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GEOTECHNICAL ANALYSIS OF TRANSFORMING A WATER MANAGEMENT STRUCTURE TO A TRANSPORTATION STRUCTURE

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Abstract.

This paper analyzes the transformation of the culvert channel under the supply channel of the Gabčíkovo Waterworks into a road tunnel structure and the impact this had on the surrounding rock environment. It presents the engineering-geological conditions in the area, the current structural-material characteristics of the culvert channel and its proposed transformation into a road tunnel. The results of the geotechnical analysis, realized through numeric modelling, are presented as a comparison of deformation changes in the rock environment with respect to changes in loading states corresponding with functional changes in the analyzed culvert.

Keywords: Culvert channel, deformation analysis, loading state, quaternary gravels, settlement, supply channel.

1. Introduction

During construction work on the supply channel of the Gabčíkovo Waterworks, a culvert channel was built under the supply channel, situated at 4.0 km. The culvert channel is used to drain seepage waters of the Hrušov reservoir captured by the left-side seepage channel under the supply channel. The captured seepage waters, from both left-side and right-side seepage channels, are drained together into the Danube river branches. The position of the culvert channel under the supply channel is shown in Fig. 1.

Figure 1. Position of the culvert channel under the supply channel

The culvert channel has been designed for a maximum flow rate of 60 $m^3.s^{-1}$, while the passage of such a volume of water is provided by five rectangular openings with dimensions 4.5 m × 2.2 m, as is shown in Fig. 2. The sixth opening, 2.0 m × 2.2 m, serves as a communication passageway that contains infrastructure.

As early as during the design stage of the projected

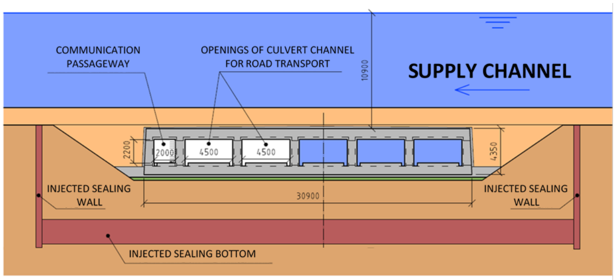

Figure 2. Cross-section of the culvert under the supply channel at km 4.0 [1]

waterworks, it was presumed that seepage into the left-side channel would decrease over time due to colmatation of the subsoils of the Hrušov reservoir and that three openings of the culvert channel would be sufficient to pass the captured seepage waters. For this reason, an alternative use of two openings for other than passage of seepage waters has been considered. The flow rates measured during operation of the seepage channels and the culvert channel situated at 4.0 km under the supply channel of the Gabčíkovo Waterworks in 1994 – 2016 confirmed the possible use of two openings for another purpose. Based on the above, an alternative use of part of the culvert channel has been considered as a road transportation structure for permanent connection of communities divided by construction of the supply channel of the Gabčíkovo Waterworks. The analysis of reliability risks for use of this water management structure as a road tunnel structure included geotechnical assessment of the culvert channel.

2. A structural engineering solution of the culvert channel

The culvert channel consists of inlet and outlet sections, which include sluice mechanisms and regulatory gates, and the middle section consists of the culvert tunnel. The overall length of the culvert channel is 715 m, with the middle section representing 499.74 m and the remaining length being represented by the inlet and outlet sections. The middle section of the culvert channel consists of a total of twenty separate dilatation units (D1 to D20), each 19.6 m long, with average width of 30.9 m, and seven dilatation units under the safety dams of the supply channel (3 under the left dam – A1, B1, C1 and 4 under the right dam – C2, B2, E, F), 12.0 to 19.6 m long, with an average width of 31.2 m. A longitudinal section of the culvert channel is shown in Fig. 3.

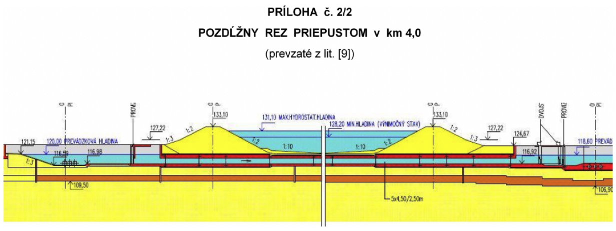

Figure 3. Longitudinal-section of the culvert channel under supply channel in km 4.0 [1]

The structure of the culvert channel is a framed reinforced concrete structure comprising 27 blocks, which is made of impermeable concrete with classification at least C 35/45, strengthened with 10 425 (V) reinforcing steel. At the points of contact between the blocks, dilatation joints were made, 20 mm wide with inner sealing around each opening of the culvert channel. The structure of the culvert channel is isolated and the surface of backfill over the ceiling is made of sealing clay.

