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ANALYSIS OF INTERACTION OF PREFABRICATED REINFORCED CONCRETE TUNNEL WITH SUBSOIL

ANALIZA WSPÓŁPRACY ŻELBETOWEGO PREFABRYKOWANEGO TUNELU Z PODŁOŻEM GRUNTOWYM

A b s t r a c t

The paper presents the results of analyses of numerical interaction between a tunnel made of reinforced concrete prefabricated with backfill and stratified ground. A number of variants of foundation have been discussed: gravel cushion, on an additional concrete strip, and on a cap based on jet-grouting columns. The grounds in the simulations were described using the Coulomb-Mohr model.

Keywords: prefabricated tunnel made of reinforced concrete, numerical analysis of interaction between tunnel and subsoil and backfill

S t r e s z c z e n i e

W artykule zaprezentowano wyniki analiz numerycznych współpracy żelbetowego tunelu prefabrykowanego z zasypką i z uwarstwionym podłożem. Rozpatrzono kilka wariantów posadowienia: na poduszce żwirowej, na dodatkowej ławie betonowej i na oczepie opartym na kolumnach jet-grouting. Grunty w symulacjach opisano modelem Coulomba-Mohra.

Słowa kluczowe: żelbetowy tunel prefabrykowany, analizy numeryczne współpracy tunelu z podłożem i zasypką

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1. Introduction

During recent years, intensive works on the building of expressways, clearways and local roads have been carried out in Poland. These routes must overcome several obstacles which necessitate the building of a large number of engineering objects: viaducts, bridges, culverts and tunnels. The participation of the costs of these objects in total road costs is significant. It can be restricted by using, where possible, prefabricated structures. Actually, a number of systems based on prefabricated elements are used: Matiere present on the British and Irish market, and in the countries of Central-Eastern Europe mediated by ABM Europe, Tech Span delivered by the Reinforced Earth Company of the Freyssinet group and BEBO offered by Swiss BEBO International AG.

Concrete reinforced, backfilled tunnels that are based on prefabricated arches have a span from 3 to 20 m, height up to 9 m and length up to 360 m. The coat thickness changes within 200 and 350 mm, exceptionally is 520 mm. The relation of arch radius to their range rises together with an increase in the coat thickness of the initial backfill. The BEBO system uses elliptic arches, circular and "shallow arch" (flattened parabolic arches) fixed one or two parts united on the build site. The Matiere system is based on three arches made of three parts two curved walls with a shaped isolated footing and a curved ceiling element. The widening of the foundation through concreting a bracket is used. Construction of the tunnel segment in Tech Span technology comprises the following prefabricated elements: the foundation, two half-arches and a wet concrete principal beam connecting them. The task of the principal beam is to brace the tunnel construction at length without moving the bending moments where it connects with the shells.

2. Description of the analysed object

The analysed object is one of a series of arches passing above a small number of obstacles of the flyover of a national road. The designers of the flyover used the Matiere system arch of range 18.128 m and height 9.787 m.

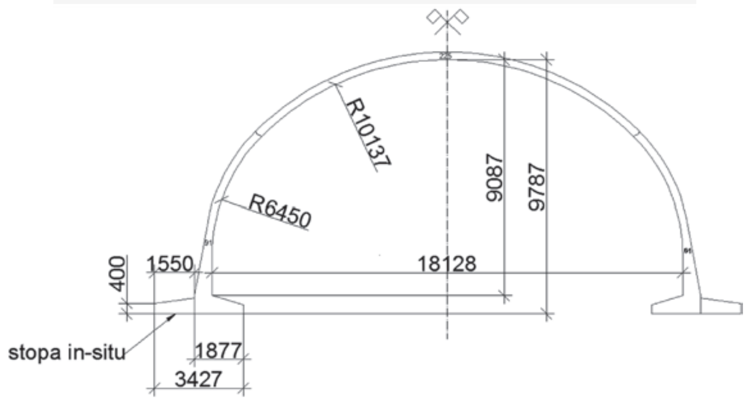

Fig. 1. Section of the prefabricated reinforced concrete element of the Matiere system arch

The geometry of this arch is presented in Fig. 1, and the method of assembling the segments for a double communication tunnel is presented in Fig. 2.

