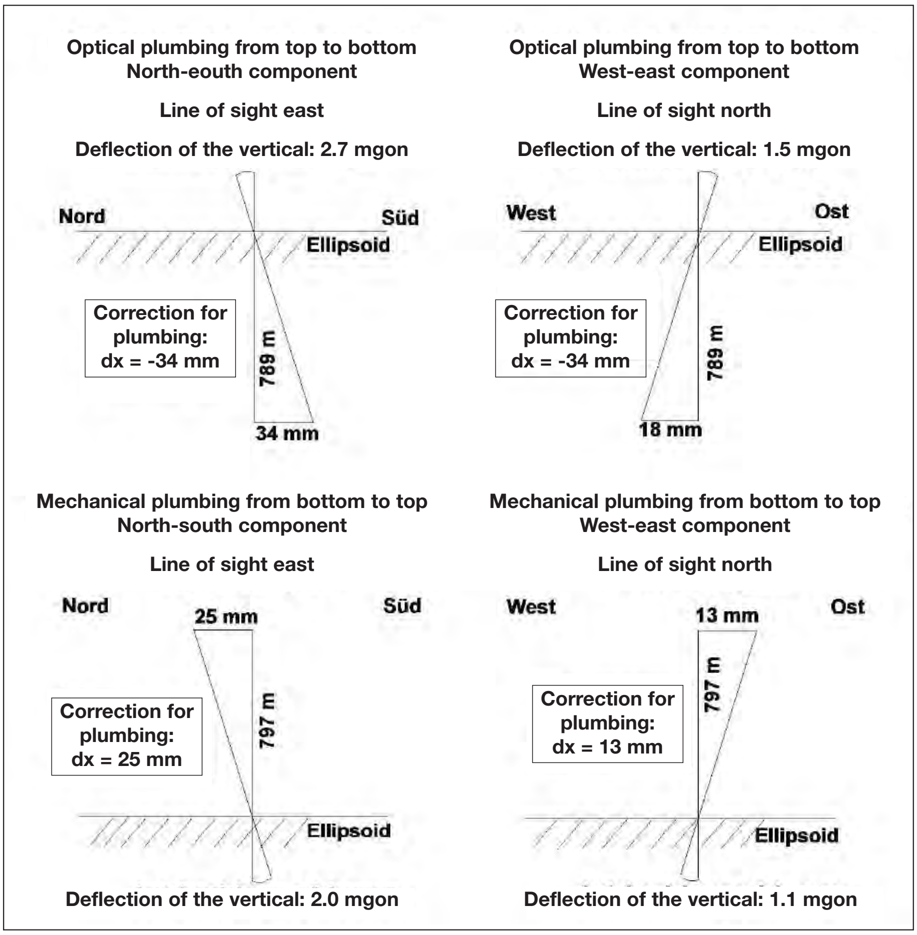


Fig. 9: Correction of plumb-line curvature for coordinate transfer in vertical shaft.

racy as a result of small, non-significant deformations between epochs was accepted in favour of high redundancy.
Only points of portal networks were introduced as fixed points, which resulted in the statistically most probable solution for all underground traverse points. Repeated coordinate changes, however, resulted in considerable complications on the construction site and in discontinuities in the control system of the tunnel boring machines. For this reason, a special method for «smoothing» the corrections was developed, with which the coordinate changes could be limited to 2 cm at most.
A target-group specific documentation and a result reporting process were established. The contractor was supplied with condensed reports with the currently valid coordinates of traverse points. Measurements and adjustments of large tunnel controls were documented in technical reports submitted to ATG Geomatik and to external experts for review.

Appraisal of Underground Accuracy and Breakthrough Prognosis

The accuracy of the position and height of traverse points could be estimated based on the overall adjustments of the tunnel networks. Due to the unfavourable error propagation, the growth of error ellipses, typical for tunnel networks with increasing drive length, could be observed. The expected theoretical breakthrough error was calculated as a relative error ellipse between the two traverse points of both drives located closest to the breakthrough point (Fig. 11). The following prediction for the four main break throughs in the Gotthard Base Tunnel was made immediately before the breakthroughs: *«The probability is 95% that the break through error does not exceed the following values:»*

7. Breakthrough Results in the Gotthard Base Tunnel

In tunnel construction, breakthroughs are huge events in many respects. On breakthrough day it becomes apparent whether the entire conceptual, theoretical, and practical work of the survey team over the course of several years was successful or not. Although all efforts aim at realizing the best possible result using the most accurate sensors, the best geodetic data, and the most reliable measuring and adjustment concepts, residual risks and doubts remain until the last metre is broken through (Fig. 12). The following accuracies were achieved in the Gotthard Base Tunnel:
Depending on the professional background and point of view, these break throughs are assessed in very different ways:

- From the *construction* point of view of the project engineer: «The breakthrough errors can be compensated for when installing the vault. Expensive profile corrections are not necessary.»
- From the *dynamic* point of view of the

Section	Length [km]	# of measurements	Unknowns	error quotient
Bodio–Faido	19.8	7535 2364	2149 821	0.80 0.53
Amsteg–Sedrun	17.3	9499 4379	2820 1170	0.92 1.10
Erstfeld–Amsteg	10.1	2846 1350	742 284	1.19 1.17
Sedrun–Faido	23.4	7205 2478	1991 799	0.80 0.62

Table 1: Observation accuracy and und error quotient a posteriori vs. a priori.

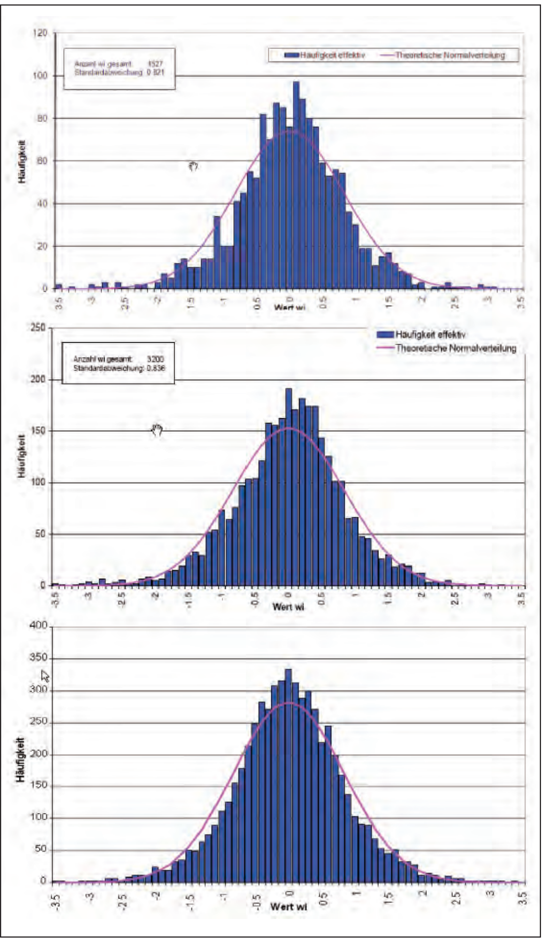


Fig. 10: Normalized corrections of observations in the sections Sedrun (above), Faido (middle), and Bodio (below).

track builder: «Breakthrough errors can be compensated for by slightly distorting the rails.»

- From the point of view of the prosaic *statistician:* «The results meet the expected values quite accurately.»
- From the point of view of the *insurance company:* «The residual risks were under control. There are no liability issues.»
- From the point of view of the *construction lawyer:* «There are no obvious surveying errors. But, are we really sure that everything was done right and with due diligence fitting to a once-in-a-century event?»
- From the point of view of the *technology minded ignoramus:* «What was the problem? Nowadays, that shouldn't be a problem with all that GPS and laser, right?»
- From the point of view of the *geodesist:* «Our models are not so bad, apparently. The result validates our work of the last years.»
- …And from the point of view of the *surveyors in charge:* «We have used less

Section	length [km]	transverse [cm]	longitudinal [cm]	height [cm]
Bodio–Faido	19.8	< 22	< 8	< 6
Amsteg–Sedrun	17.3	< 22	< 10	< 6
Erstfeld–Amsteg	10.1	< 15	< 9	< 5
Sedrun–Faido	23.4	< 27	< 13	< 7

Table 2: Breakthrough prognosis a priori (95% confidence level) for the four main breakthroughs.

Date	Section	lengths incl. access tunnels and shafts [km]		transverse [mm]	longitudinal [mm]	height [mm]
22.08.2006	Faido Bodio	4.1 15.7	19.8	92	12	17
14.10.2007	Amsteg Sedrun	13.3 4.0	17.3	137	21	3
16.06.2009	Erstfeld Amsteg	7.8 2.3	10.1	14	33	5
15.10.2010	Sedrun Faido	15.0 8.4	23.4	81	136	11
Utilization of max. tolerance (average)				32%	20%	7%

Table 3: Breakthrough results in the four main breakthroughs of the Gotthard Base Tunnel.

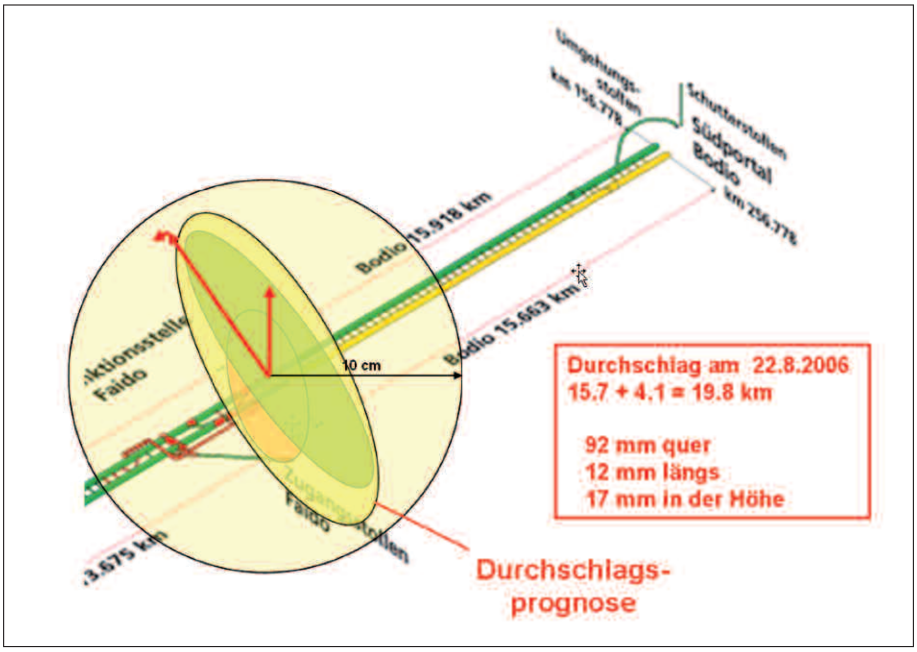


Fig. 11: Breakthrough prognosis and breakthrough error of 1st main breakthrough Bodio-Faido.

> than 1/3 of the maxi-mum acceptable tolerances. We always knew that we were on course with our accurate and reliable concepts and our proven quality management. Nevertheless, we are relieved and pleased that the worst case didn't occur.»

The breakthrough results achieved in the Gotthard Base Tunnel can also be assessed in a historic context

8. Acknowledgements

Surveying is teamwork! The Consortium Gotthard Base Tunnel Surveys co-operated very closely with a variety of organizations and companies over the past 15 years (Fig. 13). All these partners have contributed to the good results in the Gotthard Base Tunnel. We would like to extend our thanks in particular to the project managers F. Ebneter and A. Ryf from AlpTransit Gotthard AG, and to the expert Prof. em. A. Carosio for the trusting and goal-oriented co-operation.

9. Literature

A vast number of publications on the surveying in the Gotthard Base Tunnel have been published. Further publications can be downloaded from www.bsf-swissphoto.com.

Carosio A., Reis O. (1996): Geodetic Methods and Mathematical Methods for the Establishment of New Trans-Alpine Transportation Routes, Bericht IGP No. 206, ETH Zürich

Carosio A. (2010): Die Vermessung des längsten Eisenbahntunnels der Welt. Die Sicht des Experten des Bauherrn. Geomatik Schweiz, Ausgabe Dez. 2010

Ebneter F. (2004): AlpTransit Gotthard: Aufgaben und Organisation der Vermessung. XIV. Internationaler Kurs für Ingenieurvermessung, Zürich

Gesellschaft für Ingenieurbaukunst (1996): Historische Alpendurchstiche in der Schweiz: Gotthard – Simplon – Lötschberg..

Haag R., Stengele R. (1997): The Gotthard-Basetunnel. Surveying of a 57 km long Underground Project in the Swiss Alps. FIG-Symposium «Surveying of Large Bridge and Tunnel Projects», Kopenhagen

Kobold F. (1982): Vor hundert Jahren: Die Absteckung des Gotthard-Basistunnels. Vermessung, Photogrammetrie, Kulturtechnik 3/1982.

Kobold F. (1981): Tunnelabsteckungen im Gotthardgebiet von Koppe bis zur Gegenwart. Deutsche Geodätische Kommission bei der Bayerischen Akademie der Wissenschaften, Reihe E, Heft Nr. 20.

Korittke N. (1997): Zur Anwendung hochpräziser Kreiselmessungen im Bergbau und Tunnelbau. Geodätische Schriftenreihe der Technischen Universität Braunschweig, Nr. 14.

Riesen H.-U., Schweizer B., Schlatter, A., Wiget A. (2005): Tunnelvermessung des BLS-Alp-

Fig. 12: Boring head of tunnel boring machine at breakthrough.

Date	Section	length incl. access tunnels and shafts [km]	transverse [cm]	longitudinal [cm]	height [cm]
28.02.1880	Gotthard-Bahntunnel	15.0	33	710	7
24.05.1905	Simplontunnel	19.8	20	< 200	9
31.03.1911	Lötschbergtunnel	14.6	26	41	10
01.12.1990	Eurotunnel	37.9	36	7	6
28.04.2005	Lötschberg-Basistunnel	34.6			
	Mitholz-Ferden	20.9	13	10	0
	Gotthard-Basistunnel	**57.0**			
22.08.2006	Faido–Bodio	19.8	9	1	2
14.10.2007	Amsteg–Sedrun	17.3	14	2	0
16.06.2009	Erstfeld–Amsteg	10.1	1	3	0
15.10.2010	Sedrun–Faido	23.4	8	14	1

Table 4: Results of major Alpine breakthroughs and the Eurotunnel.

Fig. 13: Partner and network of VI-GBT.

Transit Lötschberg-Basistunnels. Geomatik Schweiz 11/2005.

Schätti I., Ryf A. (2004): Hochpräzise Lotung im Schacht Sedrun des Gotthard-Basistunnels. XVI. Internationaler Kurs für Ingenieurvermessung, Zürich

Schätti I., Ryf A. (2007): AlpTransit Gotthard-Basistunnel: Grundlagenvermessung, letzte Kontrollen vor dem ersten Durchschlag. XV. Internationaler Kurs für Ingenieurvermessung, Graz

Stengele R. (2007): Erster Hauptdurchschlag im Gotthard-Basistunnel: Tunnelvermessung in Theorie und Praxis. XV. Internationaler Kurs für Ingenieurvermessung, Graz.

Stengele R., Ryf A., Schätti I., Studer M., Salvini D. (2010): Vermessung im Gotthard-Basistunnel: Vortriebsvermessung, Laserscanning, Langzeit-Monitoring. XVI. Internationaler Kurs für Ingenieurver-messung, Graz.

Zanini M., Stengele R., Plazibat M. (1993): Kreiselazimute in Tunnelnetzen unter Einfluss des Erdschwere-feldes, Berichte des Instituts für Geodäsie und Photogrammetrie der ETH Zürich, Nr. 214.

Roland Stengele
BSF Swissphoto AG
Ivo Schätti-Stählin
Studio Meier SA
Dorfstrasse 53
Postfach
CH-8105 Regensdorf-Watt
roland.stengele@bsf-swissphoto.com

The (surveying) challenges at the beginning of the project, when everything was new and unknown

At the beginning of the 1990s, when the survey work for the new Alpine Rail Tunnel at the Gotthard had to be organized and developed, many things were in transition. With the reform of the official cadastral system, the introduction of the new national surveying system, the development of new automated measuring instruments and corresponding evaluation programs or new possibilities of data communication, the manifold surveying needs could be optimally realized. This article shows that the challenges at the beginning of the project with the development of the surveying organization, the delegation of responsibilities or the calls for tender and surveying assignments are as important as the use of known and new surveying technologies.

F. Ebneter

Tasks and organization of surveying

During the first contacts with the project management, we defined the surveying tasks. The laying out of the tunnel was defined as the main task. Therefore, the surveying services were entrusted with the collection, updating and management of the actual state and project geodata for all the involved parties. The surveying services were also responsible for the supervision of the building and of endangered objects within the range of influence of the project.

ATG in its function as builder of the new Alpine Rail Tunnel at the Gotthard monitored the project with a lean organization. Numerous engineering companies were commissioned with the project planning. It was a far-sighted decision, which cannot be taken for granted, to integrate a surveying team into the project management and to entrust it with the overall directorship of the surveying works. The tasks and responsibilities were divided between constructor services and surveying services of the commissioned contractors for structural work and railway infrastructure. In the sense of a dual-control principle, an external surveying expert was assigned to assist the surveying project management with the technical assessment of concepts and procedures and with the examination of inspection reports. The execution of the survey works for the builder was assigned to external surveying companies, mostly to consortiums.

Project fundamentals with official cadastral surveying data

The collection of the required project fundamentals was a special challenge. During the phase of comparison of rough and detailed variants, actual cadastre data, land cover data and topographic data on the Gotthard-Axis between Arth-Goldau and Lugano had to be collected in five cantons and 50 municipalities. There was a great range of possible tunnel routing variants at the time, which did not facilitate the fixing of a perimeter.

It was given that the project participants were to be regularly provided with updated project fundamentals over a period of 20 years. It was our aim to collect the data digitally and to ensure their continuous updates until the end of the construction works. An early and simplified data collection covering our project perimeter was arranged with the institutions of the official cadastral survey. These institutions disposed of a big part of the data in graphic form on the basis of the land register survey and were, at the time, launching the «cadastral surveying reform project» (RAV). Digital data of ground cover and terrain models were created from photometric images and their analysis. The boundaries and further information were digitalized from graphic land registry maps. As those data became part of the official cadastral survey, their continuous update is guaranteed.

Data coordination

Aside from data collection, the data exchange between the project participants (AlpTransit, BAV, SBB, project engineers from structural work and railway infrastructure, companies, cantonal offices, etc.) represented a great challenge. Using their usual systems, the different participants created documentation in the form of maps, tables, presentations and reports. These documentations are packed into files and widely distributed. It was our purpose to exchange them not only in analog but also digital form in order to guarantee efficient and high quality processing. It was our ideal goal to assure that all project participants were able to manage and process these data, among them georeferenced data, free of redundancies, in a GIS. Unfortunately, this was not possible at the time due to the large number of project participants. ATG argued that they did not wish to make demands on the commissioned parties regarding the informatics system they used. Realistically, a heterogeneous CAD/GIS environment had to be accepted by all participants. ATG decided to limit it to a CAD-performance and made requirements concerning only data structure, format and interfaces. A few years later, ATG tightened these requirements by intro-

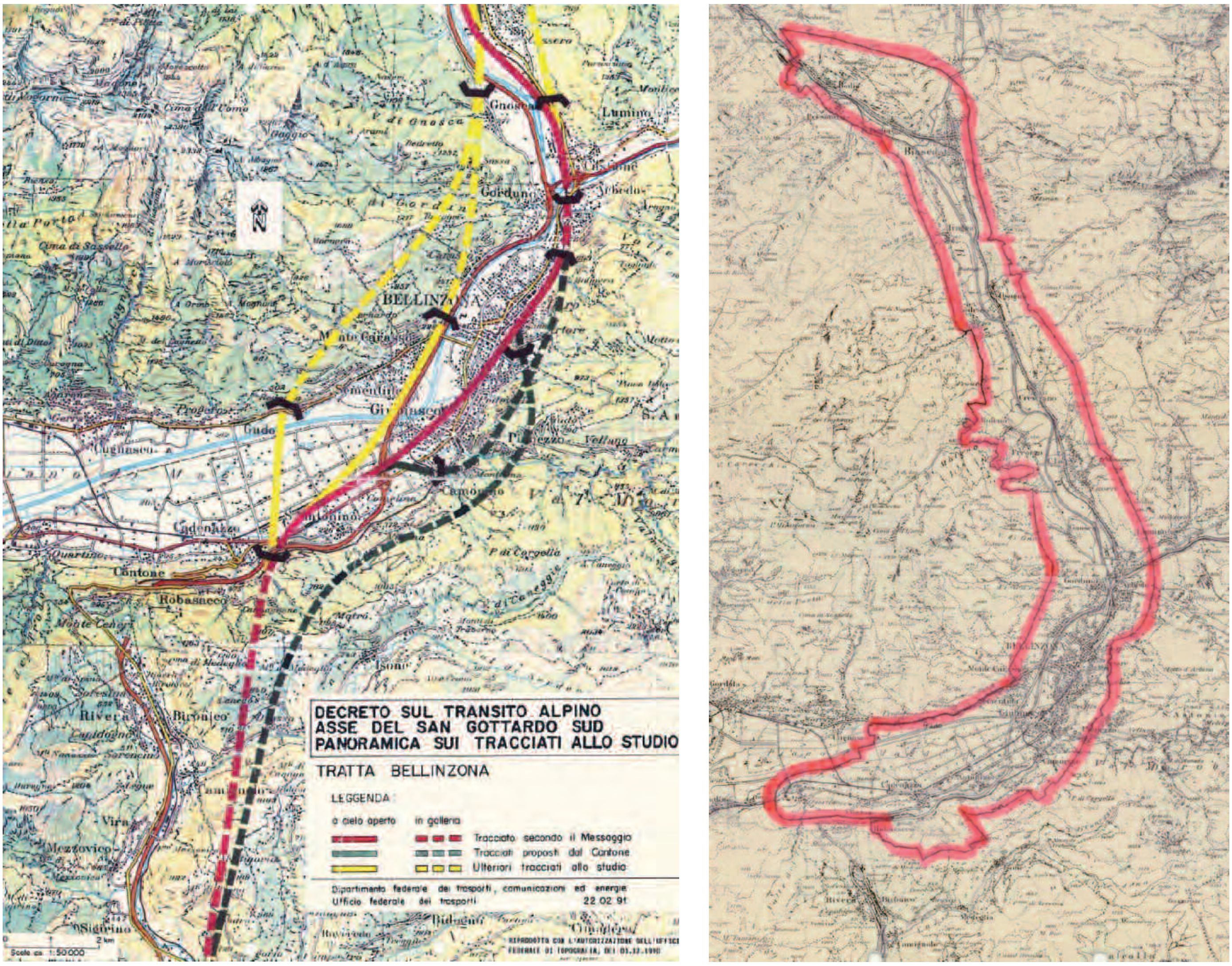


Fig. 1: Project variants and the perimeter derived from them for establishing the project basis.

ducing the CAD system for the railway infrastructure.

In agreement with the SBB, the transfer of the documentation of the structure to the future operator has to be done digitally and in conformity with the specifications of the fixed installations database, the GIS of the SBB. The data coordination office, as a part of the project management, has proved to be effective. It makes sure that the continuous project changes are immediately made available to all participants and that all of them can always access the relevant updated project data.

Tendering for survey work

It was important to attract the most efficient candidates at the most economical price for the survey work at the Gotthard and Lötschberg axes in a timely fashion before the beginning of the construction work. This was done in a two-phase selection procedure. It was a big challenge to describe the required services, the environment context, and the construction site conditions based on the then actual project and implementa-tion information in order to enable the service providers to propose appropriate concepts and realistic prices. It was impossible to provide detailed tender specifications with an approximately useful quantity framework. It was nevertheless important to indicate fixed prices for all possible surveying services. In this situation, ATG chose comprehensive flat-rate positions for the main works, such as the implementation of the above ground network or the main laying out of a whole tunnel on the one hand and, on the other hand, many individual positions for different expected control and deformation measurements, in order to fix the prices.

Tunnel layout: Requirements for project engineers and companies

In order to attain the requested high quality of measurements on the complex tunnel building sites, the necessary survey conditions had to be fixed and integrated early in the project planning phase as well as later during the call for tender and the assignment of the tunnelling and

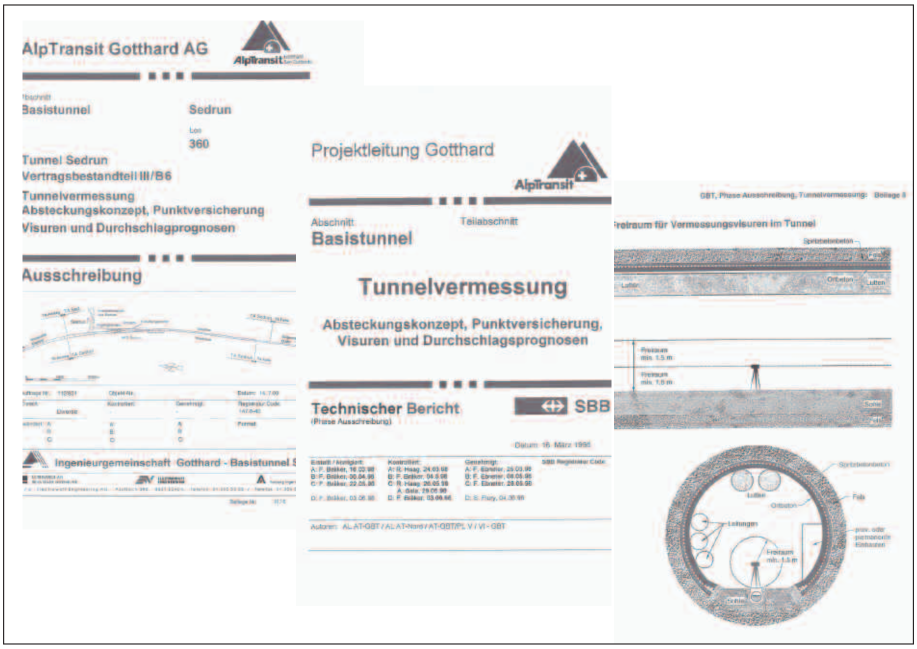


Fig 2: Parts of the contract concluded with the construction companies with the survey requirements

structural work. The big challenge was to anticipate all possible critical situations before they occurred, to get the project management to agree to the measures derived from them, and to integrate those measures in the tender documents and contracts with the companies responsible for the structural work.

Apart from design and construction measures, provisions had to be made for safety at work, the date and duration of the survey works, acceptable tunnel temperatures during the surveys, maintaining clear lines of sight, and transport of the surveying crews. It was important to confirm in the tender all possible services of the companies relating to the surveys for the constructor as completely as possible. One example of constructive measures can be shown at the 800 m long Sedrun shaft: in the survey concept, an additional mechanical weight plumbing was planned over three plumb points at the shaft wall, and an optical plumbing in the middle of the shaft. These plumbings had to be possible until the moment of the final breakthrough. For the surveying activities in this shaft, which is 8 m in diameter and crammed with the lift infrastructure and all kinds of cables and pipes, plumbing corridors had to be kept open in order to make the measurements possible.

Tunnel layout: Primary network Position/Height

A fundamental condition for the successful laying out of the tunnel is the construction of a precise and homogenous opencast network over the total project perimeter. When this network was implemented in 1995, the Federal Office of Topography was busy with the creation of a modern GPS reference net with a new height reference system, the «New National height network LHN95», which replaced the old national survey system.

ATG wanted to benefit from the high quality of the new reference system. At the same time, it had to be taken into account that all existing ATG project documentation was completely referenced to the old national survey system. It had to be decided whether all existing project documents had to be transformed into the new system or whether the network created on the basis of the new national survey system had to be integrated into the old reference system. The technical feasibility of both variants were analyzed and confirmed. Because the transformation of the existing documentation into the new national survey system was considered too expensive in terms of effort and cost and too error-prone by the project management, it was decided to adapt the network to the old system.

During the implementation, it had to be ensured with appropriate measures that the layouts already performed from the net of the old reference system were adapted to the ATG work net. For example, the access gallery to the Sedrun shaft was built using the old national survey system. It was a challenge to communicate these decisions to all project planning and surveying partners.

Control tasks

We knew from recent experience (Zeuzier, Gotthard road tunnel) that the drainage of groundwater during construction could lead to settlement on the surface. The GBT excavation from Sedrun to Faido runs underneath three dams in the critical settlement area. Within the framework of the risk analysis performed by ATG, the possible safety and operation risk of the excavation for the dams was recognized early on as a significant danger. One of the key objectives of the project, therefore, was to grant an excavation without inadmissible endangerment of the dams. Accordingly, extensive surveying and structural measures were integrated into the project.

The surveyors had to permanently identify, with a high degree of accuracy, terrain deformations at the surface in the perimeter of the dams. The surveying concept essentially included the supervision of valley cross-sections at the dam walls and their perimeter; an extensive, 100 km long leveling line net, both lengthwise and crosswise to the tunnel axis at the surface and in power station galleries, as well as several single points at locations difficult to access. The extension and degree of settlement depressions has to be analyzed at least once a year on the basis of the precision levelling and single points. In the valley cross-sections, movements of the

valley slopes have to be permanently measured with an accuracy of ± 4 mm.
The important challenge was to find a surveying company capable of meeting these requirements at an economically advantageous price. At the time of the tendering process (1989/1990), important necessary technologies and Instruments had been developed, but they were still partially in the introductory phase: fully automatic precision tachymeters, GPS-receivers, meteo-sensors, automatic control of measuring processes and data transfer via ISDN/GSM connections, autonomous energy supply, data management and processing software. The harsh climate poses particular requirements to the measuring system. Low temperatures, great amounts of snow with avalanches in winter or strong electrostatic discharges in summer should not be allowed to hinder the measuring system. An ample number of measuring points are unreachable during 5–6 months in winter. It could not be taken for granted to find a service provider capable of implementing and operating an adapted measuring system on the basis of the given components over a period of 20–25 years in this high Alpine region. After a minimum of two years of operating the measuring system without influence from the tunneling, meaningful information could be gained on the «normal behavior» of the valley cross-sections.

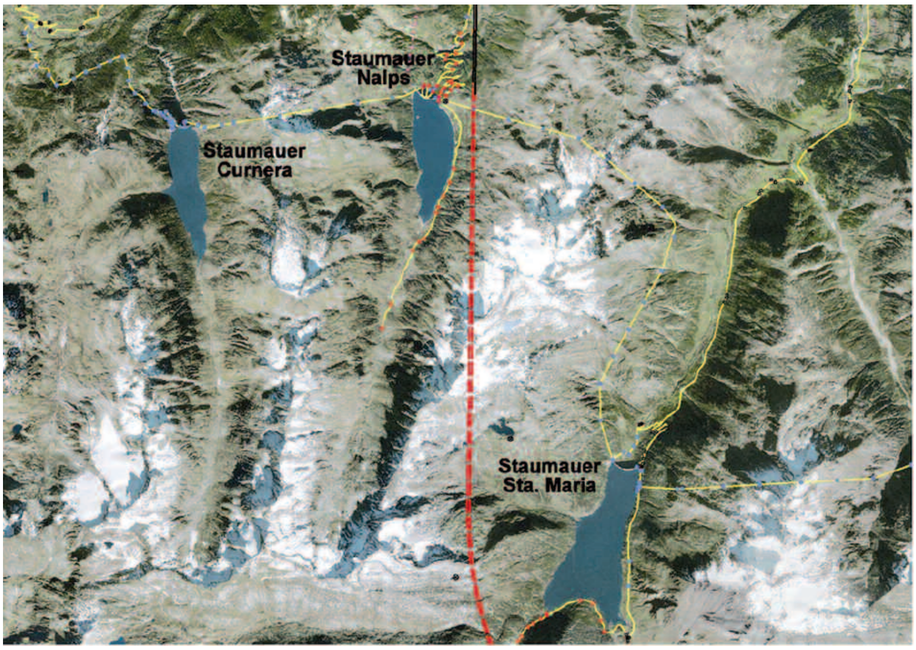


Fig. 4: Gotthard Base Tunnel routing in the area of the Curnera, Nalps and Sta.Maria dams in the project segment Sedrun – Faido.

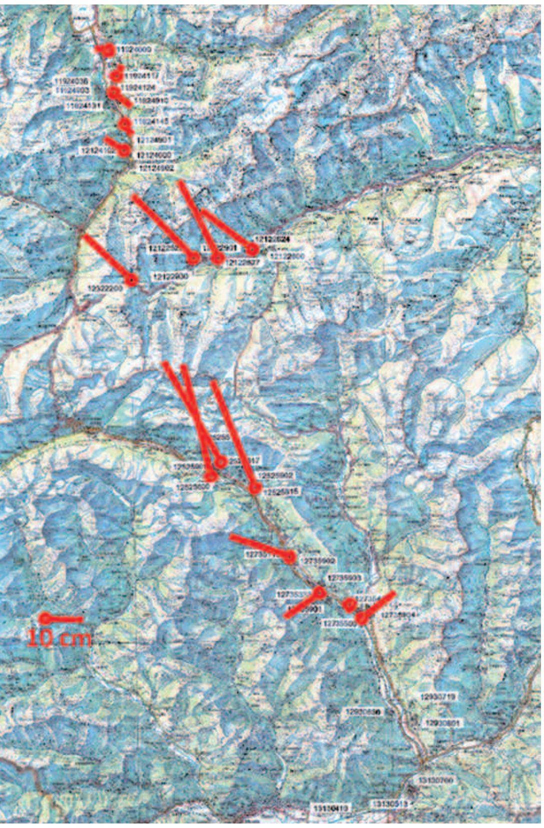


Fig. 3: Transformation variants between the Werknetz ATG and the former cadastral survey LV03.

Final remarks

These and other challenges faced by the surveyors at the GBT could be met thanks to the total engagement, know-how, creativity, and great care of all directly or indirectly involved parties. The intensive collaboration with the Federal Institutes of Technology, the Federal Office of Topography, the Federal Directorate for Cadastral Surveying and the cantonal surveying offices contributed significantly to the success of the project. The different managing directors of AlpTransit Gotthard AG recognized the importance and significance of surveying and respectfully supported the concerns of the surveyors. The other contributions in this publication show how many challenges had to be tackled and were solved by the different project participants and how many challenges will have to be met until the end of the project.

Franz Ebneter
Kreuzbuchstrasse 123
CH-6006 Luzern
fh.ebneter@hispeed.ch

Surveying the longest railway tunnel in the world

The vision of the constructor's expert

The Gotthard Base Tunnel is a great challenge of geodetic engineering. The author has worked more than 20 years as an external expert for the construction management. He thus has first hand knowledge of the needs and processes of such a gigantic project. During the long period from the first studies to the planning to the recent main tunnelling, countless decisions have been taken, problems have been solved, and experiences have been acquired. From the perspective of the engineer and the professor the author describes the most important stages of the activities, which will remain essential for future projects.

Alessandro Carosio

A challenge from all perspectives

Tunnel surveying constitutes a technical and organizational challenge for the contractor. The project lasts for several decades and thus has organizational requirements. The acquired experience has to be maintained over time. Personnel changes and reorganizations are to be expected. With the actual dynamics there has to be agreement to adapt the planned processes to the technical progress.
The surveying services have to be provided for different partners: first for the project planning engineers, then for the tunnel construction companies, the railroad engineers, and finally for the construction management for the supervision and documentation of the project. The surveyors have to accept assignments through all phases of construction and to fulfill them quickly and reliably. The construction management has to recognize and schedule all requirements on time, give the appropriate instructions, and verify and approve the results. It has to commission surveying specialists as soon as possible (for example, a surveying consortium), but it also needs its own specialized professionals who make decisions, request services and supervise them on behalf of the constructor. It is important to mention in particular that the first surveying work is needed before the consortium and the tunnel construction companies are selected.
For the Gotthard Base Tunnel, the position of the constructor was first held by the SBB. The SBB have an efficient and experienced surveying department, which had the required competence. The multiplicity of tasks, but also primarily the urgency of the necessary surveying services and studies, necessitated the appointment of an external expert to support the SBB specialists. As a newly appointed professor at the Swiss Federal Institute of Technology Zurich (ETH), surrounded by competent collaborators, and having a few years of experience in engineering and national surveying, I was interested and was appointed to this task in 1991, a position I still hold today.

Influences from the past

When the SBB decided to realize the Gotthard Base Tunnel project, they commissioned the ETH to carry out the basic surveys (high precision determination of portals to allow the control needed for the tunnel work later on). The task bordered on the impossible at that time. Distance measuring instruments were available only at the ETH. Only the latest computer technologies could deal with complex evaluations, and only a very few specialists could make use of those possibilities. Professor Fritz Kobold, head of the Institute of Geodesy and Photogrammetry (IGP) at the ETH Zurich was assigned the task. He entrusted Dipl.-Ing Peter Gerber with the technical management of the project, who carried out his task with great commitment. He created triangulation networks, calculated the achieved accuracies, provided the measuring instruments, planned the helicopter assignments and delivered all the required exact coordinates on time. The conducted studies were later summarized in a thesis (1). The political leadership, however, decided for financial reasons to forgo the immediate realization of the tunnel.
At the same time, Professor Kobold initiated studies on the geoid of Switzerland (probably without being aware of their future importance for the base tunnel) (2). These groundbreaking works were continued by his successor, Professor Dr. Max Schürer (Professor at the University of Bern, lecturer at the ETH Zurich). The result was an operational computer model of the geoid for Switzerland, which could be used by any engineering office (3).
Thus Switzerland was the only country with a geoid model accessible to all and with an operationally suitable precision (Sigma plumb line deviation 0.3 mGon, Sigma of geoid height 1 cm locally, 10 cm at the national level).
The professorship for geodesy and geodynamics continued the research under the leadership of Professor Dr. Hans-Gert Kahle who took into consideration the astrogeodetic as well as the gravimetric components and improved the instrumental infrastructure. Thus, a newer and better geoid model became operational in 1997 (Fig. 1) (4).
The new model was ready in time to be used for the analyses at the Gotthard tunnel.

My first tasks for the Gotthard Base Tunnel

When I became professor at the IGP in 1987, I observed that while the newest

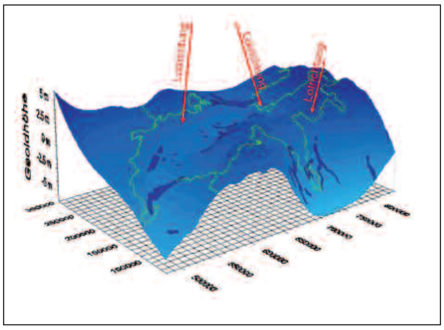


Fig. 1: The geoid model of Switzerland.

developments of modern geodesy were known, the practical experience using this knowledge advantageously in projects was often lacking. At that time, the pursuit of the Gotthard tunnel project was in discussion, and work on the Eurotunnel under the Channel was ready to start. For regional political reasons local, not particularly experienced, firms were commissioned in France and in Great Britain. Very quickly, technical problems emerged. German surveyors were called in to give assistance. They succeeded under the given circumstances. However, the 35 cm error at break-through was more important than expected. The reasons for this high error were insufficient consideration of refraction in the tunnel, disregard of plumb line deviation, and weaknesses in portal orientation. This situation was known to the IGP before the break through at the Eurotunnel.

