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Świnoujście Tunnel in Poland: Design and Construction aspects of a big diameter slurry TBM excavation under Świna Strait

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Abstract

The new 1.48 km long, bi-directional traffic road, bored tunnel connecting islands of Uznam and Wolin in the North-West Poland has been successfully excavated with a big diameter slurry TBM (outer diameter 13.46 m). The tunnel was built within mixed face conditions comprising of sand, clay and chalk layers. The tunnel underpasses Świna Strait with the minimum overburden of about 8 m and a hydraulic head of about 24 m. The use of a slurry machine permitted to complete the excavation in these challenging geological conditions in compliance with the stringent construction time schedule. The paper will describe main design aspects that were performed using innovative tools to estimate face counterpressure and surface settlements. It will also focus on comparison of the design assumption with the monitored TBM data and of the observed tunnelling induced ground settlements with the predicted ones calculated by empirical methods.

Keywords: Slurry TBM, Face counterpressure, Big diameter TBM, Settlements, Chalk

1. Introduction

Świnoujście is the city located in the Northwest side of Poland. It is one of the most popular and visited cities on the Polish coast, also known as the Land of 44 islands. It is also the only Polish city entirely situated on islands. Out of 44 islands only 3 of them are inhabited: Uznam, Wolin and Karsibór. The most of inhabitants live on Uznam island, where you can find also shopping centers, hotels and spa facilities. Only 16% of Uznam territories belong to Poland, whereas the remaining part belongs to Germany. Wolin houses commercial port, ferry terminal, shipyard, LNG terminal, train station and it's considered as a hub. Karsibór is the least populated. This area contains mainly agrotourism farms and nature protection area called "Natura 2000".

The main weak point of this interconnected system is transport between the islands. Wolin and Karsibór are connected by bridge, while the only way to Uznam island is by a ferry crossing Świna Strait. This service is dependent on weather conditions. Every year there are days when the access to the city is completely cut off – that is also a potential safety risk for the city. The average time of crossing Świna Strait by ferry is 40 minutes, however in summer season it can take up to 3 hours. Moreover, ferries are using diesel engines which pollute the environment. Considering all above inconveniences tunnel construction was considered the only solution for these problems and will allow for future development of the city.

This tunnel has been excavated with a Slurry TBM with a large diameter, passing below the strait and facing a mixed face condition (sand, clay and chalk). SYSTRA SWS has designed tunnel and access roads (open trench and top-down structures).

2. Tunnel alignment

The Contract covers the route between Uznam and Wolin Islands with the total length of approx. 3.2 km (Fig. 1). The road comprises of:

- TBM bored tunnel passing under Świna Strait, with a length of approx. 1,48 km;
- access roads to the tunnel in the form of open trench and top-down structures;
- access roads to the tunnel, manoeuvring, intersection - a roundabout on the island of Wolin and the T-intersection on the island of Uznam.

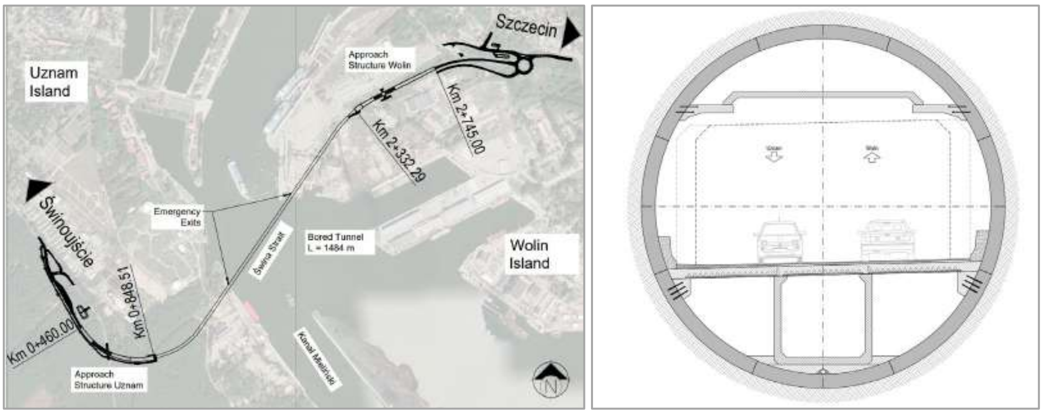

Fig. 1. Key plan of the project (left) and typical cross section of TBM tunnel (right).