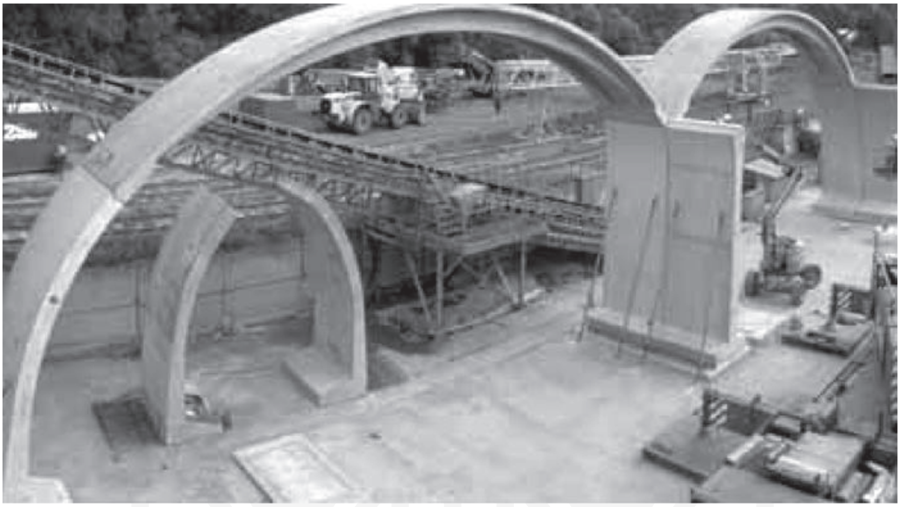

Fig. 2. Construction of the arch of Matiere system made of prefabricated elements

The foundation of the prefabricated element was widened by concreting an additional bracket 1.55 m, finally obtaining a strip width of 3.427 m. The thickness of the pod is 300 mm, and the segment length is 2.49 m. The tunnel length is is 63 m.

During creating the tunnels with prefabricated elements, the method of preparing the backfill of the integrated tunnel construction is significant. Arranging the backfill can start after setting the wet concrete. The backfill should be made of well compacted soils that have less than 10% grains, smaller than 0.05 mm, obtaining a compaction index $I_s = 0.98$. The compaction should be made on a layer thickness of 25 cm, at the difference of the level at both sides of the transverse section not larger than 50 cm. Within a distance not larger than 2 m from the shell edge, only manually controlled compaction is allowed.

The assembly of the prefabricated walls and ceiling arch of the individual segment of the tunnel requires high precision. The foundation of the shell should be made with an accuracy up to 3 mm on each 6 m of the length. Moreover, the requirements are changed that concern the acceptable deformation of the integrated construction on the plane of the tunnel transverse section. The maximum difference of foundations settlements of the opposite wall should not exceed 10 mm. Maximal settlements of the foundation layer of the road on the road layers and over the prefabricated construction cannot exceed 100 mm. In the engineer's practice, for estimation of the tunnels foundations settlements the Winkler model is used. The rigidity of the subsoil is determined by the elasticity coefficient K determined on the basis of pressiometric and dilatometric studies. The modification of the way of calculation of the modulus was introduced by J.Krizek, and details of the changes are given in reference [3].

3. Numerical analyses

The numerical model was generated in the Z_Soil sytem ver 11-07. The mesh was made step by step using the existence function. In the first step (initial state) the subsoil of the embankment with the road situated in the tunnel was erected. Additionally the initial stress state was calculated. The next step was the erection of the prefabricated arch with layers of backfill and the road situated in the tunnel.

Three variants of the tunnel foundations grounding are discussed:

a) on the foundation strip of width 3.43 m based on a soil cushion of width 4.0 m and thickness 1.56 m,
b) on the strip of width 4 m and height 0.92 m made under the prefabricated element and additional bracket,
c) on the strip based on the foundation supported by jet-grouting columns.

It should be pointed out that in the Matiere system, the additional concrete pad is made under the back of the prefabricated wall element which facilitates the construction leveling and concreting an additional bracket widening the tunnel foundation, hence the b) scheme was adopted.