In 1990, I was given my first mission for the Gotthard Base Tunnel. This consisted of comparing the newly possible GPS measurements with the Kobold triangulations of the 1970s. This was followed by investigations concerning the state of technology and the extent of existing surveying data.

The deficiencies noted at the Channel would have had devastating consequences at the Gotthard tunnel. Because of the tunnel length, the orientation had to be improved with gyroscopic measurements inside the tunnel, and the neglected irregular plumb line deviations in the Alpine region would have considerably distorted the gyroscopic true north. Far better evaluation models were needed to meet the actual requirements for high-level accuracy. This enabled me to argue for the importance of further research projects, which my research team started on its own initiative with funding from the ETH.

In agreement with my colleagues at the time, F. Chaperon and H. Matthias, I asked to purchase (at DMT in Germany) a high-precision gyro-theodolite as well as research funding for the development and testing of the necessary mathematical models. The ETH had foresight. The vice-president of serv-ices (C.A. Zehnder) accepted the financing of both projects, thus the ETH was able to perform a number of tests starting in 1992 (Fig. 2).

As we have at our disposal a climatic chamber that is fully equipped for high-precision direction meas-urements, we were able to conduct comprehensive and realistic instrumental analyses. The most im-portant work of this initial period, though, was to study on the effect that the irregular gravitational field in the Alpine region had on the gyroscopic azimuths and on the possibility to correct them mathemati-cally with the available geoid model (plumb line deviation).

Further studies concentrated on accuracy estimates of the planned measurements under actual condi-tions. This allowed a realistic estimate of the attainable alignment accuracies (5), (6), (7), (8), (9).

Knowledge transfer

As the Gotthard Base Tunnel project had been accepted by the citizens in 1992, the major concern was the urgency of transferring technology into practice. This was achieved partially through the participation in the research of colleagues or students of the department. They were able to expand their expert knowledge. The names of the authors of the studies during this period can be found in the publication index. Most of them later directly contributed to the success of the surveying works at the Gotthard tunnel as leaders in the surveying consortium, where they made use of their expert knowledge. The successful promotion of

Fig. 2: Student with F. Ebneter, A. Gisi and A. Carosio in the safety tunnel of the Gotthard street tunnel (Airolo 1992).

young researchers was therefore an indirect consequence of the expert mission.

Another important result of the expert assignment for the Gotthard Base Tunnel was a success-ful series of advanced training seminars on current topics in the field of geodetic engineering (measuring techniques, evaluation methods, geoid, gyro-theodolite, etc. [Fig.3]). These were organized in 1993 and 1994 with a view to future tunnel projects and in which the authors of our research explained the practical implications of the results.

There is good reason to believe that the results of the international tender for surveying the base tunnel were significantly influenced by these seminars, which were given several times (Fig. 4). The offers from Swiss firms were the most successful in all respects. They were able to impose themselves in all AlpTransit projects. The ETH had successfully ensured the knowledge transfer and in time had created favorable conditions for the promotion of junior surveyors.

Further research activities

During the same period, other research projects were completed, which were of indirect importance for the New Transalpine Rail Link (NEAT):

a) The reliability model for the Swiss national land survey, in practice known as «reliability rectangles» (10).

Fig. 3: Surveying diploma course in Lugano 1994.

b) The methods of robust statistics in geodesy (12) (13).
c) The combination of terrestrial measurements and satellite observations in planimetric networks (11).

These methods are still used in daily practice today and have become the standard proceedings used for the analysis and evaluation of geodetic measurements at the Gotthard tunnel. They are also used at the Lötschberg and Monte-Ceneri tunnels.

Operative cooperation

The tasks of the geodesy expert have changed over time. Whereas the focus was mostly on scientific research during the first phase, I started to deal with the operative part of tunnel surveying in 1994. Together with other experts (F. Ebneter, K. Egger and St. Flury), I was on the editorial committee of the pre-project report, in which the surveying requirements for the Gotthard Base Tunnel were formulated (Fig. 5). The aforementioned ETH-research (simulations, reliability indicators, etc.) was applied at this stage. The pre-project report was the basis for the international call for tenders for the surveying works.
At the beginning of 1995, I was a member of the evaluation panel that assessed the offers under the leadership of the director of measurements, W. Bregenzer. This led to the commissioning of the surveying consortium VIGBT for the Gotthard Base Tunnel.

After the commissioning, the constructor transferred the responsibility to the surveyors of the consortium. Nevertheless, the ETH's importance for the survey works at the Gotthard tunnel remained sig-nificant.

Research on demand

Whenever questions arose or there were uncertainties, we started to do research to clarify mat-ters. The results were immediately documented and put at the disposal of AlpTransit Gotthard AG and the surveyors (for instance, 14, 15, 16, and 17). The research work and the results were relevant on both national and international levels. They were often presented at international congresses and published in proceedings and scientific journals.

ETH

Weiterbildungsseminare
in angewandter
Geodäsie für
Ingenieure
aus der Praxis

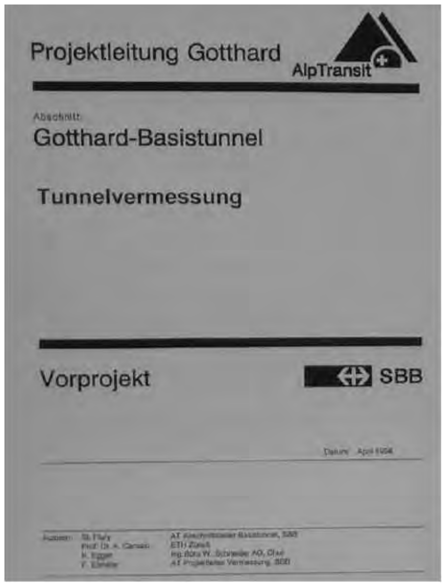
Prof. Dr. Alessandro Carosio

1994

Fig. 4: The Seminar Program 1994.

Verification of surveying work

Over time, I was asked to verify a growing number of reports (Fig. 6) containing the results of surveying work. Such controls assured risk minimization. Generally, no important deficiencies were detected. But the verification offers the opportunity to discuss technical challenges, to compare alternatives, and to plan improvements.
There were a few exceptions. In 1991, an implementation problem in the geoid model was identified, which gave different results depending on the installation. The origin of the problem was corrected before it could influence the tunnel routing. In 1998, a problem occurred with the then new high-precision digital levels. There were systematic vertical errors in the measurements underground. The source of error was identified. The surveying consortium from the Lötschberg tunnel developed a homogenous levelling staff lighted with LED. The introduction of new operating rules for these instru-ments allowed the measurements in the base tun-



Projektleitung Gotthard
AlpTransit

Abschnitt:
Gotthard-Basistunnel

Tunnelvermessung

Vorprojekt
SBB

Fig. 5: The pre-project report of April 1994.

nel to be performed in such a way as to keep systematic influences in the negligible range (Fig. 7).

Azimuth measurements with the gyro-theodolite

During tunnelling, the Institute of Geodesy and Photogrammetry (IGP) of the ETH Zurich was periodically commissioned to perform gyroscopic measurements in the tunnel (Fig. 8). As the ETH was the only institution in Switzerland to possess a gyro-theodolite with the ability to cali-brate it, such measurements were necessary.

D. Salvini, who was commissioned by the surveying consortium VIGBT, performed these works inde-pendent of my analyses. To provide independent periodical monitoring, and at the request of AlpTransit AG and VIGBT, parts of the gyroscopic azimuths were also measured by the instrument manufacturer (DMT Essen) and by the University of the German Federal Armed Forces..

The important task of the constructor's expert

In the first phases of the project, the external expert provides support for the scientific research. He also often has an assessing function. At all times, but especially during the performance of work, he has an important safety task in case of an emergency. If unexpected events occur on the technical or organizational levels, he and his staff can support or, if necessary, replace the people with primary respon-

Fig. 6: Ongoing expertises.

Fig. 7: Systematic errors and levelling.

sibility. Unexpected events cannot be planned; one can only try to create risk scenarios. AlpTransit Geomatik together with VIGBT and the author did this. Fortunately, it has been established that the planned measures were sufficient to the end. We have been spared emergency situations, but it would have been irresponsible not to be prepared for such events.

Final considerations

Surveying a modern tunnel system is not routine work. It needs competent, experienced and proven geomatics engineers, who are able to deal with unexpected events. A crucial prerequisite for awarding contracts in engineering surveying is the definition of strict criteria for the applicants, who have to show sufficient references from similar works. The candidates also have to guarantee a permanent staff, which includes engineers with university degrees and professionals with technical diplomas in the geodesy field. Training and experience cannot be improvised. It has to be taken into account that the surveying services have to be provided over several decades, and that during that time staff members who reach the age of retirement or opt for career changes will be replaced. The chosen firm has to guarantee that competence continuity is ensured in all circumstances.

The leading personnel must guarantee the tunnel boring machine (TBM) accuracy required today from the beginning of the project and continuously integrate new acquisitions into the planning concept. Unexpected events can require new services or emergency actions. Only a specialized entrepreneur able to handle a wide range of tasks and to provide personnel and competences on demand can do this. In the case of the Gotthard Base

Fig. 8: The gyro-theodolite of the ETH Zürich in action at the Gotthard tunnel.

Tunnel, these conditions were met and fortunately (or maybe thanks to the expertise of the involved parties) no emergency situations or unexpected events occurred. The organizational conditions to succeed even in such an environment were fulfilled. The surveying costs of such a project are modest compared to the global costs. High-quality surveying allows the reduction of the tunnel profile, makes subsequent profile corrections superfluous, immediately signals unexpected behavior of the rock, etc. It thereby generates substantial economies, which can easily amount to between 100 million and 1 billion Swiss Francs; even the actual amount cannot be proved. It is therefore worthwhile to invest sufficiently in surveying works in order to minimize the risks in this area.

At the Gotthard Base Tunnel, this policy has proven its worth.

Bibliography:

(1) Peter Gerber, Das Durchschlagsnetz zur Gotthardbasislinie, Doktorarbeit ETH Zürich 1974.

(2) Alois Elmiger, Studien über die Berechnung von Lotabweichungen aus Massen, Interpolation von Lotabweichungen und Geoidbestimmung in der Schweiz, Doktorarbeit ETH Zürich 1969.

(3) Werner Gurtner: Das Geoid in der Schweiz, Doktorarbeit ETH Zürich 1978, www.igp-data.ethz.ch/berichte/Blaue_Berichte_PDF/20.pdf.

(4) Urs Marti, Integrierte Geoidbestimmung in der Schweiz, Doktorarbeit ETHZ 1997, http://e-collection.ethbib.ethz.ch/eserv/eth:40540/eth-40540-01.pdf.

(5) M. Zanini Hochpräzise Azimutbestimmung mit Vermessungskreiseln, IGP Bericht 209, ETH Zürich 1992, www.igp-data.ethz.ch/berichte/Graue_Berichte_PDF/209.pdf.

(6) K. Maser, Alptransit, Portalnetz Polmengo. Absteckung des Portals des Sondierstollens zur Untersuchung der Pioramulde IGP Bericht 213, ETH Zürich 1993, www.igp-data.ethz.ch/berichte/Graue_Berichte_PDF/213.pdf.

(7) M. Zanini, R. Stengele, M. Plazibat, Kreiselazimute in Tunnelnetzen unter Einfluss des Erdschwerefeldes, IGP Bericht 214, ETH Zürich 1993, www.igp-data.ethz.ch/berichte/Graue_Berichte_PDF/214.pdf.

(8) O. Reis, Die Überprüfung des Gotthardbasisnetzes, IGP Bericht 224, ETH Zürich 1993, www.igp-data.ethz.ch/berichte/Graue_Berichte_PDF/224.pdf.

(9) O. Reis, Calculs de simulation pour la ligne de base du St. Gothard, IGP Bericht 231, ETH Zürich 1994, www.igp-data.ethz.ch/berichte/Graue_Berichte_PDF/231.pdf..

(10) A. Carosio Hsg, Zuverlässigkeit in der Vermessung, Weiterbildungstagung ETH-Hönggerberg 15. und 16. März 1990, www.igp-data.ethz.ch/berichte/Graue_Berichte_PDF/169.pdf.

(11) A. Carosio La combinaison de mesures terrestres et par satellite dans les réseaux planimétriques, Vermessung, Photogrammetrie, Kulturtechnik 10/1992, www.igp-data.ethz.ch/berichte/Graue_Berichte_PDF/311.pdf. (Siehe Kap. 14.)

(12) Fridolin Wicki, Robuste Ausgleichung geodätischer Netze, IGP Bericht 189, ETH Zürich 1992, www.igp-data.ethz.ch/berichte/Graue_Berichte_PDF/189.pdf.

(13) Fridolin Wicki, M-Schätzer, IGP Bericht 190, ETH Zürich 1992, www.igp-data.ethz.ch/berichte/Graue_Berichte_PDF/190.pdf.

(14) O. Reis Mesures gyroscopiques et déviation de la verticale, IGP Bericht 249, ETH Zürich 1995, www.igp-data.ethz.ch/berichte/Graue_Berichte_PDF/249.pdf.

(15) A. Carosio, O. Reis, Geodetic Methods and Mathematical Models for the Establishment of New Trans-Alpine Transportation Routes, IGP Bericht 260, ETH Zürich 1996, www.igp-data.ethz.ch/berichte/Graue_Berichte_PDF/260.pdf.

(16) Desiderio, R. Koch, Der Einfluss der Temperatur auf Kreiselazimute hoher Präzision, IGP Bericht 281, ETH Zürich 1998, www.igp-data.ethz.ch/berichte/Graue_Berichte_PDF/281.pdf.

(17) Dante Salvini, Deformationsanalyse im Gotthardgebiet, IGP Bericht 297, ETH Zürich 2002, www.igp-data.ethz.ch/berichte/Graue_Berichte_PDF/297.pdf

Prof. Dr. Alessandro Carosio
em. Prof. für Geoinformationssysteme und Fehlertheorie
Institut für Geodäsie und Photogrammetrie
ETH-Hönggerberg
CH-8093 Zürich
alessandro.carosio@geod.baug.ethz.ch

Gotthard Base Tunnel survey challenge from a contactor's point of view

In January 2002 the survey section from the TAT joint venture started work on the Bodio – Faido and Faido – Sedrun phases. All survey documents were handed over to the contractor from the client. In the beginning it was a one-man show, but soon more surveyors had to be employed. Because both phases were running at the same time, the joint venture decided to give the survey work for drilling and blasting in Faido for the multifunction station (MFS) to a subcontractor called Amberg Technologies. Amberg Technologies also did all of the geotechnical measurements. The mechanical advance, interior construction, and surveying for the bypasses for both phases, were incurred by the joint venture survey.

R. Deicke

The first project was to stake out the installation area and make the necessary preparations for drilling and blasting in Faido. The drilling and blasting heading was steered by a motor laser using the programmes TMS-Office and TMS-Set out. In the meantime, ten areas were being worked on at the same time. Once the survey data were loaded into the jumbo drill, the blasting holes could be drilled automatically. In the MFS the rock was very active and several cave-ins occurred, which had to be controlled, and intensive deformation measurements were taken in 3D with the involvement of extensometer, inclinometer, and tape. Capsule pressure and strain gauge made the surveyor's life difficult. New checks conducted again and again for the main measure points didn't allow the surveyors much rest. The drilling advanced over 24 hours a day, 7 days a week. Together with work in the tunnel, everything else had to be calculated and documented. After long working days over 4½ years, the drilling and blasting work was finished; ~9.500 m of different tunnels were dug.

After the tunnel boring machines (TBM) were recalibrated by the fabricator Herrenknecht and provided with control points, the first TBM started in November 2002 in the east tunnel and the west TBM in March 2003. Both TBMs are guided by a steering system from the VMT Company. Both machines had their starting point in the mountain: east by TM 2500; west by TM 1500. Before drilling started a tunnel network was measured in each tunnel to provide the TBMs with a Tunnel Guidance System. The net points are brackets based on height in the middle of the tunnel and one metre from the site. So there was nearly no refraction, which was shown by calculation of the network. Network measurements were done after every 150 m advance with an overlap of the old net. Included were the stake-out points on the floor and the points for steering. Inside the TBM we measured two polygons, one in the lane of the laser and one in the range of the floor. The polygons were connected to the network. In front of the TBM the polygons were brought together so that we had the same system for advance and stake out of the concrete parts.

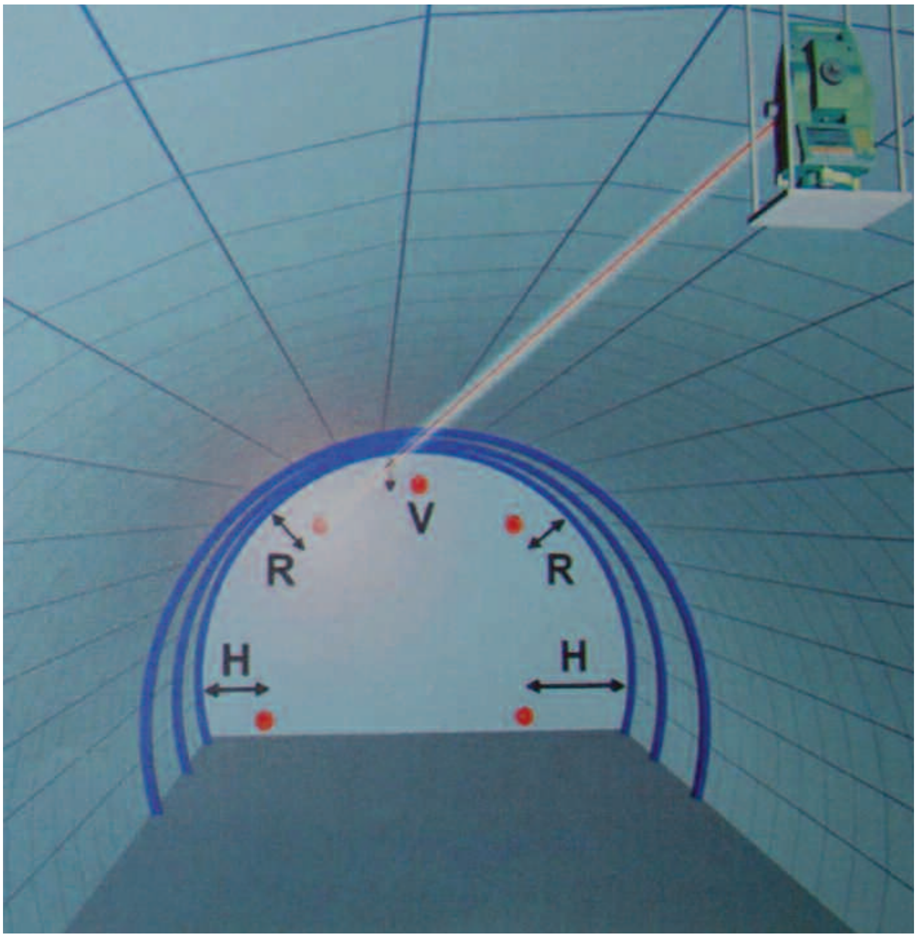


Fig. 1: Motor laser with measures for the tunnel ring construction.


Fig. 2: Illustration of the holes to be drilled.

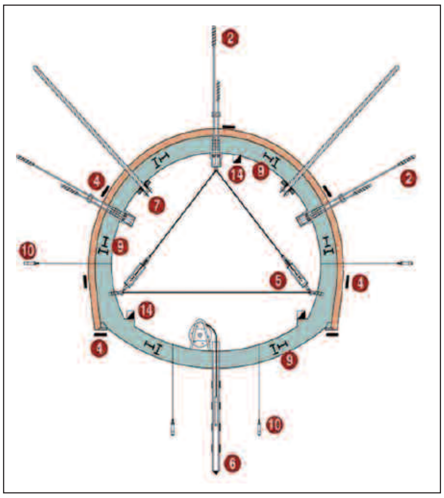


Fig. 3: Different mounting parts for deformation measurements.

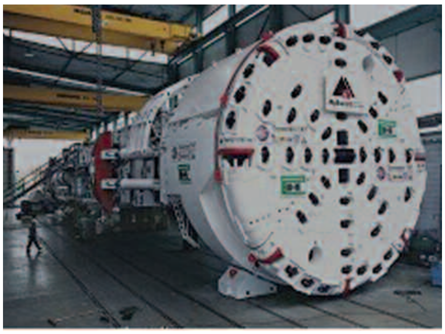


Fig. 4: Tunnel boring machine at the Herrenknecht plant

Along with nearly weekly network measurements in both tunnels, as well as support for tunnel guidance systems, and transact laser station there was work for steering the crosscuts. Added to this we constantly measured cross-sections in the areas that were in motion and in all crosscuts. Before the drilled tunnels were sealed, we scanned the tunnels. With these data we checked the planarity of the shotcrete, which is an important element for sealing. With the same data we produced cross-sections for planning interior construction.

From the set of drawings we identified the joints for the formwork. After construction of the lined tunnel we mounted station plaques and checked the tunnel once more with cross-sections. Finally, we staked out the banquettes whereby the structural work was finish. The tunnels were scanned again to verify the clearance diagram and to see whether there were cracks inside the concrete. If the cracks are too big, they have to be refurbished with concrete.

At the same time there were set out and control measurements in Faido MFS. Involved were concrete work in the four tee-junctions, connection tunnels, exhaust tunnels, and side tunnels.

The measurements of the main points from the contractor were checked by the client every 500–800 m. The differences over the years were only a few millimetres. Over the decade, teams put in 9 days work with 5 days off. At peak periods, we worked with 18 people in our section; today we are down to 9.

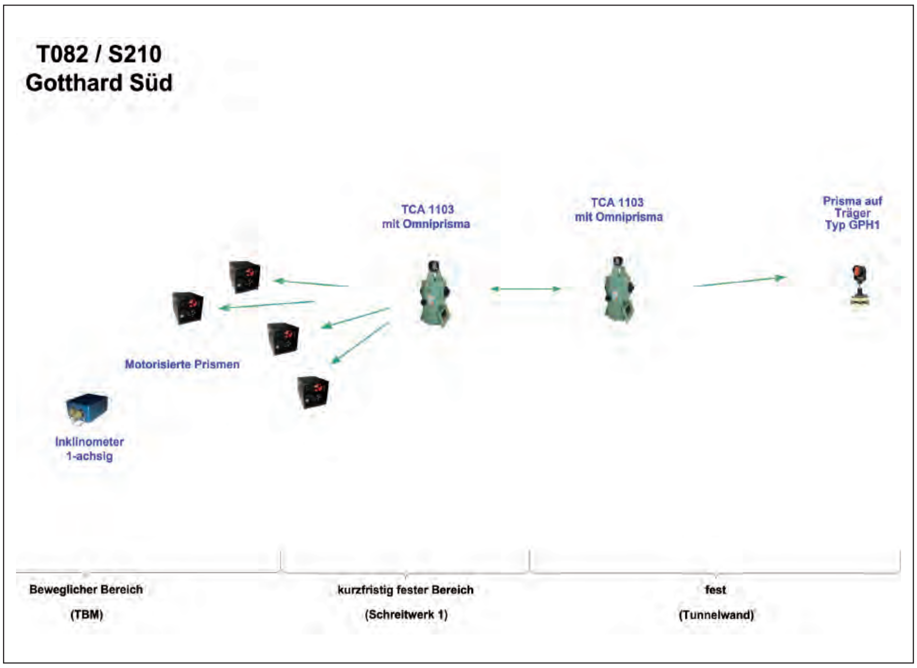


Fig. 5: Components of the guidance system.

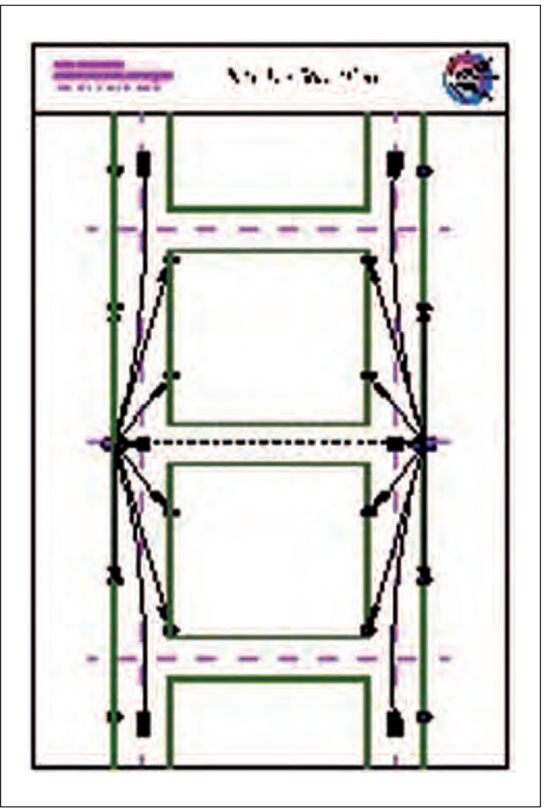


Fig. 6: Network configuration.

Fig. 7: Measurement console with footing platform.

Fig. 8: Construction of the tunnel bench.

Fig. 9: Concreted, completed tunnel.

The break through in the east tunnel was on 15.10.2010 and so the east tunnel is non-stop from Bodio to Erstfeld – 57 km. With good cooperation between client, Amberg Technologies, and the survey section contractor our break through results are 8 cm laterally, 0 cm in height, and 14 cm in length.

Good luck together.

Reinhard Deicke
Consorzio TAT
Isengrundstrasse 18
CH-8134 Adliswil
reinhard.deicke@tat-ti.ch

Navigation of the tunnel-boring machine at Gotthard

Special requirements for the construction of the tunnel drives on the Gotthard Base Tunnel meant high demands on the navigation systems of the four TBMs. Due to the necessity of tunnel works to be carried out concurrently with the advance, various factors, such as line of sight dust, heat, and vibrations, prevented a normal measuring operation. This article shows how VMT produced secure navigation of the TBMs, through the selection of suitable material and a change of measuring methods.

M. Messing

Guidance of a tunnel-boring machine (TBM) is comparable to navigating a super-tanker: it takes a long time before the effect of a course-correction is obvious. Skilled machine drivers know how «their» machine performs in different geological conditions. Therefore, a precise and reliable determination of the TBM's position is the most important information for steering control. Although the TBM moves slowly, it is possible for the machine to stray off the planned course and exceed the requested precision of 100 mm round the given axis. It is a real challenge to eliminate these deviations in such a long tunnel,, and can only be achieved with perfect coordination between surveying and machine driving. A polygonal process from outside the tunnel right up to the machine's cutter head must carry all geodetic information. Normally for this purpose, in the machine area, along the tunnel wall, there is a dedicated clear area or laser window available throughout the entire area of the trailing gear. One special characteristic of the Gotthard project was that various tunnelling activities needed to be done concurrently with the advance, thus the machine and trailer concept was designed accordingly. The navigation system had to be adapted to this situation too.

Requests on the Guidance System

A guidance system is equivalent to a navigation system. It provides information to start a control or course correction. Therefore it is indispensible that the actual position of the TBM in relation to the planned tunnel axis is continuously provided and displayed. As a 98% availability of the TBM position is required, continuous measurement of the TBM position is necessary. Additionally, the pitch and roll values of the TBM must be collected and displayed. A status indication of all relevant sensor components of the guidance system is required as well as automated direction control.

Normally, the well-known navigation systems work with GPS. But in a tunnel there is no satellite reception. So the determination of position is carried out in the classic mode with the help of motorized measuring instruments.

Characteristic of Gotthard System

For the Gotthard tunnels two different trailer concepts were in use for the north and south sectors. To cope with these circumstances different navigation systems had to be designed using the same hardware components, including motorized total stations, inclinometer, and also the software controlled shuttered prisms marking the key machine measurement points. Additionally geometric machine data (including Ram extensions) from the TBM's PLC were stored and used in the calculation of the actual position.

Concurrent with the advance, various other works needed to be done: initial shotcreting, wire mesh and arch-mounting, and rock bolt boring, which seriously interfered with the line of sight to the machine measurement points. Therefore a standard measuring method couldn't be applied. Extreme vibrations will affect all these hardware components, from total stations and computers up to the shuttered prisms.

Navigation System in the Gotthard-North – Amsteg Section

In the North Section the first three trailers were continuously pulled over rails during the advance. The following trailer units were hanging on roller-brackets on the segment and were pulled only after the advance (see Fig. 1). So this area was stable for a short time and could be used for measuring the cutter head, however, only in the lower laser window. The coordinates and orientation for the automatic total station in the lower section had to be determined again after each advance. In this section it was done by continuously carrying forward key machine measuring points in the invert area. For measuring the tracks on which the first trailer section was pulled forward, these points had to be pegged out anyway. They were also used for automatic measuring of a «free chainage» of the total station (see Fig. 2).

After each advance this trailer area was pulled forward, whereby the coordinates and the orientation of the total station changed. After the grippers were engaged again, a signal was sent to the control computer that started the automatic measuring of the total station with the present key machine measurement points. If the coordinates and the orientation of the total station were known, the TBM position could be measured by

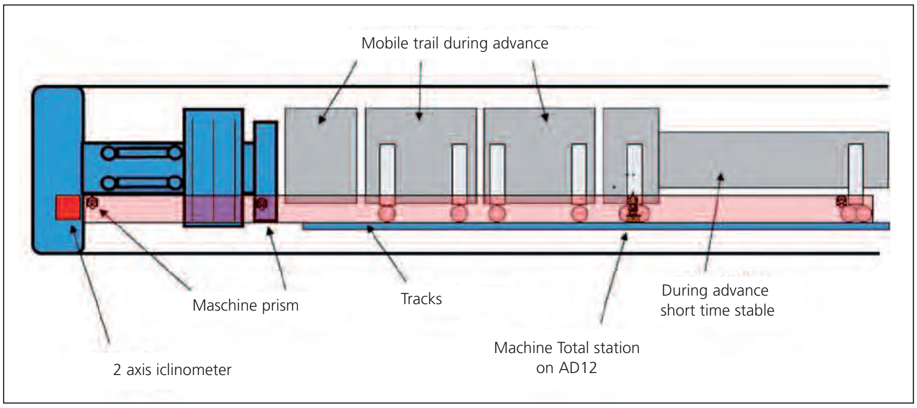


Fig. 1: Trailer concept Gotthard-North section.

the automatic machine prism at the cutter head (see Fig. 3). The total station was mounted on a self-levelling tribrach (AD-12), which compensated for any roll and pitch of the trailer and automatically levelled the total station.

Navigation System in the Gotthard South – Bodio Section

In the southern section the trailer was advanced using the two walking mechanisms, which were deployed during the advance. After the advance these mechanisms were contracted and the trailer moved ahead. Here the walking mechanisms could be assumed to be a short time, stable construction (see Fig. 4).
Four motorized shuttered prisms (machine prisms) were mounted on the machine frame (see Fig. 5) and measured on the machine axis. This «local» co-ordinate system was incorporated into the computer calculations. During the advance the machine framework moved forward. The machine station (motorized total station on an automatic tribrach AD-12) was mounted on a divert frame which was connected to the frontal walking mechanism and independent from the trailer (see Fig. 6). During the advance this mechanism did not move. It was only pulled forward after the advance. With the short time, stable machine station the motorized prisms were measured and the global coordinates calculated during the measurement cycle. Then the TBM's position was determined by a special transformation (see Fig. 7). As the TBM stays in advance mode within these measuring cycles, a track correction is added to the measurements of the motor prisms (dynamic transformation).
As with the Gotthard-North system the coordinates and orientation of the machine station were stable only for a short time. This means they changed with each

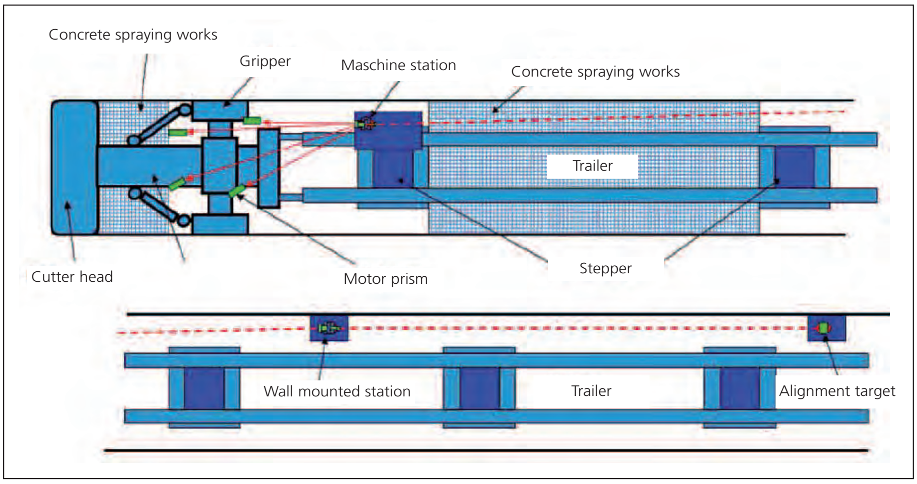


Fig. 4: Trailer concept Gotthard-South section.

Fig. 2: Total station Gotthard-North.

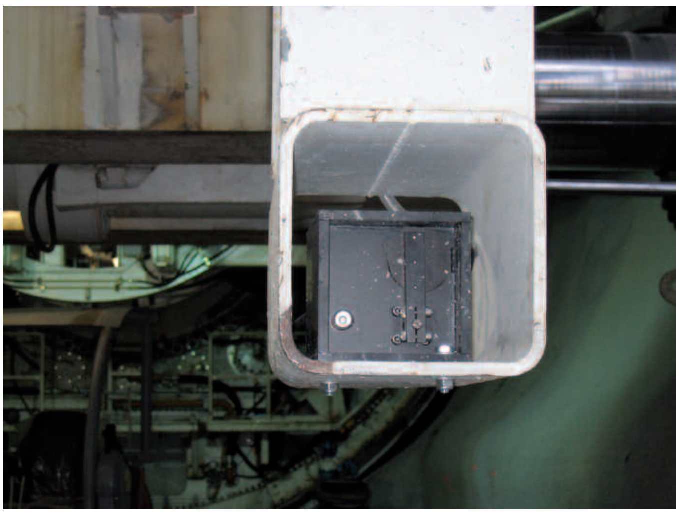


Fig. 3: Installed shuttered prisms (closed).

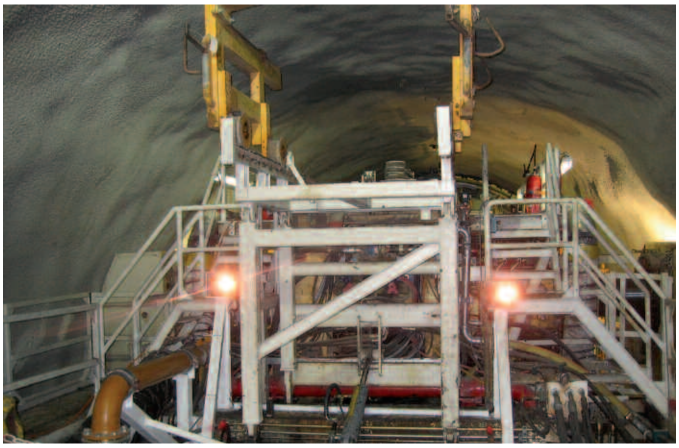


Fig. 5: Shuttered prisms on machine frame.

Fig. 6: Divert frame with machine station.

advance. When an advance was made, the grippers were contracted, moved forward, and then extended again on the tunnel wall. A signal was then given by the TBM to the control computer, which started measuring the machine station from the wall-station mounted in the rear. The measuring operation took about two minutes. Afterwards the shotcrete work in the backup area could continue.

Display of TBM Position

On the monitor (see Fig. 7) all relevant control data are displayed for the machine driver. Aside from the deviations of the planned axis (horizontal and vertical), the roll and pitch are also shown. The indication of the operating state of the connected sensor system is displayed as well as the station and the advance number. From this display the direction control and also the display of the last (historical) shield drive could be activated. The latter provides information on the performance of the TBM, which directly influences the control.

Abstract

Adapting the navigation system to the special drive-operations was doubtless a big technical challenge. The components and materials used were subject to very problematic conditions, such as vibration, dust and heat. The operating mode of the navigation system had to be fully orientated to these tunnelling operations as the driving process should in no way be affected. Several times during the advance not only were geometric system adaptations necessary but also changes in some hardware components. For example, the controller unit (data conversion and network) had to be cooled with compressed air and had to conform to at least the IP62 protection category.
The use of similar hardware components and a modular software system was beneficial as all the necessary adaptations could be done with relatively little effort. Things didn't always flow smoothly, therefore, sincere thanks are given to all parties involved, for their patience and understanding during the set up of the system and the necessary revision phases.
All things considered, this project has contributed to many enhancements of technique and methods from which many future projects will benefit.

VMT GmbH Gesellschaft für
Vermessungstechnik
Stegwiesenstrasse 24
DE-76646 Bruchsal
m.messing@vmt-gmbh.de

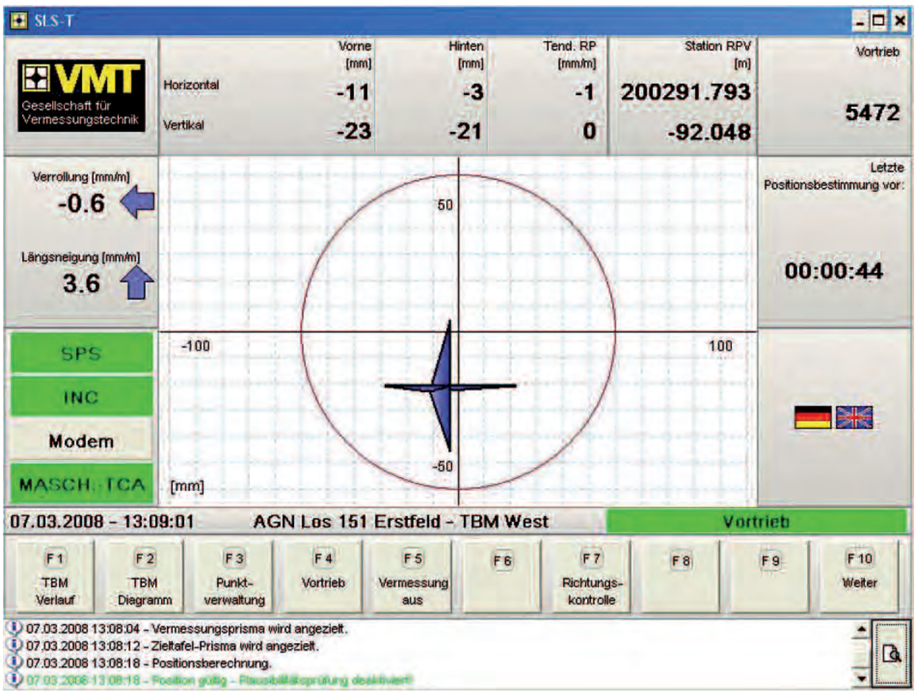


Fig. 7: TBM position in relation to the planned tunnel axis, calculated by transformation.