3. Geological conditions at the area of interest

The geological environment in the study area is composed of fluvial deposits of quaternary age reaching a thickness circa. 250 m [2]. This was successively accumulated in the Gabčíkovo-Győr depression of the Danube Basin as a result of a neotectonic basin inversion [3]. The strata consist mostly of gravelly and sandy-gravelly channel-fill facies of the Danube and Western Carpathian rivers and were accumulated in braiding depositional settings. The deposition in high sediment supply and low accommodation rate conditions caused a low content of sandy, silty and clayey layers [2]. An exception is given by the uppermost few meters of the basin fill, which were deposited during the Holocene as floodplain, mostly silty and clayey facies of the meandering Danube [4].

To characterize the geological conditions of the subsoil at the culvert channel location, we have assessed the geological survey [5] made in 1978 for construction of the culvert channel. Survey drills DKP 8 – DKP 12 were carried out for the culvert channel. Besides this, information on the geological condition was supplemented by older survey works VK 390, VK 391 and HVK 23, carried out in the past. Depths of all survey work were within 15.0 m with the sole exception of the HVK 23 survey, which was 30.0 m deep. The survey works were located at the axis of the culvert channel situated at 4.0 km. Within the examined depth of 15 – 30 m, the subsoil of the culvert channel is formed exclusively by quaternary sediments, which can be classified into three groups:

- surface layer of loamy sands or sandy clay soils 0.5 – 1.3 m thick;
- transition layer between surface fine-grained soils and gravelly soils of sands with loamy and clay ingredients;
- underlying gravel layer with 10 – 60 % of sandy ingredient where sandy or less sandy gravel positions are alternating and mutually interlocked.

The full scope of the culvert channel's footing bottom is situated within the quaternary gravel position. From the geotechnical point of view, the quaternary gravel layer, located under the footing bottom of the culvert channel is critical for analysis of the reliability risks of the culvert channel situated at 4.0 km under the supply channel of the Gabčíkovo Waterworks and its use as road tunnel. According to the survey results [5], the quaternary gravels can be characterized as well-graded (GW – G1) or poorly graded (GP – G2) gravels. The range of granular composition of the gravelly soil samples taken from the culvert channel subsoil is shown in Fig. 4.

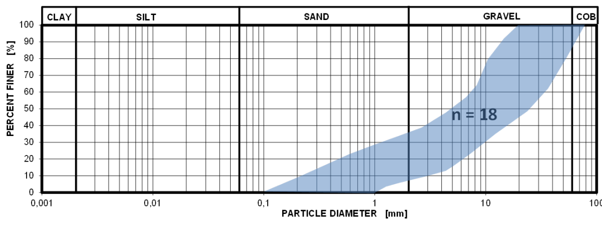

Figure 4. Range of grain size distribution of quaternary gravel subsoil

Further properties of the quaternary gravels of the culvert channel subsoil, described in the survey [5], are as follows:

- relative density: medium dense;
- deformation parameters:
  - ▷ $\beta = 0.83$; Pisson's ratio $\nu = 0.25$;
  - ▷ $E_{\mathrm{def}} = 50\,\mathrm{MPa}$ – for depths 0.0 – 5.0 m;
  - ▷ $E_{\mathrm{def}} = 100\,\mathrm{MPa}$ – for depths 5.0 – 30.0 m;
  - ▷ $E_{\mathrm{def}} = 114.5\,\mathrm{MPa}$ – for depths 30.0 – 90.0 m;

