New Developments in Automated Tunnel Surveying Systems

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ABSTRACT

The surveying requirements during tunnel construction have changed little since the first tunnels were dug centuries ago, the focus being on leaving and arriving at the required place. Over the years the techniques and facilities to achieve this have developed considerably and also the cost constraints within which they should be achieved. This paper looks at some of the current surveying techniques applied in tunnel construction today with an emphasis on flexible systems developed for the more traditional methods of construction. Examples are drawn from the Uetliberg and Gotthard tunnels where challenging schedules and rock conditions demand the application of innovative technologies.

1. INTRODUCTION

One of the most critical factors for the successful construction of a tunnel is that the finished excavation is fit for the purpose for which it was designed. For this to be achieved the tunnel must follow the designed axis (route) and be of the correct size and shape. Nowadays these factors are easy to design in an Engineering Design office with the latest CAD facilities, which can produce precise designs for complex shapes and exact 3 dimensional axes with precise absolute coordinates. However to translate this complex design data into a finished tunnel still relies on the application of surveying technology which due to the underground environment and confined spaces is a unique challenge in itself.

The development of computerised total stations with increased functionality such as Automatic target recognition, automatic target tracking, power search and remote control has provided the hardware for increasingly accurate traditional survey tasks such as the base survey over land for the start and end reference points of the tunnel and the establishment of reference stations within the tunnel as the tunnel progresses. But what about the actual tunnel construction?

2. SURVEY SYSTEMS

TBM manufacturers have always been at the forefront of tunnel guidance systems due to the critical nature of the control of the direction and elevation of the TBM and associated support in the backup. The complexity of ring build and alignment correction has been helped immensely by the advent of computer software to work out the correct order and design alignments. The more varied and flexible methods of tunnelling have traditionally still relied on the old fashioned methods for setting out the direction and dimensions of the tunnel. However this has been steadily changing over a number of years with the latest systems being very technically advanced.
<table>
<thead>
<tr>
<th>Type of system</th>
<th>Comments</th>
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<tbody>
<tr>
<td>TBM guidance</td>
<td>Several systems on the market usually tied to the TBM manufacturer Good for directional control of TBM in 3D Software can be used to calculate ring build and re-alignments Cannot use the Total Station for other activities in the tunnel such as setting out cross passages or reference stations.</td>
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<tr>
<td>Road Header Guidance</td>
<td>Assist in providing an accurate profile of the tunnel during construction Does not have a profiling check of the actual tunnel Cannot be used for other activities within the tunnel</td>
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<tr>
<td>Drill Jumbo Control</td>
<td>Very well developed systems mainly attached to Jumbo manufacturers Provides automation of drilling cycle Difficult to position the jumbo in absolute coordinates Reduces labour force by allowing one man to operate three booms Post blast scanning of excavation and feedback of results Can be used for the excavation of cross cuts and niches Cannot be applied to other tasks in the tunnel such as setting out formwork or installing arches.</td>
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<tr>
<td>Task orientated operator guidance</td>
<td>Applicable to most surveying activities in conventional tunnel construction. Cannot be used for guidance of TBM or control of drill jumbo. Can be used for operator guidance by showing the contour required on the face. Stores all project data on the total station. Used by the foreman therefore reducing repetitive setting out work to be carried out by the surveyor and improves productivity by reducing waiting time. Single package of PC based software for total management of all design data and profile reports. Same system can be used in mobile mode by the surveyor or in production mode by the tunnelling crew.</td>
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The above table is designed to give only a very general view of the different systems available. The advent of sprayed concrete as a support medium has led to the possibility for very flexible design in the shape of the tunnel profiles. This is especially useful in the design of underground metro stations or areas of enlargement such as shaft bottoms or TBM erection chambers. To control these changing profiles during the construction phase is the challenge and successful application of the available technology can not only improve the accuracy of the structure but also improve the production of the tunnel to reduce overall project costs. Therefore the focus of this paper is on the newest type of system referred to as the “Task Orientated Operator Guidance system”.

3. TUNNEL MEASUREMENT SYSTEM

The latest of this type of systems is the Tunnel Measurement System (TMS) developed by Amberg Measuring Technique Ltd. for LEICA Geosystems. This system can be divided into 2 packages, firstly the LEICA TMS SETOUT and secondly the LEICA TMS PROFILE. This software is designed to be used together as a package during the tunnelling process to provide continuously updated records of progress and performance.

