Numerical analysis of circular reinforced concrete tunnel lining

Analyse numérique du revêtment d'un tunnel circulaire avec voussoirs préfabriqués

A. Siemińska-Lewandowska
Warsaw University of Technology, Warsaw, Poland

M. Mitew-Czajewska
Warsaw University of Technology, Warsaw, Poland

ABSTRACT

The paper describes the results of a numerical analysis of reinforced concrete tunnel lining in four characteristic cross-sections, taking into account different modelling methods. The calculations were performed with the use of the finite element method and GEO5 FEM software using data from the design works related to the planned construction of the technical tunnel under the river Vistula. Owing to significant differences in momentum values, the conclusions from the study will be used to define the joints between tunnel segments and to dimension the tunnel lining in the technical design of the structure.

RÉSUMÉ

L'article présente les résultats d'une analyse numérique du revêtement d'un tunnel circulaire dans quatre sections caractéristiques tenant en compte les differentes méthodes de modélisation des joints entre voussoirs préfabriqués. Le calcul a été réalisé par la méthode des éléments finis et logiciel GEO5 FEM, en utilisant des données de l'étude de la concéption de construction d'un tunnel hydrotéchnique sous la riviére Vistula. L'examen des résultats montre les grandes differences des valeurs des moments flechissants dans les voussoirs. Les conclusions seront adaptées aux dimensionnement du rêvetement du tunnel en projet définitif de réalisation.

Keywords : tunnel, tunnel boring machine, numerical modelling, dimensioning of tunnel lining

1 INTRODUCTION

The paper presents the results of a series of numerical analyses of lining of the deep technical tunnel to be built under the bottom of the river Vistula in Warsaw. The structure in question is a circular tunnel with the length of approximately 1350m and internal diameter of 4.40m. The tunnel will be bored by a TBM (Tunnel Boring Machine) utilizing the EPB (Earth Pressure Balanced) technology. The machine allows to safely bore the tunnel in varied hydro-geological conditions with simultaneous ground excavation, supporting the mine face, removal of the output and erection of the lining. The planned depth of the tunnel coupling piece below ground surface is varied and amounts to from 3.4m to 28.0m. The variation of the tunnel depth results from significant height differences in the area (the Warsaw Escarpment) and the necessity to safely route the tunnel formation line below the washable river bottom. After the completion of the investment project the cover in the deepest point will reach 32.0m.

Taking into consideration the differences in the thickness of the ground overburden above the tunnel and the variability of the geotechnical conditions, four computational cross-sections have been chosen for the initial numerical analyses (Figure 1 and Figure 2).

2 GEOTECHNICAL CONDITIONS

2.1 Geological structure

The tunnel is to be situated within the limits of the Vistula river valley. It will start in the area of a postglacial upland and finish in the river floodland terraces. The investment area is built of Tertiary formations on which Quaternary formations occur. In the upland area, the Quaternary period is represented by fluvioglacial formations, whereas in the river valley – by fluvial formations. Tertiary formations occur as Pliocene clays.

Directly under the surface fluvioglacial formations occur in the form of sand with varied grain size – from fine grained to coarse grained and sandy gravel in the semi-compacted state. Fluvial sands and gravels, especially in the river bed, are composed of well-washed varied grain size sands as well as sandy gravels and gravels from medium dense to dense. Very often stones and pebbles, sometimes with large sizes, are found in the floor of that layer. The thickness of that layer varies from 0 to 15.0m.

Under the sandy formations Quaternary Pliocene clays are found, which occur as clays, silty clays or stiff silty clays. In the above layer there are lenses of silty and fine sands and sandy silts with thickness from 1.20 to 5.70m, which are often watered.

Two water table levels occur along the route of the tunnel. The waterbearing layer consists of sands, fluvial and fluvioglacial gravels as well as silty and fine sands and sandy silts occurring in lenses confined in the clays. The first groundwater level with free and locally slightly confined water table stabilises at the level from +0.40 to -2.80m above the river Vistula level, i.e. from 0.60 to 9.40m below ground surface. The surface of that water table depends largely on the river water level and the amount of rainfall. The tunnel, beginning at the starting shaft, will run for approximately 1050m through clays whose ceiling will be situated at the level of 16.0m above the ceiling of the tunnel, then at 3.5m in the river bed, and then the tunnel will completely exit the dense soil on the right river bank where the structure will enter watered sandy soils.