National Surveying contributions to the AlpTransit Gotthard Base Tunnel

During the 1990s the Federal Office of Topography, swisstopo, designed the new LV95 national geodetic survey of Switzerland and launched its principle element, the national GPS network. The LHN95 national vertical network and the computation of a new geoid model of Switzerland completed the new national surveying network. Thanks to its homogeneous accuracy of a centimetre for all of Switzerland, it also satisfies the basic surveying requirements for large engineering projects such as the Gotthard and the Lötschberg base tunnels. .

A. Wiget, U. Marti and A. Schlatter

The National Surveying Network 1995

The geodetic survey of Switzerland is one of the main activities of the Federal Office of Topography, swisstopo. It comprises the production, development, and maintenance of the basic geodetic works such as the terrestrial reference system and its realization through so-called reference frames using geodetic control networks and permanent networks. Beginning in the mid-1980s, it was possible to overhaul the national survey at reduced costs using the modern technologies of satellite geodesy, in particular GPS, thereby significantly improving its accuracy and applicability. swisstopo renewed the national geodetic survey within the scope of the «New National Survey LV95» project [Signer 2002]. The most important components of the LV95 are: the definition of the geodetic reference systems CHTRS95 and CH1903+, the fundamental station Zimmerwald, the national GPS network, the Automated GNSS Network Switzerland (AGNES), the positioning service swipos, the national vertical network LHN95, the national gravity network LSN2004, the geoid model of Switzerland CHGeo2004, and the kinematic model CHKM95.

Between 1989 and 1995, swisstopo developed the GPS network with over 200 stable and permanently monumented points, carried out the surveying work, and measured connections to international reference networks. Together with the GNSS permanent network AGNES, these points are the realization of the new reference frame for the LV95 national survey network, which practically replaces the LV1903 national triangulation network (1st to 3rd order). Comparative surveys showed distortions of up to 1.5 m (in some areas systematic) in the 100-year-old LV03. In contrast, the nation-wide accuracy (1 sigma) of the position coordinates of the LV95 reference frame is better than 1 cm. The new national survey has therefore improved the accuracy in position by a factor of 100.

The new LHN95 national vertical network is still based on the first-order levelling network. For the complete revision of all levelling data since 1903, the spatial variations of the earth's gravity field or the equipotential surfaces (geoid model) as well as the tectonic movements of the control points (kinematics of the earth's upper crust) are modelled and subjected to a kinematic adjustment. As opposed to the official heights of the LN02 leveling network, the heights from the LHN95 are computed and adjusted as theoretically rigorous orthometric heights above the geoid.

Therefore, the new national surveying network also includes a new geoid model (CHGeo2004) which – like the former one – is primarily based on astrogeodetic deflections of the vertical, but is additionally enhanced by GPS observations on control points of the national vertical network and by gravimetric data. The increased accuracy is mainly a result of the many additional measurements, but also due to the improved height and mass models. In order to guarantee the consistency between the ellipsoidal heights of the GPS network (LV95), the orthometric heights of the LHN95 as well as the geoid undulations of the new geoid model, their measurements and data were combined and adjusted in the so-called «Swiss Combined Geodetic Network (CHCGN)».

Preliminary project Gotthard Base Tunnel

From the very beginning, the Federal Office of Topography's ambition for LV95 – besides meeting the requirements for the official cadastral survey in Switzerland – was to fulfill the demands of large engineering projects and to create synergies for the demanding nature of engineering surveys [Schneider et al. 1996]. In research projects initiated by the Swiss Geodetic Commission (SGC), swisstopo quickly gained a leading position in GPS applications for engineering surveys thanks to early practical applications from satellite geodesy (GPS) in the national survey and the close collaboration with the Astronomical Institute at the University of Bern (AIUB) and the Institute for Geodesy and Photogrammetry (IGP) at the Federal Institute of Technology in Zürich (ETHZ). Furthermore, swisstopo had acquired long-term experience in triangulation measurements, in large-scale precision levelling and gravity field determinations as well as in deformation observations and in the necessary know-how to optimally combine these measurements. By the end of the 1980s swisstopo was engaged in different basic surveying activities for large engineering projects, especially tunnel surveys for RAIL2000.

The coordinating group «AlpTransit Survey», including representatives from contractors (SBB and BLS) and experts from federal surveying authorities and from the

ETHZ, was created in order to coordinate the basic surveying tasks for AlpTransit with the national survey and the official cadastral survey. On behalf of this group, various problems encountered in the preliminary project were remedied by the IGP as well as by swisstopo. These studies served as a basis for the public tender for the surveying work.
In order to reach the high accuracy required for large tunnel networks, particularly in the Alps, geodetic characteristics such as spatial variations of the gravity field, the kinematics of the earth's upper crust, and the influences on GPS observations caused by refraction need to be taken into account. swisstopo was able to incorporate different experiences gained from the national GPS network and the levelling network into the Gotthard Base Tunnel (GBT) project. In addition, there were findings that were not directly related to the cut-through, but nevertheless had to be taken into consideration for the overall project, i.e., the subsidence above the Gotthard road tunnel determined through levelling (see Fig. 6), which lead to a monitoring concept for the dams above the GBT during tunnelling

Horizontal reference frame

Even in the mid-1970s the recommended aboveground survey for the GBT was a combined triangulation network with directional and distance measurements [Gerber 1974]. Twenty years later a high-precision GPS network combined with conventionally observed portal networks (directions, distances, elevation angles) was indisputable. The portal networks, for which additional astronomic azimuths and vertical directions were measured, were used to transfer the positioning, the scale and the orientation of the aboveground network into the mountain with the least possible loss of accuracy.

Fundamental GPS network

With the LV95 national GPS network, in the mid-1990s swisstopo had provided a modern, high precision, geodetic reference frame (see above) that also allowed the accurate correlation to global reference systems applied in satellite geodesy. The constraints in the existing survey networks were detected through the observed relationships to the 1st and 2nd order triangulation network and the 1st order levelling network. In coordination with the concept and observation of the fundamental GBT network and the «Gotthard Süd» (Bodio – Lugano) section to the south, swisstopo established and observed additional LV95 control points in 1995. Thus, there were a total of eight LV95 points available for the fundamental AlpTransit network: Altdorf, Amsteg, Oberalp, Disentis, Dalpe, Biasca, Bellinzona and Sonvico. The first six were used for the GBT, and the latter three for the «Gotthard Süd» section.
The concept of the fundamental network was designed to establish the connection to the new LV95 national surveying network using these reference points. On the other hand, in each portal and for each intermediate access shaft local triangulation points were included in the observations to allow connections to the LV03 national survey and to the cadastral survey.
In May 1996, the coordinating group «AlpTransit Survey» made the preliminary decision (subject to further investigations) to carry out the survey work for AlpTransit primarily in the LV95 reference frame. In close cooperation with the SBB and Canton Uri, and in combination with the cadastral surveying project RAV Subito, swisstopo carried out tests in 1996 in the Reuss plain from Altdorf to Amsteg to transform spatial data from LV03 to LV95, and to obtain the optimal triangular transformation network for the FINELTRA transformation method.
The GPS observations for sections «Gotthard-Basistunnel» and «Gotthard Süd» were each carried out by the consortium Gotthard Base Tunnel Survey (VI-GBT) and the Consorzio Geodetico Sud (COGESUD), during two days in November 1995 and January 1996, respectively. The LV95 points were occupied permanently for the entire duration of the measurements in order to guarantee an optimal positioning of the network. A comparison to the coordinates of the LV95 national GPS network showed maximum differences (residuals of a Helmert transformation) of 5 mm [Haag et al. 1996]. A repeat measurement in 2005 resulted in similar differences of up to 2–6 mm [Schätti and Ryf 2007]. The LV95 points contributed not only to the greater accuracy of the fundamental network but also accounted for a significant improvement in its reliability, a vital component of tunnel surveying.

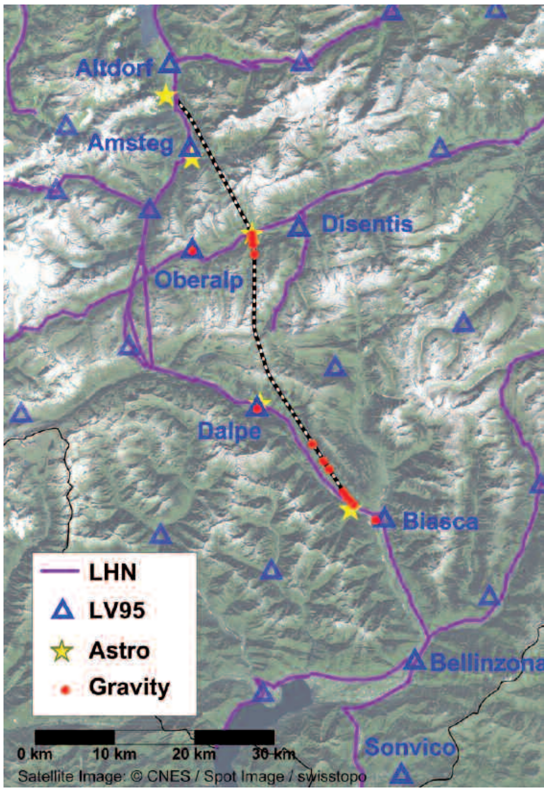


Fig. 1: Partial network LV95 showing the 1st order leveling lines (LHN), gravity and astrogeodetic points used in the fundamental survey of the Gotthard Base Tunnel.

Positioning in LV03

The result of the combined adjustment of GPS observations and conventional measurements was a set of highly precise coordinates with an internal accuracy in centimetres. This now had to be positioned in a well-defined reference frame. At the request of the two consortia and based on a new evaluation of the «AlpTransit Survey» coordinating group, in 1997 the

Fig. 2: LV95 station Biasca.

AlpTransit project management reached its definitive decision to carry out the GBT survey in the «NetzGBT Lage» local network. Even though the NetzGBT network, with 31 points, and the one for the «Gotthard Süd» section, with 21 points, relied on the highly accurate LV95 network, they were both positioned in the LV03 reference frame through transformations to minimize the misclosures around the portals and the access tunnels. The constraints in LV03 between Altdorf and Lugano, however, called for two different transformations for the GBT and section «Gotthard Süd», respectively, which differed primarily by a 10 ppm discrepancy in scale. The reasons for this choice of reference frame and the rejection of the technically ideal case (suggested by swisstopo) of constraint-free positioning in LV95 were:

- preliminary activities for AlpTransit had already been carried out in LV03
- rail surveys of the existing SBB lines (Database DfA, rail plants, track geometry) were available in LV03
- cadastral surveys of the involved municipalities were in LV03; decisions for converting to LV95 in cadastral surveying were pending
- massive cost increases were anticipated for the conversion
- collaboration with external partners would have been more difficult (confusions due to parallelism of LV95 and LV03).

It should be mentioned at this point that a different positioning reference frame was chosen for the survey of the BLS AlpTransit Lötschberg Base Tunnel: it was surveyed entirely in the new LV95 reference frame [Riesen et al. 2005]. These two solutions show that both alternatives can be carried out successfully, provided that the choice of frames is implemented consistently.

Gravity field

The earth's gravity field influences practically all geodetic observations and must therefore always be taken into consideration in a large project such as the GBT. This includes correcting ellipsoidal heights determined with GPS by the geoidal height, positioning the network by means of astronomic azimuths, correcting terrestrial measurements (especially gyroscopic measurements) by the influence of the deflection of the vertical, and correcting levelled heights by the influence of gravity (orthometric correction, see the following sections).

When construction of the GBT began, the standard geoid model was the CHGeo98, which is essentially based on measurements of the deflection of the vertical and also on GPS/levelling data [Marti, 1997]. This model is not just a simple reference surface for height determination, but also an actual 3-D model, which also allows the interpolation of gravity values and deflections of the vertical on arbitrary points within and outside the earth's surface. In 2004, CHGeo98 was replaced by the more sophisticated CHGeo2004, which is based more closely on GPS/levelling, but at the same time still on vertical deflections and in addition on gravity measurements. But the CHGeo98 model was used in the entire construction of the GBT until its completion.

Initially, it was not yet clear if the quality of the CHGeo98 would be sufficient to meet the required tolerances in the construction and breakthrough of the GBT. Therefore, additional measurements and investigations were carried out. One of the studies [Marti 2002] was designed to answer the question whether for the GBT a more sophisticated mass model, instead of the CHGeo98, would yield the accuracy required for deflections of the vertical and for the orthometric correction. Since the CHGeo98 was based only on surface observations and the mass model was fairly rudimentary, it was uncertain whether this model would pose problems in the construction of the tunnel. Consequently, a local three-dimensional mass model was generated from the available geological profiles to determine its influence on deflections of the vertical, the gravity and the orthometric correction. Comparisons to the standard CHGeo98 model showed differences up to 0.5 mgon for the deflections of the vertical that occur mainly along the edges of geological layers featuring large contrasts in density. This amount lies within the tolerance of significance for the correction of gyroscope measurements, thus it was decided to use the standard model. On the other hand, gyroscope measurements should not be carried out directly in geological transition zones. Gravity corrections obtained from the mass model produced differences of approx. 6 mGal compared to those from the CHGeo98. However, the influence on the orthometric corrections was only 2 mm at the

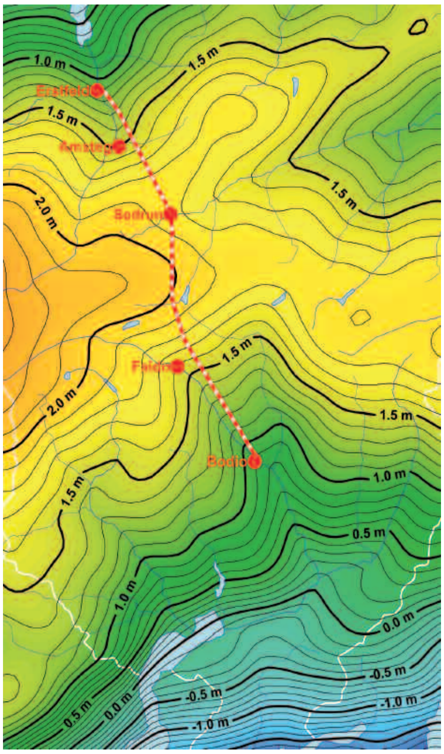


Fig. 3: Geoid model CHGeo98.

most, which meant that the standard model with its uniform density was also sufficient. This investigation established that the CHGeo98 mass models were adequate for constructing the GBT and denser models were not necessary. On the other hand, the evaluation did not answer the question whether gravity measurements should be made inside the tunnel, or whether the extrapolated values from the surface would suffice for the height correction.

For clarification, gravity measurements were carried out in 2005, in collaboration with the Institute for Geophysics at the University of Lausanne, on a few points around the portals and in the already accessible part of the tunnel and compared to values interpolated from the CHGeo98. The resulting differences of less than 3 mGal were negligible for determining orthometric corrections. It was therefore decided not to carry out systematic gravity observations in the GBT and that the CHGeo98 yielded sufficiently accurate gravity values. The investigation is documented in swisstopo Report 05–34 [Bürki et al. 2005].

As for the gravity measurements, it was also necessary to verify whether the values computed from the CHGeo98 were sufficient for the deflections of the vertical and the astronomic azimuths, or if additional observations were required. In summer 2005, the ETH Zurich together with the Technical University of Hannover carried out astrogeodetic measurements around the portals and in further access tunnels. These measurements are documented in another article in this volume [Bürki, Guillaume]. The main result again showed that the values interpolated from the CHGeo98 were adequate for the construction of the GBT and no further observations would be necessary.

The various investigations of the gravity field confirmed that the CHGeo98 geoid model of the national survey was already sufficient for large projects such as the GBT, and additional costs for further observations could be avoided. The subsequent CHGeo2004 delivered further improvements, especially for the consistency of height determination with GPS and levelling.

Fundamental vertical network

Levelling as main component

In the final report of the «Gerber network», the first fundamental network of a projected Gotthard base tunnel, there was only the following mention concerning the height:

The heights of the two portals and the three access tunnels were determined through levelling by the Federal Office of Topography… at this point it would surely be futile to make further mention of the high accuracy of the already legendary and internationally acclaimed work at the Office of Topography with its keen sense of tradition [Gerber 1974].

Basically, the first sentence also applies to the GBT. The following paragraphs, however, should demonstrate that for a project of such dimensions, further concepts, observations and computations would be required instead of complacent praise.

In fact, the vertical network of the GBT is

Fig. 4: Gravity measurements in the tunnel.

based on measurements from 1st and 2nd order levelling (substantially even on the lines from 1970–73 mentioned in Gerber [1974]) as well as on computations of the new vertical network LHN95. For the breakthrough of the 57-km-long tunnel, only approx. 30 km of additional aboveground precision leveling was required. These were used to connect the portals Erstfeld, Amsteg, Sedrun, Polmengo (Faido) and Bodio (Biasca) to stable points in the LHN vertical network. All subsequent observations to the extent of several hundred kilometres were requested for subsidence monitoring, supplements to the portal networks and tectonic investigations. They had no direct bearing on the breakthrough.

Heights in the Alps

Whereas height determination by means of levelling is a well-known and simple method, the handling of heights in geodesy is regarded rather as an academically complicated (and annoying) necessity. A levelling loop «pass road – vertical access shaft – rail tunnel», however, features special characteristics. For the experts, this means: the usual levelling heights obtained along the pass road are neither fish nor fowl, vertical access shafts yield orthometric height differences, and in tunnels with a gentle incline the heights are almost exactly dynamic ones. Using the GBT as an example for the layperson: if no corrections are applied with respect to the gravity field, the misclosure of even error-free levelling loops is around a decimetre. Together with the inevitable random errors in measuring, there isn't much leeway for attaining the required breakthrough tolerance of 12.5 cm (2. 5σ).

LHN95 as a basis

The idea of having the fundamental heights based on the (at that time) projected new adjustment of the LHN was founded on an agreement between swisstopo and the VI-GBT [Schneider and Haag 1995]. It is closely tied to the realization of the new LV95 national survey and in particular the new LHN95 vertical network [Schlatter and Marti 2007]. The same concept was also implemented successfully in the construction of the Lötschberg base tunnel [Riesen et al. 2005].

LHN95 is based on an orthometric height system and was realized through a kinematic new adjustment of all measurements made since 1903. In addition to adjusting the influences of gravity, the tectonic movements (alpine uplift of up to 1.5 mm/year) are also taken into consideration.

The following advantages, besides minimal expense and effort for new observations, are relevant for the construction of the GBT:

- high precision and improved reliability
- elimination of the influence of errors caused by the gravity field at the breakthrough
- elimination of the influence of errors caused by measurements from different epochs
- compatibility of ellipsoidal heights from GPS observations and from the CHGeo98 geoid.

Orthometric heights and vertical velocities of the portal points from a preliminary adjustment carried out on the LHN95 in 1999 (comprising approx. 6800 km of a total of 12 000 km of levelling lines) were delivered to the VI-GBT. The relative mean error (1 σ) as compared to the Erstfeld portal amounted to ± 9 mm in Sedrun and ± 8 mm in Biasca (see Tab. 1). This degree of accuracy is a result of the global adjustment of all measurements (potential differences) together with the influence of the mean gravity along the plumb line, which cannot be computed free of hypotheses.

Tab. 1 shows the differences between LHN95 and the official LN02 heights as well as the computed vertical velocities relative to the Erstfeld portal. In addition, the difference of the results of a kinematic adjustment carried out on pure levelling differences to LN02 can be seen in column «LNIV–LN02».

LN02 as frame for project heights

The reason why the difference between the official heights (LN02) and the orthometric heights (LHN95) amount to decimetres was presented in Schlatter and Marti [2005]. The most important causes in LN02 are summarized as follows:

- the influences of the gravity field (or different types of heights) were not taken into account
- precise levelling observations are still constrained into nodal points whose heights are based on the 'Nivellement de Précision' from 1864-91
- the known recent vertical changes had not been included.

Nevertheless, the project management and the VI-GBT decided to stay with LN02 since the project as well as connecting constructions had already been observed in this frame [Haag and Stengele 1999]. The realization of the Lötschberg base tunnel where LHN95 was used as the working frame proved that it also works the other way around. If the disadvantages and shortcomings of LN02 are to be counteracted, then corrections have to be applied to the height transitions during the tunnelling stages, in particular:

- influence of the gravity field in the tunnel (orthometric corrections and theoretical loop misclosures, respectively)
- influence of the differences between LHN95 and LN02 (see Tab. 1)
- influence of the different uplift rates (see Tab. 1), which should theoretically remain only slightly over 1 cm for the entire period of construction (10 to 20 years).

Orthometric corrections

Even if the surveying of the tunnel had been started with portal heights in LHN95, the tunnel levellings would have had to be corrected by the influences of gravity or at least by the expected loop misclosure. Based on the available height and density models – such as they had been used for determining the geoid – swisstopo computed for the VI-GBT a priori orthometric corrections using project coordinates. The process is shown in Fig. 5 with the example of the breakthrough Amsteg ⟷ Sedrun north. It is striking that the vertical shaft did not have any direct influence; the vertical distance corresponds so to speak to an orthometric height difference. The breakthrough error, which would have resulted from having ignored the loop misclosures, nevertheless amounts to approx. 3.8 cm.

Comments and conclusion

In retrospect it is remarkable and to the merit of those responsible at the time that

Portal	Height	Length GBT	m. F. LHN95	LHN95 - LN02	LNIV - LN02	Uplift
	m a.s.l.	[km]	[mm; 1σ]	[m]	[m]	[mm/y]
Erstfeld	460	0	± 0 (Ref.)	0 (Ref.)	0 (Ref.)	0.67
Amsteg	510	8	± 3	0.02	0.01	0.78
Sedrun	1410	21	± 9	0.13	0.01	0.80
Faido	760	40	± 7	0.11	0.05	1.25
Biasca	300	57	± 8	0.11	0.09	1.22

Tab. 1: The accuracy of LHN95, the comparison between LHN95, pure levelling heights (LNIV) and LN02 relative to the Erstfeld portal as well as the vertical velocities relative to the Aarburg reference point.

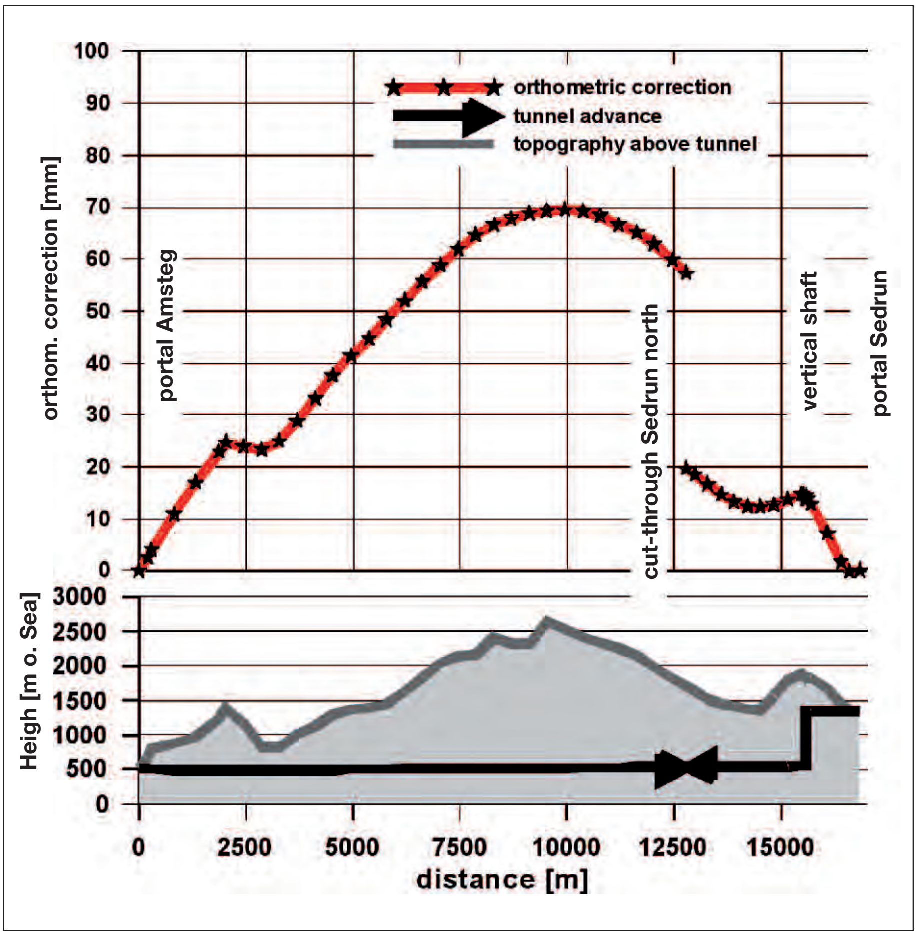


Fig. 5: A priori orthometric corrections in the tunnel based on orthometric heights in the portals.

it was possible to determine a solid height frame for the AlpTransit GBT with only 30 km of new measurements. A few additional remarks:

- Basically it doesn't matter which vertical frame is used for the construction of trans-alpine rail tunnels, as proved by the two projects Gotthard and Lötschberg. However, without the knowledge and results of the more precise LHN95, the corresponding success would not have been possible.
- It is much more important to correctly handle the various corrections, advantages and disadvantages. This far greater challenge was mastered by both project surveys in an exemplary manner.
- It is not always the newest measuring technique that bestows us with better results (see Riesen et al. [2005]). Often even 30-year-old measurements will do just fine.
- The influence of the alpine uplift on the fundamental height network is probably interesting but of minor significance to the breakthrough itself. The uplift rates in project GBT are based on the comparison of two observation epochs (approx. 1920/1970). The much greater subsidence in the Gotthard region (see Fig. 6) was detected rather accidentally by swisstopo in 1997. In retrospect, the portal areas were at risk of being influenced by unknown factors.
- The claim today (or even 15 years ago) that the elaborate and costly levelling measurements can be entirely replaced by GNSS observations is false. It is easily forgotten that today's equally necessary geoid models could at this time not have been realized without the information gained from LHN95 if one wants to reach an agreeable precision. Thus there is no sign of independence here.

The enormous praise for the successful breakthroughs belongs without a doubt to those surveyors who persistently followed their goal under difficult and sometimes abominable conditions. Without the corresponding initial results at the portals, their efforts would have been questioned. AlpTransit also posed a challenge to all those responsible for the Swiss national survey.

References:

Bürki B., M. Ganz, Ch. Hirt, U. Marti, A. Müller, P.V. Radogna, A. Schlatter, A. Wiget (2005): Astrogeodätische und gravimetrische Zusatzmessungen für den Gotthard-Basistunnel. swisstopo-Report 05–34.

Haag R., A. Ryf and R. Stengele (1996): Grundlagennetze für extrem lange Tunnel am Beispiel des Gotthard-Basistunnels. Beiträge zum XII. Internationalen Kurs für Ingenieurvermessung, Graz.

Haag R. and R. Stengele (1999): Vermessungstechnische Grundlagen und Herausforderungen beim Projekt «AlpTransit – Gotthard Basistunnel». VDI Berichte 1454, VDI-Gesellschaft Bautechnik.

Gerber P. (1974): Das Durchschlagsnetz zur Gotthard-Basislinie. Mitteilungen aus dem Institut für Geodäsie und Photogrammetrie der EHTZ Nr. 17

Marti U. (1997): Geoid der Schweiz 1997. Geodätisch-geophysikalische Arbeiten in der Schweiz Band 56. SGK 1997.

Marti U. (2002): Alptransit Gotthard Basistunnel: Schwerefeldstudie. Technischer Bericht 01–36; Bundesamt für Landestopographie.

Riesen H.-U., B. Schweizer, A. Schlatter, A. Wiget (2005): Tunnelvermessung des BLS-AlpTransit Lötschberg-Basistunnels. Geomatik Schweiz 11/2005.

Schätti I. and A. Ryf (2007): AlpTransit Gotthard-Basistunnel: Grundlagenvermessung, letzte Kontrollen vor dem ersten Durchlag. Ingenieurvermessung 2007, Graz.

Schlatter A. (2007): Das neue Landeshöhennetz der Schweiz. Geodätisch-geophysikalische Arbeiten in der Schweiz Band 72. SGK 2007.

Schlatter A. and U. Marti (2005): Höhentransformation zwischen LHN95 und den Gebrauchshöhen LN02. Geomatik Schweiz 8/2005.

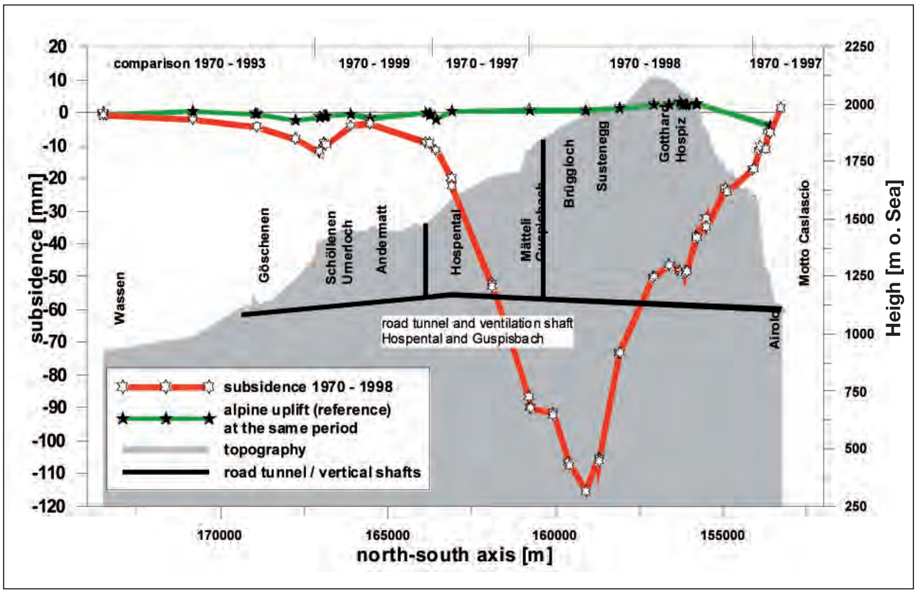


Fig. 6: Subsidence at the Gotthard Pass due to the construction of the road tunnel [Schlatter 2007].

Schlatter A. and U. Marti (2007): Aufbau der neuen Landesvermessung der Schweiz 'LV95'. Teil 12: Landeshöhennetz «LHN95». swisstopo Doku Nr. 20.

Schneider D. and R. Haag (1995): AlpTransit Gotthard Basistunnel: Höhengrundlagennetz auf der Basis des Landesnivellements. Technischer Bericht 95–22, Bundesamt für Landestopographie.

Schneider D., U. Marti and A. Wiget (1996): Die neue Landesvermessung der Schweiz LV95 als Grundlage für die Vermessung der neuen Eisenbahn-Alpentransversen «AlpTransit». Beiträge zum XII. Internationalen Kurs für Ingenieurvermessung, Graz.

Signer T. (2002): Landesvermessung LV95: Übersicht und Stand des Projektes. Vermessung, Photogrammetrie, Kulturtechnik 1/2002.

Adrian Wiget
Dr. Urs Marti
Dr. Andreas Schlatter
Geodesy Division
Federal Office of Topography swisstopo
Seftigenstrasse 264
CH-3084 Wabern
Switzerland
adrian.wiget@swisstopo.ch

Overview of railway technology in the Gotthard Base Tunnel

In October 2010, after many years of construction, all the key personnel involved in the tunnel's construction joined with politicians to celebrate the main Gotthard breakthrough. Even before this milestone had been reached, the next construction phase had been scheduled: the concrete casting of the tracks and the installation of all additional railway technology. Beginning in the summer of 2010, the installation of the entire railway infrastructure was achieved in a step-by-step fashion in the western tube of the Bodio – Faido section. During the operative test phase (scheduled for 2013) the main aim will be to verify the reliability of the overall system and to discuss potential improvements. The installation of the track for the remaining 100 km will start in 2012 and will capitalize on all the lessons learned during the first construction phase.

D. Stähli, M. Baumeler, Th. Silbermann

In October 2010 a major milestone was reached at the site of the Gotthard Base Tunnel: the main breakthrough itself. At the same time, in the Bodio to Faido section – away from the focus of attention – the first few metres of concrete slab track were laid. In an on-going process, the track is being constructed on an industrial scale within the tunnel itself. This is, in effect, the main task of the railway construction. This process demands the highest standards in terms of logistics, surveying and building processes. In a few years' time, more than 100 km of track will have been built to within millimetre accuracy in order to guarantee the safe operation of the high-speed trains travelling through the tunnel.

The railway technology comprises all the various technological units necessary to enable trains to pass safely through the base tunnel. Key here is the track and the overhead line. However, train control systems, ventilation, lighting, signaling, security systems, electrical grounding, communications and energy supply for the trains and for all technical equipment also form vital parts of the required railway technology. To illustrate the dimensions involved in this immense project, one should take a look at the following details.

In two separate tunnels (one northbound and one southbound), comprising a total length of 117 000 m of track and four crossovers, around 119 000 m^3 of concrete will be laid and 234 000 m rail will be mounted over the next few years. In addition, the 180 cross-cuts will require the installation of several hundred kilometres of cable and guidance systems to ensure that passenger and freight trains will be able to travel at different speeds through the tunnel.

Organization of railway technology contractor

The aforementioned demands require a great deal of expert know-how. Four leading companies with international experience formed a consortium called «Transtec Gotthard». This company comprises Alpine Bau GmbH, Balfour Beatty Rail GmbH, Alcatel-Lucent/Thales, and Alpiq. The consortium is divided into a number of sub-working groups to deal with the following areas: overhead line, track, cable construction, security, and train control technologies.

In this article, the main focus is on track construction, which is being carried out by a joint venture between Alpine Bau GmbH and Balfour Beatty Rail GmbH.

Outside the tunnel, there are some 20 km of ballast track to the south, 16 km of same to the north and 27 sets of points, which are also part of the overall track construction. Scheuchzer SA has almost completed the southern part of the track in the Ticino region.

Grunder Ingenieure AG, Burgdorf is tasked with all the necessary survey work for the «Transtec Gotthard» consortium.

Project requirements

The logistical challenges are far greater in a tunnel of 56 km than on an open track line. There is no place to side step. Various processes that are independent of each other must be carried out one after the other in order to maintain high productivity and minimize potential interference between these processes. The main task is the «industrial production» of the track. As different construction and surveying processes follow each other, they have to be coordinated down to the finest detail. The goal is first, to ensure optimal

Fig. 1: Training/sample track at the Biasca surface installations site.

Fig. 2: Adjustment of the training track.

construction progress, and second, to provide the necessary conditions required for surveying work (e.g., elimination of vibration).

All logistical planning is dictated by the rate of track installation itself. This has therefore, the greatest influence on all other aspects. Prior to the track section being put down, a special vehicle lays all cables in their respective cable ducts. Then there is the laying of the tracks themselves. After that, all work is carried out from track-based vehicles. This is also the case for the surveying processes.

Installation process of the slab track

On the installation site outside the southern tunnel portal, a 250 m long training/sample track was built. Here all the specifically constructed machinery is tested before being used in the tunnel. Simulations of the interaction between surveying and building processes are also performed at this site.

The planning process sees all work in the tunnel being divided into six sections, each of them between 16 and 20 km long. Two-thirds of the project is being managed from the north tunnel portal at Erstfeld and its northern installation site. The rest is being done from the Biasca installation site in Ticino. Each of the six sections is divided into working phases with a maximum length of 2,160 m. This odd number is due to the length of the rails being used (120 m each). A working phase lasts 20 days, during which the entire superstructure is built. The next working phase begins immediately after the final day of the previous one, i.e., there is no break in the construction. The first section of the tunnel is due to be completed in eight working intervals and, therefore, finished by March 2011.

A working phase consists of the following steps: At the outset, the rails for 2,160 m of track are inserted into the tunnel and put onto the concrete floor. They are fixed with the help of spacers to ensure the correct gauge and are then welded. On the following day, all booted single blocks of the LVT-system are laid out along the entire track. A specially designed wagon puts them in between the rails onto the tunnel floor. In addition, all further equipment needed to fix the track is brought into the tunnel. Hereafter, mounting the track begins with the help of a specially designed shifting system. The mounting itself is done to within an accuracy of ± 15 mm in position and –10 mm in elevation. An initial surveying process, called rough adjustment, moves the track to about ± 3 mm in position and –3 mm in elevation. This is precise enough to carry out the installation of all objects that have to be positioned relative to the track. After completing all track work and just hours before the concrete placement, a last surveying process is executed: the track is precisely adjusted to the design axis with sub-millimetre accuracy in position and elevation. On the seventh day of each 20-day working interval, the concrete placement starts.

With the help of the newly designed mobile concrete factory (based on a 480 m long train) an average of 200 m of slab track is built each day. This factory carries all necessary concrete ingredients (including cement, gravel, water and additives) into the tunnel. On site, the concrete is mixed and each load is checked and verified by the mobile laboratory. A special transportation system (which runs on the shoulders on either side) brings the concrete to the casting site. There the concrete is systematically placed around and beneath the single blocks. The casting itself lasts about 10–11 days and is followed by the various completion works. After 20 days this phase ends and the very next day, the new phase begins.

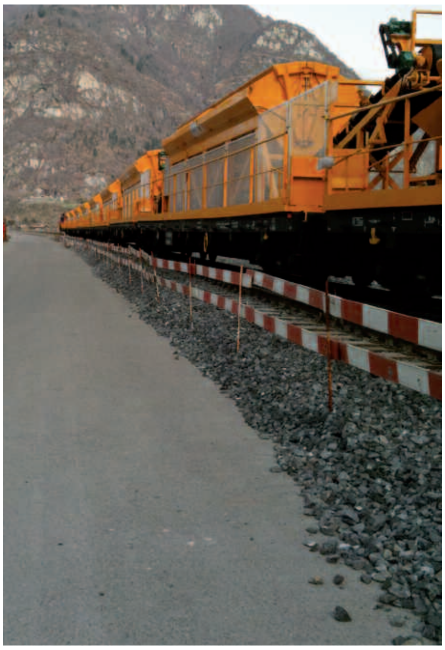


Fig. 3: Cement train heading for the Bodio portal.