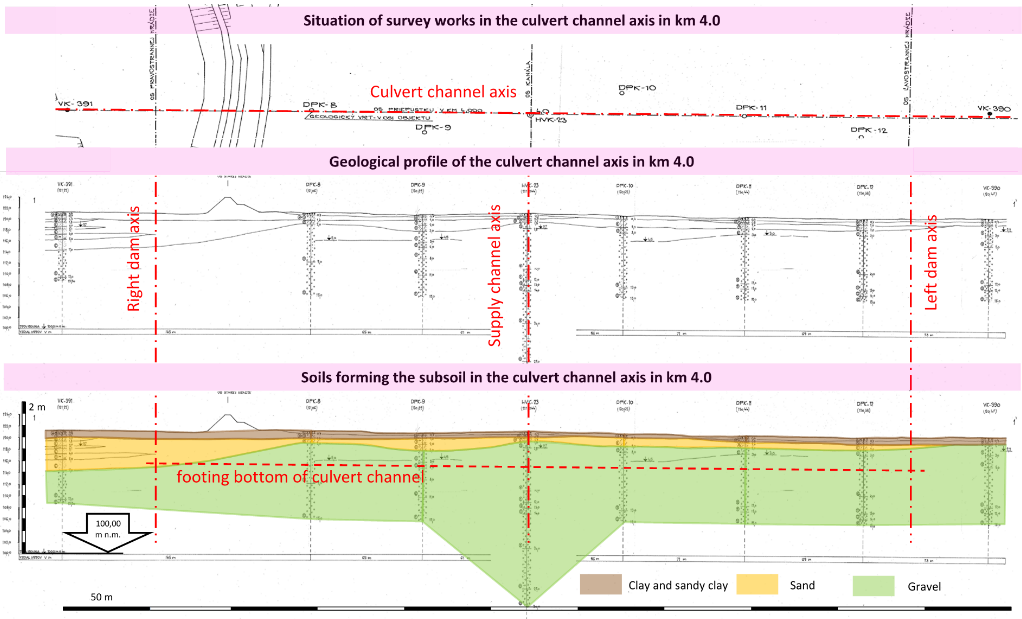

Figure 5. Engineering geological profile of subsoil [1]

- effective parameters of shear strength: $\varphi_{\text{ef}} = 38°$; $c_{\text{ef}} = 0.0\,\text{kPa}$;
- filtration coefficient: $k_f = 3.37 \times 10^{-3}\,\text{m.s}^{-1}$.

Location of the survey works with an indication of the axes of the right-side and the left-side dam of the seepage channels, as well as the axis of the supply channel and the culvert channel axis, are presented alongside the geological profile of the culvert channel axis and with an indication of the culvert channel's footing bottom position in Fig. 5.

At the time of the survey work [5], the groundwater level was encountered at 3.0 – 7.5 m underground. Subsoil in the area of interest is made of permeable quaternary gravelly sediments, which implies that before the culvert channel was constructed, the groundwater level was interconnected with the Danube. The culvert channel body was built is a sealed excavation pit. This fact can also affect the dependence of the groundwater level, and especially its fluctuations, on the Danube's water level.

4. Deformation analysis of the construction with current and new proposed operation of the culvert channel

Deformation analysis of the complex interaction problem of construction, along with both current and new proposed operation of the culvert channel was carried out based on assumptions of the theory of flexible half-space. Interaction calculations used the numerical finite element method (FEM). The task was solved as planar using the computational software GEO5 – FEM module.

In the computational models, soil characteristics of the culvert channel's subsoil were considered based on evaluation of geological conditions in the area of interest verified by all survey works [5]. Definition of deformation properties of the gravelly subsoil respected the discontinuous anisotropy, i.e. changed (increased) deformation modulus 5.0 m underground. The computations considered the original groundwater level 3.0 m below the original ground level. Characteristics of reinforced concrete culvert channel structures were considered based on results of the "Diagnostics of Concrete Structures" carried out within a separate part of this task. Characteristics of the subsoils and structural elements of the culvert channel used in the geotechnical calculations are listed in Tab. 1.

Deformation calculations were carried out in a cross profile under the supply channel, a cross profile under the crown of a safety dam (within the axis of the dam crown), and in a longitudinal profile under the dam and the supply channel for two stages. Stage No. 1 represented excavation of the pit for the culvert channel structure and Stage No. 2 represented construction and operation of the culvert channel. Considering the extensive amount of achieved computational outputs, this paper will only present the results of deformation calculations in the longitudinal profile under the supply channel for Stage No. 2 representing construction and operation of the culvert channel.