2.2 Geotechnical conditions

The following geotechnical layers were distinguished on the basis of the geotechnical documentation prepared for the purpose of the investment project:
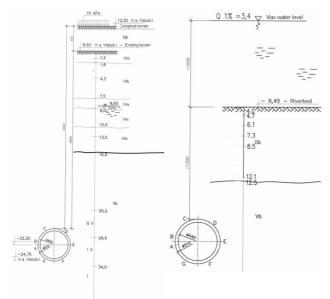
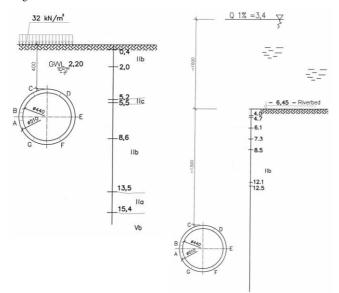Figure 1. Cross-sections 1 and 2

Figure 2. Cross-sections 3 and 4

<u>Layer II</u> – fluvial sands and gravels. The following formations were distinguished on the basis of the type and state of the ground: IIa – fine grained sands, medium dense, $I_D = 0.40$; IIb – medium and coarse grained sands, medium dense, $I_D = 0.40$; IIc – gravels and sand and gravel mixes, medium dense, $I_D = 0.40$.

<u>Layer III</u> – unconsolidated moraine formations – stiff sandy clays, clayay sands, $I_L = 0.00$.

<u>Layer IV</u> – fluvioglacial formations which have been divided into the following groups depending on their type and state: IVa – medium and coarse grained sands, medium dense, $I_D = 0.60$; IVb – gravels and sand and gravel mixes with stones, medium dense, $I_D = 0.60$; IVc – fine and silty sands, medium dense, $I_D = 0.60$,

<u>Layer V</u> – Tertiary Pliocene clays. The following formations were distinguished on the basis of the type and state of the ground: Vb – clays, silty clays, locally stiff or very stiff silty, $I_L \leq 0.00$; Vc – silty and fine sands and dense sandy silts, $I_D = 0.70$.

The geotechnical computational parameters of the above specified layers are presented in Table 1. It must be pointed out

however that most of those parameters were specified from the standards on the basis of the density index or the plasticity index of the soil.

Table 1. Geotechnical parameters of the layers

Layer	I_D / I_L	γ [kN/m³]	Φ [°]	c [kPa]	E_0 [MPa]	ν [kN/m]
II a	0,40	18,0	29,9	0	38,27	0,30
II b	0,40	19,0	32,4	0	66,92	0,25
II c	0,40	20,0	37,7	0	120,0	0,20
IV a	0,60	18,5	33,6	0	94,6	0,25
IV b	0,60	19,0	39,2	0	156,15	0,20
IV c	0,60	19,0	30,9	0	55,4	0,30
V b	0,00	20,0	13	60	22,2	0,37

3 TUNNEL STRUCTURE

The lining of the tunnel will be made of precast reinforced concrete segments. Each lining ring will contain 5 + 1 (key) segments. It is estimated that the segment lining may be constructed of simple rings, right and left concurrent, or only of right and left-concurrent rings. In both cases a correct ring placing sequence along the tunnel will allow to obtain horizontal curves as well as lifts. Within a single ring there may occur trapezoidal segments or rectangular segments with wedge-shaped key segments and trapezoidal near-key segments. Lining parameters:

- ring thickness at the tunnel cross-section - 35 cm
- ring length along the tunnel - 1.40 ÷ 1.60 m
- radial connection between the segments in the longitudinal direction: with connecting elements (pins, connectors, bolts, pivots), and without connecting elements.
- perimeter connection between the rings - dowels, (groove and key), bolts.

The space between the external surfaces of the segments and the ground created as a result of using the TBM technology will be filled with grout.

In practice there is a wide array of solutions for creating connections between segments. The rings may therefore be modelled as jointless, multi-jointed or with rigidity corresponding to the values between the ideally rigid (jointless) ring and a multi-jointed ring. In the numerical analysis of the issue the two extreme solutions have been considered: in the first option an entirely rigid lining was assumed, whereas jointless and jointed lining was assumed in the second option. Figure 3 shows a sample segment placement diagram in the cross section of the tunnel which was taken into consideration in the calculations.
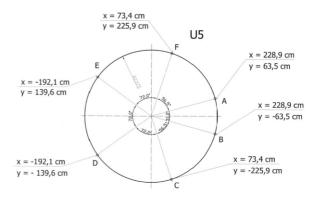

Figure 3. Diagram illustrating the placing of reinforced concrete segments in the tunnel cross-section

4 NUMERICAL ANALYSIS

4.1 *Assumptions*

Calculations were performed with the use of the finite elements method (FEM) and GEO5 FEM software in four chosen characteristic computational cross-sections shown in Figures 1 and 2. In the calculations the elastic-ideally plastic soil model with Coulomb-Mohr plasticity condition was used. The parameters of the geotechnical layers, which were used in the calculations are given in Table 1. The structure was analysed in plain strain, the dimensions of models were approximately 80m (horizontal) and from 20 to 60m (vertical), depending on the depth of the tunnel. The finite elements mesh was made of triangular six-node elements. The lining of the tunnel was modelled as three-node linear beam elements; the contact of the structure with the ground was modelled with the use of three-node linear contact elements allowing for a local reduction of ground parameters. A sample FEM model created with the use of the GEO5 FEM software is shown in Figure 4.
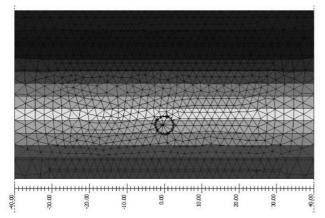