The bored tunnel starts at the launch shaft on Uznam side at chainage 0+848.51 and finishes at chainage 2+332.29 in the receiving shaft on the Wolin side where the machine was disassembled.

The internal section is divided in three sections: an upper ventilation channel, the road level with two 3.5 m lanes and 1.2 m lateral evacuation lanes, and a bottom level with emergency tunnel and technical tunnels for utilities. The central emergency tunnel and the ventilation channel are made with precast concrete elements. The maximum slope of the tunnel is about 4%.

The minimum overburden is approx. 6.6 m on Wolin side next to the receiving shaft, whereas the maximum overburden is approx. 28 m; the overburden of the under the strait section ranges between about 10 m and 11 m.

While the area above the tunnel on Uznam side is mainly within the woods with few surface infrastructures, Wolin side area is strongly urbanized with many underground utilities such as sewers, water mains, power and teletechnical networks, and several industrial buildings, petrol station, quay wall. All the structures which could be impacted by potential ground deformations due to tunnelling were monitored during the works.

3. Geological conditions

The general geological strata sequence from the ground level is: made ground, Holocene fine sand (wind/marine origin) with occasional sockets of organic silty clay, Pleistocene fine/medium sand with gravel, over consolidated sandy clay with gravel, and upper Cretaceous chalk (bedrock).

At the bottom of Świna Strait at depth of about 12-13 m, there are fluvial deposit, mainly fine-grained sands with gravel, clay, and chalk. The deepest layer at the bottom of the tunnel alignment, at depths ranging between -32.0 m and -36.0 m, lays chalk and according to the geological map of Poland it should continue to -70.0 m, thus representing the bedrock for the tunnel construction.

The tunnel route is located within the floodplain of Świna Strait (the so-called Świna Gate) between Baltic Sea and Szczecin Lagoon. The waters of Świna Strait are 70% from the Oder River transporting it to the Pomeranian Bay through Szczecin Lagoon and the two other straits Peenestrom and Dzwina. The level difference between Baltic Sea and Szczecin Lagoon is very low. As a consequence, and also due to the effect of winds, the water stream flows in both directions in and out of Świna Strait. Groundwater levels are influenced by three water intakes that provide water to local water supply systems as well as meteoric water.

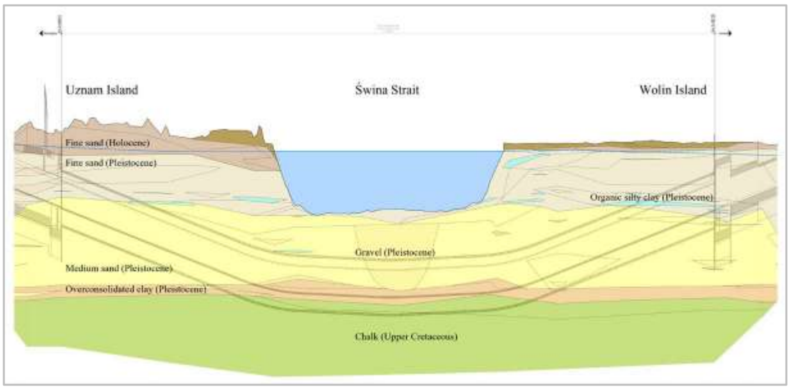

Fig. 2. Geological profile of the tunnel.

The longitudinal geological profile along the tunnel alignment is shown in the Figure 2.

In Świna area, water table level ranges between 1.5-2 m above the sea level in the area with higher dunes and -2 m near the water intakes. The water table level measured in the area where the tunnel was constructed was between -0.02 m and 0.6 m above the sea level.

4. TBM characteristics

The tunnel was constructed with a slurry TBM called "Wyspiarka" (which is a feminine noun for the Islander), manufactured by CREG, which was 13.46 m outer diameter, and forms a tunnel with an inner diameter of 12.0 m. Table 1 reports the main parameters of the slurry TBM.

The slurry, which consists of water and bentonite, was carefully selected based on the ground conditions. Slurry TBM was selected according to the ground conditions. Specifically, mainly coarse granular soils are crossed by the alignment and thus Slurry TBM resulted as the best excavation method. The continuous presence of water table above the tunnel has resulted in the use of closed mode for the whole excavation.