Loading states, representative for assessment of the reinforced concrete structure of the culvert channel and geotechnical calculations, were defined for the Stage No. 2, representing construction and operation of the culvert channel, as follows:

- **Loading state 0 (LS0):** represents the original state (effective stress in the subsoil after the excavation and construction of the sealed excavation pit) used as reference for comparison of the loading states that provide a model of stepwise construction

	Material description (structures and subsoil)	Depth from surface	Material properties						
			Poisson´s ratio	Unit weight			Deformation modulus	Angle of internal friction (effective)	Cohesion (efective)
				natural	submerget	saturated			
			ν	γ_n	γ_{su}	γ_{sat}	E	φ	c
		/ m /	/ - /	/ kN.m^{-3} /			/ MPa /	/ ° /	/ kPa/
Structures	Culvert channel - reinforced concrete (C 35/45)	-	0,15	25,0	-	-	34000	-	-
	Injected sealing bottom	-	0,20	23,5	-	-	7500	-	-
	Injected sealing wall	-	0,45	13,0	-	-	36	-	-
	Sealing bottom of supply channel	-	0,25	22,0	-	-	2000	-	-
Subsoil	Gravel poorly graded (GP) medium dense (subsoil)	0,0 - 5,0 m	0,25	21,0	11,5	21,5	50	38	0
		more than 5,0 m					100		

TABLE 1. Properties of subsoil and structural elements of the culvert [6]

of structural elements of the culvert channel and its current and new proposed operation.

- **Loading state 1 (LS1):** LS0 + realization of reinforced concrete culvert channel under the supply channel and the safety dam.
- **Loading state 2 (LS2):** LS1 + realization of backfills and rock cover over the culvert channel and in the safety dam area.
- **Loading state 3 (LS3):** LS2 + filling of all five culvert channels by water + water pressure from the water level in the supply channel at the minimum (operational) level altitude (128.2 m) + uplift of water from the water level in the left and right seepage channels at the operational level altitude (120.63 m).
- **Loading state 4 (LS4):** LS2 + filling of all five culvert channels by water + water pressure from the water level in the supply channel at the maximum (flood) level altitude (131.1 m) + uplift of water from the water level in the left and right seepage channels at the flood level altitude (123.32 m).
- **Loading state 5 (LS5):** LS2 + filling of three culvert channels by water + water pressure from the water level in the supply channel at the minimum (operational) level altitude (128.2 m) + uplift of water from the water level in the left and right seepage channels at the operational level altitude (120.63 m).
- **Loading state 6 (LS 6):** LS2 + filling of three culvert channels by water + water pressure from the water level in the supply channel at the maximum (flood) level altitude (131.1 m) + uplift of water from the water level in the left and right seepage channels at the flood level altitude (123.32 m).

The aforementioned overview of the loading states implies that the loading states 3 and 4 provide a model of parallel operation of the culvert channel with all its five channels filled at minimum (operational) water level and maximum (flood) water level. Loading states 5 and 6 provide a model of the new proposed operation of the culvert channel with three channels filled and the emptying of the other two channels (pumping off the water) of the culvert channel for road tunnel use at the minimum (operational) water level and at the maximum (flood) water level.

The results of the calculation modelling the construction and operation of the culvert channel in its longitudinal profile under the supply channel have implied the following:

- The effects of construction of the reinforced concrete culvert channel (LS1) resulted in maximum settlement of footing bottom $s_{\max} = 17.6$ mm.
- The effects of culvert channel construction and realization of backfills and rock cover of the culvert channel (LS2) (floor of the supply channel and body of the earth embankment) resulted in maximum settlement of footing bottom $s_{\max} = 50.1$ mm.
- The effects of culvert channel construction, realization of backfills and rock cover of the culvert channel and filling of 5 channels of the culvert channel by water at minimum water level in the supply channel (LS3) resulted in maximum settlement of footing bottom $s_{\max} = 47.9$ mm.
- The effects of culvert channel construction, realization of backfills and rock cover of the culvert channel and filling of 5 channels of the culvert channel by water at maximum water level in the supply channel (LS4) resulted in maximum settlement of footing bottom $s_{\max} = 46.1$ mm.
- The effects of culvert channel construction, realization of backfills and rock cover of the culvert channel and filling of 3 channels of the culvert channel by water at minimum water level in the supply