Figure 4. A sample FEM model with a finite element mesh

The calculations provided variants of modelling circular reinforced concrete tunnel lining. In each of the cross-sections two options were analysed: lining with fixed connections and lining with jointed connections between the segments. The following assembly and loading stages were taken into consideration:

Cross-section 1:
stage 1 – geostatic stresses; stage 2 — construction of the tunnel and load of 15 kPa on the surface; stage 3 – execution of a 4m high embankment; stage 4 – load on the tunnel lining resulting from clay swelling (Figure 4a); stage 5 – loads from installations and operating loads in the tunnel (Figure 4b)

Cross-section 2:
stage 1 – geostatic stresses; stage 2 – construction of the tunnel; stage 3 – load on the tunnel lining resulting from clay swelling (Figure 5a); stage 4 – loads from installations and operating loads in the tunnel (Figure 5b)

Cross-section 3:
stage 1 – geostatic stresses; stage 2 – tunnel construction and surcharge load; stage 3 – loading of the surcharge with transportation vehicles; stage 4 – loads from installations and operating loads in the tunnel (Figure 5a)

Cross-section 4:
stage 1 – geostatic stresses; stage 2 – tunnel construction and surcharge load; stage 3 – loads from installations and operating loads in the tunnel (Figure 5b)

Figure 5 shows a diagram with loads acting on the tunnel lining, resulting from the pressure exerted by the swelling clay (5a) and a diagram of installation and operating loads in the tunnel (5b).
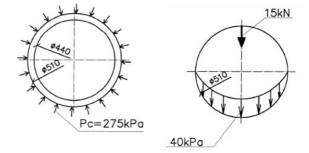

Figure 5. Tunnel loads: caused by clay swelling, b) installation and operating loads

4.2 *Calculation results*

Depending on the assumed scheme, significant differences were obtained in the values of the expected bending moments as well as of displacements of the lining. Significantly smaller bending moments are observed in the lining, whereas the deformations in the case of modelling the rings as jointed rings are larger.

Table 2 presents a list of calculation results in all cross-sections taking into account the lining modeling options. Figures 6 and 7 show sample distributions and values of moments as well as displacements in the cross-section with the largest overburden

Table 2. FEM calculation results

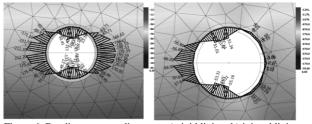|	Connections of lining segments	Bending moment in lining [kNm/m]	Lining displacement [mm]	Compressive force in lining [kN/m]
Cross-section 1	rigid	212,2	3,6	1476,6
	jointed	88,0	15,8	1434,6
Cross-section 2	rigid	151,7	39,9	949,2
	jointed	64,3	45,6	917,5
Cross-section 3	rigid	98,7	3,8	293,1
	jointed	39,3	12,0	305,6
Cross-section 4	rigid	249,9	23,2	865,1
	jointed	109,6	36	834,6

Figure 6. Bending moment diagrams: a) rigid lining, b) jointed lining
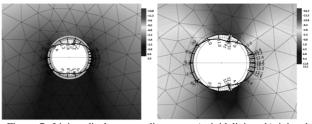

Figure 7. Lining displacement diagrams: a) rigid lining, b) jointed lining

5 SUMMARY AND CONCLUSIONS

Considering the fact that there are various methods of forming connections between segments of the tunnel lining constructed with the use of TBMs, calculations were performed taking into account the two extreme options: rigid and jointed connections. In this manner boundary conditions were specified, which have to be met while elaborating the technical design of the segments of the tunnel analyzed in the cross-section.

It is stated that when the stiffness of the connections in ring calculations is taken into account, it leads to a significant decrease of the bending moments. As a result the thickness of the lining rings is decreased.

It is recommended to perform analyses with a higher level of specificity in modelling the reinforced concrete structure of the tunnel in order to allow for a precise specification of the methods of forming connections between the lining rings. In addition to that a series of other geotechnical tests (in particular *in situ* tests, i.e. CPTU probings) must be carried out in order to establish correct parameters of the ground layers occurring in the investment area. Parameters established on the basis of the standard are not suitable for the modelling of such significant projects.

It is assumed that in the further phase of the design works a 3D version of the FEM model will be elaborated with the use of MidasGTS software.

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