At the construction stage the system provides a seamless translation of the complex design data into practical set out information at the face. This information is available to the tunnelling crew at anytime...
through the creation of task orientated software for the total station and the use of the remote control unit.

The tasks available are designed for conventional tunnel construction with an emphasis towards mechanical excavation where backhoes or roadheaders are employed and the use of computer guidance systems is less developed. The tasks for use by the surveyor are as follows:

- Point set out
- Systematic anchoring
- Cross passages / niches
- Invert formwork
- Arch formwork
- Installations

The tasks available for use by the tunnelling crew are as follows:

- Blast
- Contour
- Jetting
- Laser
- Arch

These tasks are set up on the office based PC where all the design data is managed through the common platform of TMS OFFICE.

To describe the application for the system it is easiest to look at an actual jobsite and the differences in working practices possible and the improvements in production achieved. In this case the project chosen is the Uetliberg tunnel in Zurich Switzerland.

4. UETLIBERG TUNNEL

The Uetliberg tunnel is the major part the Zurich Western Bypass, a project to reduce congestion of through traffic from Germany through Switzerland to Italy. The Uetliberg project consists of two parallel tubes 4420m long containing 2 lanes and a hard shoulder. The tubes are connected every 300m by a pedestrian cross passage and every 900m with a vehicular cross passage. The SOS niches will be 150m apart. A transport tunnel through which 1.7 million m³ of muck material are transported by a conveyer belt system to a rail loading facility near the Zurich West interchange and a special
ventilation tunnel and shaft, also belong to the project. The overall project cost is 1.1 billion Swiss francs or 770 million Euros.

The tunnel is being constructed for the client, Baudirektion Kanton Zürich by the joint venture, ARGE Uetli, lead by Zschokke Locher, including; Murer AG, Prader AG, CSC Bauunternehmung AG, Wayss & Freytag GmbH, Alpine Mayreder Bau GmbH, ZüblinSchlittlerSpaltenstein Bau AG. Amberg Engineering Ltd carries out the design and project management.

4.1 Geology
When discussing tunnelling projects, even if we are only interested in specific components of the project such as the surveying the geology should always be understood. This is because the geology will dictate the construction method. The more exact the rock support requirements the greater the need for accurate setting out within the construction cycle, which in turn has an impact on the activities of the surveyors.

![Geology of Uetliberg Tunnel](image)

Fig 3 Geology of Uetliberg Tunnel

In this case the geology is typical for areas north of the Swiss Alps. From west to east, the Uetliberg Tunnel undercuts the two parallel Ettenberg and Uetliberg hills. The Reppisch Valley with the cut and cover section lies in-between, dividing the tunnel structure into two separate tunnels during construction. Both hills have a molasse core in the middle. These molasse sections comprise flat-bedded strata hard sandstone seams and soft marl strata. The maximum overburden under the Uetliberg is approx. 320 m and the total length of the molasse sections is 500m under the Ettenberg and 2800 m under the Uetliberg.

At both ends of the Uetliberg Motorway Tunnel and in the Reppisch Valley are soft ground sections with a heterogeneous end moraine material, base moraine overlaid with slope wash, sand and clay. The total length of the three soft ground sections is 860 m. Because of the three soft ground sections
and the overall timetable, the excavation works began at three sites in 2001 more or less the same time.

4.2 Construction

Because of this varied geology and the alignment required this project utilises many different types of tunnelling techniques. There are two different types of tunnel boring machines, sections of drill and blast and also various conventional soft ground techniques being applied. At the start of the project tunnel development was being carried out on as many as 6 faces at one time. A project of this size and complexity would normally need at least 6 qualified surveyors and several assistants. However there are in fact only 2 surveyors on site for the contractor, even though the site is working 24 hours per day during the week.

This is because the ARGE UETLI are using an arrangement of LEICA TPS1100 Series total stations with TMS SETOUT (Plus) and TMS PROFILE (Plus) software packages to provide powerful flexible solutions for production efficiency. The concept behind this software solution was to identify the production tasks required and automate them so that a non-surveyor such as the tunnel foreman could do the setting out. The key benefit of this approach is that there is no delay waiting for the surveyor and the work done by the excavation crew is more accurate and productive. On this project there are as many as 8 TMS, Tunnel Measurement Systems of hardware and software employed at any one time.