The subsoil of the object is recognized as fine sands and sand with gravels in medium state, dense state, clay in hard-plastic, plastic and soft-plastic state. The modulus of elasticity E of soils was given from PN-81/B-03020. For the soil characteristic, the elastic, plastic ideal model of the ground with a Coulomb-Mohr plastic surface was adopted. The concrete of the shell, the pad foundation, capping beam and ground-cement material of jet-grouting columns were described using an elastic model. The discretisation of the geometric models for the presented tasks is shown in Fig. 3, 4 and 5. Jet-grouting columns were modelled with beam elements. The parameters of the material sections are presented in table 1. Between the concrete arch and soil, interfaces were generated ($\phi = 20°$, $c = 2$ kPa). The mesh of the FEM elements was created in Autodesk Auto CAD system and exported to the Z_Soil system.

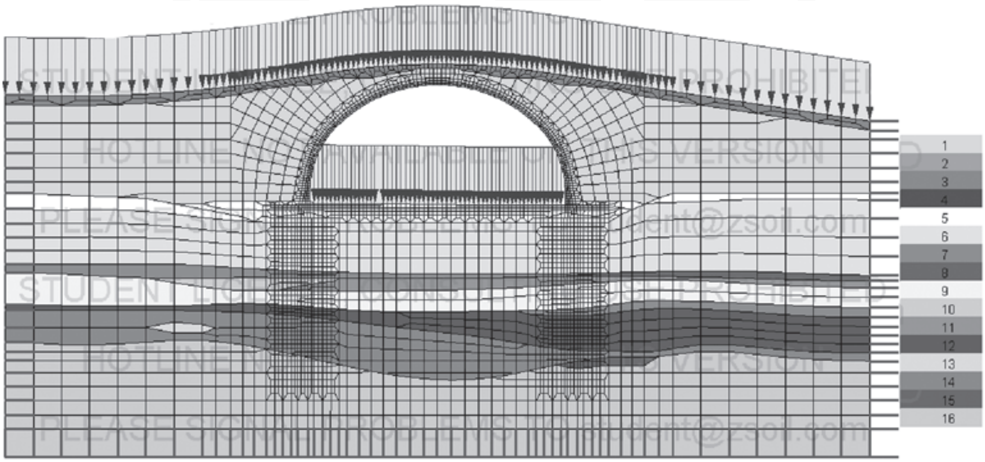

Fig. 3. Discretization of the FEM mesh of the prefabricated arch with backfill and subsoil

Table 1

Parameters of material zones of the models adopted in the numerical analyses

Lp.	Material zone	Internal friction angel [°]	Cohesion c_u [kPa]	Specific gravity γ [kN/ m³]	Poisson ratio ν [–]	Modulus of elasticity E [MPa]
1	Backfill	35	2	18	0.25	130
2	Tunnel arch	–	–	25	0.2	37000
3	Road structure	–	–	25	0.2	550
4	Concrete bracket	–	–	25	0.2	500
5	FSa. I_D = 0,58	31	2	16.5	0.3	55
6	FSa. I_D = 0,50	30.5	2	17.5	0.3	50
7	FSa. I_D = 0,50 below water level	30.5	2	9	0.3	50
8	FSa. I_D = 0,33	30	2	8.5	0.2	35
9	grS., I_D = 0,64	39	2	11	0.25	165
10	saCl. I_L = 0,61	15	26	20.5	0.3	20
11	saCl. I_L = 0,42	18	30	21	0.25	23
12	saCl. I_L = 0,05	25	50	22	0.25	70
13	saCl. I_L = 0,21	21.5	39	22	0.25	37
14	FSa. I_D = 0,51	30.5	2	17.5	0.3	50
15	grSa. I_D = 0,77	40	2	20	0.2	190
16	saCl. I_L = 0,00	25	50	22	0.25	68
17	Jet-grouting	–	–	22	0.2	5400

