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Lessons learned from the monitoring of retaining structures, built in demanding geotechnical conditions in Slovenia

Leçons tirées de la surveillance des structures de soutènement, construites dans des conditions géotechniques exigeantes en Slovénie

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ABSTRACT: A typical retaining structure built with large-diameter bored piles in soft clastic rock, and supported by pre-stressed permanent ground anchors, is discussed. Step-by-step back analyses were performed. A simplified geological structure was first used in the analyses, together with a simple Mohr-Coulomb model. The results were compared with more complex analyses using a Hardening Soil model and a more detailed geological structure. Much better results were obtained with the use of the HS model, which is more suitable for the modelling of rock of such a type, but even with the use of the MC model the final results were quite good, making the use of the observational method attractive for engineers.

RÉSUMÉ: Une structure de soutènement typique construite avec des pieux forés de grand diamètre dans une roche clastique douce et soutenue par des ancrages au sol permanents, précontraints est discutée. Des analyses ont été pas à pas effectuées. Une structure géologique simplifiée a d'abord été utilisée dans les analyses, avec un modèle simple de Mohr-Coulomb. Les résultats ont été comparés à des analyses plus complexes utilisant un modèle de durcissement du sol et une structure géologique plus détaillée. Il était évident que nous avions obtenu de bien meilleurs résultats avec l'utilisation du modèle HS, qui convenait mieux à la modélisation de ce type de roche, mais même avec l'utilisation du modèle MC, les résultats finaux étaient assez bons, ce qui rend l'utilisation de la méthode d'observation attrayant pour les ingénieurs.

Keywords: retaining structures; pile walls; ground anchors; monitoring; FEM analysis

1 INTRODUCTION

In geotechnical design, we are always faced by uncertainty when defining input data. When this fact is combined with structures of high risk, then conventional design methods often lead to an uneconomical structure. A powerful method that can reduce both the risk and the cost of construction of such a structure is the observational method (Terzaghi and Peck, 1967).

A large number of high retaining structures, with several sets of ground anchors, have been built in Slovenia over the last two decades, especially during the construction of the motorway network. Although they were constantly monitored during and after construction, the construction process did not completely follow the principles of the observational method. Nevertheless it was possible, based on the available data, to perform back analyses of the behaviour of these structures, and to simulate the observational method (Žvanut, 2002; Žvanut et al., 2003).

In recent years a database has been created for the systematic management of such structures on the motorway network, and also because of the need for central and uniform data management (Ravnikar Turk et al., 2017). Such a database forms a part of the road data bank, into which data on the monitoring and analysing of the behaviour of structures have been entered. The database provides a systematic insight into the behaviour of individual geotechnical structures. Furthermore, the results can be helpful in the future design and construction of such structures in comparable geotechnical conditions, as well as for their maintenance.

In this paper a typical retaining structure built with large-diameter bored piles, and supported by pre-stressed permanent ground anchors is discussed.

2 GEOTECHNICAL CONDITIONS

The construction of the present motorway network in Slovenia was carried out, in some sections, in very demanding geotechnical conditions.

The selected retaining structure is located in a hilly area on the Celje - Ljubljana motorway section (Figure 1), where the soft Permo-Carboniferous clastic rock is found.

The ground was modelled by using three characteristic types of strata: clayey gravel, weathered shale, and compact schist**.** The initial values of the geotechnical parameters, which were found in the geotechnical investigation report, are shown in Table 1.

Figure 1. Location of the selected retaining structure

Table 1. Initial values of the geotechnical parameters

Ground type	c (kPa)	φ (°)	E (MPa)
Clayey gravel	0	17	15
Weathered shale	30	15	50
Compact schist	100	25	100

3 THE RETAINING STRUCTURE

The discussed anchored pile wall was built of contiguous bored piles of diameter 1.0 m, spaced at 3.0 m centres (Figure 2). A layer of shotcrete, reinforced by wire mesh, was cast between the piles, which were capped by a concrete beam. The pile wall was supported by three to six rows of pre-stressed permanent ground anchors, having a declination of 30°, and spaced at 1.5 to 6.0 m centres. The anchors, which were founded in compact schist, had a free length of 14.0 m and a bonded length of 10.0 m. Each anchor consisted of five strands, and had a cross-sectional area of 6.95 cm^2, with a steel quality of f_{py}/f_{pu} = 1570/1770 MPa. The design pre-stressing force in each anchor was 600 kN. Horizontal reinforced concrete beams were used to transfer the anchor forces onto the piles.