The most noticeable application of the TMS was in the soft ground sections at the Gjuch, Juchegg and Diebis portals and soft ground geology. The Cross section is excavated by two upper sidewall galleries, which are followed at a distance of 20 to 40m by the two lower sidewall galleries. The Crown and the core follow the sidewalls. The base ring is normally finished 40m behind the crown face. As soon as the crown is excavated to a depth of 12 meters, the work switches to the base excavation. Typical total overall advances are 1.3m per day.

This construction pattern is required to produce the finished tunnel profile and also for the support of the soft ground. The surveying requirement for setting out these arches is vital because their position will dictate the final alignment, transverse slope and longitudinal slope.

To position the arches accurately would normally be the job of a site surveyor who would be called into the face when the excavation crew had finished the excavation to the approximate profile required within which to fit the arches. However this causes serious delays due to having to wait for the
surveyor. If the face has not been excavated to a large enough profile then the arches will need to be removed and excavation continued. Alternatively if the profile is made too large the quantity of shotcrete required in between the arches is increased considerably. Both activities significantly increase the costs for the tunnel construction.

However on the Uetliberg tunnel on each side of the tunnel a Leica TCRA1105 is mounted on a permanent bracket out of the way of the construction equipment. Each of these instruments contains TMS SETout (plus) on-board software with all project data loaded via PCMCIA card from TMS OFFICE on an office based PC. This is the common platform for handling all the design data, such as alignment, excavated profile, position of arches, thickness of shotcrete required etc.

For each excavation cycle the tunnel foreman first chooses the task “Contour” to indicate precisely to the crew the correct excavated profile before erecting the steel arches. The steel arches can then be positioned in the face and adjusted to the exact position by lining up the visible red laser and a pre-defined offset using LEICA TMS SETout (Plus).

Once the arches are in place and fixed, shotcrete is used to complete the primary support. Once the shotcrete is applied it is again necessary to check the overall profile of the tunnel, this is performed using TMS although this time with the TMS PROscan (plus). The entire operation is carried out in approx. 15 minutes whereas previously it may have taken several hours. The daily overall progress to date is 1.3 up to 1.4 m per working day corresponding to the stipulated progress in the contract.

Besides the savings in labour there are major potential savings in overall project costs using this system. Another application was the pipe umbrella at the portal sections of the soft ground sections to enable the full span of the crown section to be excavated. To prevent any ground loss or irregular weak spots to be encountered during the excavation it is critical to drill the pipes in a very precise fan shaped pattern from regular points on the arch. Using TMS SETout each point on the face was identified with the red laser and marked off. Then once the drilling machine had located the drill bit, by calculating the offset in three dimensions the operator was able to identify the exact position of the back of the drill carriage, in turn controlling the direction of the drill or tube being placed in the ground. Prior to the task “Jetting” being used the total marking up operation was taking up to 10 hours afterwards this was reduced so to only 3 hours. More significantly the positioning of the drill carriage previously required the presence of the surveyor and would take at least 30 minutes for each hole whereas now the foreman was able to achieve the same accuracy and reliability in only 10 minutes with all the calculation for the offsets being done in the office by the surveyor.

TMS has applications for most activities in conventional tunnel construction and many in the works carried out behind the TBM’s for the finished tunnel. All the applications in LEICA TMS are defined in TMS OFFICE and set up by the surveyor but with many production operations done by the tunnelling crew. To maintain some regulation over these activities each foreman has a password controlled user name and it is possible for the surveyor to check all the actions carried out on the total stations. By this security check it is impossible for a non-qualified person to make serious errors that can go unnoticed.

4.3 Tunnel Bore Enlarger (TBE)

The main drive through the Uetliberg molasse section is first driven a pilot tunnel with a 5 m diameter open TBM. The cutterhead of the TBE consists of a two-part cutterhead based on six boring arms. The cutterhead rotates on the inner kelly that is braced and bearing-mounted in the pilot tunnel and in the large tunnel cross-section. The cutting rollers are offset both axially and radially to the axis of the tunnel and arranged on moving slides so each roller follows a spiral path around the axis of the tunnel face with the possibility to vary the diameter between 14.2m and 14.4m. This arrangement allows a variable cross section, giving extra support in the crown and shoulder area in poor ground conditions.
The rock support for the full TBE cross sections consists of bolts, mesh, shotcrete and if necessary steel arches. The initial rock support is installed directly behind the cutterhead about 2.5 to 3.0 meters behind the tunnel face. This is then followed up by a second layer of shotcrete some 75m behind the face. Because of the amount of equipment in the back up of the TBE it proves to be very difficult to measure effectively the shotcrete thickness at this stage so final profile measurements are taken automatically using TMS PROscan under the conveyor bridge while at the same time the surveyor sets out the guide pins for the final shotcrete thickness on the sides of the tunnel.