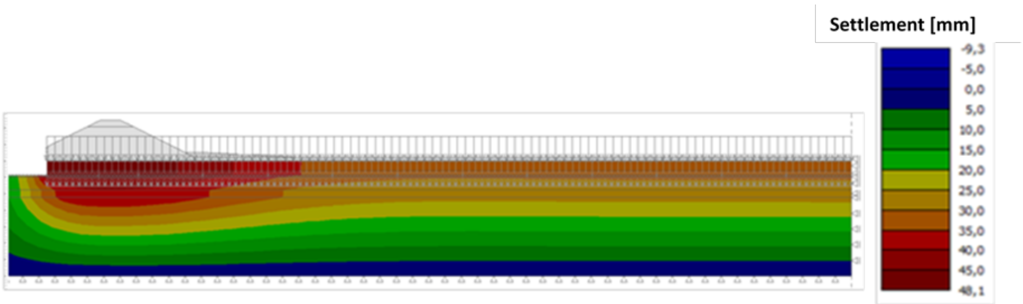

Figure 6. Isosurfaces of deformations for loading state LS3 – longitudinal profile of the culvert [6]

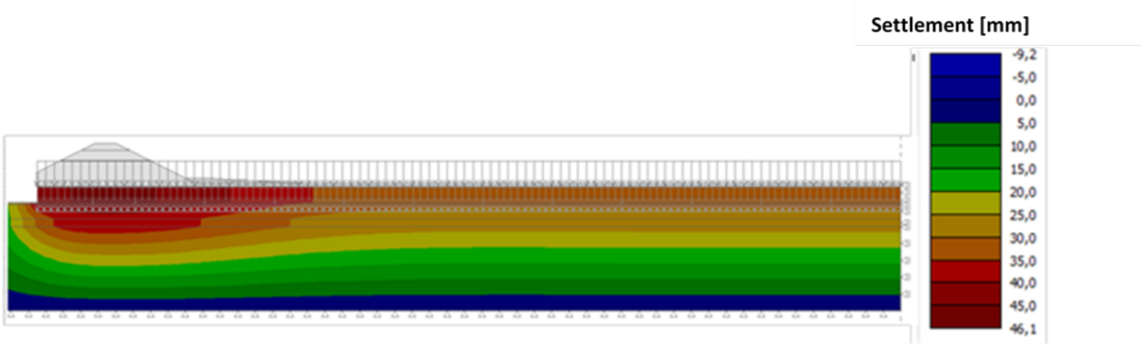

Figure 7. Isosurfaces of deformations for loading state LS4 – longitudinal profile of the culvert [6]

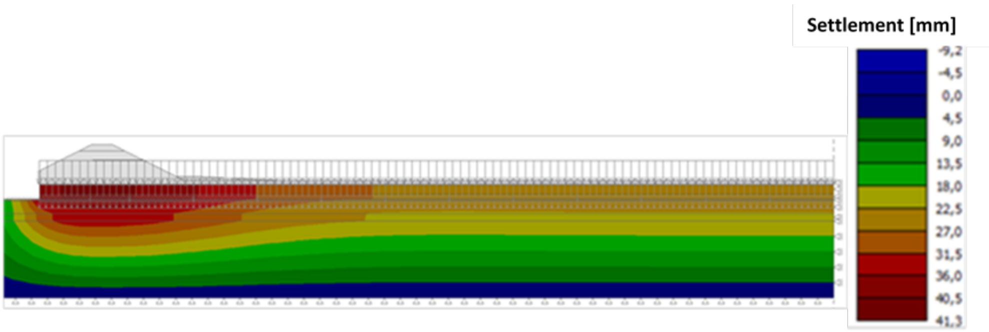

Figure 8. Isosurfaces of deformations for loading state LS5 – longitudinal profile of the culvert [6]

