

THE INAUGURATION of the Marmaray Tunnel in October 2013 realised the first phase of the Turkish dream: to achieve a subterranean connection between Europe and Asia. This tunnel has been constructed as a part of the public railway transportation network of the City of Istanbul. The second phase of the Bosphorus crossing will be finished on completion of the Avrasya Tunnel for road traffic, to be commissioned in 2016. These two new underground links are necessary to improve traffic conditions in Istanbul, currently with serious problems of congestion due to a lack of a transportation network adequate to current requirements of the city and its metropolitan area.

Avrasya Tüneli İşletme İnşaat ve Yatırım (ATAS) is the investor of the Project and founded by the partnership of Yapı Merkezi of Turkey and SK Engineering & Construction of South Korea. ATAS has commissioned YMSK Joint Venture consisting of the same partner companies for the design, construction and commissioning of

the Project. YMSK Joint Venture is using a 13.7m-diameter TBM, boring its way through the planned 3.35km-long tunnel at a depth of up to 80m below the seabed according to design specifications--following roughly 2,000m radius left curves with a longer straight, leading into a roughly 1,800m radius right curve in horizontal. Vertically the tunnel will realize a radius of 4,330m. Once complete, the tunnel will be horizontally divided to provide one level for each direction of driving. Segment production is supported by a Segment Documentation System (SDS), which helps engineers in supply and quality management of all segments for the tunnel lining.

With the laser-controlled navigation system the TBM can be guided with millimetre accuracy along the designed tunnel alignment. A Ring Sequencing System supports the calculation. An integration of SDS to the data management system (IRIS. tunnel) saves relevant information from every segment placed within the tunnel, including: ring ID, materials used, damages and pictures.

A ring management system supports the planning and logistics of transporting the needed ring segments into the tunnel. A ring planarity check tool, also integrated with ring sequencing, manages each ring regarding compliance of necessary flatness to prevent spilling form point loads.

The continuous process control of relevant TBM data is made possible via a comprehensive web-based risk and information system. It provides the management team with a detailed overview of the project via the automated data logging, thus improving the performance of shifts and machine

EAST MEETS WEST



activity connected to the planning of maintenance jobs.

LASER CONTROLLED NAVIGATION

A laser controlled navigation system guides the Hydro-mixshield Herrenknecht TBM along the designed tunnel alignment.

Based on a total station and an active target unit installed within the TBM shield, it continuously determines the current advance position. In case of hardware failure it is also possible to determine the TBM position using the last known position and current cylinder extensions, to enable navigation of four to five rings without downtime.

RING SEQUENCING SYSTEM AND INFLUENCE OF SEISMIC JOINTS

Preliminary estimations

The ring sequence prediction is based on ring design drawings and alignment information and focuses on a balanced number of left and right rings used in the tunnel construction. The result of this analysis gives information about the amount of needed left and right rings. The analysis comprises a long-term ring sequence calculation without cross-joints in neighbouring rings. Taper of left and right rings is set to 15mm on the front and back of each ring. No cross-joints were permitted during the sequence calculation.

The maximum tolerance was set to 45mm, which is the theoretical maximum tailskin clearance in case a ring is built

perfectly centred within the tailskin, according to TBM design drawings. A maximum tolerance of 100mm is the permissible limit of the clearance, as stated by the joint venture.

The number of calculated left rings is 874 and right rings is 794. These values do not take into account the further 10 rings of special type needed for two seismic joints, which will be further described.

The ring sequence of the prediction starts at chainage 0.0m and ends at 3,349.4m for the Strait Road Crossing Tunnel. It is assumed that the reference ring has its centre on the alignment without horizontal and vertical offset and the ring plane is perpendicular to the alignment without any horizontal and vertical tendency.

The calculation ran with the constraints that left rings and right rings should be used consecutively only on straight sections of the alignment. Those major straight sections are:

- 0+243.80m to 0+874.17m
- 1+922.23m to 2+431.43m



Istanbul straddles the continents of Europe and Asia

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■ 3+163.02m to 3+349.42m

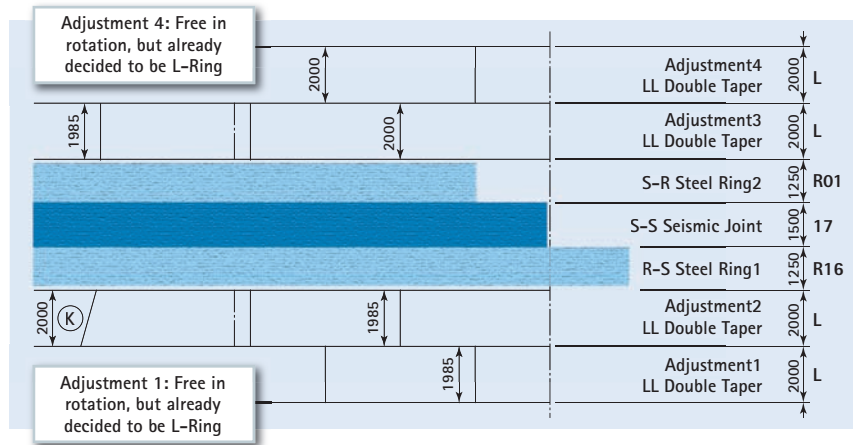
The maximum deviation of the ring centre to the alignment for the horizontal and vertical direction is +26mm and -19mm. For the worst case horizontally the calculation result states out a further vertical deviation of -4mm. This 26mm uses the maximum contractual tolerance of 100mm to 26 per cent. The main reason for this increasing deviation at this range of chainage is seen in the five rings of seismic joints with the additional two fixed left rings, which do not allow a proper tendency correction to follow the curve. This prediction was based on the geometry of ring design and alignment only and did not take into account TBM steering. Therefore deviations from this prediction are likely depending on the actual steering of the TBM and must be corrected on site with the help of the navigation system, as discussed later in this paper.

Influence of seismic joints

A further constraint on the ring calculation was the preferred installation of two fixed sequences of seven rings, acting as a seismic joint within the tunnel. A seismic joint is a composite steel-rubber structure with the central rubber part providing the necessary flexibility against possible seismic actions and with the steel rings resisting the ground pressures.

Seismic joints are designed to absorb seismic movements, as they are more flexible than concrete rings. Two joints must be placed in a total of 3,354m of tunnel length. They contain a stiff structure formed by steel rings on the central part, as it can be seen on Figure 1. Five rings are fixed with both taper (L/R) and key position. Further, two additional rings are forced to be left taper rings. The position of each middle ring was proposed by the joint venture and was applied as follows:

- The rotation of the adjustment rings and the steel rings were already decided in the pre-project phase. Only



Above: Figure 1, Disposition of segments that form seismic joints

Below: Figure 2, Hypothetical deviation scheme of the tunnel alignment for a straight section (left) and a curved section (right)

- 'Adjustment 1' and 'Adjustment 4' are free in rotation.
- Non-tapered ring (seismic joint) as ring no. 429 and 690, enclosed by one-sided, right-tapered rings on each side, each next to a "normal" double tapered concrete ring with an instructed key stone position. Note that the seismic joint (S-S17) and the two transition rings (STR116 and STR201) are of steel and shorter length of 1,500m and 1,250m respectively.

A sequence of rings like this was expected likely to increase the deviations to the alignment, as it does not give any option for direction correction, especially as the second seismic joint is placed on a curve. If the TBM has a large tendency, it is possible that the offsets may exceed the construction tolerance. This is one of the reasons why the ring sequencing system is used: to simulate certain TBM drive situations and examine how the steel ring structure might worsen the situation if the TBM does have a bad approach. The aim is to raise awareness of the possibility so it can be managed by engineers on site.

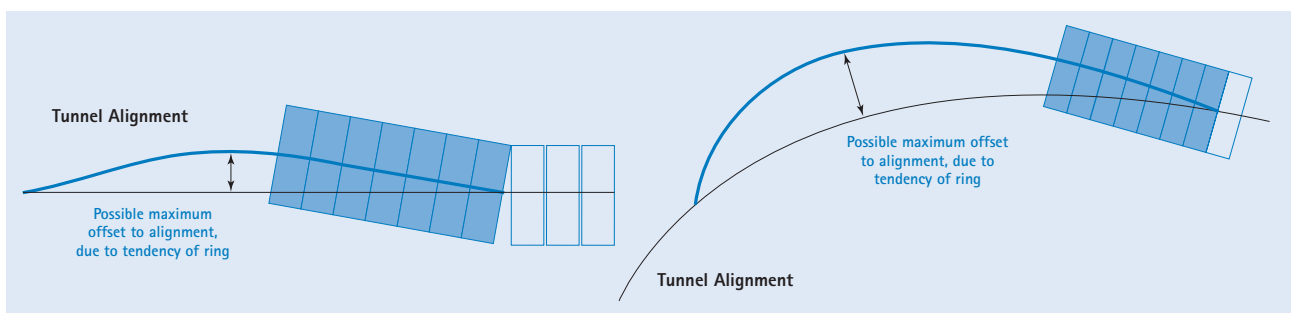
Having limited possibility for tendency correction on a straight line is not an issue when the TBM is approaching the alignment correctly.