Fig. 4: Track laying in the section Bodio – Faido West.

Survey work

All rail technology-related surveying tasks are listed below.

After the hand-over and verification of the project data, such as axis, cross-profiles and surveying points, the dimensions of the completed tunnel have to be checked and verified. Are the floor and shoulders built to within accepted tolerances in terms of position and elevation? This information is very important in order to ensure a smooth installation process for the track. In a further step, survey points are set out every 20 m along a shoulder. These are used as reference points for mounting the track to an accuracy of ±15 mm without the need for surveying staff on site. During this process, rail inclination is also aligned and the single blocks are mounted onto the rails with the correct distance between them.

A track measurement trolley is used to align the track to a very exact degree. The alignment is done in two runs. The accuracy requirements are within a tiny range of just a few tenths of a millimetre. Therefore, the most accurate devices on the market are used. All process steps are optimized in terms of the law of error propagation, in order to get best possible results. Permanent monitoring and reporting of all surveying steps is an integral part of the applied quality management. This includes protocols of the track position before and after the concrete is poured.

All track adjustment processes are realized with the track measuring system from Intermetric GmbH. This system is basing on a fixed laser chord, which determines position and elevation of the track. Leica T30 Total Stations are set up as free stations by using eight surveying points and then measuring the start and end of these chords. After the laser chord is aligned, it is then pointed onto an active target board mounted on the trolley. Depending on the laser position on the active target board, the track position is calculated and the offset of the track to the design position/elevation is shown in real time by the system.

This method ensures a high relative accuracy of the constructed track and one that is far beyond the accuracy of systems without a laser chord. Experience so far has shown that the system ensures the daily performance targets in terms of quantity and quality are achieved.

Thereafter, the stakeout of all remaining railway system installations is done with the help of hydraulic lifts. This includes the overhead wire, radio cable mountings, beacons and signage for the main signals. This is carried out on the section between the portal and the furthermost point of the laid track. This means the track has to be used daily by the train with the mobile concrete factory. All stakeout work, even if far apart, has to be coordi-

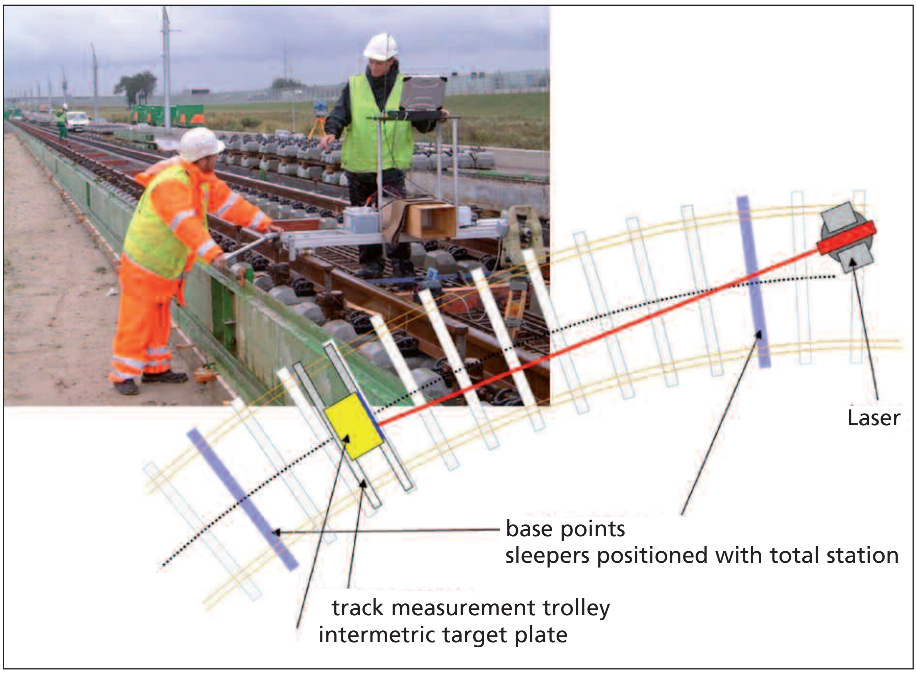


Fig. 5: Functional diagram of the track measurement trolley.

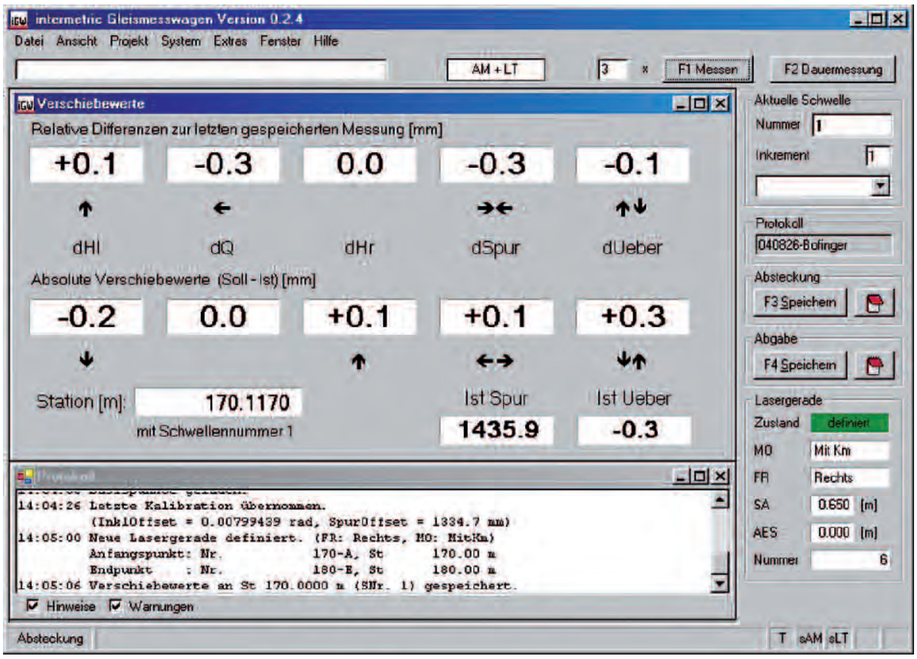


Fig. 6: Measurement screen of the track measurement trolley.

nated within the entire construction process.
After completing the railway technology installation, every single part is measured in terms of its absolute position and the data are imported into the Swiss federal railways' infrastructure database.

This initial phase of the track installation is a very interesting one. The first few hundred-metres inside the tunnel have been built but more than one hundred kilometres have yet to be completed over the coming years. It is immensely satisfying to be part of such an interesting undertaking and to be able to contribute our efforts towards the successful completion of this record-breaking project.

Daniel Stähli
dipl. Kulturing. ETH
Grunder Ingenieure AG
Bernstrasse 21
CH-3400 Burgdorf
daniel.staehli@grunder.ch

Martin Baumeler
dipl. Ing. ETH
Grunder Ingenieure AG
Bernstrasse 21
CH-3400 Burgdorf
martin.baumeler@grunder.ch

Ing Thomas Silbermann
Transtec Gotthard Consortium –
Track Construction
Alpine Bau GmbH
Hansmatt 32
CH-6370 Stans
thomas.silbermann@afttg.ch Illustrations

Measurement Uncertainty of Gyro-measurements in the Construction Works of the Gotthard Base Tunnel

In large tunnel projects like the Gotthard Base Tunnel (GBT), with a length of 57 km, additional gyroscopic measurements are very important contributions of geodetic control measurements. This article once again demonstrates the unfavorable propagation of random and systematic errors in the unavoidably long stretches of the measuring configuration of tunnels. In contrast the increase in of accuracy is discussed when the orientation is supported by gyro measurements. The main emphasis, however, is in the discussion of the influential quantities of these specific measurements and on the realistic estimation of the standard uncertainty of the orientation measurements carried out in the GBT during the whole construction period. Furthermore, it is proven that these measurements could not only increase accuracy and reliability but also reveal by an adequate measurement layout such systematic errors as horizontal refraction.

H. Heister, W. Liebl

Today gyroscopic measurements are an essential contribution to geodetic control measurements in connection with large tunnel construction projects. On the one hand this lies with on the fact that tachometer measurements, in particular with regard to the unavoidably long stretches of the measuring configuration, produce an unfavorable propagation of random and systematic errors. On the other hand, the systematic measuring errors – mainly the horizontal refraction – can hardly be compensated for by modified measuring arrangements.

Although much has already been reported in detail in the past on optimized setups of gyroscope measurements (Tárczy-Hornoch, in 1935, Halmos, in 1972), some differences in error propagation of gyro and tachometer measurements are presented again here as an exemplification.

For a one-sided connected, stretched traverse with n equal legs d and a total length L one can state the approximation formula for the statistical uncertainty of the lateral error as

$$q_w \approx L \frac{s_w}{\rho} \sqrt{\frac{n}{3}} \quad ,$$

in which is the standard deviation of a measured angle.

The same approach can be considered for a gyro traverse in which every leg is oriented by a gyroscopic measurement with a standard deviation S_k. Now the lateral error yields

$$q_k = L \frac{s_k}{\rho} \frac{1}{\sqrt{n}} \quad .$$

In the following Fig. 1 the statistical lateral errors - calculated by both formulae - represented a special but typical case of equal side lengths of *d* = 250 m and different traverse lengths *L*. It should be emphasized again that for the default values of the standard deviations for the angle as well as the gyroscopic measurements, only random measuring errors were presumed. Therefore only a probability of *p* = *68%* can be allocated to the statistical values calculated by both equations. For additional probabilities of *p* = *95%* and *p* = *99%* the appropriate values can be taken as well from the graphs. It should be mentioned that the last case has a special relevance, because the hereby given interval ± *q* can directly be compared with an indicated measuring tolerance.

In summary, however, it can be read from the two graphics that both measuring procedures differ in the expected lateral error by a factor of approximately 20; even by considering only random measuring errors in the traverse measurements it holds that the given measuring tolerance can no longer be kept, especially in longer tunnel constructions. Therefore, additional precise gyro measurements will be inevitable either to increase accuracy or for reliability aspects.

Note, for different reasons it will not be feasible to independently orient every traverse leg with gyro measurements. Therefore, the question that frequently arises is how often and at which positions should gyro azimuths be measured. In principle, this question can be answered properly only for known, practical projects. But there are theoretical considerations that can support at least the decision for this. After Halmos [1976], the optimization problem yields the following solution: in principle only the optimum is then achievable, if the orientation measurements are symmetrically distributed over the total traverse length *L.* Thus, for a free traverse, in which a number of z gyro measurements are planned, the following general rule can be applied:

$$\frac{L}{2z}, \frac{3L}{2z}, \frac{5L}{2z}, \frac{7L}{2z}, \ldots$$

If *z* = *1,* then only one gyro measurement is intended. The location for this measurement lies around *½ L* that means in the middle of the traverse. For *z* = *2* the zones can be quoted as *¼ L* and *¾ L.* For

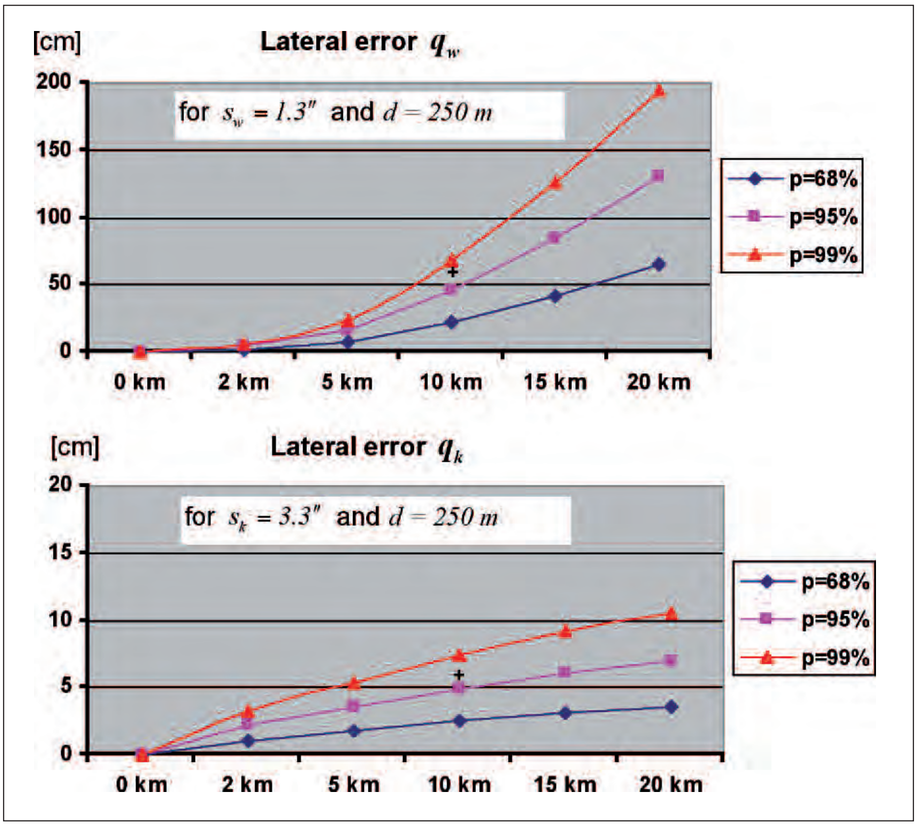


Fig. 1: Statistical lateral errors in stretched traverses, without and with gyro measurements.

z = 3 the zones finally are located at *1/6 L, ½ L* and *5/6 L,* etc.
Through *only one* gyro orientation of q_w the last traverse leg, just before the heading face in a free traverse, the value of q_w can be *cut in half.* If additionally in the *middle of the traverse another orientation* is measured, then the lateral error can be reduced again by the *factor 0.5.* If instead *two* symmetrically distributed gyro azimuths were determined, the reduction *factor yields 1/9* [Jordan, Eggert, Kneißl, 1967, p.582]. This makes clear that by relatively few but accurate gyro measurements the statistical lateral error, even assuming a probability of *p = 99%,* can be minimized considerably within the given measuring tolerance.
These statements are not new, however, the conclusions are based only on the consideration of *random errors* and the herein related experimental standard deviations s_w and s_k. For this reason the focus of the following explanations is to additionally include the main systematic influence quantities, which can occur in tunnel surveys, to the uncertainty budget. These can arise typically in the instrument as well in the environment of the measurements.

The concept of measurement uncertainty

In the last decade in geodetic/surveying measurement techniques the concept of *uncertainty in measurement* became widely accepted. The definition and general rules of *uncertainty* as a quantitative attribute to the final result of measurements was developed in the 1990s and first published in the *Guide to the Expression of Uncertainty in Measurement (GUM)* as an ISO document in 1995 [BIPM, 2008].
The definition of the term uncertainty is, that the measurement result, obtained after correction of all *recognized* systematic effects, is only an *estimate* of the value of the measurand, because of random effects and the imperfect correction for systematic components.
In the preceding explanations for the determination of the expected lateral error only random effects were considered, but this concept allows for the inclusion of systematic errors.
The quantitative evaluation of the uncertainty generally comprises the determination of several components, which may be grouped into two categories:

A: Components, which are evaluated by statistical methods.
B: Components, which are evaluated by other means.

The *components of type A* will be stated by the empirical standard deviation si and its degree of freedom ν_i. The computational methods like least squares, the combination of standard deviations by the law of propagation, and the consideration of correlations are well known to all geodesists. The uncertainty component $u_{Ai} = s_i$, based on these statistical methods, is called the *standard uncertainty.*
The *components of type B* can be regarded as *approximations of an associated standard deviation* and are characterized by $u_{Ai} = s_i$, which is usually based on scientific judgment using all relevant information available. Unfortunately this approach is rarely applied in geodetic metrology. The proper use of the pool of information is a skill that can be learned only with experience and practice. It should be recognized that a type B evaluation of standard uncertainty could be as reliable as a Type A evaluation.
The estimated standard deviation, which can be attributed to a measurement result, is obtained by combining all individual standard deviations, whether arising from a Type A or Type B evaluation and is denoted u_c, *combined standard uncertainty.* It is calculated by the law of propagation of uncertainty:

$$u_c = \sqrt{u_{A1}^2 + u_{A2}^2 + \ldots + u_{An}^2 + u_{B1}^2 + u_{B2}^2 + \ldots + u_{Bm}^2}\ .$$

In a normal case, it is sufficient to report the uncertainty u respectively u_c as a positive value together with the measurement or measurement result. But for some applications, especially where higher confidence intervals are required – e.g., tunnelling – or where the relation to tolerances must be specified, it is advised to indicate an *interval* as a measure of uncertainty. The uncertainty intended to meet this requirement is termed *expanded uncertainty U,* and is obtained by multiplication with the *coverage factor k:*

$U = k \cdot u_c$

In general the range for $k = 2$ is chosen, which will define a level of confidence of approximately 95%. To specify the interval, the value of the expanded uncertainty is quoted with signs ± *U.*

The proper and complete estimation of all influence quantities requires comprehensive knowledge of the internal measuring process of all instruments used, the conception of the measuring method, and finally the effects of the environment. In this context, all classical, statistical methods will not provide a solution to quantify a measure of accuracy, thus approaches are demanded for realistic and representative estimations of Type B uncertainties. This also is meaningful in all cases where the redundancy of the measurand is very poor and, therefore, its empirical standard deviation has a very large variance.

For practical calculations the GUM will provide various possibilities to allow input quantities of different distributions and probabilities:

- normal distribution with a probability of 50%, 68% and 100%;
- uniform distributions in an interval a – to a + ; symmetric and asymmetric with respect to the best estimate of the measurand;

symmetric triangular distribution;
- etc.

This short summary of the guidelines for evaluating and expressing the measurement uncertainty was targeting the application in tunnel survey and particularly for gyro measurements. A more extensive description for calculating standard uncertainties under different probability and distribution requirements is given in Heister [2005a, 2005b] and BIPM (GUM).

Uncertainty components of gyro measurements

With the *GYROMAT* of the Westfälische Berggewerkschaftskasse (WBK, today DMT, Essen, Germany) at the end of the 1970s [Eichholz, K. and Schäfler, 1978] the first automated high precision gyro theodolite was presented and commercially available on the civilian market.

This instrument can be considered as a reference in tunnel projects and was therefore utilized as well by different institutions in the *Gotthard Base Tunnel.* Though this instrument has reached a high level of automation and can look back to a long history of development, there will still remain some quantities of influence, which can affect different types of systematic errors. Some of them may be corrected, but some will still remain and influence the measuring result. All this has to be considered in the uncertainty budget of the measuring result – the gyro azimuth. In principle the uncertainty components can be distinguished in

- instrument related components,
- components due to corrections (reductions),
- components caused by influence quantities of the measuring environment.

It is impossible to discuss all influences in detail in this contribution – for this reason refer to Halmos [1971], Heister [1990; 1992], Korritke [1997], and Grillmayer [2003]. In this contribution, only the most important, prior systematic effects will be discussed.

Stability of the calibration value

Though the band suspended north seeking gyro theodolite is an absolute measuring system, the numerical relationship between gyro and theodolite readings is provided by an instrument constant called the *calibration value E.* Due to assembling of the instrument, transportation and shocks as well due to maintenance and

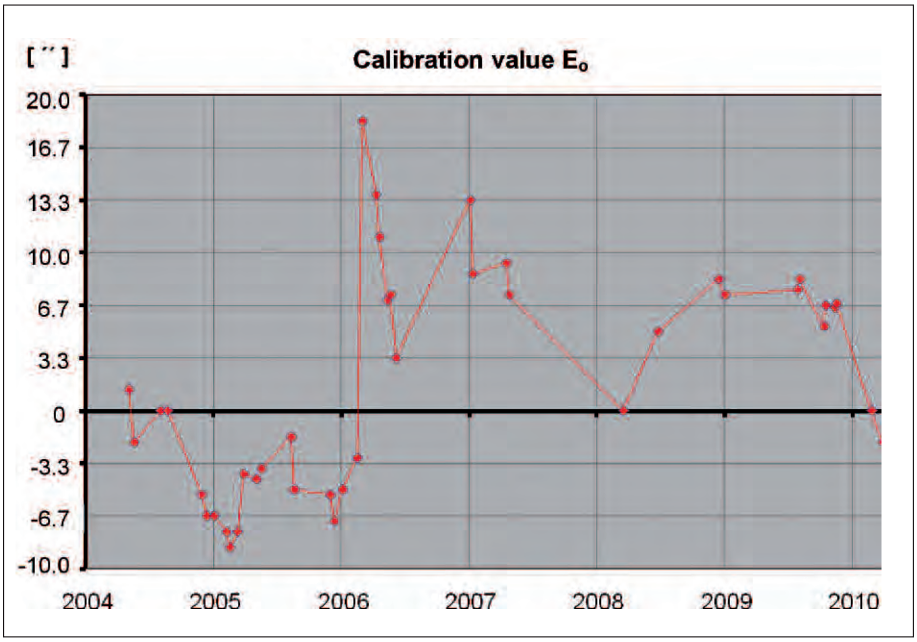


Fig. 2: Changes of the calibration value of the *GYROMAT 2000,* Ser. No. 225 during use in the GBT.

aging this value can change. Therefore it is necessary to regularly check or re-determine this important constant. An important possibility to detect changes of *E* lies in the design of the measuring concept.
Fig. 2 demonstrates the changes in the calibration value of the *GYROMAT 2000,* which was used during construction works of the GBT.

Internal temperature changes of the instrument

The *GYROMAT* is a highly complex opto-electronic but also a mechanical measuring system, in which temperature changes in different components effect measuring errors. This requires a comprehensive test program during the manufacturing process in order to determine temperature dependent corrections. Intensive investigations have revealed [Heister, 1992, Grillmayer, 2003] that nevertheless significant residuals – differing from instrument to instrument – will still remain. For this reason the *GYROMAT* of the Institute of Geodesy was again calibrated independently for these temperature effects. The results are presented in Fig. 3.
From this one can derive a calibration function, which provides individual temperature corrections for each measurement. The reference temperature is 20 °C. Fig. 2 as well demonstrates clearly, that large temperature differences, that may occur in wintertime between measurements taken outside in the portal network and in the tunnel just behind the TBM, cannot be neglected.

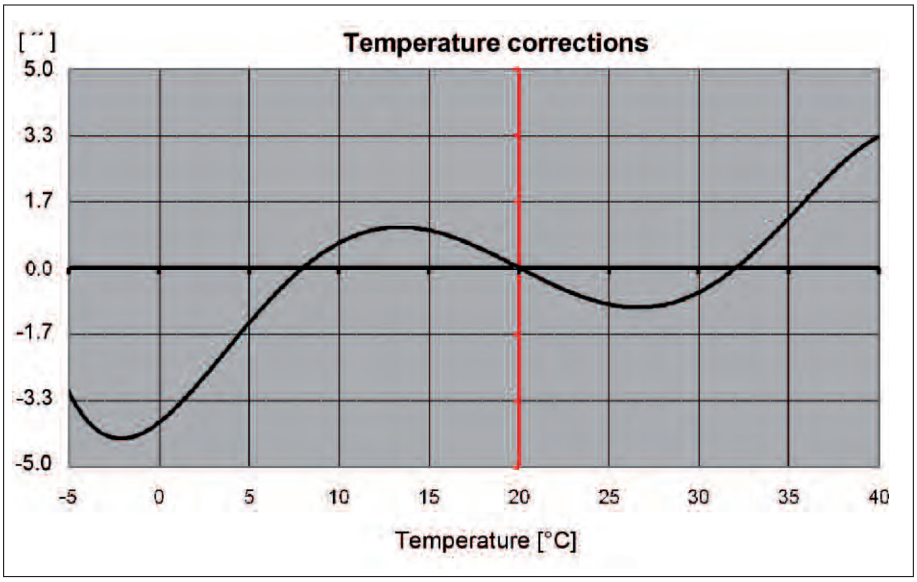


Fig. 3: Changes of the measurand of the *GYROMAT 2000,* Ser. No. 225 as a function of the internal instrument temperature.

Horizontal refraction

The deflection of the optical line of sight by the horizontal temperature gradient produces in almost all geodetic measurements an influence quantity, which causes considerable systematic measuring errors. In particular in tunnel surveys these systematic effects must be observed very carefully. Practical investigations have proved [Heister, 1997] that measuring errors in the horizontal angle of some 10" are no rarity. In principle this phenomenon can be minimized by an appropriate measuring setup. Hence, the following advice should be considered:

- sightings near the wall should be avoided in all cases;
- around the center line of the tunnel a thermally stable area exists that allows almost refraction free measurements;
- diagonal sightings are 70% less influenced by refraction than sightings near the wall;
- for orientation transfer near the portal of the tunnel, the thermally unstable area should be widely bridged.

To estimate possible refraction influences *δ(t)* the following approximation formula can be applied:

$$\delta(t)_{['']} \approx 0{,}11 \cdot D_{[m]} \cdot grd\, t_{[°C\,/\,m]}$$

E.g., for a D = 300 m long sighting and assuming a horizontal temperature gradient of *grd t = 0,3 °C / m* the refraction angle *δ(t)* already yields 10".
All this points out that, on the one hand, the horizontal refraction will influence the accuracy of the lateral error considerably, while on the other hand, the refraction angle *δ(t)* is a function of parameters, which in praxis cannot be captured adequately so that corrections of the measured angles can be determined.
It is still worthwhile to mention that by forward and reverse gyroscopic measurements the refraction influence will become measurable. The difference of both measurements can be explained inter alia by these effects [Heister, 1992]. Therefore gyro measurements are suited to locate sightings, where the influence of refraction potentially may occur.

Gyro measurements in the GBT

In the context of the unique *Gotthard Base Tunnel* project, the Institute of Geodesy of the UniBw Munich, among other technical institutions, was assigned to perform the orientation measurements for monitoring the routine tunnel survey by high precision gyro measurements with the *GYROMAT 2000.* To establish the concept for these measurements, the authors benefitted from the practical experiences at the Lötschberg Base Tunnel.
Control measurements for orientation took place in the five portal networks of Erstfeld, Amsteg, Sedrun, Faido, and Bodio and, of course, in the intervening tunnel sections. In the period between August 2004 and April 2010 six field campaigns took place. In this period with the *GYROMAT 2000,* Ser. No. 225, measurements were performed permanently as

well reference measurements on the azimuth calibration baseline of the Geodetic Laboratory of the UniBw Munich and four extensive temperature calibrations in the environmental chamber.

Concept for the gyro measurements

All measuring procedures for the transfer of orientation were designed so that

- the specified measurement uncertainty of < 3,3" could be ensured,
- all measurements were verified independently,
- changes in the calibration value were detected,

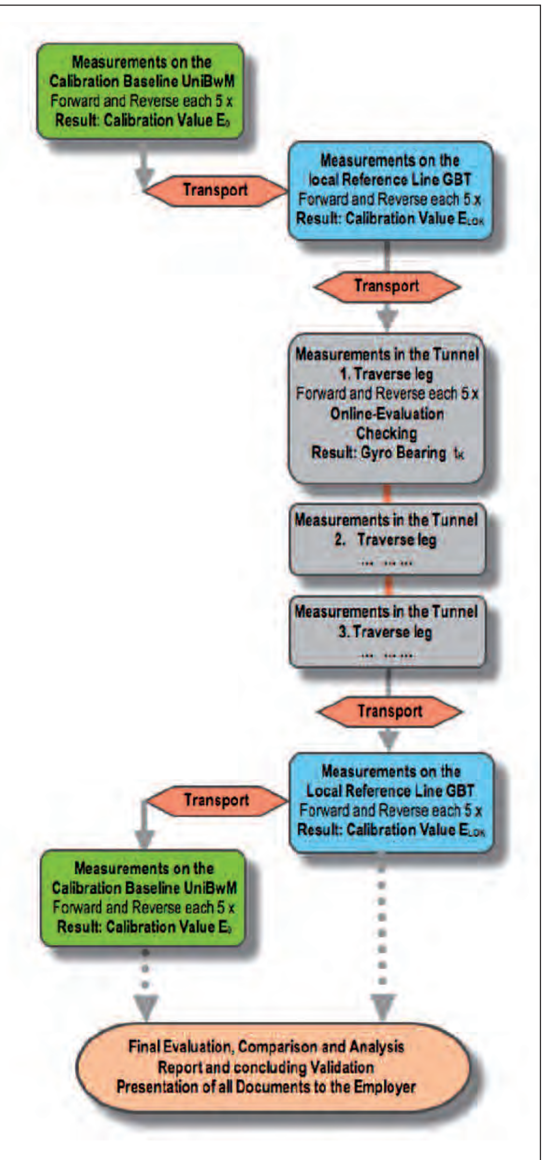


Fig. 4: Operation chart for gyro measurements in the GBT.

- refraction influences were recognized, and
- the stability of the local reference lines could be monitored.

The operation chart for a measuring campaign resulting from these conditions is given in Fig. 4.

All gyro measurements by the *GYROMAT 2000* were controlled wirelessly by a PDA so that manual interventions at the instrument during the sensitive measurement could be avoided. The automated data transfer immediately offered the evaluation including all corrections and reductions of the gyro bearing t_K in the projection system of the Swiss legal survey:

$$t_K = A + E_0 + \Delta E + v_T - dA + da - c + dT ,$$

where

- A the raw azimuth (original gyro measurement),
- E_0 calibration value, determined on the calibration baseline of the UniBw Munich,
- ΔE local correction of the calibration value: $E_{LOK} = E_0 + \Delta E$,
- v_T temperature correction, reference 20 °C,
- dA correction due to the deflection of the vertical,
- *da* reduction due to the height of the target point,
- *c* meridian convergence,
- *dT* reduction of the bearing into the projection system.

Over all in this project 1383 gyro measurements were taken for the following reasons:

- 130 measurements on the calibration baseline of the UniBw Munich, before and after each campaign at the GBT;
- 555 measurements for temperature calibration in the environmental chamber of the Geodetic Lab of the UniBw Munich;
- 100 measurements on the calibration baseline of the UniBw Munich, before and after temperature calibration;
- 598 measurements at the GBT in 116 series of measurements.

Fig. 5: Gyro measurements with *GYROMAT 2000,* Instr. No. 225, version Unibw (wireless controlling, data transfer and evaluation with PDA).

This high magnitude of gyro measurements allows for some statistical analysis concerning accuracy and influences of the environment. First Fig. 6 represents the empirical standard deviations of all single measurements and means of the series of measurements.

Averaging over all series of measurements the following accuracy conclusion can be stated as compiled in Table 1.

The environment outside and inside of the tunnel can be characterized by the prevailing temperatures. These values and the resulting corrections are listed in Table 2.

The differences of forward and reverse measurements on the reference lines and on the traverse legs in the tunnel allow conclusions to be drawn concerning the horizontal temperature gradient and possible horizontal refraction.

The compilation in Table 3 demonstrates clearly that on average – except in a few cases – there was no significant effect of potential horizontal refraction. This indicates as well a good reconnaissance of the local reference lines and a good location of the tunnel traverse. Here the arrangement in the middle of the tunnel was preferred, where we – as already

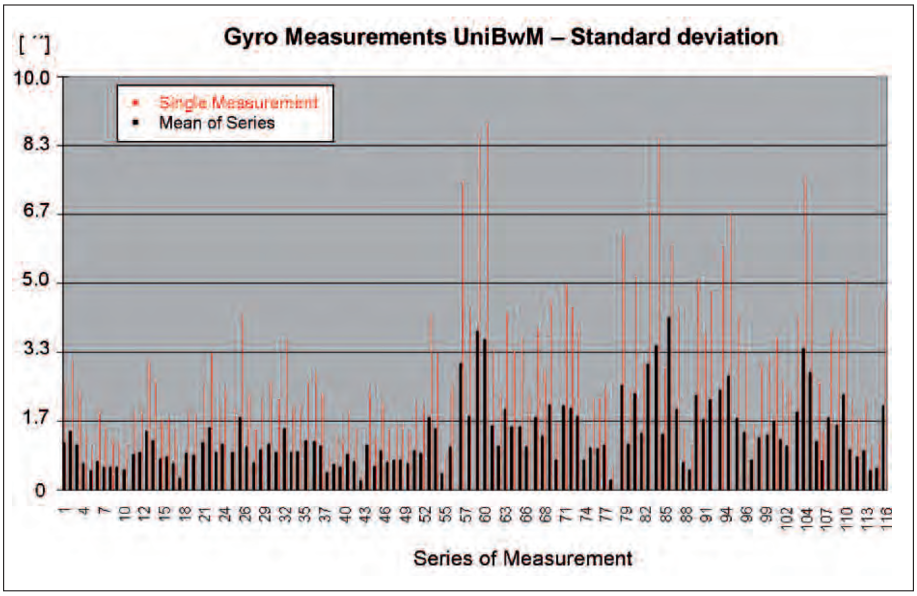


Fig. 6: Standard deviations of the single gyro measurements and the mean of the measurement series.

Standard deviation of	Mean ["]	Minimum ["]	Maximum ["]
the raw azimuth a : s_a	3.4	0.4	8.9
the mean A : s_A	1.5	0.2	4.2
the mean of forward a. reverse measurements $\overline{A}$: $s_{\overline{A}}$	1.1	0,1	2.9

Table 1: Standard deviations of raw azimuths (original gyro measurements).

	Gyro-Temperature [°C]		Temperatur Corr. v_T ["]	
	Portal network	Tunnel	Portal network	Tunnel
Maximum	26.6	31.9	2.3	4.8
Minimum	–5.5	12.7	–4.1	–0.4
Mean	10.2	25.1	–0.9	1.5

Table 2: Gyro temperatures and corrections.

Differences of gyro bearings t_K between forward and reverse	Mean ["]	Minimum ["]	Maximum ["]
Portal network	1.2	0.0	4.5
Traverse legs in the tunnel	1..	0.0	5.3

Table 3: Differences of gyro bearings between forward and reverse measurements.

proved – have minimal influence of refraction. Once again this advantageous measuring set-up has been proven in the GBT project and has positively influenced the error propagation in horizontal angle measurements.

Estimation of influence quantities

To come to a representative quotation of the measurement uncertainty of gyro measurements according to the GUM, it is necessary to estimate as completely as possible the uncertainty components of a Type A and Type B evaluation. In agreement with formulae given above and the systematic effects discussed in the previous paragraphs, we can assemble the following uncertainty budget:

1. Measurements on the reference line in the portal network and determination of the local calibration value E_{LOK}.

Gyro measurement (mean of forward a. reverse) (s. table 1)
$u_{\overline{A}\ ref}$ = 1.2″ (Typ A)

Temperature correction v_T
(s. calibration sheet)
u_{v_T} = 0,7″ (Typ A)

Correction for the deflection of the vertical dA
with s_η = 0,5″ yields approximately $s_\eta \approx u_{dA}$
u_{dA} = 0,5″ (Typ B)

Locally derived bearing t_R
u_{t_R} =1,3″ (Typ B)

Centering error of the instrument e
e = ± 0,3 mm (uniform distribution)
u(e) = 0,58 e = 0, 17 mm (s. Heister, 2005 a,b)
assuming for the distance 500 m between instrument and target point
u_e = 0,1″ (Typ B)

Horizontal refraction can be neglected, as there was no significant detection at all GBT measurements.

Following the law of uncertainty propagation for the local calibration value E_{LOK} the combined standard uncertainty yields:

$$u_{E_{LOK}} = \sqrt{1.2^2 + 0.7^2 + 0.5^2 + 1.3^2 + 0.1^2} = 2.0''$$

2. Gyro measurements of the traverse legs in the tunnel (analog to 1.)

Gyro measurement (mean of forward a. reverse)
$u_{\bar{A}} = 1{,}2''$ (Typ A)

Temperature correction v_T
(s. calibration sheet)
$u_{v_T} = 0{,}7''$ (Typ A)

Correction for the deflection of the vertical *dA*
with $s_\eta = 1{,}0''$ yields approximately $s_\eta \approx u_{dA}$
$u_{dA} = 0{,}5''$ (Typ B)

Centering error of the instrument *e*
e = ± 2,0 mm (uniform distribution)
u(e) = 0,58 *e* = 1,2 mm (s. Heister, 2005 a,b)
assuming for the distance 350 m between instrument and target point
$u_e = 1.0''$ (Typ B)

3. Uncertainty budget for determination of orientation of a tunnel traverse leg (s. previous formula for calculation of a gyro bearing)

For the combined standard uncertainty of the gyro bearing t_K we obtain

$$u_c(t_K) = \sqrt{u_{\bar{A}}^2 + u_{E_{LOK}}^2 + u_{v_T}^2 + u_{dA}^2 + u_e^2}$$

Regarding the numerical values, obtained under 1. and 2.

$$u_c(t_K) = \sqrt{1.2^2 + 2.0^2 + 0.7^2 + 1.0^2 + 1.0^2}$$

and finally

$u_c(t_K) = 2.8''$.

Attributing a grade of confidence to the gyro bearing of the tunnel traverse leg (analog to the statistically defined confidence interval) one can state with the coverage factor *k = 2* the expanded uncertainty

$U(t_K) = k \cdot u_c(t_K) = 2 \cdot 2.8''$

Hence the expanded uncertainty of a gyro bearing derived from the orientation of the portal network yields for the GBT project

$U(t_K) = \pm\ 5{,}6''$

This accuracy statement can be regarded as an interval, in which with a probability of approximate 95%, the measuring result can be located.

Final conclusion

It was demonstrated that in large tunnel projects, where lengthy stretches of measuring configurations cannot be avoided, gyroscopic measurements are indispensable, for accuracy augmentation as well as for reliability. Additionally we can obtain important information with regard to the instantaneous measuring environment and the resulting systematic effects. The gyroscopic measurements, carried out at the Gotthard Base Tunnel, have shown that the measuring concept of orientation transfer has led to reliable measuring results. Even over the long duration of this project, changes in the local reference lines in the portal networks could be detected. The intended objective to provide for the independent orientation transfer of an uncertainty of better than 3.3″ was clearly reached. With this high accuracy, it could be verified significantly that the proven measuring configuration in the middle of the tunnel (Heister, 1992, Korittke 1997) prevented largely systematic effects, e.g., horizontal refraction.

Finally it can be pointed out that the compilation of an uncertainty budget in accordance with the Guide to the Expression of Uncertainty (GUM) can offer, aside from the introduction of statistical quantities, the consideration of additional information including practical knowledge of specific measuring procedures [BIPM, 2008]. Hence, a much more representative quantification of the specific measure of accuracy, the uncertainty, is given. In particular, the statement of the expanded uncertainty, an interval similar to the tolerance, can facilitate the interpretation and use of the derived results for all colleagues not so familiar with statistical estimation theories.

References:

BIPM (GUM) (2008): Evaluation of measurement data – Guide to the expression of uncertainty in measurement. JCGM 100.

BIPM (2008): Evaluation of measurement data – Supplement 1 to the «Guide to the expression of uncertainty in measurement» – Propagation of the distributions using the Monte Carlo method, JCGM 101.

