The Gotthard Base Tunnel - a challenge for geodesy and geotechnics

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Abstract

The planned tunnels of the AlpTransit project of the Swiss Railway Company (SBB) represents a big challenge for geodesy and geotechnics. With the requirement of less than 10 cm lateral and 5 cm vertical standard deviation in all breakthroughs, the construction management has fixed limits that call for a refinement of known measuring technologies and for a search of new alternative methods. The complex arrangement of the different intermediate attacks like, for instance, the 800 m deep shaft of Sedrun requires special instruments to transfer position, height and orientation to the underground. Independent methods should help to increase the reliability of the surveying tasks.

1 The Gotthard Tunnel project and its requirements

The Swiss Railway Company (SBB) is realising a new railway route traversing the Swiss Alps from north to south, approximately two thirds of it in tunnels. The central part of the project called „AlpTransit“ is the Gotthard Base Tunnel from Erstfeld to Biasca. This tunnel will be 57.5 km long and, thus, the longest all over the world in high mountains.

In order to realise this project within a reasonable period of time (10 years), the excavation starts simultaneously at six points: the entrance portals (Erstfeld and Bodio), three intermediate tunnels (Amsteg, Sedrun, and Faido) and an exploring adit in the Piora region. The basic requirement is a breakthrough result in all sections of $\sigma_{lateral}$ <10 cm and $\sigma_{vertical}$ <5 cm.

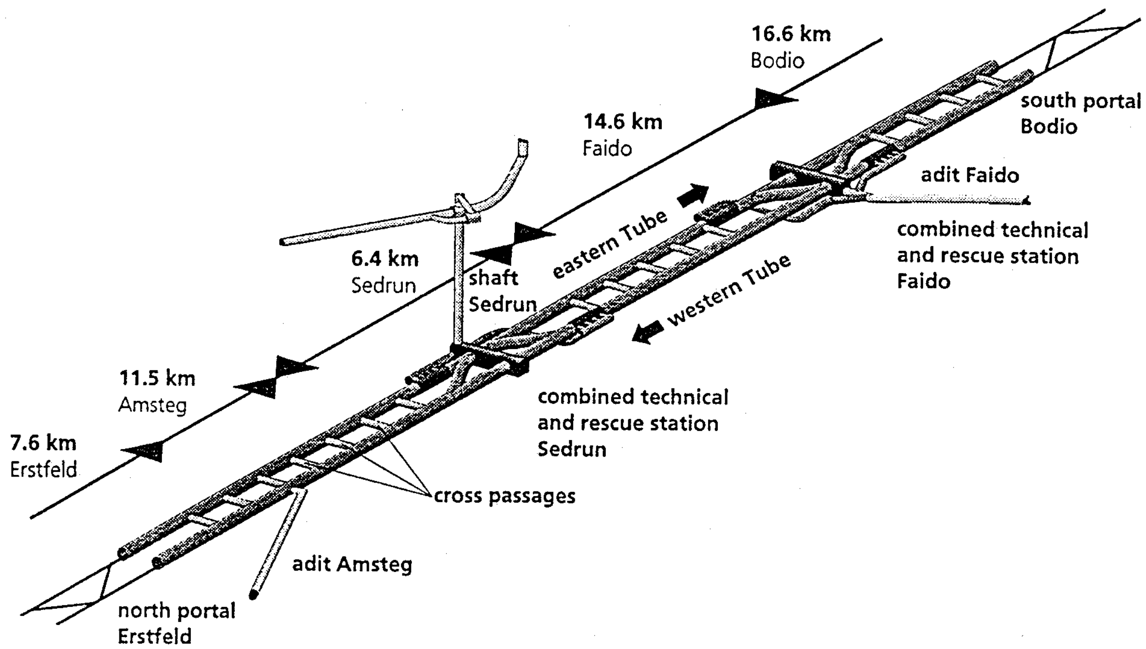

Fig. 1: General view of the project

The project has a dual-tube design with connecting tubes positioned at distances of 325 m, in addition several intermediate tunnels, vertical shafts, exploring tunnels, and bypasses have to be staked out. The tunnel will have a maximum coverage of 2400 m and temperatures T > 40 °C are expected. General aspects of the project „Gotthard Base Tunnel" are described in more detail in Ebneter [1996] and Bräker [1997].

Required breakthrough results	**1** s	**Tolerance (=2.5** s **)**
lateral	10 cm	25.0 cm
longitudinal	3 cm	7.5 cm
vertical	5 cm	12.5 cm

Fig. 2: Required breakthrough results

2 Setting out the Gotthard Base Tunnel

2.1 The project network

The basic requirement for the project are 3D-coordinates (y, x, H) at each tunnel portal within a relative accuracy of less than 1 cm (1 σ).