Behind this come the installation of the waterproofing membrane and the casting of the invert. The profile check is important to ensure the correct thickness of cast concrete and that the formwork will fit properly. Both the positioning of joints between the concrete pours and the shaping around the cross cuts are set out using TMS SETout(plus). The invert form will have a number of targets placed so that each time the formwork is set up the foreman can check that it is in exactly the correct place using the Total Station and remote control with TMS SETout(plus). The expected overall driving speed is about 9 m per workday.

5. AS BUILT SURVEY - GOTTHARD BASE TUNNEL

The challenge of achieving the correct profile for the application of the waterproof membrane has been taken one step further on the NEAT projects in Switzerland. Because of the great depths worked at and the high design criteria set for these projects, not only must the overall profile be correct but also the regularity of the surface of the shotcrete. This is “Welligkeit” in German and is translated as “waviness” in English. The requirement here is that at no point should the variation of surface profile be greater than one in ten. For example in an area of 1m by 1m the maximum distance between the peak and trough would be 10cm.

Over the full length of the Lötschberg and Gotthard Base tunnels this called for an innovative approach to the profiling that could produce a sufficient density of points to be able to show these variations. On the Gotthard a new system is being applied to this challenge supplied by Amberg Measuring Technique Ltd.
The hardware applied is a laser scanner called the PROFILER 5003 specifically designed for tunnel scanning by Amberg Measuring Technique Ltd. The scanner is capable of up to 33 rotations per second with 20,000 points per rotation and a vertical view of 310°. It has a variable speed horizontal rotation with full 360° rotation. The geometry measured is distance and angles and the reflectivity measurement is greyscale.

This application calls for a measurement and processing to detect all the areas on the shotcrete surface, where the specified tolerance is exceeded with a measured point density on a grid of 20mm x 20mm. The processing must report in flattened coordinate system all areas so the contractor can correct the problematic areas before applying the sealing membrane.

For a typical operation of the PROFILER 5003 a 10 meter tunnel length from one station would be measured. The first measurement may take a little longer for the setting up and establishing the absolute position of the Total Station and the Profiler however for subsequent measurements they may only take some 2 minutes for each 10 meter. In a clear tunnel with experienced operators it is possible to measure up to 150m per hour.

As with all systems it is the combination of hardware and software that dictates the success of the measurement operation. In this case it is possible to utilise the same powerful data management functions in TMS OFFICE for the presentation of the Profiler 5003 results. It is possible to create reports giving the profile at any position along the tunnel axis, a tunnel map viewed in derolement showing areas outside of the specification. Also reflectivity pictures and 3-D images are possible.

Because of the common platform of TMS OFFICE the future applications of these technologies will come considerably closer with the potential that the scanning data can be immediately loaded on to the Total Station and then areas of under and over specification may be identified by the red laser for remedial action.
6. CONCLUSION

The improved hardware in Total Stations offer many potential applications for the storing and translation of design data into the finished tunnel. This should not only improve the quality of construction but also give more responsibility to the operatives to enable them to excavate the right shape, size and direction first time. The user passwords and administrator check facilities prevent any mistakes or changes being made by unqualified personnel which should also lead to a safer construction. In turn the application of high speed laser scanning technology provides huge amounts of accurate absolute coordinate data that can be processed giving complete information on the finished tunnel. This is useful not only for the final costing and payments but also in the future, should any maintenance work be required. Regular checks in the tunnel may also be carried out using this technology and the results directly compared for analysis.

The key factor in the successful application of all modern surveying technologies is the handling of the data through imports and exports between the various different applications. For the hardware to really effective it should be the goal of the industry to create a standard system or format so that all applications can use the same absolute data for the more efficient and safer excavation of underground space.

REFERENCES

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