Eichholz, K. und Schäfler, R. (1978): «Gyromat», ein automatischer Vermessungskreisel hoher Genauigkeit und kurzer Messzeit. Mitteilungen aus dem Markscheidewesen, Jg. 85, S. 281–293.

Grillmayer, E. (2003): Untersuchungen systematischer Fehlereinflüsse bei Messungen mit dem Kreisel DMT Gyromat 2000. In: Brunner, F.K, (Hrsg.): Schriftenreihe des Instituts für Ingenieurgeodäsie und Messsysteme der technischen Universität Graz, Shaker Verlag, Aachen.

Halmos, F. (1971): Systematic and random errors of direction measurements with gyrotheodolites. MOM Review, 4, S. 24–32.

Halmos, F. (1972): Zeitbedarfs- und Genauigkeitsuntersuchungen bei Polygonierungen mit Orientierungs- und Winkelmessungen. Das Markscheidewesen in den Sozialistischen Ländern, Bd. 6, S. 5–67.

Heister, H., Lechner, W., Schödlbauer, A. (1990): Zur Genauigkeit und Kalibrierwertstabilität automatisierter Vermessungskreisel. In Schödlbauer, A.: Moderne Verfahren der Landesvermessung, Schriftenreihe des Studiengangs Vermessungswesen der Universität der Bundeswehr München, Heft 38-2, S. 501–528.

Heister, H. (1992): Zur Anordnung von Kreiselmessungen unter besonderer Berücksichtigung von systematischen Fehlereinflüssen. In: Matthias, H.J., Grün, A.: Ingenieurvrmessung 92, Beiträge zum XI. Internationalen Kurs für Ingenieurgeodäsie, Bd. 1, Ferd. Dümmler's Verlag, Bonn, S. I 7/1–7/ 14.

Heister, H. (1997): Experimentelle Untersuchungen zur Horizontalrefraktion im Tunnelbau. In: IX. Internationale Geodätische Woche Obergurgl 1997 – Fachvorträge, Institut für Geodäsie, Universität Innsbruck, Institutsmitteilungen, Heft 17, S. 79–91.

Heister, H. (2005a): Zur Messunsicherheit im Vermessungswesen (I). Geomatik Schweiz, Geoinformation und Landmanagement, 11/2005, S. 604–607.

Heister, H. (2005b): Zur Messunsicherheit im Vermessungswesen. Geomatik Schweiz, Geoinformation und Landmanagement, 12/2005, S. 670–673.

Jordan/Eggert/Kneissl (1963): Handbuch der Vermessungskunde. Band II, Metzlersche Verlagsbuchhandlung, Stuttgart, S. 572 ff.

Korittke, N. (1997): Zur Anwendung hochpräziser Kreiselmessungen im Bergbau und Tunnelbau. Geodätische Schriftenreihe der Technischen Universität Braunschweig, Nr. 14.

Tárzcy-Hornoch, A. (1935): Die durch den Einrechnungszug erzielbare Orientierungsgenauigkeit. Mitteilungen der Berg- und Hüttenmännischen Abteilung, Sopron.

Prof. Dr.-Ing habil. Hansbert Heister
Dipl.Ing. Wolfgang Liebl
Institute of Geodesy of the UniBwM
DE-85577 Neubiberg
h.heister@unibw.de

Automatic Monitoring of large Dams in the Swiss Alps during Construction of the Gotthard Base Tunnel (57 km)

A variety of automated geodetic measuring systems have been installed at the three dams, Curnera, Nalps and Sta. Maria, in the Swiss Vorderrhein valley to monitor possible terrain deformations caused by the construction of the Gotthard Base Tunnel. After several years of experience it can be said that the systems serve the intended purpose, that valley sides – contrary to expectations – experience natural cyclic movements, and that the impact of the tunnel construction can be significantly measured at the earth's surface.

D. Salvini, M. Studer

1. Introduction

1.1 Initial situation

In spite of the depth of rock of up to 2500 m, tunnelling of the 57 km Gotthard Base Tunnel through the Swiss Alps is noticeable at the earth's surface. Mountain water emerging from the subsurface and running off through the tunnel results in drainage of the rock. This leads to subsidence at the earth's surface. Based on theoretical analysis, these subsurface dynamics were already understood during the planning phase. It was shown that surface subsidence of several centimetres could occur near the dams if appropriate measures, such as systematic and rapid sealing, are not taken during the tunnel drive. Such ample subsidence cavities can reach an expanse of several kilometres and may cause closures, openings and shear movements of opposite valley sides (Fig. 1).

On the basis of the predicted surface deformations, the impacts on the three dams – Curnera (height 153 m, crest length 350 m), Nalps (height 127 m, crest length 480 m) and Sta. Maria (height 117 m, crest length 560 m) – in the Swiss Alps have been studied more closely. The line of the 57 km Gotthard Base Tunnel passes underneath the dams' area of influence. Risk analyses have been conducted that assessed the probability of the occurrence of a damaging event as very small, but the resulting damage as very large. Therefore, a variety of risk reduction measures have been imposed. Among other things, it was decided to intensify the monitoring of the terrain surface in the vicinity of the three dams with regard to the specific requirements of tunnel construction. A three-level concept was proposed for this purpose. At level 1, comprehensive geodetic measurements are performed every 5 years, and the dam operators implement manual and automated monitoring. Permanently installed devices like plummets, seepage water meters, and gap measuring devices check the dams continuously for possible changes. Level 2 is comprised of special distance and angle measurements, which in some cases are performed several times per year. This paper elaborates only the concept and implementation of the level 3 monitoring system and the experience after 10 years of operation. The third level is comprised of monitoring measurements on behalf of AlpTransit Gotthard AG, the builder of the Gotthard Base Tunnel, for the control of project risks when passing underneath the dams.

1.2 Assignment

The broad scope of level 3 includes the wide area monitoring of the terrain in the vicinity of the three dams in the Alps (approx. 2000 m asl). More specifically, it involves the mapping of the natural state of the terrain at geologically representative locations before any possible impact by the tunnel construction. Furthermore, the natural behavior of the terrain is to be understood and the surveying systems are to be calibrated accordingly. The third and probably most important task is the immediate and reliable detection of unusual surface movements during tunnel construction that compromise the safety of

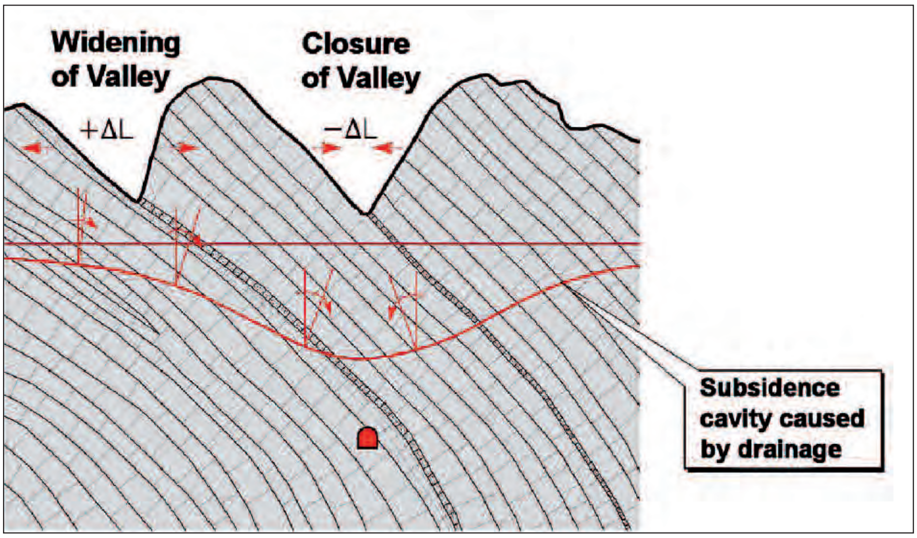


Fig. 1: Schematic representation of mountain drainage.

the dams and require an immediate stop of the tunnel drive.
During the implementation of such a monitoring system, the requirements of the client regarding accuracy (valley side movement ±4 mm, height changes measured by levelling 2.5 mm/km) and reliable accessibility of results had to be taken into account. Also, the challenges of the installation and year-round operation of surveying systems in alpine surroundings during at least 12 years under the most adverse climatic conditions and facing natural hazards (avalanches, lightning) were not to be underestimated.

2. Implementation

2.1 Concept

The concept offered by the contractor, a consortium of three surveying companies under the leadership of BSF Swissphoto AG, suggested a multi-level monitoring system that makes use of individual strengths and advantages of different geodetic measuring technologies. The dams and their immediate surroundings are monitored by automated total station systems. Each monitoring object is equipped with one or two precision total stations, which execute measurements of angles and distances at prisms. The prisms are either directly attached to the rock or placed on surveying pillars several metres high surveying pillars due to the depth of snow expected in winter. Coordinates of each prism are derived daily from these measuring elements. Based on a comparison of the spatial position of two points, transverse and longitudinal movements relative to the valley and movements in height can be determined directly (Fig. 2).
Autonomous GPS measuring stations, also year-round record selective information on possible terrain movement. Precision levelling along roads or through pressure tunnels is used to determine with high accuracy the spatial extent and the depth of wide-area subsidence with high accuracy. If levelling continues far enough beyond the subsidence cavity, absolute height movements can be derived.

2.2 Construction and Sensors

Off-the-shelf equipment was used for the geodetic sensors and the accessories of the automated measuring systems. Even for most of the electric and electronic devices, standard components could be used. The big challenge during the installation of the measuring system was the choice of the right materials, mountings, and data communication solutions. They had to be optimized for each location in order to implement a system that could properly function year-round under the local conditions. The harsh mountain climate presents tough challenges for all installations: neither low temperatures or strong winds, nor large amounts of snow or electrostatic discharges of thunderstorms must interrupt the availability of the measuring system longer than one day (Fig. 3).
Monitoring the cross sections was implemented by putting two total stations on each of the three dam crests, and by installing one total station either on the bottom or on a side of the valley in each of the three fore field cross sections (see Fig. 2). Including an additional tachymeter installed as a connection between one dam and fore field cross section; ten total stations have been in operation since 2000. Monitoring of single height benchmarks is achieved by ten dual frequency GPS receivers. When choosing the GPS sites, natural hazards (e.g., avalanches) had to be taken into account in addition to the geological situation. The individual GPS measuring stations are equipped with an independent power supply (solar) and da-

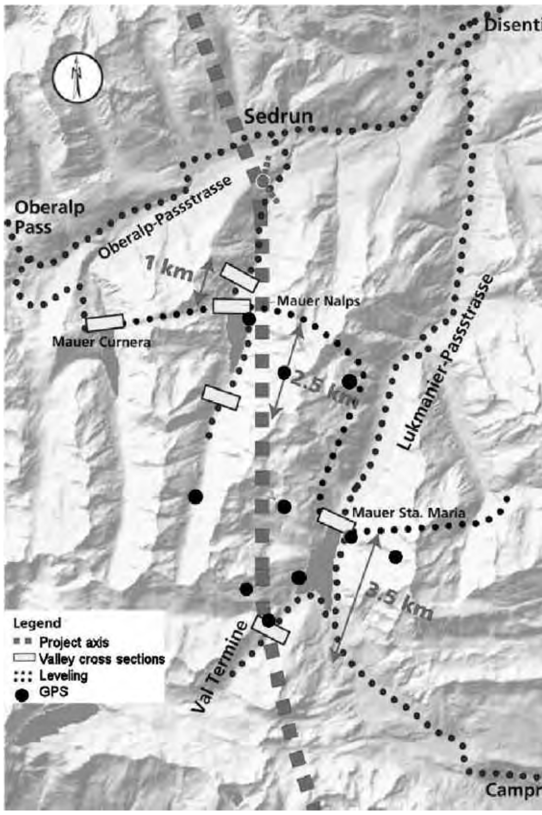


Fig. 2: Monitoring perimeter and measurement methods.

Fig. 3: Impressions of installation works.

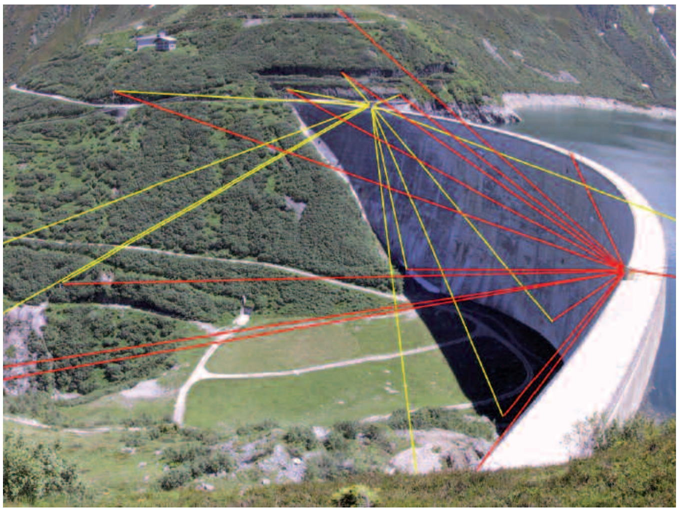


Fig. 4: Panoramic view of total station network in Nalps.

Fig. 6: GPS station above Nalps dam.

ta communication (GSM network). Furthermore, six multiple extensometers have been installed and integrated into the automated measuring process on the fore fields of the Nalps and Sta. Maria dams. These extensometers are expected to register possible rock movements in the immediate vicinity of the dams.
From organization of processes and uninterrupted data flow via the programming and automation of data processing through to submission of results, a high level of technical and professional know-how is required. After some constructional improvements based on the experiences of the first winter experiences the measuring systems achieve an availability of nearly 100% all year round.

2.3 Operation of measuring systems

The automatically operated tachymeter systems measure the surrounding monitoring points at hourly intervals at night. Meteorological data required for the computation of the exact three-dimensional coordinates of the points are recorded concurrently with the geodic measurements. The data measured nightly are preprocessed the following morning by the control computers on site and transferred via email to the computing center in Regensdorf where they are processed automatically. Before the submission of results, an engineer checks the most recent graphs to ensure that no obvious errors are present in the submission data. Despite mature processing algorithms and filter methods, one cannot rule out the possibility that isolated errors may grossly distort the results.
The GPS measuring stations are controlled directly from the computing center. They record the satellite signals weekly during the nights from Friday to Monday. The transmission of data to the computing center is also done automatically, but the data processing and analysis is done manually.
Levelling is limited to the snow-free season (usually May to October). In August and September, two teams of three surveyors measure a levelling network of nearly 100 km in length along roads, trails and pressure tunnels, according to the quality standards of the Swiss federal levelling network (Fig. 4).

2.4 Processing of measurements

Usually, deformation measurements rely on points that are assumed to be fixed and not subject to movement. In the present case, however, terrain movements must be expected in wide areas, thus the evaluation concept must be adapted, i.e., the tie points are considered observation points at the same time. For this purpose, geodetic statistics provide the adjustment method of so-called stochastic network fixation positioning.
Based on the spatial distribution of the points in the monitoring area, point pairs can be established that describe the transverse and longitudinal movements relative to the valley and also movements in height within a certain period of time. The information is summarized numerically in the form of a half-full matrix and provided to the client. The results are also plotted graphically as time/path diagrams for easier legibility and interpretation (Fig. 5).
GPS measurements are processed with

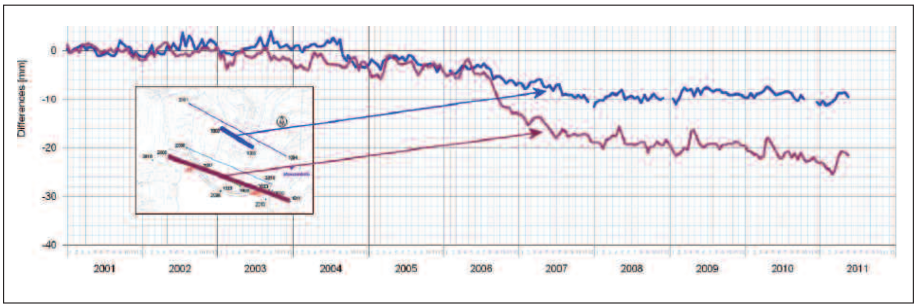


Fig. 5: Graphic representation of valley closure near Nalps dam.

the standard GPS manufacturer's processing software and subsequently improved using an expanded meteorological correction model. This is necessary in order to reach the highest accuracies with meteorologically affected GPS measurements. The annual levelling is processed after completion of the measuring campaign by means of an overall adjustment. The results are also edited in numerical and graphical form (Fig. 6).

3. Results

The first years of operation surveyed the state of the terrain surface when the construction of the Gotthard Base Tunnel was still several kilometres away from the monitoring area. During this time, the normal behavior of the terrain was established, and the instruments and processing methods were calibrated. Unexpected valley openings between the beginning of summer and the end of winter and rapid valley closures in early summer were observed. These movements show a cyclic correlation with the seasons and thus with the level of mountain water. These seasonal, reversible movements were detected in all valley cross-sections, however, to varying degrees. The maximum cyclic movements amount to up to 16 mm between points on opposite valley sides. Similar seasonal variations were observed at the GPS measuring stations. With the approach of construction from north and south, irreversible movements on the terrain surface were detected, which undoubtedly had a causal relationship with the construction of the Gotthard Base Tunnel. They came in the form of subsidences and concurrent valley closures (see Fig. 5). Movements ranged from millimetres to centimetres depending on location with a maximum subsidence of 6 cm at the moment. Due to the comparatively small amount and uniformity of the movements in the vicinity of the dams, neither theoretical hazards nor damages of the dams to any kind have been noticed.

Even the behavior of the GPS points is clearly affected by the tunnel drive. The positions of all measurement stations move in the direction of the tunnel axis, and subsidences in the range of centimetres have been detected.

4. Findings and conclusions

The entire measuring system has now been in operation for 10 years and is delivering reliable and accurate results on a daily basis. During this time, valuable findings have been collected that have also attracted interest outside the geodetic world:

- Due to changing ground and mountain water levels, seasonally recurring valley openings and closings in the range of centimetres occur in mountain valleys. Up to now, this phenomenon was unknown even to geologists.
- By levelling, a subsidence cavity can be monitored in «absolute» terms. However, the network must be designed large enough so that tie points are positioned outside the subsidence area. Furthermore, using the same levelling paths for several years has proven very successful. In doing so, long term movements can be interpreted much more reliably and usually far below the significance threshold according to the theoretical measurement accuracy.
- Autonomous GPS measuring stations can be operated reliably even in an alpine environment. Provided careful processing and trend analysis are performed, they meet the highest accuracy requirements in the millimetre range.
- The combination of manual and automated measuring systems has proved ideal in various ways between the conflicting priorities of maximized safety and an economical use of financial resources.
- In order to eliminate or minimize errors that cannot be compensated for (e.g., induced by temperature), special actions must be taken (e.g., limitation to night measurements, periodic calibration of total stations by the manufacturer, and so forth).
- The combination of manual and automated data flow and analysis processes has two advantages: automated processes are time efficient and avoid human errors, while the surveying specialists, using their know-how, check the plausibility of results before they are submitted to the client.
- Wide areas of interest must be monitored with sufficient lead-time in order to establish the situation unaffected by construction activities and to properly calibrate the measurement systems.
- Regular reporting to and exchange with the client ensure an equal understanding of the measuring systems and their limitations (e.g., as a result of short-term adverse weather conditions). This is equally valid for the interpretation of the resulting tables and graphs.

Dante Salvini
Mario Studer
BSF Swissphoto AG
Dorfstrasse 53
CH-8105 Regensdorf-Watt
dante.salvini@bsf-swissphoto.com
mario.studer@bsf-swissphoto.com

Versatile surveying outside the tunnel at Altdorf–Erstfeld, Amsteg and Faido

Since 1995, IG GEOSWISS has carried out the constructor's surveying assignments on behalf of AlpTransit Gotthard AG (ATG). The work covers a wide spectrum of engineering surveying tasks: maintenance of the control network, pictures for project planning and documenting the implemented buildings, analysis of buildings, staking out of the principal axes, and monitoring various objects in order to detect deformations. All those tasks are challenging for the surveying specialists who sometimes must operate in very confined spaces and sometimes on vast building sites. Depending on the assignment, the surveyors have to fulfill different requirements in terms of precision. The work has to be completed according to schedule in order not to jeopardize the functioning of the huge NEAT building site. And sometimes a strong foehn or heavy rains require even more efforts from the surveying teams.

U. Bättig, S. Bühler, D. Eberhart, R. Bänziger

IG GEOSWISS

In 1995, the engineering association IG GEOSWISS was assigned the survey work for the construction sites outside the Gotthard Base Tunnel at the Altdorf/Erstfeld, Amsteg, and Faido sections. The IG GEOSWISS is composed of four engineering firms. These are:

- Gruner AG, Basel (BS)
- Kost + Partner AG, Sursee (LU)
- Markwalder & Partner AG, Burgdorf (BE)
- Ingenieurbüro Robert Bänziger, Niederhasli (ZH)

The management lies with Gruner AG. Together and on behalf of ATG, we carried out the surveying tasks at the outstations of VI Nord (surveyor Nord), VI-A (surveyor Amsteg) and VI-F (surveyor Faido).

Task

On behalf of ATG, IG GEOSWISS carried out the builder's surveying assignments at the exter-nal construction sites (outstations) of Altdorf/Erstfeld, Amsteg, and Faido (see pictures 1, 2, and 3). Work included densification and maintenance of the basic control network at the construction sites, layout work, control and monitoring, as well as different mostly smaller surveying tasks on behalf of the construction management and the local site management.

Control network Altdorf to Erstfeld

One of the main tasks aside from the surveillance and control work lies in the densification and maintenance of the geodetic base network (NetzGBT) at the construction site. This serves the companies as a basis for their surveying work and for specific building layout work, control, and monitoring.

Building site control network

The building site control network is mainly based on the governing base system NetzGBT of ATG and constitutes a densification of that system. Aside from the so-called NetzGBT, the geodetic points of the Swiss Federal Railway (SBB) rail network are also included in the determination of the building site's basic control network. It thereby becomes possible to assure that the construction work, while taking into account the required accuracy of the geodetic points, can be adapted in an ideal way to existing infrastructures.

Today, the building site control network in the Altdorf/Erstfeld sector contains about 120 points.

Required accuracy and determination methods

The accuracy requirements for the construction work are stringent. Therefore, the control network used has to satisfy certain minimum requirements with respect to accuracy. Basically, the accuracy between neighboring points may not exceed 15 mm in position and height.

The determination of the position of the geodetic points is done terrestrially with the help of total stations: the determination of height through levelling. Due to this choice of method, the required accuracy can be achieved. The obtained accuracies in all areas lie within the subcentimetre range.

Maintenance

As a result of intensive construction activity at the different sections, the maintenance of the control network is of upmost importance. Damaged geodetic points and «broken» sight lines are daily occurrences. In order to ensure accuracy over the long term, new points are secured as often as possible with SBB-bolts on or at the buildings.

Due to the speedy construction progress and the newly erected buildings or excavated material storage, the visibility between control points can rapidly change. For this reason, the site control network constantly alters and has to be regularly completed with new points.

Control points for precision monitoring

For the millimetre-precise monitoring of objects, as for instance the SBB main line, local networks are used on the building site control network. With these local networks, which are exclusively used for

Fig. 1: Overview of the construction site of Altdorf/Rynächt up to the section of Erstfeld.

these special monitoring tasks, accuracies in the range of 1 σ = ± 1 mm can be achieved. For the settlement measurements performed by levelling, the attained accuracies lie within the sub-millimetre range.

Monitoring

The task of VI (surveyor) is to monitor deformations of various objects, namely natural objects, existing structures, and new ATG buildings. According to the object, different accuracies and monitoring intervals are required. There are two main reasons for such monitoring: on the one hand, the safety of the ATG building sites, and on the other hand, the security and unlimited functionality of the existing infrastructures have to be guaranteed.
Most monitoring tasks are performed to guarantee the safety of the existing infrastructures and for the early detection of deformations in order to take appropriate measures. Some objects are also monitored, for evidence-protection, to document structural damage caused by deformations. As there are a great number of infrastructures in a confined zone, which often lie inside the construction perimeter at the ATG building areas from Rynächt to Altdorf, in Amsteg, and in Faido, a great number of monitoring tasks are necessary. The objects to be monitored have been included by ATG in a global monitoring concept. In the following, typical examples of objects to be monitored are described in more detail.

Altdorf/Erstfeld SBB main line – the centerpiece

The longest and certainly most important object to be monitored is the SBB main line between Altdorf and Erstfeld. The SBB tracks are monitored over a distance of approximately 3.6 km. This monitoring can be considered as the centerpiece of all monitoring. Thus at the center is the security and the guarantee of free north-south circulation: the rail traffic may not be restricted by the construction work, which takes place very close to the existing SBB tracks. The whole monitoring perimeter is divided into 7 sections, whose monitoring intervals vary according to construction activity. In the sectors with high building activity the controls take place every week, and in the sectors with low building activity only twice a month. The monitoring accuracies in position and in height lie in the range of 1 σ = ± 2 mm. To achieve such accuracies, an individual control network has been created. In this network, the «free station method» is used. The SBB catenary support poles are monitored. They were equipped with reflecting foil and can thus be measured without stepping on the railway tracks. The results are used by ATG management as well as by SBB experts as a basis for possible interventions.

Railway bridge Altdorf/Erstfeld, track and sheet pile wall Stille Reuss

Next to the existing railway bridge over the Stille Reuss another railway bridge was built, on which the approach tracks

Fig. 2: Overview of external structures and Amsteg section access tunnel.

of the Gotthard Base Tunnel will lie in the future. As the building works were approaching the existing tracks up to about 1 m and were also touching the existing railway bridge structure, additional local monitoring had to be set up. The monitoring of the SBB main line could not sufficiently cover the local needs with the catenary masts. A special monitor-ing concept was required. The existing SBB tracks, the bridge superstructure as well as the bridge foundations were monitored. In a later phase, the sheet pile walls for the excavation safety of the new railway bridge were also monitored.

During the first phase, when the sheet pile walls were driven in overnight at a distance of one metre beside the tracks, the tracks had to be measured in lengths and height and the super elevation/distortion on both tracks had to be controlled over a distance of approx. 50 m every morning between 4.30 and 5.00 o'clock. The evaluation had to be done reliably on site within half an hour in order to allow for the possible use of the tamping and straightening machine between 5.00 and 6.00 o'clock, because at 6.00 o'clock the main line had to be open for the rail traffic on both tracks. The required accuracies for height and position were in the range of 1 $\sigma = \pm 1$ mm. An intervention of the tamping and straightening machine became necessary at a position shift of > 4 mm, subsidence of > 20 mm, or distortion of > 2‰. At the bridge, different values applied for subsidence: alarm value = 50 mm and intervention value = 100 mm.

For monitoring, the method of «free station» again was used. The tracks were controlled with a track gauge and the bridge with permanently mounted SBB track displacement measurement systems. This made it possible to very rapidly control the position and level of the track centerline as well as the super elevation. The control-values were summarized in tables and continuously discussed with the SBB experts.

In the second phase, during the construction work of the bridge, a weekly monitoring was required. The monitoring concept was maintained, as it was equally useful for the weekly monitoring under traffic. Also during this second phase, the sheet pile wall monitoring was initiated.

Altdorf/Erstfeld RUAG Reusshalle

The RUAG Reusshalle in Altdorf is an example of an object to be monitored that is situated outside the construction perimeter. The high precision machines, installed in the hall, are very sensitive to tilting and shock. For this reason, the hall was monitored using two different methods. On the one hand, a precision levelling was done for the evidence-protection inside the hall to observe the settlement behavior due to the adjacent building activities; on the other hand, vibration mea-

Fig. 3: Overview of landfill site Chiggiogna/Cavienca, south of the Faido access tunnel.

surement devices were installed next to the shocksensitive machines and a limit value for vibrations was fixed. The vibration measurement instruments recorded the vibrations at given sampling intervals. The results could be viewed online by the management.
As vibration measurement devices secured the permanent monitoring, only a reference survey and a final survey were done with the levelling. The accuracy of the levelling was 1 $\sigma = \pm 0.3$ mm.

Faido landfill site Chiggiogna/Cavienca and Polmengo
In Chiggiogna/Cavienca and Polmengo landfill sites were implemented between 2000 and 2002 near the main road and the railway line. In Polmengo, it is a temporary deposit that will be completed. In Chiggiogna/Cavienca (see picture 3), a permanent landfill is being created. For this reason, the existing infrastructures, particularly the existing Gotthard railway line, needed to be monitored. As a result of detected movements during the ground survey, the measurement range was continuously extended concerning the number of objects to be monitored and the expansion of the zone. Today, the following infrastructures are monitored in position and height over a distance of nearly 2 km: the foundations of the catenary support poles, the protective wall along the railway line, the main road near the railway line, and terrain points (Golena-points). All the points requiring monitoring are situated in a very confined area. Similar to the Altdorf/Erstfeld SBB mainline, the security and the unobstructed north-south circulation are priori-ties.
The responsible project engineer initially defined the measuring intervals of the subsequent surveys of the different objects. Today they range from biannual surveys, to quarterly surveys, to monthly surveys during critical phases. Position is measured tachymetrically with free stations and the height with precision levelling. The accuracy for the monitoring of position is $1\sigma = \pm 2$ mm and for height $1\sigma = \pm 0.5$ mm. It was particularly challenging to place the control points on safe terrain. For the position, three control points were mounted on consoles on the opposite rock. The rock had to be chosen as a solution because the entire valley basin is situated in the monitoring perimeter and is subjected to movements. At the beginning, the height control points were situated on the railway track outside the monitoring perimeter. During the basic measurements, however, it was discovered that the height control points were also subjected to movements. For this reason, the monitoring perimeter had to be extended gradually, and the geodetic points were fixed in the network of cadastral surveys at the rock faces and in the villages, far outside the monitoring perimeter.
Important differences in subsidence and position shifts have been noted spatially. But the settlements and position shifts of the individual objects correlate spatially. Since the ground survey in 2000, significant shifts in height and position of up to 0.30 cm were measured at individual objects (especially at the mast foundations of the Gotthard main line, which lies on a dam).
The various and interesting surveying tasks for this project of the century represented a technical, logistical and personal challenge for the surveyors of the engineering association. We can proudly affirm that we have mastered this challenge successfully. Our engineering association IG GEOSWISS has grown together to form a united whole.

Urs Bättig (Gruner AG, Basel)
Samuel Bühler (Kost + Partner AG, Sursee)
Daniel Eberhart (Markwalder & Partner AG, Burgdorf)
Robert Bänziger (Ingenieurbüro Robert Bänziger, Niederhasli)

IG GEOSWISS
c/o Gruner AG
Gellertstrasse 55
CH-4020 Basel

Monitoring Measurements at Portal Erstfeld

The first 600 m of the Gotthard base tunnel in the Canton of Uri was not created by mining, but as a surface tunnel. Up to 30 m deep, the surface tunnel cuts into the ground at the foot of the mountainside in Erstfeld. Slope protection, fill and the surface tunnel are to be monitored by surveying during the entire building phase. This requires the highest standards of accuracy, reliability and flexibility of the measurement technique.

Surface Tunnel in Loose Rock

The actual north portal of the Gotthard base tunnel is located where the alignment meets compact rock and where mining can excavate the tunnel. Leading up to this point, there is a 600 m-long surface tunnel, which is embedded into the mountainside of loose rock (Fig. 1). In order to keep the settlement caused by the extra impact from the surface tunnel to a minimum, the whole area is compacted with fill several metres high. Directly in front of the underground tunnel portal, the cut into the mountain has been reinforced over a length of about 200 m for the construction of the surface tunnel by using drilled piles of up to 30 m in height, which are anchored into the rock through concrete beams at various levels.

Monitoring Tasks

Surveying must monitor and following objects for safety reasons:

- Pre-fill
- Drilled pile retaining wall
- Surface tunnel

Especially with the slope stabilization and the building work, any changes must be known early and then compared with the predicted values.
For this purpose, both geodetic and geotechnical instruments are used.

Construction of the Benchmark Network

As the basis for all geodetic monitoring tasks, a benchmark network was established, so that the stability and accuracy requirements could be met. In addition, it must always be available for use and remain in place even if the construction site installations are constantly changing. The benchmark network consists of approximately 40 points fixed in location and height distributed around the portal area. Of these there are 10 points on top of or on the side of buildings in the valley within distances of up to 600 m from the portal. With the help of a local helicopter company, the prefabricated measuring pillars were transported onto the flat roofs of chosen buildings. The points in the rock above the portal operations had to be installed with climbing equipment.
(Fig.3). The benchmark network is seamlessly incorporated in the superior GBT network.

Monitoring the Fill

To monitor the eventual settlement, which was provoked by the compaction, steel rods were anchored into the ground in various places. The rods were brought to the surface in manholes and depending on the settling behavior, could be extended or shortened at will. The heights of the 21 levels were determined by using precision levelling.

Fig. 1: The portal area in Erstfeld: The drilled pile retaining wall on the right secures the mining slope area immediately in front of the tunnel entrance. To the left of it, the surface tunnel has already been created. Conveyor belts and the installation area surround the construction site (Photo: AlpTransit Gotthard AG, Adrian Wildbolz).

Fig. 2: The approximately 30-m-high drilled pile retaining wall (Photo: Basler & Hofmann).

In addition, two exploratory boreholes were monitored with an SE probe.
With the SE probes, compressions underground can be determined. The eventual measured settlement of up to 35 cm met the predictions.

Fig. 3: Attaching the measuring points above the mining tunnel portal (Photo: Basler & Hofmann).

Drilled Pile Retaining Wall Safety

To ensure that work can be done safety in front of the tunnel portal, the two sidewalls must be monitored for deformations during the entire construction period.
The forces on at least five percent of the rock anchors are automatically monitored. When exceeding the limit of tolerance, an automatic alarm is triggered, and the local construction site management is directly informed.
Additionally, in a three-month cycle, 60 points on the side of the drilled pile retaining walls are geodetically monitored. The monitoring points are made up of permanently attached mini prisms and are each defined by the benchmark network. One measurement cycle consists of 10 to 15 occupied stations on the drilled pile wall edge so that each point can be measured from at least two occupied stations. As the situation constantly changes with the building progress, the occupied measuring positions must remain flexible to allow adjustment. Geodetic measurement enables the significant determination of position shifts greater than 5 mm.

The inclinometer-pipes embedded in the piles are also measured in three-month cycles. Here, a probe is introduced into the pipe, which measures the deviation from the axis of the borehole at intervals of 60 cm. This way a statement can be made about the deformation behavior of the piles and the stability of the slope.

The Surface Tunnel

The surface tunnel consists of two parallel tubes. The surface tunnel is created starting from the north since the area directly in front of the mining tunnel portal must be kept free to assemble and disassemble the tunnel-boring machine. Inside the tunnel, approximately 30 cross-sections are monitored each with seven points. Here, a measure of tolerance of 4 mm has to be maintained for the spatial shift between two epochs. The monitoring points at the top of the tunnel profile are equipped with mini prisms; those at the bottom with wall bolts and M8 adaptor bolts. At the same time, at approximately 35 cross-sections, settlement measurements are monitored on the bottom plates of the tubes. In summer 2009, the first profiles were installed in the surface tunnel. Since then ongoing follow-up measurements have been performed.

Shifts to the South

The results of the first follow-up measurements show displacements of up to 15 mm in the tunnel's longitudinal direction. They decrease in a southern direction. Displacements in the tunnel's longitudinal direction are unusual, as one would expect a deformation of the profile to occur. The reason for the displacements lies in the construction of the tunnel: The individual sections were created in a monolithic block with continuous reinforcement. The temperature-induced expansion of the concrete body, therefore, is not absorbed as usual by the expansion joints, but instead accumulates. Depending on the temperature, the tun-


Fig. 4: Geodetic surveying on the drilled pile retaining wall (Photo: Basler & Hofmann).

nel contracts to or expands from the current focal points. Since the focal point of the tunnel shifts to the south 10 m a week with the advancing construction, the displacements move in this direction as well.

Flexible Monitoring

The construction environment demands from the surveyors a high degree of flexibility: conveyor belts, ventilation units, air tubes and portal cranes frequently block the view of the fixed points. In order to maintain the geodetic monitoring measurements, new occupied stations must be sought (Fig. 4).

The mini prisms on the drilled pile retaining wall were often so badly polluted by the underlying conveyor belts, which removes the excavated material from the tunnel, that they had to be cleaned using abseiling.

On the other hand, the results can be considered positive for the civil engineers: At no time did the monitored objects pose any danger to the construction site. All deformations stayed within the calculated tolerances. The measurements of the drilled pile retaining wall and the surface tunnel are to be continued until the completion of the back-fill.

Jörg Gämperle, Michael Furrer
Basler & Hofmann
Fachbereich GIS und Geomatik
Forchstrasse 395, Postfach
CH-8032 Zürich
joerg.gaemperle@baslerhofmann.ch

The role of surveying in the construction of the Ceneri Base Tunnel

The role of surveying in construction projects is often neglected. For the implementation of challenging structures such as the Ceneri railway base tunnel, however, it is a basic element. In the preparatory phases the surveying specialists collect and provide the basic geodata for the project planning. After that, they define the control network outside the tunnel and determine the main points inside the tunnel to guarantee the correct orientation of the tunnelling work. Moreover, as work progresses, the tunnel profiles and the external constructions (existing as well as under construction) have to be controlled in order to detect possible deformations at an early stage. Finally, the reference points for the laying of rails and for all technical installations of the high-speed rail have to be moved and defined with high accuracy (under one millimetre).

C. Bernasconi

The construction of the Ceneri Base Tunnel extends over a length of 15.4 km and has a total length of ca. 40 km of tunnel and galleries (Fig. 1). The north portal is in the Magadino plain on the grounds of the Camorino municipality at a height of approx. 220 m above sea level, whereas the south portal is located in Vezia at a height of 300 m above sea level. For technical and logistic reasons big parts of the tunneling work were done from the Sigirino access tunnel. From Sigirino, the Operations Control Centre, or «Caverna operativa centrale» CAOP, can be reached through a tunnel of 2.3 km (the so-called «access window Sigirino»).

The surveying experts have been involved in the project since the 1990s. They produced the cartographical base data for the tunnel and the access route project planning. The best-suited means for the data collection was the aerial photogrammetry, which resulted in precise topographic models of the extensive perimeter as well as hundreds of profiles and terrain cross-sections available to the project planning engineers in a relatively short time.

In 1995, the SBB launched a public call for tender in order to transfer the role of the client's surveying engineer to an external expert. He accordingly bears the responsibility for the surveying work linked to the correct realization of the whole Ceneri Base Tunnel. The tender was won by COGESUD, a consortium consisting of five surveying companies from Ticino (see box).