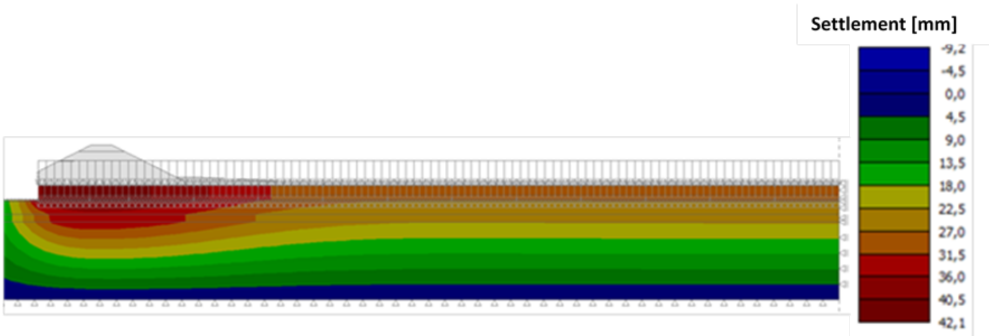

Figure 9. Isosurfaces of deformations for loading state LS6 - longitudinal profile of the culvert [6]

channel (LS5) resulted in maximum settlement of footing bottom $s_{\max} = 41.2$ mm. Relative change due to pumping off the water out of two channels of the culvert for the planned use (transportation) resulted in a maximum rise of the footing bottom $s_{\max} = -\ 6.9$ mm.

- The effects of culvert channel construction, realization of backfills and rock cover of the culvert channel and filling of 3 channels of the culvert channel by water at maximum water level in the supply channel (LS6) resulted in maximum settlement of footing bottom $s_{\max} = 42.0$ mm. Relative change due to pumping off the water out of two channels

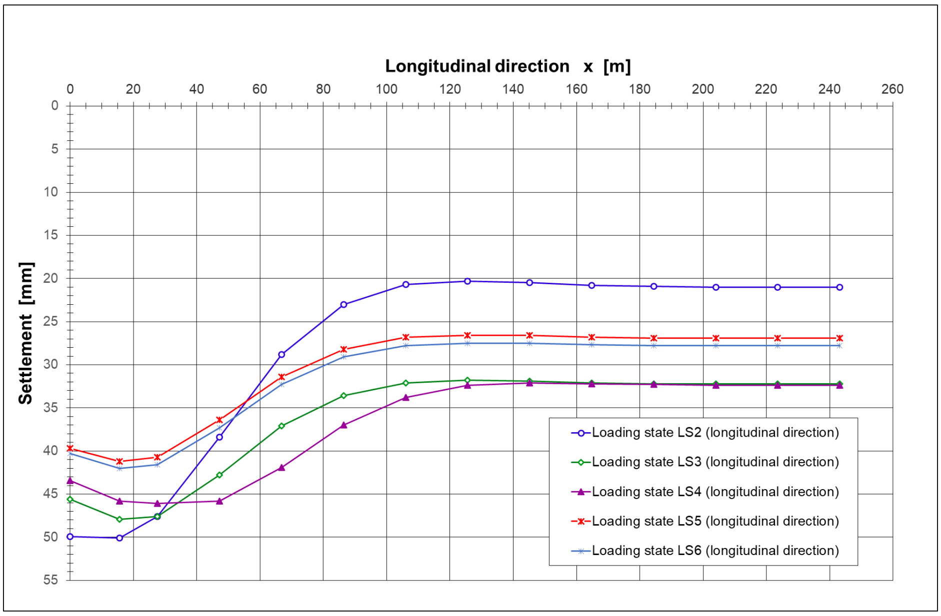

FIGURE 10. Deformations resulting for loading state LS2–LS6 – longitudinal profile of the culvert [6]