The tunnel was designed as segmentally lined with two different types of universal rings, with different lengths 1.5 m and 2.0 m. Each ring consists of eight precast segments, with the key being the same size as other segments (big-key system), 500 mm thick, mainly reinforced with steel fibre concrete (FRC) beside sections adjacent to two emergency exits and launch/reception shafts where conventional reinforcement with steel cages were installed. Rings of 1.5 m length were installed along the alignment where the minimum horizontal radius of 300 m was designed, for the remaining stretch 2.0 m long rings were installed.

The backfilling of the annular gap between ground profile and segmental lining has been done with two-components bentonite grout.

A total of 784 rings (6272 segments) were installed for the tunnel. The average advance rate was 7 to 8 rings per day with the maximum of 9 rings per day. The maximum distance reached in a day was 18 m.

Table 1. Summary of TBM parameters

Cutterhead diameter	13.46 m	Shield tail diameter	13.37 m
Length	13.8 m	Maximum pressure	4.5 bars
Maximum torque	35750 kN m	Maximum power	4200 kW
Maximum thrust	135114 kN	N° of jacks	2 x 24
Excavation tools	6 centre twin disc cutters + 64 single disc cutters 18" + 120 scrapers + 28 gauge scrapers		

5. Design of TBM excavation pressure and induced settlements

The estimation of excavation face counterpressure and the evaluation of settlements induced by excavation are among the main topics for slurry TBM. These two aspects, often approached in a disjunct fashion, are strictly linked because settlements are dependent on the face counterpressure applied. Therefore, in order to optimize the face pressure value, the constrains imposed by surface structures and infrastructures vulnerability must be considered. This calls for many sectional computations resulting in a time-consuming iterative work. Therefore, an automated process for tunnelling design, called Digital Project®, has been developed (Maltese et al. 2019). Property of this tool is of SYSTRA SWS. With this tool an extremely large number of simulations are performed in a reduced timeframe. The data flow automation allows to perform optimizations or parametric analyses to fine tunnel design parameters and obtain the optimal combination with a multivariate analyses. The Digital Project® considers analytical methods as they are widely established, they can be easily programmed, and because they have the significant advantage of being able to consider different parameters and understand the different relationships between them. The evaluation of settlements is based on the work of Loganathan (2011) that has introduced the possibility to relate volume loss, settlement and expected damage with face pressures.

The operational range of face pressures is evaluated considering the following extremes:

- the lower limit pressure to ensure the minimal support pressure, evaluated according to Broere (2001),
- the upper limit pressure to avoid a break-up of the overburden or blow-up of the support medium, computed as 0.9 times the total vertical stress in the tunnel crown.

The design value of face pressure is defined, within the above-mentioned limits, in order to have acceptable surface settlements. Safety margins on the evaluation of the face pressure thresholds and on the driving error of the TBM pressure have been considered according to DAUB (2016).

Figure 3 shows the design value of TBM counterpressure at crown evaluated along the alignment of the tunnel with the tool. In the first part of the tunnel, on Uznam Island, the design pressure is quite close to the minimum required pressure to guarantee the face stability because there are no structures on the surface and thus the constrains due to settlements less relevant while on the Wolin side, where the tunnel passes under the harbour structures the aim to limit settlements at surface requires to increase the counterpressure. Figure 3 also reports the thresholds limits for minimum and maximum pressures evaluated at the crown. The most demanding part of the route is below Świna Strait. In this section the blow-up pressure, that governs the upper threshold, is very low due to the low overburden (minimum 10 m) while the stability pressure is high because this is the deepest section of the tunnel. This results in demanding condition of having just about 0.3 bar range among the minimum and maximum allowed pressures and thus great attention had to be taken during TBM operation.

6. Observed values of settlements and excavation pressure

6.1. Face counterpressure

Figure 3 also shows comparison between the design values and the face pressure measured during excavation. The use of a slurry TBM permitted to follow the design requirements with high accuracy. Following of the predicted pressures permitted to avoid blow out during excavation in the areas with lower overburden.