The first work phase for COGESUD was the elaboration of the base network: a reliable primary network on which all future surveying work would be based. Shortly after its completion the first tunnelling was initiated at the Sigirino exploratory tunnel (2.7 km in length), which was necessary for the preliminary geological and geotechnical analyses. In connection with this construction work the surveyors of COGESUD were given the task to carry out the indispensable underground measurements in order to direct the tunnelling precisely to the location of the future Operations Control Centre, CAOP. Since then, the consortium COGESUD has fulfilled the contractual obligations it has been entrusted with to support the contractor (thereinafter AlpTransit Gotthard AG) and has concentrated on issues related to the surveying, specifically the conceptual, organizational and surveying aspects. COGESUD's direct partner is the geomatic section of the contractor (ATG Geomatik). With the beginning of the main tunnelling at the Ceneri Base Tunnel during 2010, the work has now entered the most complex and fascinating phase of the project.

Control networks

ReteSUD (South network)

The basic positioning network for the realization of the Ceneri Base Tunnel consists of the ReteSUD (South network),

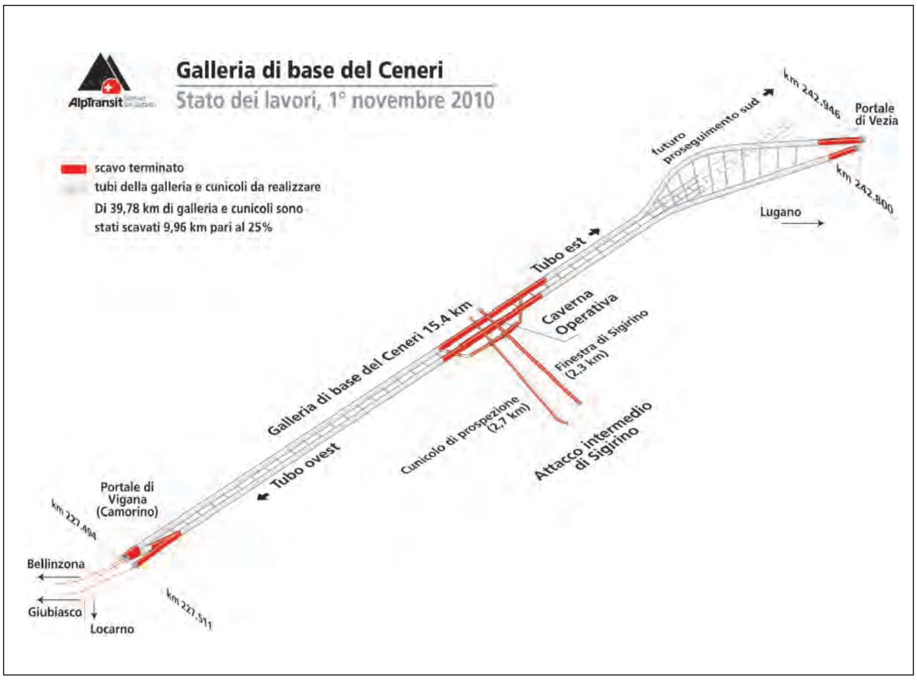


Fig. 1: Diagram of the Ceneri Base Tunnel.

Fig. 2: Staking out in the tunnel.

which is composed of 24 geodetic points. Those points are situated between Biasca and Lugano and are simultaneously part of the global base network for AlpTransit between Erstfeld and Lugano. AlpTransit Gotthard AG and COGESUD initiated the complex determining works for this network in the middle of the 1990s. Due to the high requirements of these works, the Swiss Federal Institute of Technology Zurich (ETHZ) was involved as consultant in a first phase. Later, combined measuring campaigns with GPS receivers and tachymeters were done. During the subsequent calculations, several variants were compared in order to obtain a homogenous and reliable geodetic base network. The inner accuracy was ± 1 cm.

ReteSUD altezze

(South network altitude)

In connection with the construction of the Ceneri Base Tunnel it was necessary to establish a special height control network for the levelling underground and on the surface. The Swiss Federal Office of Topography (swisstopo) was assigned this preparatory task. The factors influencing the theoretical deviations at the moment of connection of the tunnel advances, especially the gravimetric influence and the influence of possible constraints between the height control points of the LN02 height reference framework had to be determined. The conclusion of the swisstopo report showed that the influences compensate themselves to a great extent, so that the theoretical error is negligible. Using the LN02 height reference framework (official heights) allows for the attainment of the requested final accuracy. In July 2004, levellings were carried out at the three portals in order to exclude local subsidence between the control point groups in LN02. The control results showed only minimal movements.

Portal and construction control network

In order to obtain a perfect stakeout of the main points in the tunnel and to connect all construction sites with sufficient accuracy to each other, a densified control network is needed. Therefore, the base network (length and height) was strengthened at the portals of the tunnel and at the access galleries. This resulted in the definitive form of the portal networks (with high accuracy, for the staking out of the tunnel) and the construction networks (low requirements for the needs of the construction sites outside the tunnel). In those networks the sight line between the control points and the remote target points have to be kept free, which does not happen as a matter of course at such complex building sites. A geologist previously assessed the stability of the zones, in which the new control points are set.

At the end of 2005 the height control networks for the construction sites were complemented with subsequent levellings. On the basis of a few height control points of the national levelling network, new control points were fixed in the rock closest to the portals. On the section between Biasca and Lugano, a total of 42 new height control points were installed. The national levelling points were used as bearing points. To avoid tension

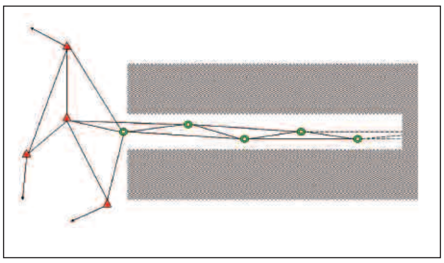


Fig 3: Diagram of the main traverse.

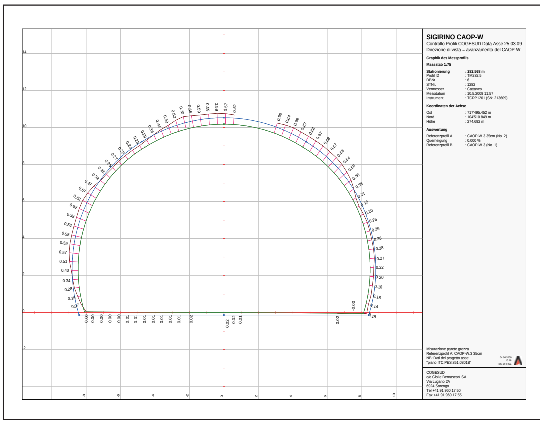


Fig 4: Monitoring of the excavation profiles.

inside the networks a free positioning was chosen. The differences to the heights from LN02 were less than 3 mm.

The planimetric densification followed in 2007 and 2008. Portal and construction site networks were established in Camorino, Sigirino, and Vezia. They were then integrated into the base network using GNSS and terrestrial measurements.

Portal network Sigirino

From the Sigirino access tunnel, important parts of the base tunnel were staked out and excavated, which makes this portal particularly important. The base control network had already been partially consolidated in relation to the staking out of the Sigirino exploratory tunnel, but for the new main access gallery a few important additions were necessary. Four new control points were added, amongst them the main portal pillar on the extension of the access gallery axis. Furthermore, a reference route was installed for the gyro, which will later be useful during the stakeout controls in the tunnel for the independent orientation controls. This reference route is 500 m long and includes two pillars in the southern section of the portal.

Portal network Camorino/Vigana

According to the work plans, only a few hundred tunnel metres are excavated from the Camorino portal. Depending on the other tunnel excavations, an optimal

Fig. 5 Monitoring on the building sites.

Fig. 6 Vezia preliminary cut.

extension of 2 km in the southern direction is possible.
In Camorino, three new surveying pillars were prepared. These are situated on the mountain flank above the portals and are fixed to the rock. This slope is the only geologically stable zone in the region. The new control points are a good basis for the determination of the portal points on the Magadino plain. Because the Magadino plain consists of alluvial soil, this region is subjected to subsidence and cannot be considered stable. Therefore, the portal points have to be newly determined for each new operation.

Portal network Vezia

The Vezia reverse-drive consists of a Tagbautunnel (cut-and-cover tunnel) and a tunnel that is excavated conventionally in the rock. The whole section is 500 m long. The staking out of the tunnel in the rock is done from the preliminary cut, which has been carried out before. The cut-and-cover tunnel will be created only later on in the preliminary section. The external situation does not leave free space for creating a stable and secure portal network. A control point was created on the only existing rock outcrop. It is situated to the north of the portal along the SBB railway line. The main portal pillar was built relatively far from it on a meadow in the extension of the new tunnel axis in the direction of Lugano. The difficulty with this construction site is the fact that it overlaps locally and temporally with the construction of the road tunnel Vedeggio – Cassarate. This situation requires a great coordination effort for all parties involved, including those responsible for the surveying.

Staking-out of the main control points in the tunnel

The staking-out of the underground main control points is the most challenging and at the same time the most fascinating of COGESUD's tasks (Fig. 2). All work by construction companies involved are based on those points. This procedure guarantees that the correct drive direction is maintained. As the contractor's mandated surveying consortium, COGESUD has to assure that the tunnel drives are joined with a tolerance within the centimetre range at the point where the project engineers have planned it. At the moment of the breakthrough, the maximum admissible error is 25 cm. The main control points in the tunnel are secured about every 200 m with special bolts. Shafts with covers capable of handling traffic secure the bolts. At the tunnel walls, securing points are fixed which serve to control the stability of the main points. The heights are determined by levelling on the basis of the vertical control points of the portal network.

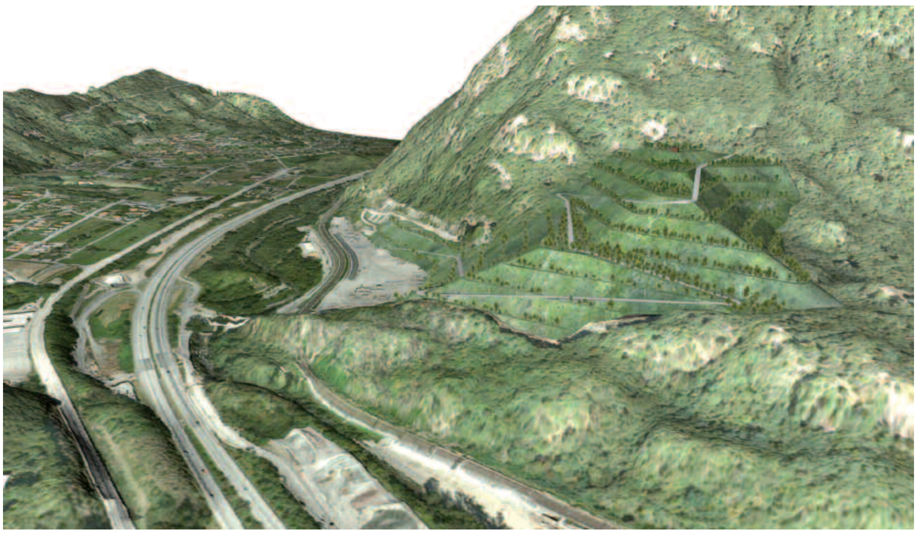


Fig. 7 Three-dimensional visualization of the Sigirino landfill site.

The determination of planimetric position is done by measuring a complex traverse with forced centering (Fig. 3). The measurements on all underground points were performed several times during different campaigns in order to obtain the required redundancy and to minimize the error risk due to negative influences. The global traverse begins at the main portal pillar of the corresponding portal network. From this station all points of the portal network, as well as the first points of the underground network, are measured to obtain the best possible connection between the exterior and the underground networks. In the tunnel network, there is no possibility to directly control the orientation on the basis of exterior points of the south portal (ReteSUD), and all coordinates are based on the accuracy and reliability of the underground measurements. Many different rules help to avoid possible negative influences. Often there are also very simple measurements such as the double reading of the height of an instrument or taking into account the necessary acclimatization time for the instruments in the case of temperature changes. Every detail is important and has to be recorded!

In the calculation phase, the inner accuracy of the performed measurements has to be assessed with a free adjustment. In rare cases and only on the basis of clear indications, conflicting measurements are eliminated. In consequence, it has to be verified if the stochastic model, which contains all a priori accuracies (depending on the instruments used and the measuring conditions), is confirmed. During the following global adjustment, in which the new measurements are combined with all previous measurements, further parameters are taken into consideration, such as deviations from the vertical, geoid undulations, and distance reduction on the basis of the Swiss map projection.

Excavation profile monitoring

In combination with the stakeout controls of the main points in the tunnel, excavation profile or tunnel lining controls are performed. Proceeding from the coordinates of the known main points, the profiles are measured without reflectors in accordance with the demands of the project management. The measured profiles are analyzed with the appropriate software and compared to the reference profiles defined by the project engineer (Fig. 4).

It is thus possible for the project management to control the subcontractor's compliance with the excavation accuracy and to quantify the necessary volumes for the concrete lining.

Monitoring of construction

Another important task of COGESUD is the stability monitoring of the construction outside the tunnel situated within the influence range of the Ceneri Base Tunnel construction site. The objects to be monitored include existing buildings or buildings under construction in the sensitive zones of the project for which an assessment of the current state for the future («prove a futura memoria» (assessment)) has been established. Amongst the chosen methods for these measurements are precise measuring procedures to assess the current situation and the developments over time.

Aside from the existing objects, a great number of new objects, such as walls, viaducts or other construction, which are built in connection with the base tunnel in the portal sector or along the railway lines, have to be constantly monitored (Fig. 5). Of these objects, the preliminary Vezia cut (Fig. 6) can be mentioned as an example. The elaboration of this monitoring project was challenging due to the whole environment that had to be considered potentially unstable (two big construction sites in progress). Therefore, the localization of stable points posed a certain number of problems. In addition, several factors were hindering numerous sight lines. Those factors include the relatively deep excavation (more than 20 m), the curvature of the preliminary cut, as well as the infrastructure and activities of the construction site. In spite of this difficult situation, the project engineer's accuracy requirements to detect possible movements of the monitoring points were very high (simple standard deviation for the determination of the points: ± 1–2 mm). An appropriate monitoring system was created by adapting the densification of the construction network and using a complex configuration of control points and measuring stations (which had to be newly determined at each intervention). The measurements at the beginning of the excavation were carried out every fortnight, but the rhythm has slowed down in the meantime to quarterly control measurements.

Another example of complex monitoring on the Vezia construction site is the anchored pile wall situated about 100 m south of the tunnel portal. Because the SBB railway lines, which are in constant operation, run on both sides of the mountain, it is important to monitor the stability of this construction. Therefore, tachymetric measurements are performed proceeding from the control points of the portal network. Every fortnight, COGESUD transmits the movements of a few selected points from the wall to the project engineers. The required accuracy for the determination of the coordinates is analogous to the one for the points of the nearby preliminary cut.

Tunnel stakeout monitoring and special measurement techniques

In its role as commissioned surveying consortium for AlpTransit Gotthard AG, COGESUD also has the task to control whether all structures are built in the right position and with the required tolerances. The project engineers have previously fixed these factors. This means that height and position of all structures built on the site have to be monitored regularly. The local construction management coordinates these interventions, and plays an important role as intermediary between construction companies, project engineers, and COGESUD.

Members of the COGESUD consortium

- Gisi e Bernasconi ingegneria e misurazioni SA
  Via Lugano 2a, 6924 Sorengo
- Studio Meier SA
  Via Architetto Frizzi 26, 6648 Minusio
- Studio d'ingegneria Antonio Barudoni
  Via San Gottardo 20, 6600 Muralto
- Studio d'ingegneria Antonio Bottani
  Via Stazione 7, 6987 Caslano
- Studio d'ingegneria Maderni-Capezzoli-Forrer Sagl
  Via San Salvatore 3, 6900 Massagno

Characteristics of the consortium

- experienced specialists
  12 engineers / 40 technical personnel / 8 staff members in administration
- a full range of surveying services
  classic geodetic surveying, photogrammetry, terrestrial laser scanning
- fast availability and flexibility
  ca. 150 operations (5000 hours) / year

Contractual tasks

- Provision of the required geodetic and topographical base data for the project planning and the construction of the Base Tunnel and the adjoining buildings.
- Control that all planned buildings are constructed at the right place and with the required accuracy.
- Detection and monitoring of potential deformations of the terrain and other affected objects, before, during and after the implementation of the work.

Key activities

- elaboration of the control networks
  Base network / portal networks / site networks
- construction companies' stakeout controls for the constructions outside the tunnel and for the installation of the railway infrastructure
- «Prove a futura memoria» (assessment) and monitoring of buildings and adjoining constructions Levelling / tachometric measurements / photographic data
- staking out of expropriated surfaces and elaboration of construction profiles for the projects outside the tunnel and for the public in-spection
- special recording techniques for the project engineers
  topographic models / laser scanning / photogrammetric Analysis / orthophotos

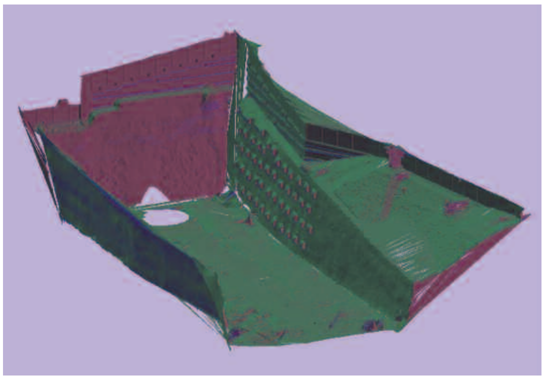


Fig 8. Laserscan of the Vezia preliminary cut.

As the work was progressing, the surveying specialists also had to accomplish very special tasks, such as the elaboration of a 3D-model of the Sigirino excavation material storage facility. On the basis of this model, a virtual film has been realized to show the situation at the end of the excavation work (Fig. 7). In addition, laser scanning has been used in the «prove a futura memoria» (assessment) in order to document the state of the road geometry and surfaces or, in the case of the Vezia preliminary cut, to precisely determine the excavated volumes and to calculate the cross sections (Fig. 8).
Finally, the monitoring works in connection with the track lying in the tunnel should not be forgotten. This task still lies in the future, but it will be another important challenge in the project. All stakeout and monitoring tasks in relation to the installation of the railway infrastructure (rails, etc.) will be based on rail benchmarks, which will have to be determined with sub-millimetre accuracy. The rail benchmarks will later be used by the SBB for the maintenance works of the new railway line, on which the trains will run at over 200 km per hour!

Cristiano Bernasconi
ing. dipl. ETH
Capo progetto
COGESUD
Via Lugano 2a
CH-6924 Sorengo

Geomonitoring at the North Portal of the Ceneri Base Tunnel

The crossing beneath the A2 motorway is one of the important challenges in the northern sector of the Ceneri base tunnel. Aside from manual measurements, an automatic monitoring system constitutes the centerpiece of the monitoring for the A2 during construction of the crossing. Throughout the two years of excavation, the monitoring system guaranteed the safety of the transit traffic on the A2 motorway.

Th. Heiniger

North of the Ceneri, the planned NRLA railway line climbs over a viaduct in the Magadino alluvial plain to the height of the tunnel portal. The portal is situated directly under the most important north-south transit road, the A2 motorway. The alluvial plain is unavoidably affected by the train path construction and had already caused subsidence of up to 1.2 m during different building projects in the past.
To guard against the expected settlements, prior to work starting on the tunnel, the whole plain was loaded with excavation material from the Gotthard Base Tunnel in the area of the future railway path. In order to verify the consequences of the filling and to guarantee the safety of the A2 motorway during the crossing excavation through the Ceneri Base Tunnel, it was decided to monitor the plain focusing on the A2 motorway crossing. The crossing of the A2 is situated in the first 50 m of the tunnel in the excavation material of the motorway embankment..

Lot704: Monitorraggio sedimenti

A call for tender was published for monitoring as a separate lot. The IG Ceneri-Monitor with Amberg Technologies as lead-management company, together with BSF Swissphoto, obtained the contract to monitor the areas described below. Both companies have their headquarters in Regensdorf and already monitor the surroundings of the three dams located above the Gotthard Base Tunnel.

Manual monitoring

The subsidence of the plain is periodically controlled at over 110 points. At the beginning of the fill, settlement level points were installed, which are adjusted according to the growth of the embankment. The measurements of these level points are performed geodetically using total stations with regard to a higher-level reference framework. The maximum subsidence in this area is 90 cm, which corresponds to the accuracy established by the project engineer. In addition, the points from the existing SBB railway embankment, including the bridge, are also controlled during the same measuring campaign. The measuring interval is flexible and adapted to the construction activities, with the normal interval being every two weeks. These measurements make it possible to document the long-term settlement behavior over a large area.

Automatic monitoring of the A2

The network based DC3 monitoring system is used to monitor the A2 railway crossing. This system registers relevant deformations in the area of the motorway and ensures safe operation of Switzerland's most important north-south connection with an automatic alarm system when limit values are exceeded. In the area of two planned viaduct pillars in the Magadino plain, subsidence and water level measurements were connected to the monitoring system in order to control the settling behavior, during the preload, in different depths up to 60 m.

Geodetic monitoring on the surface

Forty-eight prisms have been installed on the slopes and in the area of the projected portal along the A2 motorway. These are measured every hour with two Leica

Fig.1: Vigana: View of the Vigana north portal, over which the A2 passes – one of the two main traffic axes through Switzerland.

Fig. 2: Survey pillar: Automatic monitoring along the A2 motorway – the monitoring system detects movements to a predetermined sensitivity of 3 mm.

TCA 1800 type total stations.. The collected data are used to monitor deformations at the surface. This system, which also covers the long-term monitoring of the dam body in particular, detects movements with a predetermined sensitivity of 3 mm, which puts a high demand on the stability of the system. The results of the long-term monitoring indicate that under good weather conditions these requirements are met. In order to monitor the long-term stability of the fixed points, four GPS points have been added.

Underground geodetic monitoring

In case of an unexpected event, total stations are unsuitable to detect movements as quickly as possible. These movements are therefore recorded with a dense network of geotechnical sensors at intervals of about 3 minutes. The sensors were installed in up to 50 m long horizontal boreholes between 4 and 8 m under the road surface. At the valley side border of the dam body 30 m deep borings were equipped with sensors.

The following sensors were used:

- 4 horizontal borings with 70 interlinked uniaxial inclinometers
- 6 vertical borings with 75 interlinked biaxial inclinometers
- 2 vertical borings with 3 long measurement sensors each
- 2 uphill borings with 5 piezometer sensors each

The linked horizontal inclinometers measure subsidence, and the vertical biaxial inclinometers measure transverse movements in two axes. The elongation sensors measure shifts along the vertical boreholes and, hence, the settlements underground. Piezometer measurements show the water pressure in the different water-bearing strata of the dam body. The total stations measure the absolute shifts and subsidence of the boreholes. Thus, the results of the borehole measurements can be more adequately interpreted and compared with geodetic measurements.

Analysis

The data of the automatic measurements are directly analysed and managed in the

Fig. 3: GEOvis: With the web interface GEOvis all measuring data can be interactively consulted at any time.

system on site. This provides an automatic graph generation at each measurement process. The graphs are uploaded to the GEOvis web-based data visualization portal of Amberg Technologies at predefined intervals. The project managers are able to consult the updated graphs anytime and to acess archived data as well. The manual data are analyzed within a day, and the diagrams are also provided in the GEOvis system.

Alarm

The project engineer has set two-stage limit values for maximum allowable movements. If after a measurement cycle, an excess of those pre-set values is detected, the monitoring system automatically alerts the responsible persons by SMS and over the telephone by voice message. The recipients are forced to actively confirm the receipt of the messages; otherwise the messages are forwarded to their deputies. In case of an alarm, the newest graphs are immediately made available in the GEOvis system and are at the disposal of the responsible persons for situation analysis.

Conclusion

The automatic measurements were started about one year prior to the beginning of the tunnel excavation. This is necessary in monitoring projects of such complexity in order to gain experience with the system and to become familiar with the behavior of the system in different environmental conditions. In November 2008 the alarm was set on «high» and the critical phase of the underground crossing was successfully mastered by mid-2012. The measured subsidence of max. 14 cm lie within the range established by the project engineer. Thanks to intelligent internal system controls, false alarms could be avoided with two exceptions. While the geotechnical sensors were not widely influenced by environmental conditions, thus having no affect on the functioning of the alarm system, the geodetic measurements posed a certain number of challenges. The quick growth of the vegetation and the heavy rainwater spray demanded a continuing effort to grub-up the ground around the sight lines and clean the prisms. Very deep snow made it almost impossible to see the prisms. Often we had to face the destruction of the measuring points due to accidents on the motorway, construction work, and vandalism.

In conclusion, it can be stated that the chosen measuring and alarm concept has proved to be totally efficient, although the 24-hour on-call duty was a great burden for the IG Ceneri-Monitor personnel. Therefore, not only the people involved in the project but also the monitoring specialists of IG Ceneri-Monitor are relieved that the A2 motorway crossing has been successfully completed and are looking forward to a future without mobile phones at their bedsides.

Thomas Heiniger
Amberg Technologies AG
Trockenloostrasse 21
CH 8105 Regensdorf-Watt
theiniger@amberg.ch

Astro-geodetic measurements of vertical deflections and azimuths for ALPTRANSIT

Before beginning work at this century's most complex construction site, the Gotthard Base Tunnel project required an extensive feasibility study in addition to a study concerning the accuracy of the surveying work. In order to provide and increase the accuracy of the survey work, all possible and independent measurement techniques had to be considered. More specifically, the systematic effects of the gravitational field, which affect observations depending on the vertical such as tacheometric, gyroscopic or levelling measurements, needed to be known or to be determined with the highest precision. This translated into the need for precise knowledge of the geoid, the deflections of the vertical, and the vertical acceleration of gravity g. This article describes the astrogeodetic control surveys that were carried out by ETH Zürich in the summer of 2005 on behalf of the VI-GBT surveying consortium, in order to verify the values of the corrections applied to the gyroscopic measurements. Moreover, the CHGeo98 geoid model used in this project had to be validated in order to verify whether it provided the desired accuracy or if new vertical deflection surveys were necessary in combination with the new CHGeo2004 geoid model. 04.

Beat Bürki and Sébastien Guillaume

1. Introduction

The successful management of an ambitious project, such as the new transalpine rail link (NEAT) with the Gotthard Base Tunnel, depends on many different factors. In addition to technical and financial questions, as well as the parliamentary obstacle course, a tremendous number of questions concerning the technical, economical, and ecological conduct of the work had to be resolved. To achieve this, an army of planners, engineers, geologists, hydrologists, traffic and energy experts, mining engineering experts, legal experts, and last but not least geomatic engineers dealt with a broad spectrum of problems arising from such a project. In terms of survey techniques, the challenge lies in meeting the accuracy requirements needed by the prime contractor. In order to satisfy these mandatory requirements, all error sources and their effect on the final accuracy have to be studied and added to the surveyor's task lists.

The building of a structure such as the Gotthard Base Tunnel, at the unprecedented length of 57 km, poses a major challenge to surveyors. The division of work into five segments resulted in an acceleration of the construction, as the maximum segment was 16.8 km (Faido-Sedrun construction site). In spite of this simplification, each segment was a great challenge regarding the quality of the measurements. Due to complications involving environmental conditions on the construction sites, the preliminary calculations of the directions for the tunnel boring machines (TBM) had to be performed with utmost care and had to take into account all possible error sources [Haag et al. 1996, Stengele 2007, Schätti and Ryf 2007]. Reporting the portal network directions on the front of the tunnel excavation using classical direction measurements resulted in polygonal and superimposed lines.

With the help of pre-analyses calculations of geodetic networks, the Gotthard Base Tunnel (VI_GBT) surveying consortium was assigned all the surveying work by the main contractor and they had determined the average excavation errors at the different meeting points to be 10 cm (1 sigma) on the lateral component and 5 cm on the altimetric component. Moreover, the horizontal coordinates had to be determined with an external accuracy of 25 cm (maximum permissible error) and the altitudes with an accuracy of 12.5 cm (Haag et al. 1996, Stengele 2007). These accuracy and reliability requirements can be met only thanks to independent methods such as, e.g., gyroscopic measurements. Moreover, gyroscopic measurements on calibration bases at the portals could be controlled independently and efficiently with measurements of the astronomic azimuth and vertical deflection, which increases the reliability of the global surveying work.

In the context of underground construction, such as the Gotthard Base Tunnel, the effect of the earth's gravity field is of utmost importance for the measurements. The visible impression of the gravity field will appear in the form of a vertical deflection, which will be expressed by a local deviation from the normal range at the reference ellipsoid. This deflection is normally described by two components: north-south and east-west

north-south component: $\xi = \Phi - \varphi$ (1)

east-west component:

$\eta = (\Lambda - \lambda) \cdot \cos\varphi$ (2)

with Φ, Λ = astronomic latitude and longitude defined by astro-geodetic methods (for example, using a zenith camera) or calculated on the basis of reference points and digital mass models.

φ, λ = geodetic latitude and longitude (ellipsoidal) defined by GNSS or from Cartesian coordinates converted on the reference ellipsoid.

The obliquity of the physical vertical in relation to the mathematical vertical systematically influences the angular observations because the vertical axis of the instrument is also subjected to the same obliquity. A direction correction, dr, caused by the vertical deflection, depends on the azimuth α, the line of sight, and the zenithal axis z.

$$dr = -(\xi \cdot \sin\alpha - \eta \cdot \cos\alpha) \cdot \cot(z) \quad (3)$$

Laplace's equation describes the difference, dA, between the astronomical and ellipsoidal azimuths:

$$dA = -\eta \cdot \tan\varphi - (\xi \cdot \sin\alpha - \eta \cdot \cos\alpha) \cdot \cot(z) \quad (4)$$

In the past, the deviation of the main axis of the instrument was not adjustable due to the positioning of the instrument. As a result, it was impossible to distinguish it from the systematic influence of the vertical deflection. Modern instruments, such as tachymeters and total stations, which are equipped with dual-axis compensation (tilt measurements), can measure the deviation of the principal axis and calculate and correct its measurements (provided that the compensator is activated). Therefore, only the vertical deflection influences the measurements according to the formula (4).
When reducing the azimuths measured by gyroscope by the components ξ and η of the vertical deflection, the curvature of the gravity line must also be taken into account. The results of a comparison at the Sedrun vertical shaft, for example, showed that the vertical deflection over the 800 m between the top and the bottom of the shaft varies between –6.1 cc (-0.61 mgon) in the north-south direction and –3.2 cc (–0.32 mgon) in the east-west direction. After an accurate analysis according to Laplace's equation, these values applied to the tunnel height result in the following corrections:

First term: from –49 cc to +20 cc

Second term: from –0.11 cc to +0.05 cc (for lines of sight at 0 degrees azimuth), and from –0.35 cc to +0.11 cc (for lines of sight at 90 degrees azimuth).

These values show that the first term is significantly higher than the precision of the measurements. Consequently, it is essential to take this into account to reduce the gyroscopic azimuths measured on the reference ellipsoid of the Swiss reference system in order to compare them to the azimuths of the basic control network determined by GNSS. The second term can be neglected due to the fact that it is significantly smaller than the precision of the measurements.
In theory, there are other corrections to consider.

Instrument-independent corrections

- Current position of the earth's axis of rotation → reduction to the average value of the position of the pole. CIO Pole (Conventional International Origin)
- Convergence of meridians → reduction in the north of the map
- Altitude of the sight line over the sea (obliquity of the ellipsoid reference at the sight line in relation to the ellipsoid reference at the measuring point)
- Reduction of the direction ellipsoid-sphere-plan (geodetic line-big circle-straight line in the projection plan)

Instrumental corrections of the gyroscope

- Correction of point zero (calibration)
- Correction of drift effect (temporary behavior of the calibration value).
- Accounting of temperature variations

In practical terms, this means that at the construction site the surveyor or the GIS specialist responsible for the measurements has to regularly perform control measurements under good conditions and absolutely needs to know the local gravity field.

2. The gravity field in the region of the Gotthard Base Tunnel

2.1 Vertical deflections

Vertical deflections can be observed directly at the site (i.e., with the help of a zenith camera) or on the basis of calculations integrating mass and terrain models. The attainable accuracy depends on the quality and the density of the gravity field measuring station network. In Switzerland, there is a network of 650 vertical deflection observation stations used for the determination of the geoid. This is the basis for the interpolation of the vertical deflections on a given point on the terrain with accuracy between 0.8" and 1.0". In this project, vertical deflections have been calculated along the tunnel axis with the help of the CHGeo98 geoid model.
The graphic representation of Fig. 1 shows the vertical deflections as well as the position of the astro-geodetic stations of the ETHZ in the project sector.
A profile of the vertical deflections based on geoid model calculations along the tunnel axis is shown in Fig. 2.

2.2 Geoid-ellipsoid separation

The planimetric determination of control points is easily done by referring to the mathematically perfectly described surface of the Bessel ellipsoid regarding the geodetic datum of the Swiss national survey. For the determination of heights, the reference surface is not mathematical but physical–the geoid. In fact, the geoid cannot be as easily represented in a model as an ellipsoid because it is dependent on the distribution of land masses and therefore closely correlated with the topography. For this reason, planimetric and altimetric determinations in principle are separated as in the LTOP adjustment software. In the AlpTransit project, the LN02 altimetric reference frame has been used and new rigorous LN95 orthometric heights have been taken into account. The corresponding reference surface results from the CHGeo98geoid model. Fig. 3 shows the profile of the geoid along the tunnel axis.

3. The astro-geodetic control measures of the ETH Zurich

The Geodesy and Geodynamics Laboratory (GGL), of the ETHZ through the consortium «Pesanteur suisse», has been giv-

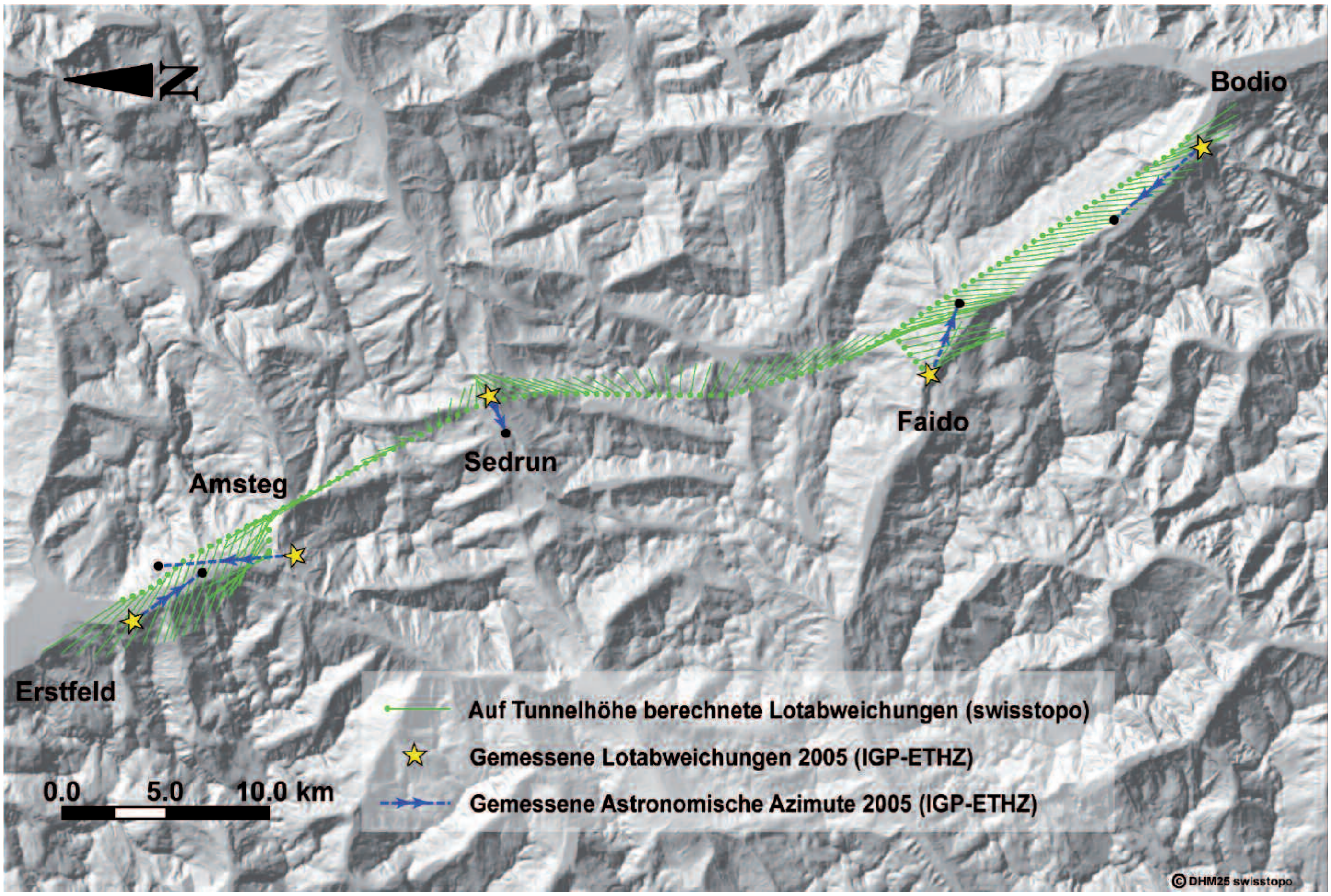


Fig. 1: Variations of vertical deflection at the altitude of the Gotthard Base Tunnel. The yellow stars represent the positions of the astro-geodetic measuring stations by zenith camera and the blue arrows show the measured astronomic azimuth (3 columns).

en the mission by VI-GBT (renamed ATG géomatique since September 1st, 2010) to validate and carry out an independent control of the correction values for the gyroscopic measurements and the vertical deflection. The assignment consisted of measurements of vertical deflections and astro-geodesic azimuths at the calibration networks of the Amsteg, Bodio, Erstfeld, Faido, and Sedrun portals (see Fig. 1).

3.1 Azimuth survey

Students David Grimm, Florian Buol and Sébastien Guillaume under the supervision of Dr B. Bürki and engineer A. Ryf have done the astro-geodetic measurements of the azimuths in the context of a diploma course at ETHZ. In order to achieve this, the AZIMUT real time measurement developed by GGL had to be used. This automatic measuring system consists of a Leica Geosystems TCA 1800 total station equipped with a prism, a special GPS receiver for time acquisition with a manual switch, an interface device, and a terrain calculator along with the appropriate software (see Fig. 2). The terrain calculator contains a star catalogue. It steers the motorized theodolite and centralizes data processing by providing real-time accuracy information on the terrain.