The calculated values of the normal stiffness (EA) and flexural rigidity (EI) of the pile wall and its anchors are presented in Table 2.

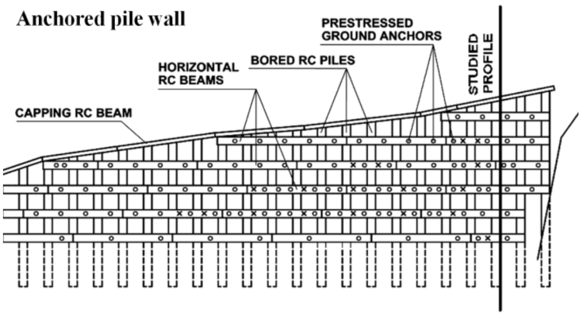

Figure 2. View of the retaining structure

Table 2. Elastic properties of the anchored pile wall

Pile wall		**Anchors**
EA (kN/m)	**EI (kNm^2/m)**	**EA (kN)**
2.62 E6	1.64 E5	1.38 E5

4 MONITORING

The retaining structure was monitored during and after construction. The monitoring system included the following measurements: vertical and horizontal displacements, anchor forces, and visual inspections. The most reliable parameters obtained from the field monitoring were the horizontal displacements measured by vertical inclinometers, and the anchor forces, which were obtained from the anchor load cells.

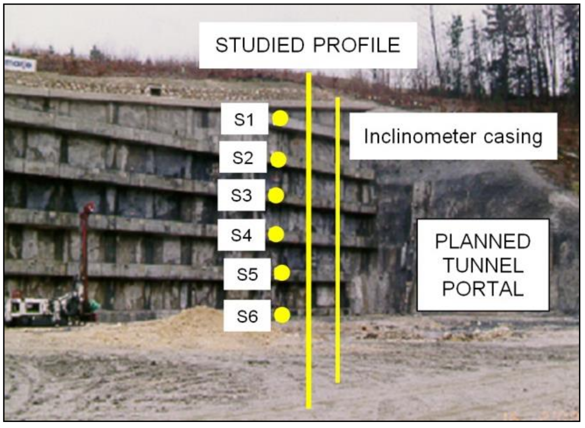

Figure 3. Monitoring system at the studied profile

At the studied profile (Figure 3), which was close to the location of a planned tunnel portal, where the pile wall had a height of 23.5 m and a depth of embedment of 5.5 m, six anchor load cells (S1 to S6) were installed as well as one inclinometer casing, which was attached to the full-length of the reinforcement cage.

5 FEM ANALYSES

Analyses of the retaining structure were carried out using a finite element method (FEM) based computer program Plaxis (Brinkgreve et al, 2002). All stages of the construction process were taken into account (installation of the piles, partial excavation, installation and pre-stressing of the anchors, and so on). The Mohr-Coulomb (MC) model and a simplified geological structure were initially considered in the performed plane-strain analyses.

The geometry of the analysed retaining structure and the finite element mesh, at the studied profile, are shown in Figure 4.

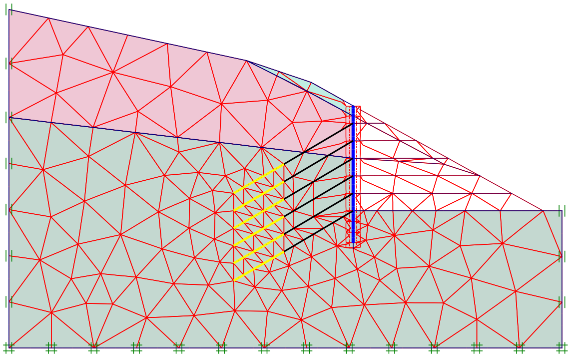

Figure 4. Geometrical model at the studied profile

The next section presents the results of the performed FEM analyses of the pile wall at the studied profile, which were compared with the results obtained using a Hardening Soil (HS) model and a more detailed geological structure.