Figure 2 (left side) shows the effect of a bad approach. The maximum offset of a ring centre to the alignment could occur after the erection of the seismic joint because for a smooth return to the alignment the ring calculation software will try to initiate a curve.

As the second seismic joint structure will be installed on ring 687 on a curved alignment of radius 2,000.8m, the effect would be even greater as can be seen in Figure 2 (right side)

The drafted issue has been analysed with multiple revisions of a ring sequence study.

In this critical section of a left curve where seismic joint 2 is located, even a slight positive tendency of the rings (TBM facing right relative to the alignment) can have a massive effect on the offsets of the ring to the alignment. A minor tendency of +3mm/m is likely to exceed the tolerance limits. Negative



offsets and negative tendencies as well as the combination of positive offsets and negative tendencies don't harm the tolerance greatly.

A further reason for this study was to improve segment production. It checked the possibility to build the tunnel with a balanced number of left and right rings, which formed the basis for planning segment production. A correct ring building process supported by the ring sequencing calculation is of vital importance, as the TBM advances with underground pressures greater than 10bar and no leaks or cross joints are acceptable.

Control of deviations

Previous sections of this paper covered the theory of why it is necessary to approach the seismic joint regions carefully. However, if something went wrong, the additional module called "Steering Curve" is implemented on the navigation system to ensure that the TBM operator has all the required information to follow the steering curve. The steering curve is automatically calculated to bring the TBM smoothly back to the alignment while following a minimum radius.

A risk exists because seismic joints are only able to realize a certain large radius. Preliminary studies indicate that poor steering could result in the TBM going off the designed tunnel alignment. As it is as "going blind," the TBM operator will need help to ensure that this "going of track" is done driving an actual curve.

This additional functionality of the navigation software shows the offsets of the TBM relative to both the actual alignment and the steering curve. During the ring sequence calculation, position of rings along the ring curve are calculated. It is recommended the steering curve has the same transition point as the ring curve, an option that can be easily activated within this module.

SEGMENT DOCUMENTATION SYSTEM

Besides the ring sequencing system, other software applications can be used to encourage project performance. In the Avrasya Tunnel, a number of segments for the tunnel lining are installed every day. Tracking these segments from production up to installation within the tunnel is of great importance for smooth project process as well as quality assurance. To assist the logistics and quality management tasks, the Segment Documentation System (SDS) has been developed. This is needed to achieve good planning on the

job site and to produce the rings that provide the tunnel lining. From pouring concrete until installation in the tunnel, SDS ensures that each segment is produced according to client specifications and that each logistical step in the construction chain is tracked. Customers have access to all material, production, storage and usage data and this functionality enables extension to adjacent processes by means of comprehensive quality management features. It combines gathering data using portable scanners to control systems for segment production including inventory management, transport and time-controlled procurement.

For the Avrasya Tunnel Project, segments are manufactured by Yapı Merkezi's prefabrication branch in their segment production plant located 20km away from the construction site. The ring sequencing system described previously provides an estimation of the type and number of segments needed. However, the final definitive planning is done on site in real time, reacting to the actual tunnel advance. Realistic predictions guarantee a segment provision not further than three rings forward, so the logistics chain can be organized: the segments that form each ring can be sent into the tunnel and arrive on demand. To do so, the system must account for the actual drive and live position of the TBM, not only ring geometry and a theoretical alignment.

One ring consists of nine segments. A maximum of 27 segments may be in a dispatched state between the segment factory and onsite storage, which holds approximately 50 rings. To determine requirements of the following 50 rings, the site planning engineer uses the ring sequencing system to order segments from the factory and maintain work progression.