A project network of totally 33 points was established in 1995. Additionally to the 6 LV95-points (national GPS-network), the following points at each portal and each intermediate attack were included: one observation pillar near the portal, 3 points in a distance of 2 to 6 km for orientation purposes, and 3 points of the existing official triangulation (LV03). GPS-measurements on all 33 points and terrestrial measurements in each portal region were taken in November 1995.

A quality control of the GPS-network was realised by a Helmert-transformation using all 6 LV95-points as transformation points. The differences amounted to a few mm. The results of the data processing were y- and x-coordinates with an accuracy of less than 7 mm and heights with an accuracy of less than 20 mm (Ryf et al. 1996, Haag et al 1997).

2.2 Geodetic datum and network transformation

Concerning the network-datum two main solutions were discussed: The official triangulation LV03 versus the high-precision GPS-reference frame LV95. Although the latter would have had many advantages, LV03 was chosen due to the following: The existing cadastral and railway surveying as well as all maps and plans created during the project planning are based on the LV03-reference system. With this solution, however, network distortions of more than 30 cm over the 60 km have to be accepted.

Considering all aspects of the project, the adequate and „best" geodetic datum is given by the points of the official triangulation (LV03-points) in the areas of the north- and south-portal of the tunnel. The residuals of a Helmert-transformation (project network to LV03) are less than 8 cm in the portal areas, 20 cm in Sedrun and 25 cm in Faido. Nevertheless, the high accuracy of the project network is still maintained.

2.3 Height reference system

To avoid extensive precise levelling work between all 6 portals in an alpine region (> 120 km levelling line), the existing first order levelling network (LN02) is going to be used for the project.

However, some special aspects have to be considered: LN02 was established in 1902 basing on 19th-century measurements; gravity measurements were not included; strictly orthometric heights are not available; a least-square adjustment of the complete levelling network was not performed.

Therefore, various geodetic works are actually done to increase the precision of LN02 and to make it suitable for the project:

All precise levelling measurements of the 20th century are used for a recalculation of the first order levelling network. This recalculation includes also gravity measurements, a least-square adjustment is performed, and a kinematic model for the raising of the Alps (approximately 1 mm/year) is created. Using the new national geoid (1997) which has an accuracy of a few cm, the precise ellipsoidal heights of the LV95 GPS-network provide further information.

To connect the national height network with the tunnel project from all 6 observation pillars at the portals to the next national height points (totally only 30 km) levellings were done in 1996.

2.4 Recent geological problems in the Gotthard area

In 1997 precise levellings were realised in the Gotthard highway tunnel and along the road across the Gotthard pass. The height changes in the tunnel which occurred during the 17 years since the opening of the tunnel confirm the known effect of the raising of the Alps. The levelling points in the middle of the tunnel were subject to vertical movements of about +2 cm regarding the points at the portals [Swisstopo].

The levellings across the pass produced very astonishing results. In several completely rocky areas (600 m above the tunnel) vertical movements of up to −10 in comparison to the last measurements in 1970/77 were detected. Presumably those sags are caused by the construction of the Gotthard highway tunnel in the Seventies.

For the AlpTransit project these discoveries have the following consequences: Several dams of hydroelectric power plants above the future Gotthard Base Tunnel have to be monitored more thoroughly during and after the construction of the new railway tunnels. The geodetic deformation networks of the dams have to be extended, tectonic movements have to be supervised more frequently, continuous measurements of the dam movements, for instance, with permanent GPS-stations, have to be taken into consideration.

Another critical aspect is the Piora depression, a dolomite formation which probably has to be passed. 270 m above the tunnel level, this dolomite is of fluidal sugar consistency and has a pressure of about 100 bar. To go through this critical area there are several proposals to harden this material by injecting concrete, epoxides or other composite materials.

3 Transfer of direction and coordinates in the vertical shaft

For the intermediate attack at Sedrun, the project requires a precise three-dimensional coordinate transfer and a direction transfer from the surface (1340 m) to the tunnel level (540 m). This has to be done by plumbing and distance measurements in a vertical shaft with a diameter of 8 m and with a depth of 800 m. In addition, a vertical direction transfer from the surface network at the entrance to the bottom of the shaft has to be realised.

The precise direction transfer from the surface network to the tunnel's level will be carried out with gyroscope theodolites. For that purpose actual gyroscopes, as Gyromat, DMT, will give the best results.