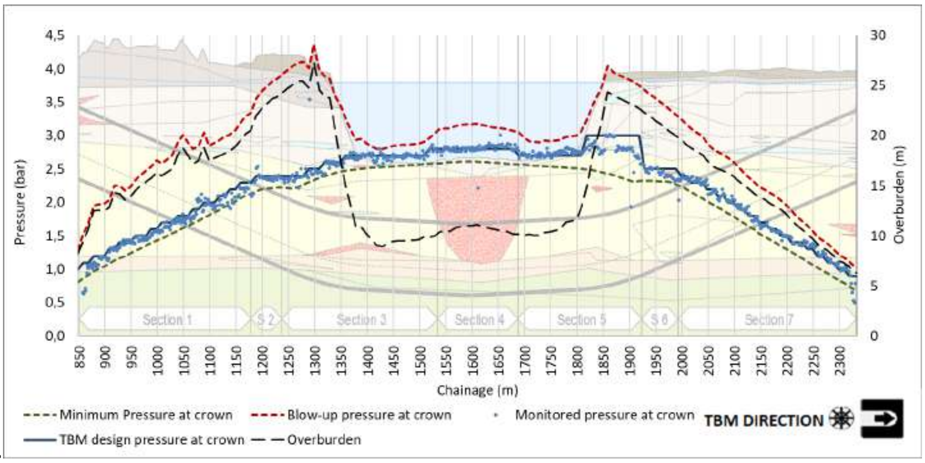

Fig. 3. TBM pressure comparison.

6.2. Settlements at surface

For measuring the tunnelling-induced ground vertical movement, and addressing corresponding volume loss, numerous geotechnical monitoring instrumentations were installed on/below the ground and at the structures (e.g. buildings, quay walls). Topographic surface settlement points have been installed on the axis of the tunnel and in sections transversal to the tunnel direction, in order to measure surface induced settlement curve.

Eight cross sections at Uznam side, and nine cross sections at Wolin side are selected to examine the observed actual ground surface settlement and evaluate the actual volume loss due to the tunnel excavation with back-analysis of the monitoring data. Back-analysis is made by fitting the monitored data with a gaussian curve by changing the volume loss and the parameter k, defined as

$$k = \frac{i}{z}$$

with i position of the inflection point of the settlement curve and z depth of the tunnel from the surface (O'Reilly and New, 1982).

Table 2 shows parameters for best-fit settlement curves.

Table 2. Summary table of actual settlements and volume losses caused by tunnelling.

Section No.	Road chainage (km)	Tunnel depth (axial value) z_0 (m)	Maximum settlement (mm)	k (-)	Volume loss V_L (%)	Measurement type
Uznam side:						
S02	0+900	18.5	34	0.4	0.44	manual
S03	0+950	20.1	19	0.32	0.22	manual
S04	1+000	22.5	21	0.35	0.5	manual
S05	1+050	25	45	0.42	0.83	manual
S06	1+100	23.5	34	0.44	0.61	manual
S07	1+150	25	44	0.42	0.81	manual
S08	1+180	26.5	21	0.42	0.4	manual
S11	1+325	30	33.6	0.36	0.64	manual
Wolin side:						
S27	1+862	30.5	15.2	0.35	0.29	automatic
S28	1+900	29.7	15.9	0.33	0.27	automatic
S29	1+950	28	10.7	0.35	0.18	automatic
S30	2+005	25.5	20.2	0.42	0.38	automatic
S31	2+056	23.8	25.8	0.33	0.36	automatic
S32	2+100	22.5	27.2	0.45	0.48	automatic
S33	2+150	21	97.7	0.4	1.44	automatic
S34	2+200	18.2	58.4	0.55	1.3	automatic
S35	2+250	16.5	38	0.75	1.65	automatic

* - value at the tunnel axis

The maximum back-calculated volume loss is 1.65%, however the majority is below 0.9%. Figure 4 shows the comparison of volume loss between design and field data. The maximum observed value of settlement on Uznam side is 45 mm, on Wolin side it is twice as big because is almost 100 mm, with the majority of settlement values being below 40 mm.

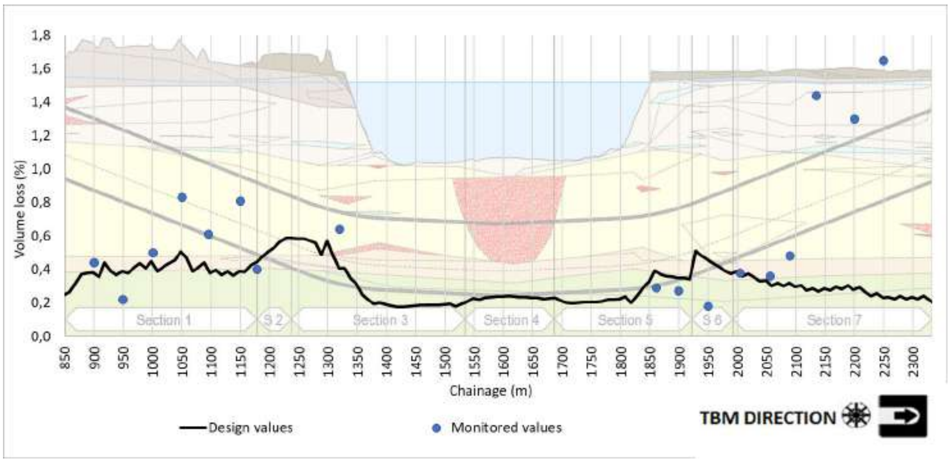

Fig. 4. Volume loss comparison.