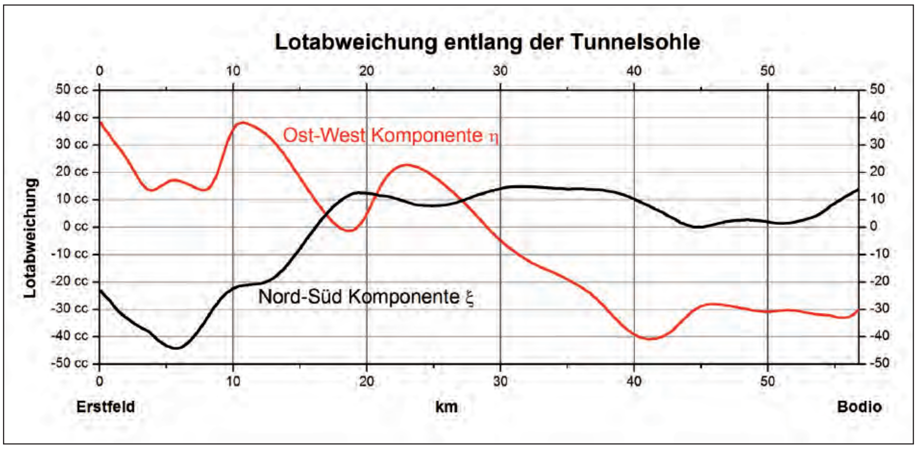


Fig. 2: Variations of the vertical deflection in its components ξ and η along the tunnel axis.

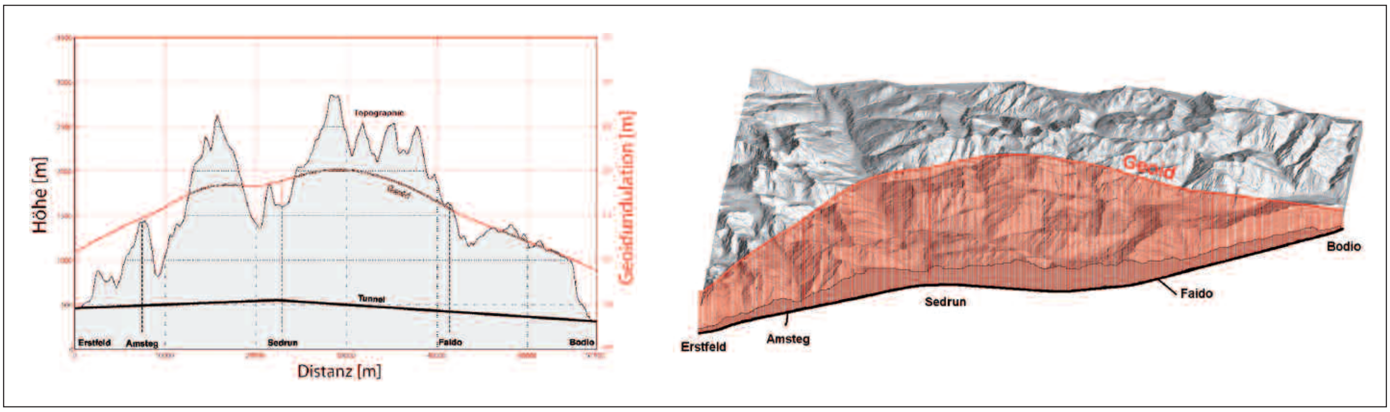


Fig. 3: Comparison of CHGeo98 and CHGeo2004 solutions. Although the new solution shows undulations over 7 cm, the effects on the height differences at the intersection points remain acceptable.

After careful verification of the different mires (targets for astro-geodetic measurements of the azimuths), the standard circular prisms of the non-illuminated total station, and with the automatic function (ATR), have been used.
During the measurements, the ATR method has proven its reliability. The target search was not easy and was done using a strong flashlight to scan the approximate direction of the target. Subsequently, the measurements were performed in a semi-automatic way with the AZIMUT system, which records the position of the targets. This procedure simplifies performing the measurements and avoids reading errors.
All azimuth measurements were performed in the two positions of the lens and, depending on the metrological conditions, measured up to five times. The results of the five azimuth measurements resulted in an internal accuracy between 0.1 and 0.8 arc-seconds (0.03 and 0.24 mgon), which can be qualified as very good given the nominal precision of the TCA 1800 of 1" respectively 0.3 mgon as indicated by the manufacturer.

3.2 Vertical deflection survey

The vertical deflections have been measured with the help of two very analogue zenith cameras during a common measuring campaign. The DIADEM (Digital Astronomical Deflection Measuring) system of ETHZ and the TZK2-D (transportable ZenitKamera2 -Digital Version) system of Leibniz University in Hannover made it possible to perform a reciprocal control of the gravity directions according to the requests of the contractor.

3.3 The measuring principle of zenith cameras

Zenith cameras, such as those developed by the GGL of ETHZ and the Institut für Erdmessung at Hannover University (IfE), are used for the very precise determination of the physical direction of the plumb line using the photographic measurement of the stellar directions. The stellar field measured by a CCD camera is compared to the reference stellar field. This reference field is calculated from the position of the station, the exposure time, and a stellar catalogue (e.g., Tycho-2 or UCAC). The DIADEM system, in addition to excellent optics and an appropriate CCD camera, includes three pairs of highly sensitive inclinometers mounted in pairs at right angles.
After introducing the inclination values filtered in real-time and numerous corrections, the projection of the camera's rotation axis in the interpolated stellar field gives the physical direction of the plumb line expressed by the astronomical latitude and longitude. Then, using the formulas (1) and (2), the components of the vertical deflection ξ and η are determined. With the new version of the zenith camera, an accuracy of 0.05 arc-seconds can be obtained on the components of the deflection.

3.4 Survey works

In theory, the measurements of the vertical deflections should be done on geodetic pillars. This of course being impossible, the observations have to be done in as close proximity as possible. Due to difficult and partially impossible access, the cameras had to be mounted relatively far from the theoretical measuring points.

Fig. 4: Geomatic engineering student and co-author of the present article S. Guillaume, measuring an astro-geodetic azimuth between terrestrial mire and the polar star (alpha Ursae Minoris).

This unusual installation, however, was not problematic because the determination of the ellipsoid coordinates by RTK-GNSS measurements at the camera's real point is easily done. Moreover, it is possible to transpose the deflection values from the real to the theoretical measuring point (from the eccentric point to the center of the pillar) by using mass models. The first series of observations with the two-camera systems were performed on July 13, 2005 at the Amsteg, Bodio, Erstfeld and Faido stations (see Fig. 4). At each station, the vertical deflection had been determined on the basis of between 40 and 80 solutions. During a second observation night on July 19, 2005, 130 solutions had been observed during 6 hours by using the DIADEM system. This long measuring period was due to the bad weather conditions, as the cloud cover made the astronomical observations difficult.

4. Survey results

4.1 Vertical deflection

The results of the measurements of the plumb line's direction can be described in the form of a simple and global table. Table 1 shows the directions of the plumb line Φ at the center of the observation pillars as well as the deflections deducted from them by using the formulas (1) and (2). The accuracy of each component can be estimated at $\sigma(\xi,\eta) = 0.1''$

4.2 Azimuths

The automatic data processing on the site with the help of the AZIMUT program made it possible to proceed to an unproblematic elimination of aberrant values. Therefore, major measurement errors are virtually impossible.

To ensure the required reliability the following aspects have been examined at the end of the measuring process.

- The calculation exactitude of the series of azimuth measurements on the basis of observations derived from the AZIMUT system.
- The exactitude of calculations of the apparent positions (α, δ) of the pole star taking into account all the effects that can be modeled, such as proper movement, precession, nutation, parallax, optical aberration and the movement of the poles.
- The exactitude of the calculations of the astronomic azimuths based on apparent positions.

The controls of the apparent positions carried out at the Astronomical Institute of the University of Bern [Ploner, 2005] as well as by Hirt, [2005] were perfectly concordant with the values obtained by AZIMUT. The results were therefore considered reliable and handed over to the contractor (see Table 2).

5. Comparison of the CHGeo98 and the CHGeo2004 geoids

To control and ensure the adequacy of the geoid–ellipsoid separation and the vertical deflection used to date (CHGeo98), a comparative calculation with the new geoid (CHGeo2004), including the new vertical deflections, could be carried out by U. Marti from swisstopo (see Table 1).

5.1 Comparison of the geoid-ellipsoid separation

The differences calculated between the CHGeo98 reference model used in the AlpTransit project and the new CHGeo2004 model improved by the new measurements are small (see Fig. 5), so that no significant influences are to be expected.

5.2 Comparison of the vertical deflections

The differences of the vertical deflections are shown in Table 3.

This comparison shows that the CHGeo98 geoid was able to meet the accuracy requirements of AlpTransit.

The comparisons of CHGeo2004 in Fig. 6 remain in the range of measuring errors or even below.

6. Conclusions

The results of the astro-geodetic control measurements have provided the following conclusions:

1) Not only the azimuths but also the measurements of vertical deflections were carried out with great precision and the results are reliable. They meet the high accuracy requirements imposed by the contractor.
2) The astronomic azimuths do not differ significantly from those obtained from GPS coordinates [Ryf 2007].
3) The astronomic azimuths were used as observations to calculate overall com-

Fig. 5: The two zenith camera systems of the Leibnitz University of Hannover (left) and the ETHZ (right) during the survey at the Erstfeld portal pillar.

pensation in LTOP to determine the coordinates of the basis network and envision a small rotation of the north portal network, which, however, remains well below the limit of statistical significance.
4) The differences in the gyroscopic azimuths are tolerable and have no effect on the accuracy at the crossing points.
5) The results of the measurements of vertical deflections combined with the new CHGeo2004 geoid model validates the CHGeo98 geoid model used for the project.

In summary, we can say that astro-geodetic measurements are important and useful to validate the reduction values of Earth's gravity field applied to the observations and for the improvement in reliability of all measurements related to the tunnel.

References:

Bürki, B., M. Ganz, Ch. Hirt, U. Marti, A. Müller, PV Radogna, A. Schlatter, A. Wiget (2005): Astrogeodätische und gravimetrische Zusatzmessungen für den Gotthard-Basistunnel. Vergleiche zwischen Astogeodätischen und gravimetrischen Messungen vom Sommer 2005 mit modellbasierten Werten. Swisstopo-Report 05–34.

Haag, R., A. Ryf & R. Stengele (1996): «Grundlagenvermessung für extrem lange Tunnel am Beispiel des Gotthard-Basis-Tunnels.» XII. Internationalen Kurs für Ingenieurvermessung, Graz.

Vertical deflections in the datum CH1903 in relation of the North of the map				
Station	ξ ["]	η ["]	ξ [cc]	η [cc]
Bodio pillar	3.67	**13.64**	11.32	**42.12**
Faido pillar	–4.93	9.79	–15.22	30.23
Erstfeld pillar	16.74	10.72	51.64	33.09
Amsteg pillar	**18.85**	–9.15	**58.17**	–28.24
Sedrun pillar	2.25	4.41	6.93	13.62

Table 1: 2005 measurements of the vertical deflections used to control the geoid solution and of the corrections applied to the gyroscopic measurements of the NEAT project.

Station		Result	A posteriori accuracy
Bodio	pillar 12735901	final azimuth 12735901 → 12735902 = 320° 40′ 26.55″	σ(Az) = 0.10″
Faido	pillar 12525901	final azimuth 12525901→ 12525902 = 111° 57′ 24.43″	σ(Az) = 0.21″
Sedrun	pillar 12122901	final azimuth 12122901→ 12122930 = 244° 51′ 55.96″	σ(Az) = 0.41″
Amsteg	pillar 12124902	final azimuth 12734902 → 11924910 = 356° 13′ 05.80″	σ(Az) = 0.40″
Erstfeld	pillar 11924903	final azimuth 11924903 → 11924145 = 145° 40′ 10.17″	σ(Az) = 0.81″

Table 2: Astronomic azimuths for the control of the gyroscopic measurements.

Deflection difference (CHGeo2004) – observed deflections (datum CH1903, northern part of the map)							
		CHGeo2004 model		measurements		difference CHGeo2004-measurements	
Station		ξ calc. ["]	η calc ["]	ξ obs. ["]	η obs. ["]	dξ ["]	dη ["]
Bodio	pillar	3.66	13.19	3.67	13.64	**–0.01**	**–0.45**
Faido	pillar	–5.37	9.10	–4.93	9.79	**–0.44**	**–0.69**
Erstfeld	pillar	16.87	10.09	16.74	10.72	**–0.13**	**–0.63**
Amsteg	pillar	18.53	–9.79	18.85	–9.15	**–0.32**	**–0.64**
Sedrun	pillar	1.24	4.37	2.25	4.41	**–1.01**	**–0.04**

Table 3: Comparisons of the geoid solutions CHGeo98 and CHGeo2004 according to the vertical deflections.

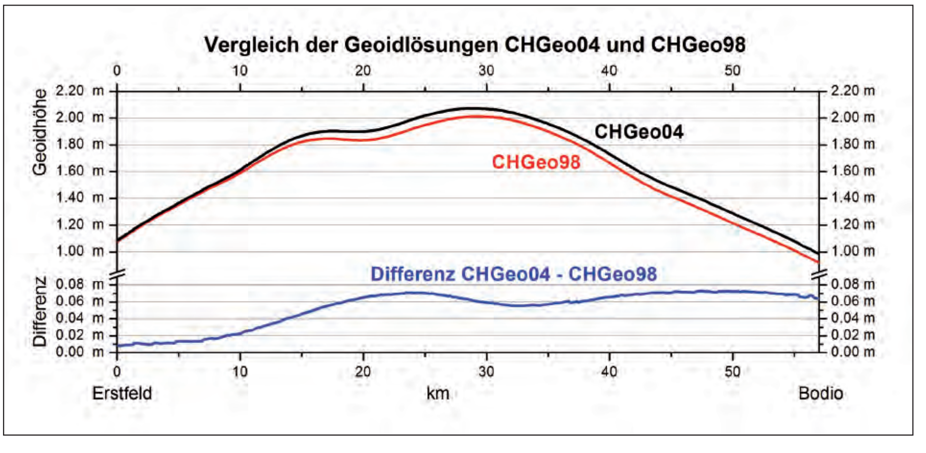


Fig. 5: The difference of the global vertical deflection between the CHGeo98 and CHGeo2004 geoids remains within a narrow band of ± 1.7 cc (0.17 mgon) proving that the CHGeo98 model has totally fulfilled the accuracy requirements.

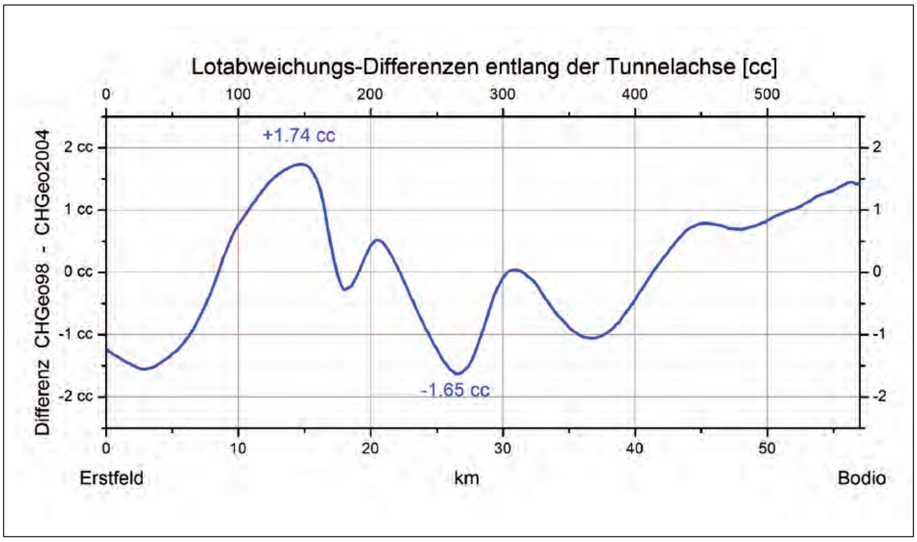


Fig. 6: The difference of the global vertical deflection between the CHGeo98 and CHGeo2004 geoids remains within a narrow band of ± 1.7 cc (0.17 mgon) proving that the CHGeo98 model has totally fulfilled the accuracy requirements.

Haag, R., F. Bräker & R. Stengele (1998): «A 57 km long Railway Tunnel through the Swiss Alps and its planned Survey.» Proc. XXI. International Congress FIG Brighton,

Haag, R. & R. Stengele (1999): «Vermessungstechnische Grundlagen und Herausforderungen beim Projekt Alp-Transit-Gotthard-Basistunnel.» Moderne Sensorik für die Bauvermessung, VDI-Gesellschaft Bautechnik, Bericht 1454, S. 225–240.

Hirt, C. (2005): Communication personnelle.

Hirt, C. und Bürki, B. (2002): «The Digital Zenith Camera – A New High-Precision and Economic Astrogeodetic Observation System for Real-Time Measurement of Vertical Deflections». Proc. of the 3rd Meeting of the International Gravity and Geoid Commission of the International Association of Geodesy, Thessaloniki (ed. I. Tziavos): pp. 161–166.

Ploner, M. (2005): Communication personnelle.

Schätti, I. (2006): «Herausforderungen bei der Absteckung des Gotthard-Basis-Tunnels.» Geomatik Schweiz, Heft 06/2006.

Schätti, I. und A. Ryf (2007): «AlpTransit Gotthard-Basistunnel: Grundlagenvermessung, letzte Kontrollen vor dem ersten Durchschlag.» XV. Konferenz für Ingenieurvermessung, Graz.

Stengele, R. & R. Haag (1998): «Geodätische Aspekte bei der Vermessung des 57 km langen Gotthard-Basistunnels.» Messen in der Geotechnik 98, Mitteilung des Instituts für Grundbau und Bodenmechanik TU Braunschweig, S. 301–312.

Stengele, R. (2007): «Erster Hauptdurchschlag im Gotthard-Basistunnel: Tunnelvermessung in Theorie und Praxis». 15. Internationaler Kurs für Ingenieurvermessung. Graz.

Zanini, M., R. Stengele & M. Plazibat (1993): «Kreiselazimute in Tunnelnetzen unter Einfluss des Erdschwerefeldes», Berichte des Instituts für Geodäsie und Photogrammetrie der ETH Zürich, Nr. 214.

Beat Bürki und Sébastien Guillaume
ETH Zürich, Institut für Geodäsie und Photogrammetrie
CH-8093 Zürich
buerki@geod.baug.ethz.ch
guillaume@geod.baug.ethz.ch

From potential theory to the subsidences at the Gotthard Pass

What began as a potentially harmless theoretical academic field test before the beginning of construction of the Gotthard Base Tunnel ended in 1997 with the surprising discovery of massive subsidences at the Gotthard Pass. A short look back to how the search for confirmation of the potential theory led to a very different discovery.

A. Geiger, A. Schlatter

What does the potential theory have to do with a tunnel?

This question is seldomly asked as long railway tunnels are built. Nevertheless, the answer to the question is particularly important in the context of the construction of the currently longest railway tunnel, the Gotthard. Although the answer does not look particularly scientific, it briefly highlights a small side aspect of geodetic research.

In the 1990s, anybody remotely interested in geology knew that the Gotthard massif did not ultimately stand fixed and unchanging. It was part of the uplift of the Alps. After the works of F. Jeanrichard and E. Gubler (consecutive directors at the the Federal Office of Topography swisstopo) and after the tireless geodetic-tectonic investigations by H.-G. Kahle (at that time professor of geodesy at the Swiss Federal Institute of Technology, ETH, and president of the Swiss Geodetic Commission), it became clear that the Alps are lifting up a few millimetres. In other words, there are deformations of the solid bedrock.

Aside from the widespread tectonic processes, local Late Quaternary distortions are apparent on the slopes of the Rhine-Rhone valley line. These differential shifts, clearly visible on the terrain and forming crevasses (so-called Nackentälchen) on the mountainside, also emerge above Andermatt. There, at Stöckli – Lutersee, geodetic measurements performed by the Institute for Geodesy and Photogrammetry of the ETH showed small vertical differential movements of several tenths of a millimetre per year. P. Eckardt et al. (2/1983) describe these distortions in an article in «Vermessung, Photogrammetrie, Kulturtechnik», the predecessor journal of «Geomatik Schweiz». The deformation problems arising shortly after the tunnel opening at «Kilometre 4» of the road tunnel are possibly due to this moving mechanism. Above Sedrun, in the area of the Caschlé Alp, high above the planned Gotthard Base Tunnel, these postglacial disruptions were also observed. They have been geodetically surveyed repeatedly in the 1990s by the Gotthard Base Tunnel Surveying Consortium (VI-GBT) in the knowledge that movements may occur.

D. Schneider, the head of the former Geodetic Bases Section of swisstopo and promoter of the integration of deformation theory findings in the national survey, developed a concept for repeated measurements of the road tunnel levelling, specifically in relation to deformations. The measurements were performed by VIGBT and swisstopo during an interruption in operations caused by maintenance work in June 1997. Lively discussions took place between the GBT surveying project manager, F. Bräker, and R. Haag from VI-GBT, swisstopo and IGP (ETHZ), which focused on what additional knowledge could be gained from further measurements. On the one hand, there was the question of the correlation between surface and tunnel deformations and, on the other hand, the potential-theory interest in the investigation of a vertical levelling loop. The test site is ideal because the surface levelling between the Hospental and Guspisbach ventilation shafts run exactly above the levelling of the tunnel. At the ends of the levelling lines the «top and bottom heights» can be directly linked by a vertical distance measurement. The length of the plumb line can therefore be directly measured, so to speak, in the earth's interior, at two points which are so close that the connecting levellings are very accurate and can be performed with reasonable effort. Briefly, the site is ideal for geodetic testing and who can afford to ignore a geodetic laboratory with a tunnel and two vertical shafts of 320 m and 530 m long?

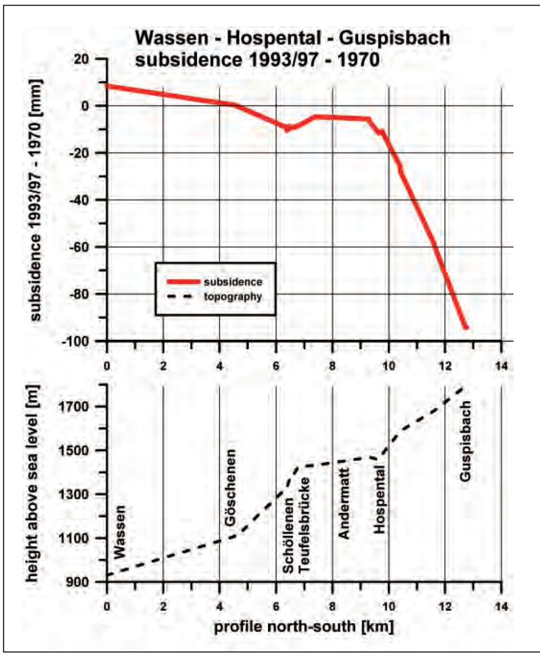


Fig. 1: Subsidence at the Gotthard pass between Wassen–Göschenen–Hospental and Guspisbach; Original graph from the first publication of the press communiqué dated January 22,1998 (Schneider, Schlatter 1998).

From the measurements to the great surprise

The cooperation of all involved parties and the additional financial help from the Swiss Geodetic Commission and the Swiss Academy of Sciences made it possible to perform the measurements immediately. They had to coincide with the tunnel maintenance. From September 23 to 25, 1997, there were very few afternoon hours left to perform the distance measurements in the vertical shafts using a Kern Mekometer 5000. At the end of the same month the levelling along the pass road was done by swisstopo and VI-GBT. The first analyses of the surveys from Hospental to Guspisbach (5 km long and 330 m height difference) differed considerably from the former pass levelling of 1970. There were 8 cm of subsidence! An entire world for a leveller. After further control measurements and analyses, it could not be explained away: the rock between Hospental and Guspisbach had sunk . In January 1998, this moving mountain result was published in a swisstopo press communiqué (see Fig. 1 from Schneider, Schlatter 1998). The authors talk about the most important bedrock subsidence phenomenon ever observed in Switzerland. As a consequence, the rest of the Gotthard pass levelling was repeated from Guspisbach to Airolo. The analysis the levelling data confirmed the already feared, very worrying results. In the central section of the alp excavation, there must have been signs of subsidences. A summary of the subsidence (Schlatter, 2007) is shown in Wiget et al., 2010.

These discoveries prompted the supervisory authorities and the constructor to initiate extensive investigations coupled with the first geodetic zero-measurements in the whole AlpTransit region. The zero-measurements aimed to document the current state, which can be referred to later. Thus, wide-range levelling surveys were performed by swisstopo over the Furka, Oberalp and Lukmanier passes and down to the Val Nalps. In the context of surveying and monitoring assignments, the deformations of the undercut dams had also to be monitored geodetically. With hindsight regarding the Zeuzier case (dam deformations, for example Bierdermann 1980) everybody agreed upon a proactive, forward-oriented strategy for the geodetic monitoring measures. The influence of rock drainages on the drilled rock in particular had to be viewed in a new light. Who has failed to look for something precise and found something else entirely? Should we not seize the occasion of the next long period of tunnel closure to verify the potential theory again? Will there be further surprises?

References:

Biedermann, R. (1980). Ausserordentliches Verhalten der Staumauer Zeuzier. Wasser, Energie. Luft, 72. Jahrgang, Heft 7/8.

Eckhardt, P., H. Funk, T. Labhart mit Beiträgen von W. Fischer und E. Gubler (1983). Postglaziale Krustenbewegungen an der Rhein-Rhone- Linie; Vermessung, Photogrammetrie, Kulturtechnik, 2/83.

Schlatter, A. (2007). Das neue Landeshöhennetz der Schweiz LHN95. Geodätisch-geophysikalische Arbeiten in der Schweiz, Band 72, Schweizerische Geodätische Kommission, 373 Schlatter, A., E. Gubler, B. Mattli, D. Schneider

(1997). Neues Landeshöhennetz LHN95: Deformations-Analyse Gotthard. Untersuchungen der Senkungserscheinungen im Bereich des Gotthard-Strassentunnels. Technischer Bericht 97-40, Bundesamt für Landestopographie, Wabern.Seiten. ISBN 978-3-908440-16-1.

Schneider, D. (1997). AlpTransit Gotthard-Basistunnel: Deformationsmessungen im Gotthard-Strassentunnel (A2). Technischer Bericht 97–13, Bundesamt für Landestopographie, Wabern.

Schneider, D., A. Schlatter (1998): RCM – Analyse Gotthard. Pressecommuniqué, L+T, 22.1.1998.

Schneider, F. (1978). Nivellement und Schweremessungen am Gotthard. Bericht 17, Institut für Geodäsie und Photogrammetrie, ETH Zürich.

Wiget, A., U. Marti und A. Schlatter (2010). Beiträge der Landesvermessung zum AlpTransit Gotthard-Basistunnel, Geomatik Schweiz, 12/2010.

Alain Geiger
Institut für Geodäsie und Photogrammetrie
ETH Zürich
Schafmattstrasse 34
CH-8093 Zürich
alain.geiger@geod.baug.ethz.ch

Andreas Schlatter
Bundesamt für Landestopografie swisstopo
Seftigenstrasse 264
CH-3084 Bern-Wabern
andreas.schlatter@swisstopo.ch

Surveying work at the Lötschberg Base Tunnel after the final breakthrough

The Lötschberg Base Tunnel, together with the already existing Simplon tunnel, is the first high-speed north-south connection through the Alps. For all the specialists involved, the Lötschberg Base Tunnel project was a challenge. Surveying such a long tunnel also constituted a very demanding task. The article «Tunnelvermessung des BLS AlpTransit Lötschberg-Basistunnels» in the professional journal «Geomatik Schweiz» 11/2005 addresses the main issue of tunnel surveying up to the main breakthrough. Aside from a summary of the results after the final breakthrough, the present report explores the following three surveying tasks: error of breakthrough compensation, monitoring of the ballastless tracks, and installation of the structural monitoring.

H.-U. Riesen

Project description

The Lötschberg Base Tunnel leads from Frutigen in the Kander valley (Bernese Oberland) to Raron in the Rhone valley (Canton of Valais). It is 34.6 km long and is designed as a one track, two-tube railway tunnel (separated by direction). For financial reasons, the tunnel was constructed in various phases. In the first expansion phase, the west Steg bypass with the Niedergesteln portal as well as the west tunnel from Ferden to Mitholz remain shell constructions. In the Mitholz-Frutigen section, only one tunnel tube has been excavated. The exploratory Kandertal tunnel built from 1994 to 1996 runs parallel to this track.
Construction work at the base tunnel tubes was initiated in 1999. The final breakthrough between the Cantons of Valais and Berne, which concluded the excavation work, was celebrated on April 28, 2005. The interior work and the railway infrastructure installation lasted until November 2006. The opening ceremony and the handover to the operator BLS AG took place on June 15, 2007. In time for the timetable change of December 2007, the Lötschberg Base Tunnel could be added to the route network.
The Lötschberg base tunnel was constructed simultaneously from five building sites. Aside from the two portal building sites Frutigen and Raron, there were the intermediate headings of Mitholz, Ferden and Steg/Niedergesteln. The two Rhone bridges at Raron as well as the cut-and-cover Engstlige tunnel at Frutigen were important outdoor constructions (Fig.1). The total length of the excavated tubes and galleries amounts to 88.1 km. Eighty percent of the tunnel system was excavated by drilling and blasting, the remaining 20% were driven using tunnel boring machines (Fig. 1).
According to the system option chosen, it was decided to build two parallel single-track tunnels, which are linked to each other every 330 m by galleries. This variant constitutes the optimum solution regarding the criteria of construction (costs, building time, environment), operation (operational requirements, preservation and maintenance, aerodynamics and thermodynamics), and safety (acceptance, risk).

Project participants

Project surveyor

In a two-level bidding procedure, the engineering association Berne/Valais (IG BeWa) was assigned the mandate of project surveyor by the contractor BLS AlpTransit AG. IG BeWa was composed of the following companies:

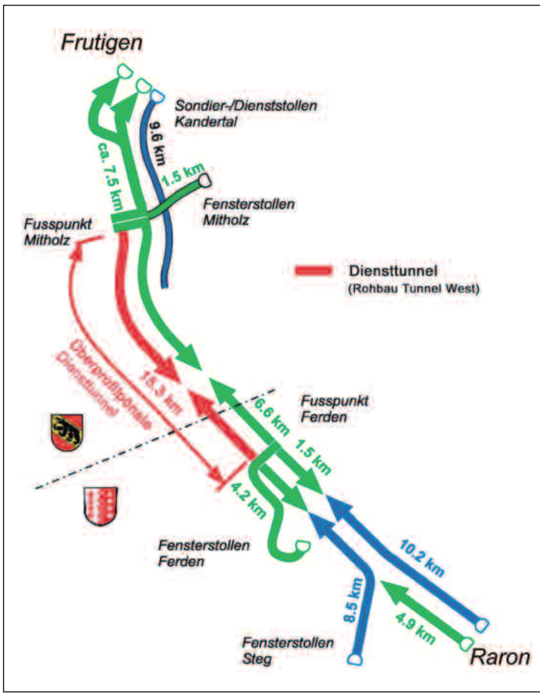


Fig. 1: Schematic representation of the different boring methods (green and red: driving by drilling and blasting; blue: TBM).

- ristag Ingenieure AG (formerly Riesen & Stettler AG), Urtenen-Schönbühl
- BSAP Ingenieure und Berater, Brig-Glis
- Häberli + Toneatti AG, Spiez
- Klaus Aufdenblatten Geomatik AG, Zermatt.

Specialists

To create and complement the above-ground base network, the Federal Office of Topography swisstopo was called in as subcontractor. The Lötschberg Base Tunnel layout was done completely within the reference frame of the new LV95 (GPS) national survey and on the basis of the LHN95 national height network.
Several institutes as subcontractors performed the gyroscopic measurements:

- ETH Zürich, Institut für Geodäsie und Photogrammetrie (IGP-ETHZ)
- Universität der Bundeswehr München, Institut für Geodäsie (IfG), Deutschland

BLS Netz AG

The surveying section of BLS Netz AG was responsible for elaborating and updating the track geometry project and the system documentation (GIS DfA).

Breakthrough between	Lateral- [deviation in cm]	Height [deviation in cm]	Longitudinal [deviation in cm]
Steg – Ferden	8.6	0.5	2.4
Raron – Lötschen	10.4	1.1	2.3
Mitholz – Frutigen	1.5	0.6	0.0
Lötschen – Ferden	2.0	0.3	0.4

Table 1: Results of the partial breakthroughs.

Error	Effective [cm]	Tolerance at 99% [deviation in cm]	Level of tolerance used
Lateral	13.4	25.0	54 %
Height	0.4	12.5	3 %
Longitudinal	10.3	–	–

Table 2: Results of the main breakthrough.

Results of the tunnel excavations

Due to the limited monitoring possibilities in the tunnel, the surveyor had to live with a certain degree of uncertainty until the end. Only after the final breakthrough was it possible to verify, with connecting measurements, whether the accuracy requirements had been met, with regard to whether our model assumptions were correct. Table 1 summarizes the results of the most important partial excavations.
On April 28, 2005, the final breakthrough (620 392/142 841) was achieved at 2026 m beneath the Balmhorn between the Bernese Oberland and the Canton of Valais (Mitholz – Ferden). At the breakthrough, the control measurements revealed the following error of a tunnel advance of 20.9 km (see Table 2).
Thus all partial excavations as well as the main breakthrough at the Lötschberg Base Tunnel showed very satisfying results. The requirements of the constructor were completely fulfilled.

Error of breakthrough compensation after TBM-excavation

In the tunnel sections where tunnel boring machines (TBM) were used the final tunnel floor including kicker (preparation for the inner shell) was installed just behind the TBM. Thus the position of the inner shell and also of the benches was already determined. After the breakthrough and the conclusive calculation of the control point coordinates, the excavated tunnel arch was measured using the overall combination measurement method (laser scanning). This basis allowed us to establish cross sections every 2.5 m to permit the comparison of current and target profiles.
With the help of this profile evaluation, the interaction between the different error components was analyzed. The total deviation between the shell construction and the project axis consisted of three components:

1. Laying out error of the project surveyor (PS)
2. Laying out error of the company surveyor (CS)
3. Deviation of the TBM-approach from the laying out axis of the CS

The analysis showed that all involved parties had met their tolerance requirements. Because the errors accumulated unfavorably at some places, major global variances occurred. The most important deviations amounted to up to 24 cm (see Fig. 2). By slightly adapting the track geometry over the whole tunnel length – without loss of driving dynamics – these deviations, however, could be easily accommodated.

Error of breakthrough compensation after blasting

In the tunnel section with drilling and blasting excavation, the tunnel floor, inner shell, and benches were finished in concret at the back already during the excavation. At the moment of the breakthrough, about 75% of the benches were completed and only roughly 4 km were missing.

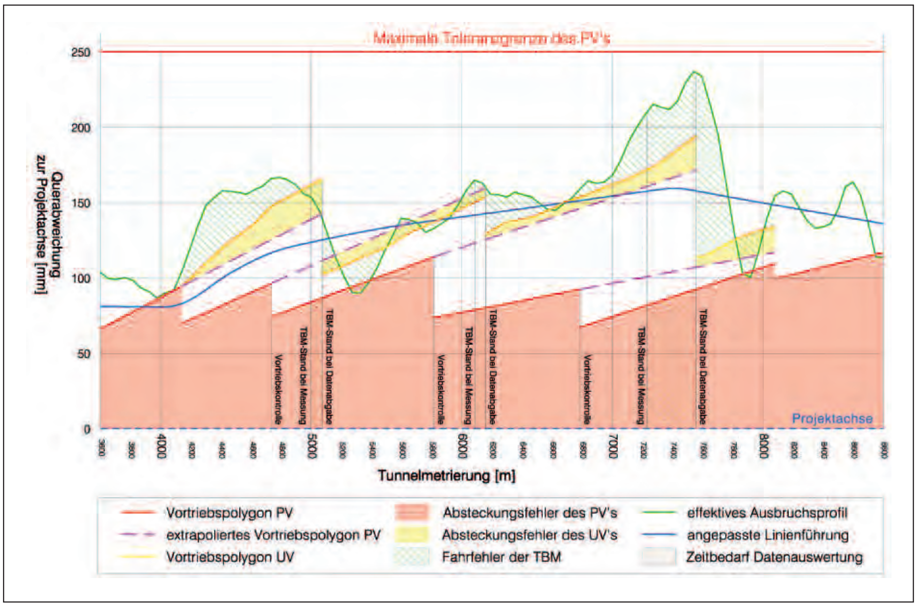


Fig 2: Profile measurement analysis Steg – Ferden.

Fig. 3: Track gauging trolley RACER.

The front edges of the benches were measured in height and position on the basis of the new control point coordinates (one control point every 25 m). As a result, the track geometry was slightly adjusted in the Mitholz – Ferden section in order to place the new track axis exactly between the already concreted benches. The error of breakthrough could thus be compensated for and minimal distance inequalities between banquette position and reference position could be corrected with an axis optimisation. The effective errors of breakthrough were therefore compensated for with a minimal adjustment of the track geometry. Depending on the situation, this would not be possible without posterior profiling of the point of breakthrough. Fortunately, this was not the case in the Lötschberg Base Tunnel, because the error of breakthrough was relatively small and because the general tendency in the drilling and blasting excavation of the tunnel was to excavate with an overage.

Slab track control measurements

A new track measurement vehicle (RACER – Rapid Automated Control Equipment for Rails) was especially developed for the precise control of the track setting (Fig. 3). The new surveying concept enables the contractor to carry out totally independent slab track control measurements.

System concept

- The motorized total station is fixed on the track measurement vehicle
- 3D-positioning of the track axis by free stationing over known connection points
- Automatic measuring of track gauge, longitudinal and transverse inclination
- Motorized locomotion of the measurement vehicle with variable increment
- Online-analysis and comparison between required and existing result values

In collaboration with the vehicle's development partners, the measuring system was developed, the control software was programmed, and a prototype of the measuring trolley was constructed. The operation procedure was optimized with extensive testing and a system calibration was carried out. These comprehensive comparative measurements using an independent system showed the following average measurement errors (1σ) (Table 3).

Measurement	Measurement errors (1σ)
Position	< 0.4 mm
Height	< 0.5 mm
Track gauge	< 0.3 mm
Gradient	< 0.3 ‰

Table 3: average measuring errors RACER.

The contractors' requirements

The contractor defined the installation tolerance requirements for the slab track (Table 4). A distinction is made between absolute and relative installation tolerance. The absolute tolerance values refer to the maximal deviations in both horizontal and vertical directions to the project axis. The relative tolerances are used to evaluate characteristics relevant to driving dynamics. The measuring interval was fixed at 2.5 m. This resulted in a measuring section performance of about 150 m per hour with the RACER track measurement vehicle, which corresponds to an average measuring section of one kilometer in 6.5 hours.