The error budget of the direction transfer by gyroscopes can be expressed as follows:

$$s_{total} = \sqrt{s^2{}_{net} + s^2{}_{east-west-comp} + 2 * s^2{}_{theodolite} + 2 * s^2{}_{gyro} + s^2{}_{tempfunction}}$$

s_{net} = inner accuracy of a GPS-based network direction (<=0.3 mgon)
$s_{theodolite}$ = accuracy of a optical direction transfer (= 0.3 mgon)
s_{gyro} = inner accuracy of a gyro (0.7 mgon)

$s_{tempfunction}$ = standard deviation of the temperature correction function
This is a function of the temperature difference between both direction transfer stations (= 0.5 mgon).
$s_{east\ west\ component}$ = accuracy of the deviation of the vertical derived from gravimetric measurements and extrapolations (= 0.3 mgon).

This gives a theoretical accuracy of s_{total} = 1.3 mgon for the direction transfer with gyroscope theodolites. In order to independently verify the gyroscopic direction transfer through the vertical shaft, additional concepts of direction transfer in the vertical shaft have to be taken into account. These are among others:

- precise plumbing with the dispersometer using mercury plumbing instruments
- polarised dual-wavelengths light
- inertial systems

The initial coordinates of the underground network should not exceed a standard deviation of 10 mm, including all the known error sources as well as non-detectable systematic effects. The height transfer in the shaft will be performed by vertical distance measurements, using the Mekometer ME5000. Additional gravity measurements will allow the transformation to Swiss orthometric heights.

For the x- and y-coordinate transfer by plumbing two fundamental solutions were examined:

- mechanical plummets with a plumb bob suspended by a wire
- optical plummets

Plumbing a shaft mechanically means that a wire with a diameter of 2-3 mm is lowered into the shaft using a winch and a guide weight. The determination of the position of the freely hanging plumb bob is subject to a variety of influences, such as:

- error of the vertical position
- error of the rest position of the plumb bob
- mechanical load
- thickness and stiffness of the wire
- mechanical stretch
- precision of position detection

The rotational oscillation of the plumb bob is overlapped by longitudinal oscillations of the wire. If these are asymmetric to the pendulum oscillation, then additional movements are induced, this can cause a significant shift of the apparent rest position. Electronic recording including a frequency analysis will solve this problem computationally by means of continuous observation and signal processing. There are several different solutions for the determination of the position of the points plumbed at the bottom of the shaft:

- opto-electronic X-Y pick-up of the plummet wire on fixed centring consoles at the bottom of the shaft
- observation by theodolites

A new approach devised at ETH is the use of a tracking tacheometer. Prisms are fixed on the plumb bob, allowing the oscillating plumb bob position to be continuously observed and, thus, its zero position to be determined. The accuracy of the determination of the position derived from three plummet positions will meet the requirements. However, the accuracy of the transfer of directions is not sufficient when applying this method.

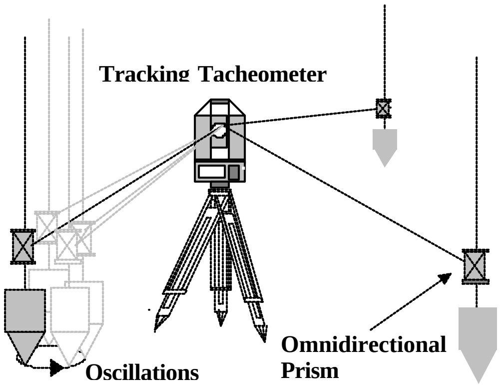

Fig. 3: Determination of the plumbed position using a tracking tacheometer

With an optical plummet a special target is set up in order to determine the foot-point by vertical observation. Because of the possible effects of atmospheric refraction, the accuracy specifications are too optimistic, and do not cover all likely error sources. Regarding refraction and scintillation which occur due to variations in the density of the atmosphere (caused, for example by temperature, dust or humidity) a visual determination meeting the stated requirements is difficult. The biggest effort for the mechanical plummet is the recording of the disturbing effects, and the installation of devices, such as tubes, to minimise these influences. Automated observations of mechanical plummets permit easier detection of error sources than procedures using optical plummets do (mainly because of atmospheric refraction).

For the optical plummet, the set-up of the instrument with adequate levels, mercury horizons or electronic inclinometers is simple. The biggest impact is in the detection of the refraction effects. However, new instrumental developments such as the dual-wavelengths laser dispersometer promise refraction-free measurements in the foreseeable future (Ingensand et al. 1997, Hennes et al. 1998). Thus, at the present time, optical procedures in general are not considered suitable for this application.