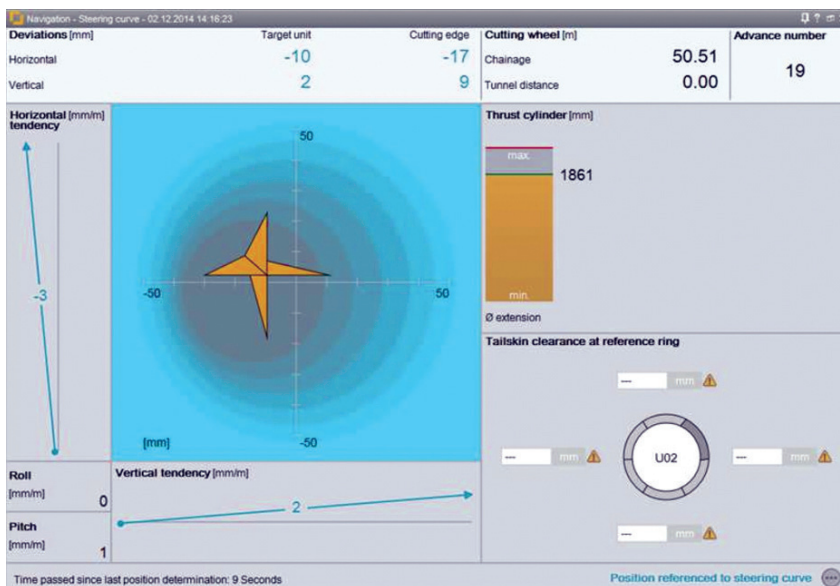
Aside from the logistical approach provided by the SDS, there is also a more exact geometrical approach through the ring sequencing system: no cross joints and negative machine tendencies can be reduced. Ultimately it increases quality and efficiency.

Other complementary products not described here for monitoring and installation of segments in the tunnel include ring convergence measurement, ring planarity check, grout pressure as well as systems for calculating the available space in the tailskin.

DATA MANAGEMENT

There is an ever increasing flood of information and data in tunnelling,

Below: Figure 3, Software system for control of deviations by setting a steering curve during TBM progression



which has motivated the appearance of independent software systems that support the data management and data analysis of construction sites, leading to a transparent construction process.

The evaluation and management of data are integral parts of the process controlling of large construction projects. Such systems support site teams in the evaluation and analysis of tunnelling data. The systematic storage and automated reports provide reliable continuous documentation of the tunnelling process.

The overall data management of the Avrasya Tunnel is done by the use of a web-based platform called IRIS tunnel, which integrates data from several processes, such as the TBM navigation, ring sequencing, interactive map visualization of TBM advance and reporting. Key features of the system include the following:

- Systematic preparation and archiving of tunnelling data from ongoing construction projects in the form of monthly, weekly and daily reports. Shift evaluation takes place in interactive shift logs
- Evaluation of TBM data (e.g., tail grouting, cutter wheel pressure, hydraulic jack forces, cutter wheel revolution, etc.) in combination with geological parameters from preliminary exploration (if present)
- Analysis of survey data to evaluate the TBM position, the driving precision, etc., and visualization of these data in appropriate diagrams.

Figure 4 is a screenshot of the web based data management system showing the TBM position relative to the geology profile. Map visualization provides helpful information for the project team



Above: Figure 4, IRIS tunnel data management system. Screenshot of the geology map visualization with the TBM position in real time

regarding data interpretation and analysis, especially when processes are performed underground in difficult conditions.

An interface exists between the SDS and IRIS tunnel, which uploads data from installed segments to the corresponding "Segment Management" module. This data is available for evaluation and further quality control by the responsible team at the jobsite and technical office. Data from surface monitoring can also be stored within the same database as TBM data to enable a combined analysis if needed.

This is not the case of the Avrasya Tunnel where the alignment is located beneath the seabed, though positively contributes to the development of such data management systems in underground works.


However, it is remarkable that after completion of the double-deck tunnel with single precast concrete lining, it could be possible to install a long term monitoring sensor network to evaluate ring convergence and deformation, plus possible damages due to seismic vibrations, which would be integrated in the shared data management platform for data analysis and risk assessment during maintenance.

CONCLUSIONS

The article presents the practical applications of a number of monitoring systems that contributes to enhanced project performance for the Avrasya Tunnel including: TBM navigation, ring sequencing and segment management for a comprehensive quality management chain manufacturing plant and installation on site. The tunnel includes two seismic joints on its alignment, which represents a challenge for segment prediction.

A previous estimation of ring sequencing was carried out, although the final planning depends on the tunnel progression because unexpected deviations of the TBM track may occur. These must be corrected on site with the help of the navigation software depending on the actual steering of the TBM.

Lastly, a brief introduction of integrated data management systems being extensively used in underground projects is presented. Such systems are very useful to manage the large amounts of data produced during construction and maintenance.

The monitoring activities during construction are essential for challenging projects such the Avrasya Tunnel, as it passes under the seabed crossing the Bosphorus Strait, through difficult ground conditions and a high risk seismic area 

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