Results

The results of the final control were compiled in the form of differences to the nominal value. The statistical analyses showed that the installation tolerances in relation to the project axis have been adhered to at over 99% (Table 5). The few tolerance deviations do not exceed 1 mm. For a clear presentation, all control measurement results were displayed graphically by chart bands showing the differences to the nominal value [mm] (Fig 4). During the period between July 2005 and November 2006, after the installation of the slab track, measuring campaigns were regularly carried out in sections. In the course of several measuring campaigns, over 51 km of tunnel track was controlled. In summary, the control measurements show excellent results that confirm the high quality installation technology used for the slab tracks on the one hand and on the other hand the accuracy and reliability of the RACER. The implementation of innovative solutions and the resulting saving of time and costs made it possible to submit the required results in time and with a reasonable effort to the contractor.

Structural monitoring

A structure this size needs long-term monitoring. In October 2003, IG BeWa

Survey Parameter	Tolerance
Position	± 3 mm
Height	± 3 mm
Track alignment error [1)]	< 2 mm
Cant	± 2 mm
Track gauge	–1/+3 mm

Table 4: installation tolerances 1) On a measuring basis of 20 m the difference between two neighboring track alignments, measured in the middle of the string every 5 m must be less than 2 mm in horizontal and vertical directions.

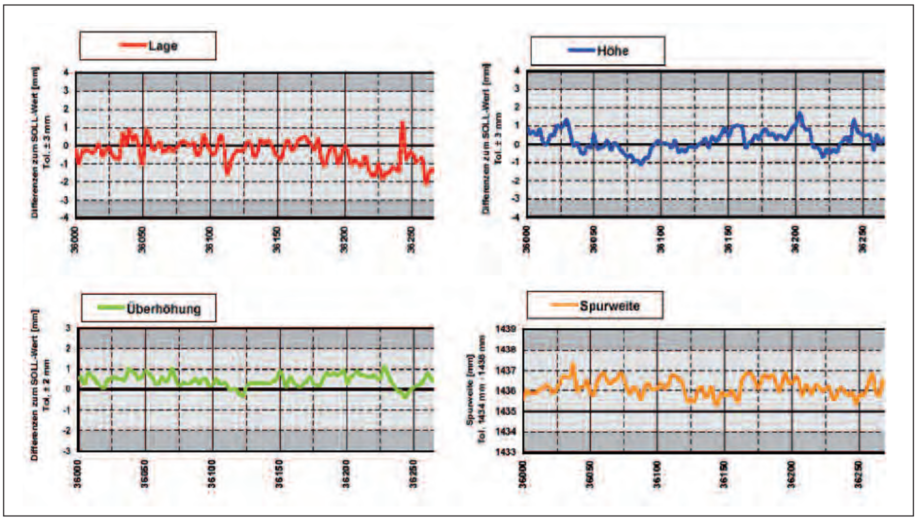


Fig. 4: Differences between the effective geometry of the ballastless track and the project axis.

asked swisstopo if they were interested in measuring a land levelling line through the Lötschberg Base Tunnel before it becomes operational, which they accepted. The high-precision double levelling carried out under the supervision of swisstopo in November/December 2006 provided IG BeWa a high accuracy determination of the vertical control points in the LHN95 height reference frame. Furthermore, swisstopo was able to complement their national height network and to control the loop short cut over the Lötschberg mountain line as well as the mountain tunnel.

Point groups at every crosscut along the whole tunnel as well as intermediate points on the eastern bench side were fixed with bolts and rivets. In the critical fault zones «Autochthon Nord», «Karbon» and «Jungfraukeil», the density of the control net was increased with additional control points on the western bench side.

For structural monitoring, heights were stocked at a height control point in the portal sector of the Frutigen connection. The choice of the LN02 height reference system enables on site follow-up measurements without using the orthometric correction system as well as the comparison of measured height differences.

Final consideration

From the beginning until the opening of the tunnel, IG BeWa was assigned the surveying tasks at the Lötschberg Base Tunnel. Worldwide there existed very few projects of such importance and requiring such accuracy worldwide and therefore there was little experience in the laying out of tunnels. The task thus represented a big challenge to us.

The results of the different breakthroughs prove that we have mastered the challenge well. The project offered us many exciting moments and we were able to gain valuable experience. Thanks to the excellent collaboration with all persons involved in the project – contractor, project engineers, geologists, construction managers and companies – the Lötschberg Base Tunnel project will always remain among our best memories.

		Absolute installation tolerance			Relative installation tolerance	
Number of measurements	Position	Height	Cant	Track gauge	Track alignment error Horizontal	Vertical
	> 3mm	> 3mm	> 2mm	> –1/+3mm	> 2mm	> 2mm
20 440	29	108	11	136	3	1
100%	0.14%	0.53%	0.05%	0.67%	0.03%	0.01%

Table 5: Number of deviations from tolerance.

Hans-Ueli Riesen
ristag Ingenieure AG
Eigerweg 4
CH-3322 Urtenen-Schönbühl
h.riesen@ristag.ch

Railway Infrastructure surveying for the Lötschberg Base Tunnel

Between 2004 and 2006 the Lötschberg Base Tunnel was equipped for railway operations. The construction costs amounted to CHF 791 million. Wild Ingenieure AG from Küssnacht am Rigi were authorized to carry out the surveying contract. The main job was to position the 51.6 km long ballastless track in the base tunnel. With the help of the HERGIE track surveying trolley and the lifting wedge system, developed by Rhomberg Bahntechnik AG, the tracks were laid in their specified positions during several operations. The high standards of accuracy required for the track laying represented a considerable challenge. The railway infrastructure installation was carried out in a three-shift operation, which required the surveyors to be highly flexible and to closely collaborate with the track construction team. Constant time pressure, shift work, and full on-call availability during the entire construction period put a huge strain on every single surveyor.

B. Tanner

The railway infrastructure installation was carried out by the general contractor «ARGE Bahntechnik Lötschberg» under the leadership of two construction companies, Implenia AG and Rhomberg Bahntechnik AG. The consortium included more than 35 specialized companies covering the twelve independent areas of railway technology. Wild Ingenieure AG was assigned the surveying mandate for the railway infrastructure and was primarily active in the areas of road surfaces, catenary systems, and logistics (construction infrastructure). Three full-time and up to three additional occasional survey teams were employed to carry out the surveying work over a period of more than two years.

Ballastless track

The construction of the ballastless track (BT) was the most complex among the railway infrastructures. From autumn 2004 to summer 2006, about 100 workers were on three-shift duty seven days a week in conditions of about 28° Celsius and high humidity.

For a BT, the ballast is replaced by another stable material such as concrete. The essential track stability as well as lower maintenance and operational costs are advantages in comparison to ballasted tracks. The BT provides a service life of 50 to 60 years. Disadvantages are significant investment costs and higher airborne sound emission values.

At the Lötschberg baseline, a BT was built in the base tunnel and in the Engstlige tunnel (2.4 km in Frutigen); the rest of the tracks (4.6 km) were constructed as ballasted tracks. The rigid structure of the BT requires a higher track-laying accuracy in order to guarantee high-quality driving dynamics (driving comfort and rail wear). The railway infrastructure surveying for the Lötschberg project started in February 2003 at the Mitholz test gallery of the Lötschberg Base Tunnel. The first BT construction tests were carried out on two tracks of about 54 m and 36 m in length. In 2004, two more tests followed in Dornbin (A) (Fig. 1). Together with Wild Ingenieure AG, Rhomberg Bahntechnik AG conducted tests for the BT installation with a true-to-scale tunnel cross section on a 70 m long track. The task consisted of testing and developing the installation procedures and the performance of the lifting and alignment system for track positioning.

Alignment system

The alignment system developed by Rhomberg consists of two components: a lifting wedge, which permits the stepless adjustment of the tracks in the submillimetre range (Fig. 6), and the HERGIE track surveying trolley, which displays relative and absolute positions (Fig. 2).
Real-time verification was carried out with the total station guided HERGIE track surveying system. The track surveying trolley is made of aluminum and weighs only 25–30 kg. It is fitted with a 100% weatherproof industrial PC and a touch screen. An external keyboard can be added and it is equipped with a PCMCIA-slot.
A LEICA TCA2003 total station was used. The communication between tachymeter and surveying trolley was handled via a radio connection. The position of the TCA2003 was determined with the help of a free station based on track security reference points.
The HERGIE track surveying trolley consists of the following components:

- Electronic precision inclination sensor for cant (slope or tilt) measurements (accuracy of cant measurements: ±0.4 mm)
- Distance measurement sensor for the track gauge (accuracy of track gauge: ±0.4 mm)
- Electronic precision inclination sensor for rail inclination measurements
- Industrial computer with touch-screen (Fig. 3)
- Reflector

HERGIE is based on high-precision, three-dimensional, real-time single point positioning. Each measurement point is determined by seven parameters: its 3-D coordinates, rail cant, track gauge and the inclination of both tracks. Thus the following track geometry quality features can be defined:

- the transverse position of the reference rail (In practice, the reference rail is adjusted, not the rail axis),
- the top edge of both rails

Fig. 1: Test track at Dornbirn (A).

Fig. 2: HERGIE track measuring vehicle.

- the rail cant (transverse gradient of the carriageway),
- the track gauge (distance between the inner edges of the rails),
- the railway kilometrage and
- the cant of both tracks (the tracks are inclined inwards at a ratio of 1:40).

The measured data are stored in the HERGIE database and can be displayed graphically or in list format (ASCII format). The fixed point coordinates and the route parameters of the track constitute the basic data for the rail inspection. These include horizontal and vertical geometric data as well as cant data. As the track geometry axis is not identical with the kilometerage axis there is the possibility to add the kilometrage axis geometric data. In order to improve reliability, the different components (sensors) can be easily monitored and calibrated at any time. In addition, the orientation of the total station can always be controlled and adjusted from the track surveying trolley. HERGIE is powered using a 12 Volt car battery (45 Ah), which ensures the continuous operation of the system for twelve hours.

Installation tolerances

Due to the rigid construction of the BT, the installation tolerances are much higher than for ballasted tracks. This is the only way to guarantee high-quality driving dynamics (for example, driving comfort and rail wear). The following requirements were defined for the BT (see box)

The most difficult task was to meet the requirements regarding track alignment error in horizontal and vertical dimensions (internal geometry). The tolerance (= 98.8%-probability) for the adjustment of a support point was ±0.6 mm and required careful and experienced alignment. All other requirements easily could be met with our system.

Installation of the track

The construction of the BT required five surveying procedures:

1. Surveying for the placement of the track sections
2. Rough alignment of the track panels
3. Final alignment of the track panels
4. Monitoring during the concrete paving
5. Demonstration of the quality of the track geometry

The installation of the BT was carried out in 2160 m cycles. For logistical reasons, 18 m long preassembled track panels, including the track sleepers, were transported to the base tunnel and assembled together.

In order to install them with as much precision as possible, the extended carriageway and the axis distances at the benches were marked beforehand. The stakeout was essentially surveyed with a total station on the basis of a track stakeout application program. Every 12 m, a point was determined left and right on the bench walls and then continuously marked with the help of a snap line (chalk line). The main difficulty lay in the precise positioning of the track panels by the track layer. He was required to lay the track panels on the adjustable supporting legs with an accuracy of ±10 mm in position and ±5 mm in height (Fig. 4). As it is easier to lift a track than to lower it, the track panels were positioned at 1 cm below the real height.

During the rough alignment process with the HERGIE system, the aim was to align the track panels at ±3 mm in position and 0 mm to –5 mm in height. With the help of a mechanical lift-adjustment device (Fig. 5), the track is lifted at a distance of 3.6 m, moved to the final position and fixed to the adjustable sleeper boots.

In order to set the track continously in the required position, iterative alignment procedures were necessary. Depending on

Fig. 3: Touch Screen with measuring data display.

Installation tolerances in horizontal and vertical directions *(external geometry; measurement basis: adjusted control network)*	±3 mm
Track alignment error *(internal geometry: horizontal and vertical, measurement basis 20 m, difference between two neighbouring track alignments <2 mm, measured every 5 m in the middle of the chord)*	<2 mm
Installation tolerances cant	±2 mm
Deformation	≤0.5‰
Installation tolerances track gauge	–1/+3 mm (standard deviation ≤1 mm)
Installation tolerances rail inclination	min. 1:45, max. 1:35
Installation tolerances longitudinal support point distance	±10 mm angle accuracy: ±10 mm

the precision of the track positioning and the accuracy of the rough alignment, one to three alignment procedures were necessary. One difficulty lay in the fact that, as a result of overcorrecting, the position of the global track could shift again in the completed and already corrected positions. This procedure required a high degree of skill: on the basis of the required muscle strength to move the track, it had to be determined if the preceding track panels was positioned more to the left or the right of the intended final position. This was therefore taken into account when adjusting the position.

In addition, the rail inclination was controlled during the first alignment procedure. The rails had to be curved inward at a ratio of 1:40. With the help of 0.1 mm to 0.5 mm thick fastening clips, the required rail inclination could be adjusted at the track holder.

In the next step, the track panels were fixed every 1.8 m with concrete supports and the now unnecessary sleeper boots were folded upwards. The track supporting slab, about 25 cm high, was then set in concrete, thus fixing the concrete supports.

The sleepers were still exposed, but from that moment on the tracks could only be moved only over a small area with the help of lifting wedges, it was very important to perform the preceding rough alignment with sufficient accuracy. Even small deviations made the final adjustment with the lifting and alignment system difficult or even impossible and time-consuming emergency solutions had to be found.

The final adjustment of the tracks (Fig.. 6) was carried out with the HERGIE track surveying trolley and the lifting wedge system as well, this being the last adjustment procedure before concreting the track sleepers. The final adjustment required maximum accuracy, the tracks having to be adjusted at ±0.2 mm in position and height. Experience has shown that the air flows and turbulence inside the tunnel were problematic. To counteract this, only two track panels (36 m) per total station setup were positioned.

The track was adjusted every 1.8 m with the help of a pair of lifting wedges fixed under both rails. One wedge served to adjust the position and height of the right rail and the other the position and height of the left rail. This procedure required

Fig. 4: Installation of the 18 m long track panel.

Fig. 5: Rough track positioning.

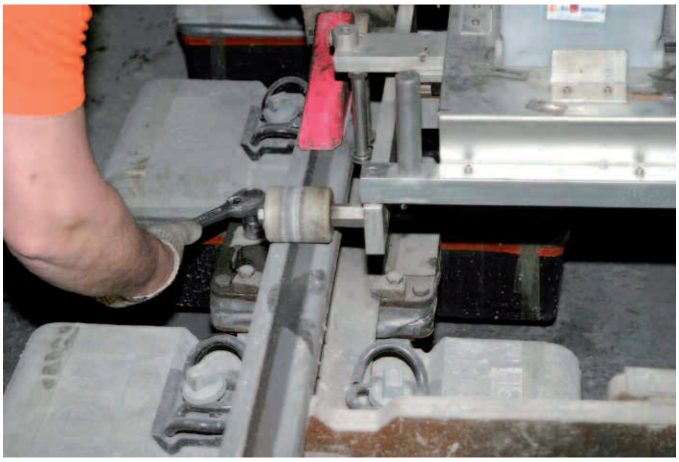


Fig. 6: Fine adjustment of the track panel with the mechanical lift-adjustment device.

Fig. 7: PLASMA longitudinal chord-based track.

great precision and several iterative alignment procedures. Overall, the BT rails were adjusted with the help of more than 57 300 lifting wedges and by muscle power.
Half a work shift (about 4 hours) later, the adjusted tracks, with the track sleepers, were set in concrete. During the placing of the cast concrete, monitoring was carried out by a longitudinal chord-based track. The Rhomberg PLASMA longitudinal chord-based track (Fig. 7) was directly connected to the concrete paver unit, pulled behind. It surveyed the relative height and position change, cant measurement, track gauge, and distortion. The measurements served to maintain quality assurance of the track geometry during the concreting. If the PLASMA track had measured deviations in the adjusted track geometry an audible alarm signal and rotating beacons would have been activated.
After the concrete had cured the 18 m long track sections were detached from the concreted sleepers and removed. Long-welded rails (running rails) 120 m long were then placed in the sleepers. The final control of the running rails was carried out on these long-welded rails with the HERGIE track surveying trolley. The results were displayed graphically by a diagram and with a list containing statistical key figures. The measuring drives with the SBB diagnostics vehicle confirmed the excellent quality of the track geometry. The 51.6 km long BT was installed without requiring rectifications and could be handed over to the constructor for test drives in June 2006.
Of decisive importance for this perfect achievement were, above all, the excellent collaboration and the great mutual helpfulness of all people involved. Together with specialist knowledge, regular maintenance, adjustments, calibration of the instruments, and the track surveying trolleys lead to success. The HERGIE track surveying trolley was perfectly suited to the task because it was reliable, solid, and of light construction. The precise and dense base network in the tunnel was another basic prerequisite for the good results.
Despite the seemingly monotonous and repetitive adjustment measurements the task was anything than boring for the surveying team. In fact, the surveyors were faced with and challenged by new and unexpected problems on a daily basis. The intense time pressure was not just a burden, but could be motivating as well.

Track supporting slab

Once a few kilometres of BT had been installed on the Wallis side, the shell work on the Berne side could be completed during the second half of 2005. For the first time, the tunnel infrastructure could be installed from both sides of the tunnel. To speed up the work, it was decided to install 7.3 km of track supporting slab on the Berne side beforehand, which considerably reduced the subsequent construction time for the BT (Fig. 8). The assignment was to provide surveying services for the total-station controlled slipform paver. The installation of the track supporting slab was performed during normal daily shift operations and was supervised by a surveyor. He was assigned the task to reposition and realign the total station for the paver control system every 50 m and to monitor the automatic control of the paver by periodic sampling. Moreover, in a one-man operation, he had to monitor the cured track supporting slab.

Track holder

Over 10 000 points had to be staked out at ±10 mm and ±3 mm for the 60 km long catenary system. Most points were staked out in catenary support structure shell. The staking out was performed with a total station and a track stakeout application program, taking into account the track cant. The staked out points were secured with a borehole and color mark that defined one of the nine different drilling patterns for the anchor drillings. The staking out of the about 100 tension wheels for the re-tensioning system of the catenary wire was particularly time-consuming with 14 points each. In the drilling and blasting sections, a formwork curved

Fig. 8: Installation of the track-supporting slab with the formwork finisher.

over two radii was staked out beforehand on the irregular shotcrete surface. This was done with the help of metres-long, tear-resistant plot templates that were fit over three staked-out points and on which the curved surface line was traced. The staking out of the catenary points was performed during the few days of preparation preceding the next BT installation cycle.

Ballasted track

The 4.6 km long open aboveground sections of the Lötschberg baseline were equipped with a ballasted track that included a 160 m long high-speed switch. The conventional rail construction required relatively few stakeouts. The main task was therefore the transfer and management of the numerous different track geometries and temporary track reference points in each construction phase. The collected data served as a basis for providing installation lists and tamping machine files for the tracklayers.

Logistics

Logistics played a central role in this large-scale project. Five-hectare surface installation sites for the railway infrastructure were set up in Raron and Frutigen. Among other things, they included among other things an important street and rail bound transfer point, two large halls each, a concrete batching plant, a residential mobile home camp and several office trailers. The temporary railway tracks consisted of roughly 9 km of track and 37 track switches. The staking out of those temporary installation sites was also part of the surveying assignment.

Additional surveying services

Aside from the main surveying work for the track, the catenary system and the logistics, many additional surveying tasks were performed for other specialist areas. They were often limited to special calculations on the basis of track geometry data or to simple stakeouts or recordings.
One of the tasks consisted of establishing requirement profiles for laser scanning pictures and their acquisition. The tunnel tube tolerances data provided by the constructor were insufficient for an optimized installation of the BT. The exact position of the tunnel floor, the shells, and especially the drainage shafts located inside the track were of major importance for a smooth course of construction. It soon became clear that precise and complete recording of the base tunnel's overall structural work could save a lot of time for the installation of the BT. Along with the tunnel shell, the railway technology surveying team took over the track displacement monitoring network and thus its maintenance. The client's surveyor performed the elaboration of the basic control network. A few track reference points had to be replaced and newly determined. One of the last tasks was to update the project point collection for the Federal Railway's central data base (DfA) and its structured data supply.

Success, challenges and thanks

The surveying of the railway infrastructure was in all respects an interesting assignment for Wild Ingenieure AG. Thanks to a good organization, and motivated and flexible surveyors, we were able to carry out all tasks reliably, quickly and without incidents. Our fundamental knowledge on railway construction contributed to this success.
For the major and time-restricted surveys, the surveyors had at their disposal a complete roster of measuring equipment, ranging from spanners to track surveying trolleys and total stations, in double and multiple versions. All reserve material was transported along in a material container on rails and was therefore always at hand and available. To recharge the various batteries, a power supply was available every 333 m in the cross-galleries. Continuous processes permitted clear transfers at shift changes, even in hectic circumstances. A real puzzle was the installation of the two 160 m long high-speed switches in the BT. This was hardly astonishing as the construction tolerances for the concrete sleepers were higher than the predetermined installation tolerances for the switch. After numerous adjustment procedures of the main track and the safety track, the switch was adjusted in parallel using two track-surveying trolleys. A few hours later, the switch was positioned inside the required installation tolerances and could be concreted. With great experience and confidence, the adjustment

of the second switch was undertaken half a year later. Although the knowledge and tricks gained from the first installation caused fewer headaches, the adjustment of the second switch didn't take less time. After about 48 hours, the second high-speed switch was also installed within the required tolerances. One of the greatest challenges for the surveying team, however, was to work in three-shift operations under difficult climatic conditions. The surveyors were furthermore required to be available and competent for emergencies around the clock during the shift cycle assigned to them.
The surveying work was strictly bound by the operational processes and work progress of the tracklayer team. It is well known that surveyors usually have to adjust at very short notice to the timetables of others. It was no different during the construction of the BT. Shifts were regularly cancelled or had to be doubled in order to maintain the optimal operating cycle.
A normal shift for a surveyor usually began 1–2 hours before the actual start of the shift. From the surface installations site, he contacted the surveyor inside the tunnel by radio and enquired about the progress of work and possible problems. He then boarded the staff train for a 1–2 hours journey to the front of the installation site. When taking over the work, he first checked at which niche the replacement batteries where charged and then performed a complete calibration of the sensors. After eight hours of work in the tunnel, the staff train took him back to the surface installation site. A long and tiring 10–12 hour working day ended with a warm meal and a beer in the canteen.
During the installation of the BT, our surveyors were exclusively assigned to three-shift operations. In the 3–5 days of preparation for the next work cycle, the remaining survey works, analyses and protocols had to be completed.
Over the term of two years, this project required extraordinary efforts from our surveyors. This was only made possible through their exceptional personal commitment and compromises in their private world. I would like to express once more my sincere gratitude to our surveying team and their families.

Bruno Tanner
Pat. Ingenieur-Geometer
Wild Ingenieure AG
CH-6403 Küssnacht am Rigi
bruno.tanner@wilding.ch

Deformation Monitoring – Challenge Accepted

Building activities, like the NEAT, always include a large number of challenges. The participating companies need and are willing to face these challenges. Of course, this is also true for deformation monitoring, aboveground and underground. This short article deals with some of these challenges, with a hint of humor.

M. Bertges

Today, deformation monitoring is part of daily work for most surveyors. Being asked about the dedicated tasks for monitoring, they will use terms like «measuring», «analyzing», and «visualizing». This is correct for the standard, manual monitoring. But for automated deformation monitoring, one very important term is missing: «data transmission».
The necessary skills for this task normally exceeds what a geomatics engineer had been taught. This is not a serious deficit in teaching geomatics. The skills are the ones of a communication specialist, like an electrical engineer. This demonstrates perfectly the interdisciplinary cooperation in engineering today.

GBT – ARGE Los349

In summer 2002, we were asked to provide an automatic deformation monitoring system. The challenge was «just» the communication between the sensors – the measurement modules – and the main computer – the «analyzing module». So what was the problem? During construction of the tunnel and the Sedrun multifunction station, ARGE Los349 had been assigned to monitor the movement of selected points in the terrain. It was decided to use GNSS, but the points were at an altitude of between 2000 m and 2700 m in a high mountainous area. Solar was the first choice for a power supply and the suitable GNSS receivers had already been selected, but how to establish a reliable communication link? Of course, mountaineering is great fun during holiday but during normal working time, it's just too expensive. Unfortunately, for more than half a year, the only real option for accessing the GNSS stations is a helicopter. And to add insult to injury, the weather conditions are harsh, with only GSM, no GPRS/UMTS access, and no spare frequencies for point-to-point radio links. To complete this challenge successfully, a network of autonomous sensor systems was necessary.
ARGE Los349 had chosen to use the DC3 deformation control system. The DC3 uses small microcontrollers, which permanently monitor not only the GNSS sensors but also the GSM modules. In case of any malfunction or abnormal operation, the microcontroller resets and reinitializes the sensor and GSM module. There is an integrated scheduler that can be used for offline measurements. A user ID and password control access to the system.
Everything was working fine, but all participants had to experience the special characteristics of GSM cells first. During the skiing season, occasionally some of the stations were not accessible due to a GSM cell overload. The low signal power of the GSM signals in this high mountain area could be handled by using directional antennas. For a proper pointing to the cell base station, the integrated test operations of the system could be used. During the first winter, the DC3 server lost contact with one station. A checkup by helicopter proved the theory of solar panel operations being correct. A solar panel needs sun to produce power. If the panel is mostly snow-covered, the remaining power is not enough to drive a GNSS deformation monitoring station … quot erat demonstrandum. The loss of contact with another station during the summer was caused by some «smart guys», who had the idea those solar panels, the charger and the batteries (about 60 kg weight!) could be used perfectly in a new environment, like a cozy mountain hut or something similar. Unfortunately, they decided to prove their theory.
By summer 2007 five additional DC3 GNSS monitoring stations had been installed. A network of ten GNSS stations now monitors the movements above the base tunnel.

Fig. 1: GNSS-Station.

Faido MFS–Amberg Technologies

In spring 2006, several rock bursts occurred during construction of the Faido MFS. The general public experienced the rock bursts as seismic events. Responsible for the rock bursts were fault zones in the

mountains near the Faido MFS. To assist the geological research of the fault zones, two autonomous working monitoring systems had to be installed in the Faido MFS. Two identical DC3 systems with a total station, a software module for convergence analysis but without active alerting were installed.
The challenge was the power supply. Having no permanent access to the 230V power lines, the only possibility was to use a connector in one of the many power distributions on the construction site. So the two DC3 systems had to share their needs of 230 V-power with the needs of the tunnellers. A UPS served as a buffer for about 1.5 hours of operation. The available means of alarm of the DC3 system were intended to warn the tunnellers to plus in the DC3 power connectors after removing their tools from the power distribution. During installation, a large number of power sockets were available. So nobody expected any problems for the future.
The following 1–1.5 years proved this idea to be wrong. We found out that the number of available power sockets was not enough. Two flashing lights were added to the illumination of the Faido MFS and during their 1.5 hour of operation, they alerted nobody to anything, especially not to reinsert the power connectors of the monitoring systems. Luckily, during each of their shifts, the surveyors made their way along the two systems, thus they were able to minimize the loss of data.

CBT – IG Ceneri Los704

The northern tunnel portal crosses below the A2 highway, which leads to the Ceneri pass. This is the only north-to-south highway through this part of the Alps. The worst-case scenario would be a deformation or a soil flow during construction. The resulting blockage of the highway would cause severe traffic jams. Any complex system, especially with human interaction, has many sources of false alarms. Bearing in mind the universal validity of «Murphy's Law», the worst-case scenario would happen during holiday season and a weekend. No doubt this was something that no one was willing to imagine. So the challenge was to deliver a system with extremely high reliability and complex but robust mechanisms for alerting.
The first step was to distribute the different sensors – geotechnical sensors, total station and GNSS – to several separated deformation-monitoring systems. The communication inside each monitoring system and the interconnection of all the systems were IP based. The main servers and communication modules in an air-conditioned 19"cabinet had been placed in a container near the construction site. The second step was to divide the geotechnical sensors into two groups, each handled by an autonomously running DC3 system. Both systems were using UPS to be able to work for about 90 minutes with no main power supply. In case there was a complete breakdown of the cable connection between the two geotechnical-monitoring systems and the container site, backup Wi-Fi links had been installed.
As a last step, special software was developed that allowed the analysis of the sensor values with regard to the causal interconnections between sensors in one borehole, sensor groups, and neighboring boreholes. The result of this analysis had been the alert levels «hardware alert», «warning – yellow alert», and «red alert».
A multilevel concept was necessary to fulfil the needs for alerting different user groups. The first alert was sent by SMS to the first person in the user group. If no acknowledgement was received in a defined timespan, a second alert was sent by a voice call and a prerecorded voice message. SMS text and voice messages depended on this kind of alert. If no acknowledgement was received from the person, the alert was handed over to the next person in the group.
Of course, some of these smaller «challenges», all participants can hopefully smile about today. Like the broken cable, which had to be repaired temporarily because of time pressure and was drowned with the next rain on the next day, deep inside a borehole. Or the spiders that found the rain protection of a prism to be very suitable for their new home. The infrared beam of the total station could not penetrate the spider's nest. And don't forget the ants around the electronic boxes in one borehole, and that piece of hosepipe, which suddenly appeared to be a snake. Not to mention the radio link, which worked perfectly for a long time … until someone else on the site started using the same frequency … occasionally.
Last but not least, it is a pleasure to thank all the colleagues of the participating companies for the cooperation during the past years. Only in cooperation like this, is it possible for us to accept all these challenges and to make our contribution to the construction of the Gotthard Base Tunnel.

Martin Bertges
Dr. Bertges Vermessungstechnik
Flurstrasse 7
DE-66887 Neunkirchen am Potzberg
mbertges@drbertges.de
www.deformationsmesstechnik.de

300 surveyors acknowledge many years of precise work

Masterly surveying performances in the world's longest railway tunnel: only eight centimetres horizontally and one centimetre vertically – those were the deviations at the final breakthrough of the Gotthard Base Tunnel on October 15, 2010. At a specialist conference held at the Swiss Federal Institute of Technology (ETH) in Zurich, some 300 surveying experts from Switzerland, Germany and Austria paid tribute to the precision that was achieved.

R. Probst, D. Fasler Isch

Specialist event marks final breakthrough of the Gotthard Base Tunnel

At the specialist conference, «With millimetre accuracy through the Gotthard» held at the Hönggerberg Science City of the ETH Zurich, the many different challenges of underground surveying were discussed. The event took place on October 29, 2010, exactly two weeks after the successful final breakthrough in the Gotthard Base Tunnel between Sedrun and Faido. Around 300 surveying specialists and geomaticians from Switzerland, Germany, and Austria were in attendance. The event was organised by AlpTransit Gotthard Ltd. and the ETH Zurich (Institute of Geodetic Metrology and Engineering Geodesy, Professor Dr. H. Ingensand). The challenges presented to surveying by tunnel construction, and the Gotthard Base Tunnel in particular, were examined from a theoretical and practical perspective. Hilmar Ingensand, Professor of Engineering Geodesy, described the various new and further developments in the field of metrology and precision instruments that were stimulated and accelerated by the AlpTransit project. From the viewpoint of the Gotthard Base Tunnel Surveying Consortium (VI-GBT), which was tasked with responsibility for surveying in the Gotthard Base Tunnel by the tunnel owner, AlpTransit Gotthard Ltd, Roland Stengele described the discrepancies between theory and practice that were encountered during work on the tunnel in the last 15 years.

Overview of the diverse surveying tasks

In the afternoon, a series of brief presentations by surveying specialists who were involved provided an impressive overview of the numerous tasks of the geomatics discipline. The spectrum ranges from control of the drives through monitoring of dams and motorways to laser scanning of the tunnel vault. It also includes monitoring the laying of the permanent railway track in the tunnel, which must be accurate to as little as one tenth of a millimetre.

Cordial thanks to participants and sponsors

Significant contributors to the success of the event were: The organisation team of Professor Ingensand's Institute of Geodetic Metrology and Engineering Geodesy at the ETH, led by Susanna Naldi; the Head of the Construction Hall, Dominik Werne, and his team; Daniel Bäni, who coordinated setting up the exhibition; SV Service, who provided the excellent meals throughout the day and evening; the audio-visual team, who were responsible for the video and audio systems, as well as the Media Office and Geomatics Department of AlpTransit Gotthard Ltd. Without the generous contributions of the spon-

Fig. 1: The specialist audience attentively follows the presentation by Professor Dr. U. Weidmann.

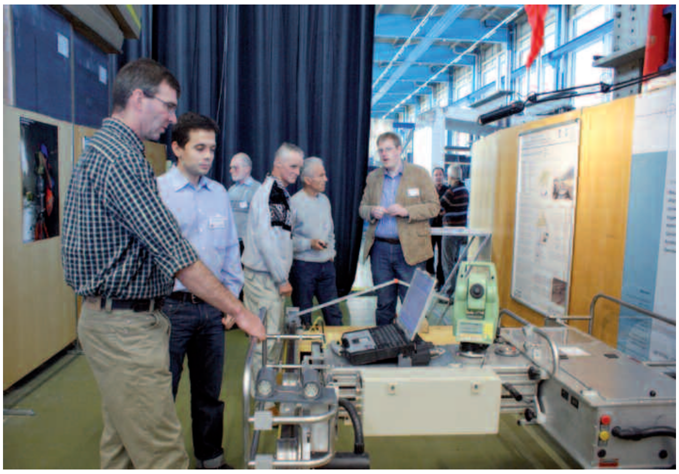


Fig. 2: Participants at the conference obtain information about the latest developments in metrology.

Fig. 3: Former and current employees of the Gotthard Base Tunnel Surveying Consortium (VI-GBT) and AlpTransit Gotthard Ltd.

sors, the event could not have taken place. We wish to thank the Gold Sponsors, BSF Swissphoto, Grünenfelder and Partner, the TAT Consortium, and the Federal Office of Topography; the Silver Sponsors, Amberg Technologies, Gisi e Bernasconi / Geofoto and Studio Meier; and the Bronze Sponsors, Dr. Bertges Surveying Systems, Goecke, Grunder Engineers, Ingenieur-Geometer Schweiz, and Ristag Engineers. Special thanks also go to the Gerold and Niklaus Schnitter Fund for the History of Engineering, ETH Zurich, for its supporting contribution.

Rahel Probst
Daniela Fasler Isch
AlpTransit Gotthard Ltd.
Zentralstrasse 5
6003 Lucerne, Switzerland
rahel.probst@alptransit.ch
daniela.fasler@alptransit.ch

Exhibitors at the specialist conference

In addition to networking and culinary aspects, the event «With millimetre accuracy through the Gotthard» also provided the opportunity to obtain information about innovations in the geomatics field at the numerous stands of the following exhibitors:
Amberg Technologies, Fahrbahn TTG Consortium, Grunder Engineers, BSF Swissphoto, Grünenfelder and Partner, Federal Office of Topography, Department of Civil, Environmental and Geomatic Engineering ETH, DMT, Dr. Bertges Surveying Systems, Society for the History of Geodesy in Switzerland, Goecke, Leica Geosystems, Ristag Engineers, Schenkel Surveying, Technical University Munich (Chair of Geodesy) and VMT.

Ingenieur-Geometer Schweiz (IGS)
Ingénieurs-Géomètres Suisses (IGS)
Ingegneri-Geometri Svizzeri (IGS)

We guarantee 750 billion Swiss francs of mortgage loans for our economy

Trading in land and property is an important part of the Swiss economy. Land can however only be traded if the property rights are clearly defined and documented.
We, the Engineering Surveyors, master this challenge with the official cadastral survey. We therefore contribute to guarantee 750 billion Swiss francs of mortgage loans for the Swiss economy.
As engineering surveyors, we intervene more than any other professional group at the interface between public and private action. Since more than 100 years, we help to ensure property by means of a clearly defined distribution of labour according to the well proven principle of Public Private Partnership.
Only people who have passed the federal patent examination are allowed the title of «engineering surveyor». We set the highest standards for the professional competence and the personal aptitude required for our special tasks in the service of the official cadastral survey.

We are organized into an association of Swiss Engineering Surveyors (IGS)

The Swiss Engineering Surveyors (IGS) is the Swiss employers' organization of Engineering Surveyors. Our commitment is primarily focused on developing our profession – in geomatic engineering, land management and corporate management. As employer's organisation, IGS represents the interests of the profession externally, for instance vis-à-vis public authorities, the political world, the public, the economy and partner organizations in Switzerland and abroad.
We are committed to a healthy economic competition among our members. IGS promotes entrepreneurial thinking and acting in compliance with the ethical principles of our profession. As employer's organization, we are working to create a favourable framework for entrepreneurial freedom encouraging independent thought and action, as well as for the personal and professional development and performances of our employees. Although Switzerland is not a member of the EU we are actively involved in European associations.

Retaining our own autonomy, we act for an education at the highest standards and a professional practice of equivalent quality. We also represent our interests on an international level, for example in the International Federation of Surveyors (FIG).
The association represents around 230 surveyor's offices with roughly 370 Engineering Surveyors and 3300 employees throughout Switzerland.

We provide private developers with comprehensive land information

We quickly and reliably supply any required updated land information and in doing so support the realization of constructional concepts.

We provide information about:

- Various access options
- The position of all underground utilities networks
- The boundaries of neighbouring properties
- Possible use of the property
- Minimal distance line (for example to brooks)
- Building volume or building view of the neighbouring properties in the listed village centre
- the public legal restrictions on landownership for your property

We ensure efficient project progress for architects and engineers

We offer support for the realisation of construction ventures and strategic planning at all stages.
Our services as well as the close collaboration with all parties involved contribute substantially to the efficient handling of projects.

Engineering Surveyors:

- Establish the demand for land and the corresponding plans for dividing the land into parcels
- Provide and analyse the required basic data
- Collect data required for the planning on site
- Support and supervise projects regarding the surveying services
- Provide new possibilities to various industrial sectors using land management methods
- Consult and coordinate in an objective and independent way

We collaborate with municipalities, cantons and the Federal Government on the basis of a Public Private Partnership

With our activities, we contribute to the sustainable development of our limited and endangered habitats. To achieve this, we rely on a co-operative approach in the sense of the Public Private Partnership.

Model projects:

- Hydraulic engineering, flood protection, renaturation
- Land management for agricultural soils and constructible land
- Collection, management and updating of land-related data
- Creation and management of municipal and regional GIS-centres
- Operation of Cadastre of public-private ownership restrictions
- Implementation and updating of the official cadastral survey according to the standards AV93 and DM01
- Engineering surveys

Ingenieur-Geometer Schweiz (IGS)
Ingénieurs-Géomètres Suisses (IGS)
Ingegneri-Geometri Svizzeri (IGS)

Contact

Ingenieur-Geometer Schweiz (IGS)
Kapellenstrasse 14 | Postfach 5236
3001 Bern, Switzerland
Phone +41 (0)31 390 98 84
Fax +41 (0)31 390 99 03
info@igs-ch.ch | www.igs-ch.ch