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Back analyses of anchored bored-pile walls

Rétro analyse des parois en pieux avec tirants d'ancrage

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ABSTRACT
Four anchored bored-pile walls have been studied. Step-by-step back analyses were performed and it was observed that a sufficiently accurate numerical model could be obtained in the early stages of the construction sequence. It was shown that even with the use of a simplified model the final results are very good, which makes the use of back analyses and the observational method even more attractive for practising engineers. Finite element method (FEM) prediction of the behaviour of another similar retaining wall in similar ground conditions, using suitable material parameters from previous back analyses, was in good agreement with observed behaviour.

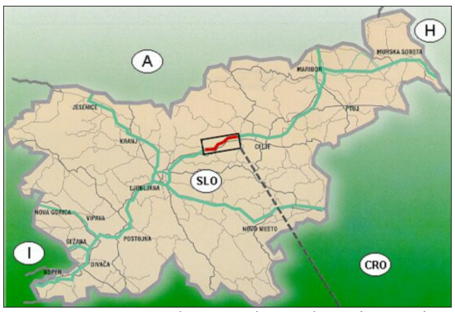
RÉSUMÉ
Cet article présente les résultats de l'étude de quatre parois en pieux avec tirants d'ancrage. Des rétro analyses successives ont été exécutées qui ont démontré qu'un modèle suffisamment précis peut être obtenu déjà dans les phases initiales de la construction. Il est aussi démontré que même un modèle simplifié donne des résultats excellents, ce qui fait la rétro analyse et la méthode d'observation un outil pratique extrêmement utile. A l'aide de la méthode d'éléments finis a été effectuée une prédiction du comportement de l'ouvrage additionnel de soutènement en conditions de sol semblables, en utilisant les paramètres matériaux obtenus par des rétro analyses précédentes. Les données obtenues par la méthode d'éléments finis sont en accord avec celles obtenues par les observations sur place.

1 INTRODUCTION

Efficient design in geotechnical engineering is not easy. Almost every geotechnical project has to make some assumptions and take risks, with unexpected occurrences. These circumstances are the unavoidable result of having to deal with natural materials such as soil and rock. Field monitoring of the performance of retaining structures is therefore necessary in order to confirm the validity of the design assumptions. Field data can be collected into a case record, which is then available for improving the numerical model, i.e. the fitting of parameters in order to obtain a representative numerical model.

A large number of demanding bored-pile walls with several sets of geotechnical anchors have been recently constructed in Slovenia. The design and construction did not follow completely the principles of the observational method, but all the gathered data enabled back analyses of structural behaviour and simulation of the observational method.

The new Celje – Ljubljana motorway passes through a hilly area between Vransko and Blagovica (Fig. 1), where there were many deep cuttings, which had to be supported by anchored, large-diameter bored-pile walls.



The Vransko – Blagovica section

Figure 1. The planned motorway network in Slovenia

The behaviour of four such walls, one of which is referred to as the »Back-analysed« retaining wall, as well as that of another similar retaining wall in similar ground conditions, referred to as the »Predicted« bored-pile wall, is the subject of the investigation described in this paper.

2 GEOTECHNICAL CONDITIONS

The permo-carboniferous clastic rocks occurring in the area of the analysed retaining structures were originally classified into three characteristic strata. The values of the ground parameters given in the geotechnical investigation reports for the »Back-analysed« bored-pile wall are shown in Table 1.

Table 1. Original ground properties for the »Back-analysed« pile wall

Ground type	γ (kN/m³)	ν (-)	E (MPa)	c (kPa)	φ (°)
Clayey gravel	21	0.33	15	0	17
Weathered slate	24	0.33	50	30	15
Compact slate	24	0.33	100	100	25

3 THE BORED-PILE WALLS

The »Back-analysed« bored-pile wall was built of bored piles of diameter 1.0 m, spaced at 3 m centres. A layer of shotcrete, reinforced by a wire mesh, was cast between the piles. The piles were capped by a concrete beam. The pile wall was supported by three to six rows of ground anchors having a declination of 30°, and spaced at 1.5 to 6 m centres. The prestressed anchors, founded in compact slate, had a free length of 14 m and a bonded length of 10 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 prestressing force in each anchor was 600 kN. Horizontal reinforced-concrete beams were used to transfer the anchor forces onto the piles (Fig. 2).