6 RESULTS

6.1 *Back-calculated ground properties*

Step-by-step back analyses were performed, and it was observed that a sufficiently accurate numerical model, i.e. the simple Mohr-Coulomb model using back-calculated values of the ground properties (see Table 3), could be obtained already during early stages of the construction process. For this reason the critical stages at the end of the construction works could be verified with confidence well in advance.

Table 3. Back-calculated values

Ground type	c (kPa)	φ (°)	E (MPa)
Clayey gravel	5	24	15
Weathered shale	15	23	55
Compact schist	40	30	100

6.2 *Horizontal displacements*

The measured and back-calculated (MC, HS) horizontal displacements at the top of the studied profile of the investigated retaining structure, at individual stages of the construction, are presented in Figure 5.

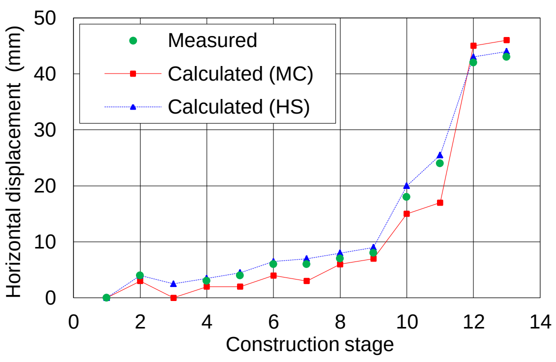

Figure 5. Measured and calculated displacements

It is clear that the back-calculated displacements obtained by using the HS model fit the corresponding measured values very well, whereas the back-calculated displacements obtained by using the MC model deviated slightly from the measured values (the difference is greatest at the construction stage 11, where it amounts to 7 mm).

6.3 *Anchor forces*

The measured and back-calculated (MC, HS) anchor forces at the six measuring anchors (S1 to S6) of the studied profile of the investigated retaining structure, at individual stages of construction, are presented in Table 4.

Table 4. Measured and calculated anchor forces (kN)

			Measured			
Stage	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
3	595					
5	573	596				
7	593	642	588			
9	611	691	670	352		
11	616	706	701	397	644	
13	647	750	783	502	756	621
			Calculated (MC)			
3	600					
5	604	600				
7	615	617	600			
9	620	633	629	550		
11	627	646	652	598	600	
13	678	688	713	724	692	600
			Calculated (HS)			
3	600					
5	606	600				
7	613	661	600			
9	618	722	686	550		
11	625	737	727	586	600	
13	669	785	814	682	727	600

It can be seen that the measured values increased considerably (at measuring anchors S2 to S4 by more than 150 kN). It is clear that the back-calculated anchor forces using the HS model are in very good agreement with the corresponding measured values, despite the fact that they are slightly larger than the latter. As opposed to the HS model, the back-calculated anchor forces using the MC model were lower compared to the measured ones. This difference can be partly attributed to the fact that the prestressing force in anchor S4 was 350 kN instead of 600 kN, but mostly to the fact that the MC model is not the most suitable for the accurate modelling of the behaviour of such an anchored pile wall.

7 CONCLUSIONS

In this paper the behaviour of a typical retaining structure built with large-diameter bored piles in soft Permo-Carboniferous clastic rock, and supported by pre-stressed permanent ground anchors, is discussed. Step-by-step back analyses were performed. It was clear that better results were obtained when using the HS model, which was more suitable for the modelling of soft Permo-Carboniferous clastic rock, but even when the MC model was used, the final results were fairly similar to those using the more sophisticated model, which makes the use of the observational method more attractive for engineers.

8 REFERENCES

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