4 Refraction-free staking out in tunnels

Especially on the occasion of the direction transfer at the tunnel entrance, the optical direction can be extremely affected by refraction effects. There are a lot of concepts to determine the refraction

corrections by calculating loop misclosures and using available gyroscopic observations. However, the best method to eliminate refraction effects is the two-colour method. The so-called dispersometer technology for the elimination of the refraction effect bases on (atmospherical) dispersion. It utilises the wavelength dependence of the refraction index involving that the difference angle $\Delta\delta$ between two light beams of different colours (with the refraction angles δ_1 and δ_2) is to first approximation proportional to the refraction angle δ_1 or δ_2,
respectively. Hence, the observation of the dispersion angle can be used for calculating the refraction angle from

$$\Delta\delta = \delta_2 - \delta_1 = \nu\delta_2$$

with ν describing a constant depending on the wavelengths used. With the current light source (λ_1 = 430 nm and λ_2 = 860 nm) ν has the magnitude of 0.024. The small value for ν requires that the dispersion angle must be measured more than $1/\nu$ times more accurately than the desired accuracy for the refraction angle itself. This is one of the major technical problems in the development of a dispersometer. A further problem is the generation of a dual-wavelengths light.

The ETH dispersometer uses the effect of frequency doubling of a semiconductor laser diode by passing a $KNbO_3$ crystal. The light source generates an output power of 3.5. mW at 860 nm and of 4.2 mW at 430 nm. The receiving unit is a special telescope with an focal length of 300 mm. This means that a displacement resolution of better than 10 nm on the four-quadrant detector is required. To achieve this resolution a special positioning technique known as the gap technology, has to be utilised. At the moment, the ETH dispersometer is being tested in a lab function status.

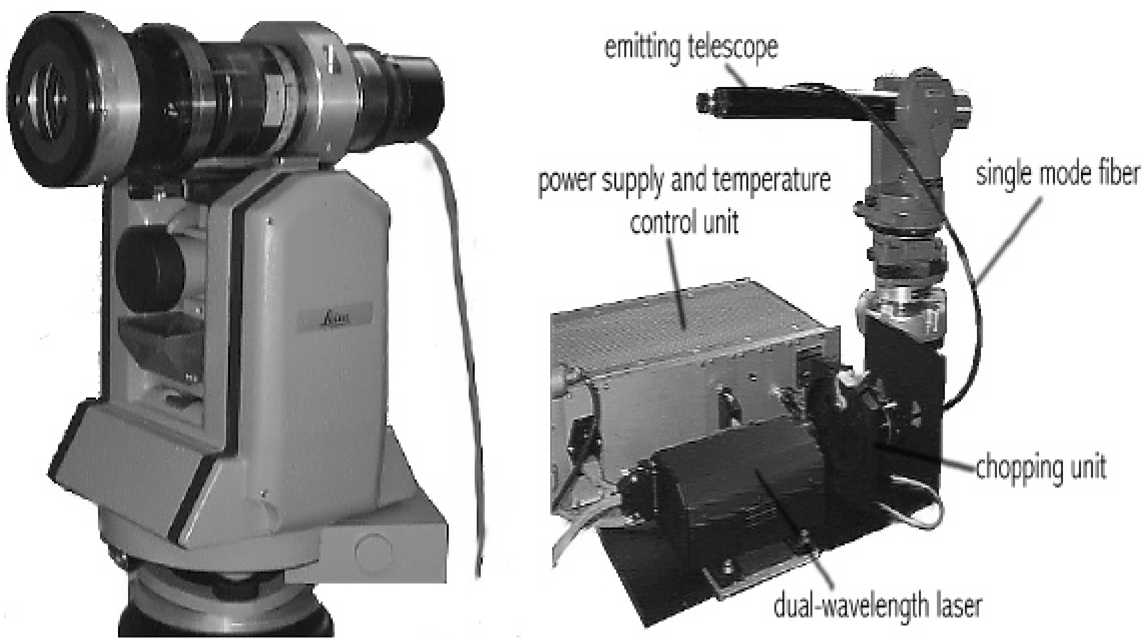

Fig. 4: The ETH dispersometer

5 Conclusion

The Gotthard Base Tunnel is one of the most ambitious projects in the world. Special high-precision measurement methods are required and new instruments as dispersometers, electronic plumbing methods, and special direction transfer have to be developed.

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