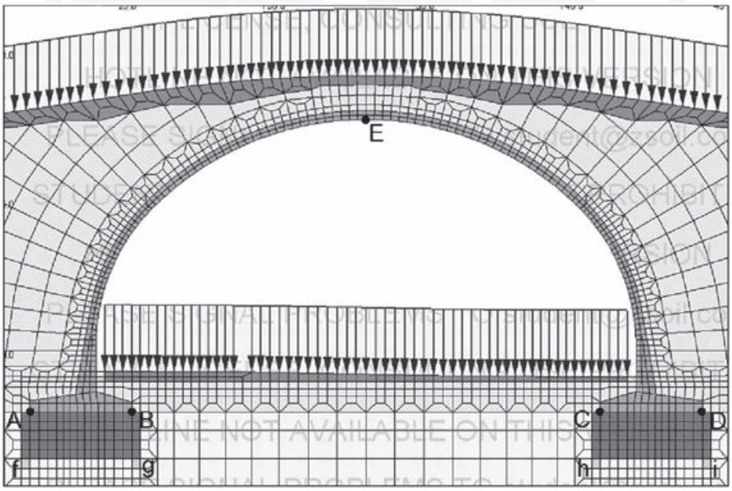

Fig. 4. Scheme of FEM mesh of the model of tunnel supported on gravelly cushions

For controlling model sensitivity, numerical analyses for different thicknesses of subsoil were carried out. Settlements of the tunnel increase with changing the thickness of analysed subsoil but the differences were small. In case of tunnel foundation on jet-grouting columns and deepened subsoil under columns up to 10 m, settlements increase to 2 mm.

The analyses were made for two schemes of road loading on the tunnel arch:

a) the load exists on the whole embankment,
b) the load exists over half of the embankment.

The parameters of the jet-grouting columns material were taken from monograph [1], and the parameters of the soil cushion were adopted on the basis of paper [4]. In the numerical analyses, the displacements of nodes marked in Figures 3 and 4 and stress in the subsoil under the gravelly cushion and the base of the jet-grouting columns were observed. The results of the analyses were given in the tables 2 and 3.

Table 2

The comparison of the tunnel construction displacements for three variants of foundation at symmetrical load

Type of foundation	Gravelly cushion	Strip foundation	Jet-grouting columns
Average settlements of the tunnel construction [mm]	49.8	49.6	29.7
Vertical displacement U_{YY} of E node (mm)	52.8	51.7	33.3
Settlements difference of the opposite foundation in the tunnel transverse section [mm]	7.4	7.3	1.8
Maximal settlements of the embankment [mm]	55.1	54.3	49.1

Table 3

The comparison of the tunnel construction displacements for three variants of foundation at nonsymmetrical load

Type of foundation	Gravelly cushion	Strip foundation	Jet-grouting columns
Average settlements of the tunnel construction [mm]	43.3	42.7	24.9
Vertical displacement U_{YY} of E node (mm)	45.5	44.6	27.4
Settlements difference of the opposite foundation in the tunnel transverse section [mm]	20.2	18.9	9.9
Maximum embankment settlement [mm]	55.7	55.1	49.2

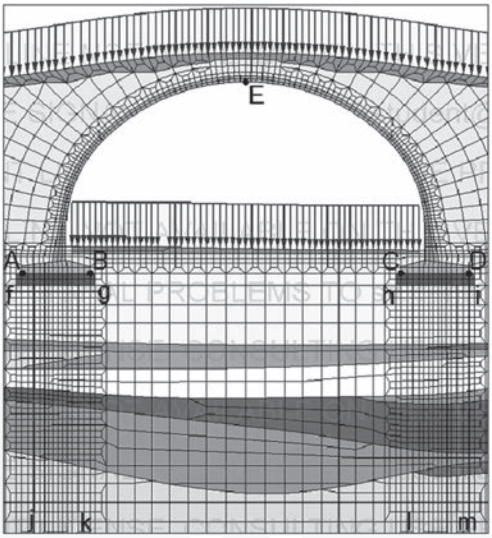

Fig. 5. Scheme of FEM mesh of the tunnel foundation on jet-grouting columns

4. Conclusions

Taking into account the results of numerical analyses, it can be concluded:
- for asymmetrical load the acceptable difference of opposite foundation in tunnels cross-section was satisfied only in the case of tunnel foundation on jet-grouting columns,
- for each case of tunnel foundation the maximum value of vertical displacements of road bed situated on the tunnel the limits were not exceeded.

In the future, for numerical analyses carrying out for interaction of prefebricated tunnel with subsoil, a soil model which describes the changes in the rigidity of the soil within very small deformations should be used. This model will improve the precision of estimating subsoil changes.

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