6.3. Backfilling of the annular gap

The injection at the tail of the shield reported no problems or deviations compared to the theoretical values, with an average value of injected volume equal to 1.1% of the theoretical one. The theoretical value has been evaluated as the area of the annular gap between excavation diameter and lining external diameter (Figure 5).

7. Discussion

Design values of TBM parameters and settlements are quite well reproduced by the monitored data.

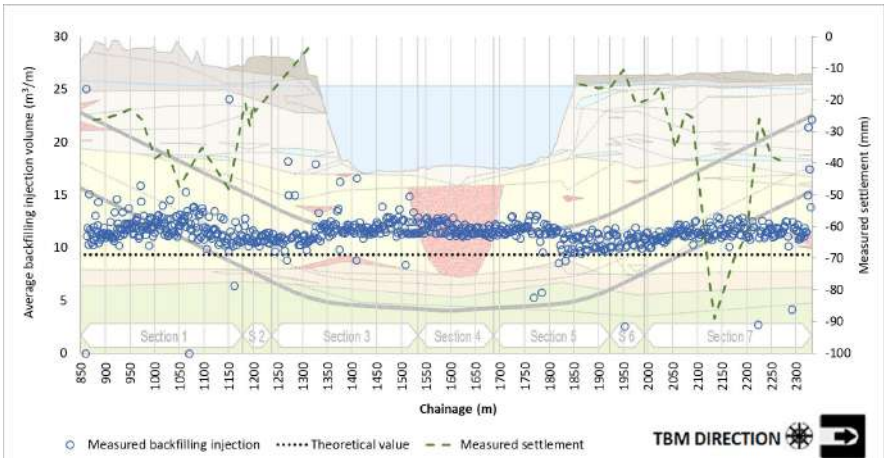

Fig. 5. Backfilling injection volume.

In the last sections, from chainage 2+150 on Wolin island, data does not fit the predicted values. In those positions the settlements have exceeded the predicted values and the volume loss has reached high values (max 1.6%). A possible reason for such a big difference in subsidence in these areas is the ground conditions that consists of organic soil strata made of alluvium and peats laid. Unfavourable ground is located at a depth of 25 m below ground level to approximately 2m thick layer next to the receiving chamber on Wolin island. The biggest impact on settlement can be observed in the last three sections, where the geological condition combines with very low overburden (about 7 m). Nevertheless, the increased settlements in those sections have not resulted in unacceptable damages on the surface infrastructures.

The larger the TBM the more critical movement measurements are in order to assess the ground behaviour and minimize ground loss and potential settlement. 1% of ground loss on at 13,46 m diameter tunnel yields 1,4 cubic meter/meter of ground loss almost 4 times ground loss from a metro size TBM.

Similarly, the larger the TBM the wider settlement trough, in this case the trough was between 20 to 35 meters depending on the tunnel depth.

The parameters of the TBM machine were controlled in all areas and remained within the design limits along all the excavation.

8. Conclusions

Świnoujście tunnel was constructed without major issues within the agreed contractual milestones with a large diameter Slurry TBM by passing below Świna Strait. Slurry TBM has allowed to excavate the 1.48 km tunnel of 13.46 m excavation diameter with no major problems. The comparison of the observed ground surface settlements with the predicted values has been addressed. Generally low values of settlements have indicated a successful slurry TBM operation, which delivered safe tunnelling experience for the future tunnelling projects in similar ground conditions. In most cases volume loss achieved were far below 1.0%. TBM face pressure and backfilling volume have always followed the design requirements, demonstrating a very good performance of the TBM drive.

The purpose of this paper is to share this case study of slurry TBM excavation and provide reference for both designers and contractors what the ground is behaving and what can be expected during underground works in similar ground conditions with a big diameter tunnel and undersea passage.

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