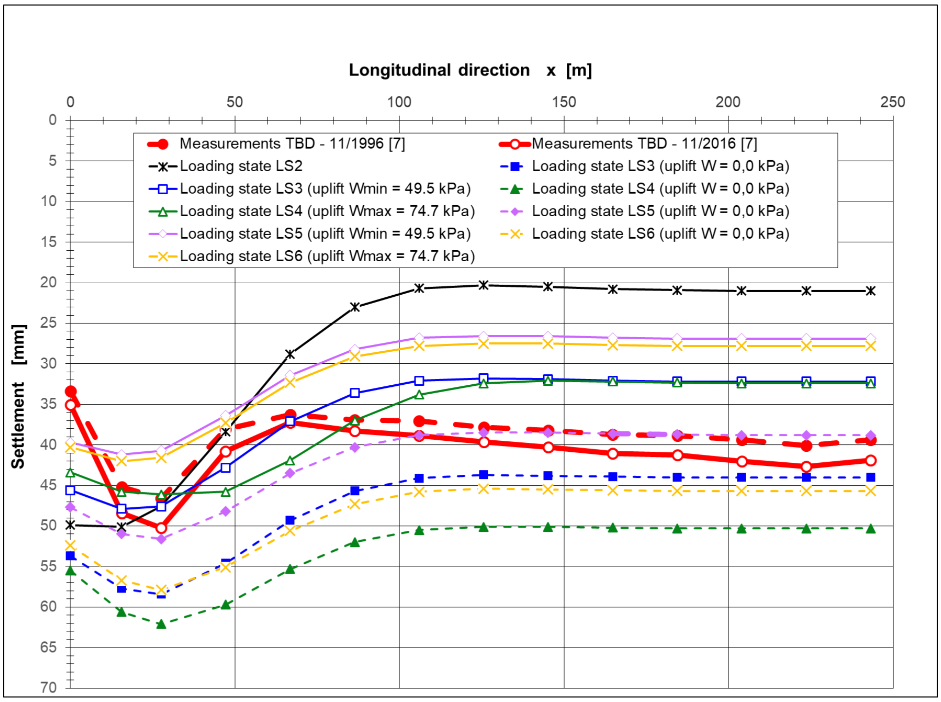

FIGURE 11. Comparison of measured and calculated deformations for loading state LS2 – LS6 – longitudinal profile of the culvert [6]

of the culvert for the planned use (transportation) resulted in maximum rise of the footing bottom $s_{\max} = -\ 9.6$ mm.

The resulting deformation values from the numerical calculations for Stage No. 2 are presented as deformation isoplanes for the loading state 3 in Fig. 6, loading state 4 in Fig. 7, loading state 5 in Fig. 8 and loading state 6 in Fig. 9. For comparison of deformation magnitudes in the respective loading states, deformation values are graphically evaluated for representative points of the culvert channel's footing bottom in the longitudinal profile in Fig. 10. Besides the resulting deformations for the loading states 3 to 6, Fig. 10 also presents deformations resulting from the loading state 2, which represents construction of the culvert channel before putting the supply channel and the actual culvert channel into operation, that is without water in the culvert channel and in the supply channel. Results of deformation calculations are presented in Fig. 6 to Fig. 10 for a half length of the culvert channel in longitudinal direction because the computational model also made use of the symmetry in the critical section of the culvert channel.

5. Comparison of measured and calculated deformations

During technical safety supervision, the structure of the culvert channel was subject to measurements of deformation in 11/1996 and in 11/2006 [7]. These measurements were used as a reference for comparison of the calculated deformation values for respective loading states. Comparison of measured and calculated deformations in the longitudinal direction of the culvert channel for half of the longitudinal profile is shown in Fig. 11.

6. Conclusions

The results of measured deformation values presented in Fig. 11 provide general information on the magnitude and distribution of subsoil deformations under the culvert channel in the longitudinal direction triggered by operation of the culvert channel as a water management structure. The results of calculated deformation values presented in Fig. 11 provide general information on the magnitude of deformation triggered by change in the culvert channel operation – part of the water management structure to be transformed into a transportation structure. Additionally, Fig. 11 also indicates the considered uplift effect of water on the floor of the culvert channel. Measured deformation values are within the range of calculated deformations considering the uplift effect of water on the culvert channel's floor depending on the maximum or operational water level in the supply channel and deformations not considering the uplift effect of water on the culvert channel's floor. Comparison of the results of geotechnical calculations (LS1 to LS4) and in situ measurements of vertical deformations of the assessed structures implies that the measured and calculated values are in significant agreement. Based on observable experience, it can be assumed that the forecast values of vertical displacement for the considered change in culvert channel use (LS5 and LS6) will be in good alignment with reality after the proposed changes have been implemented.

Evaluation of maximum values of the final settling as well as values of irregular settling for the assessed loading states of the culvert channel (LS1 to LS6) indicate the possible transformation of the culvert channel structure under the supply channel of the Gabčíkovo Waterworks into a road tunnel structure while still meeting the conditions for a reliable and desired state pursuant to the European (EUROCODES) and Slovak (STN) standards in force.

In solving the relatively complex engineering problem of the interaction of a building structure with the subsoil, the numerical finite element method was used the suitability of which has already been verified in solving similar interaction problems [8], [9], [10].

Acknowledgements

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