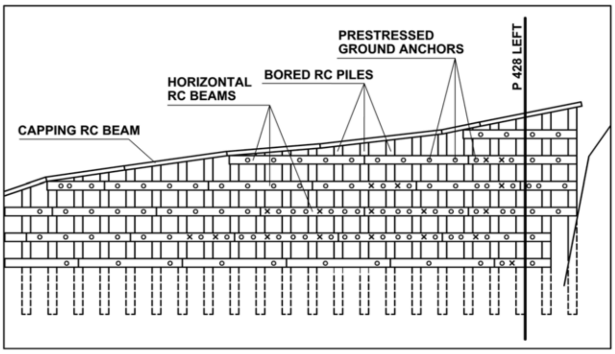


Figure 2. Front view of the »Back-analysed« pile wall

The height of the »Back-analysed« pile wall at the investigated cross-section (profile P428-left) was 23.5 m, and the depth of embedment was 5.5 m. At the selected profile six anchor levels were applied, with an out-of-plane distance of Ls = 3 m. The material properties of the pile wall and of the anchors are presented in Table 2.

Table 2. Properties of the pile walls and their anchors

Pile walls			Anchors	
EA (kN/m)	EI (kNm^2/m)	ν (-)	EA (kN)	Ls (m)
2.618 E6	1.636 E5	0.16	1.376 E5	3.0

The »Predicted« pile wall (Fig. 3) was made of bored piles of diameter 1.0 m, spaced at 3 m centre to centre. The pile wall was supported by two to four rows of ground anchors having declinations of 30° and 35°, and spaced at 3 to 6 m centres. The prestressed anchors, which were anchored in compact slate, had free lengths of 14 m and fixed lengths of 10 m. The anchors consisted of 4 to 5 strands. The prestressing force in each anchor was 350 and 600 kN, respectively.

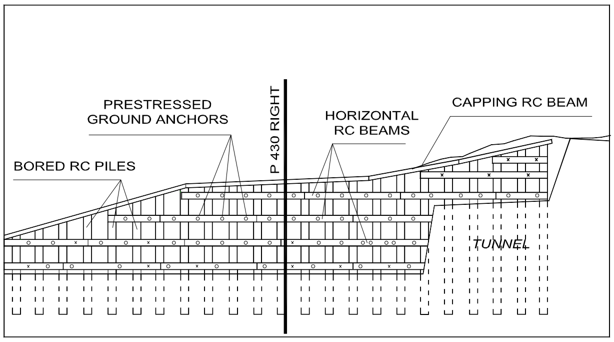


Figure 3. Front view of the »Predicted« pile wall

The height of the »Predicted« pile wall at the investigated cross-section (profile P430-right) was 16.75 m, and the depth of embedment was 5.75 m. At the selected profile four anchor levels were applied. Characteristic values of the pile wall, as well as the parameters corresponding to the anchors, are presented in Table 2.

The construction process of the »Back-analysed« and »Predicted« pile walls involved the following stages:

1. Installation of the bored piles
2. Excavation to the 1st level of the anchors
3. Installation and prestressing of the anchors

4.-9. Repeat steps 2 and 3 for the 2nd to 4th level of the anchors (»Predicted«)

4.-13. Repeat steps 2 and 3 for the 2nd to 6th level of the anchors (»Back-analysed«)

4 MONITORING

The most important and 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. The inclinometer casings were installed at various locations along the walls, through void formers in the piles, and attached to the full-length reinforcement cage. A monitoring system was constantly in operation during and after the construction of the bored-pile walls.

The lengths of the casings in the »Back-analysed« pile wall were between 13.5 and 23.5 m. Six anchor load cells were installed at all anchor levels of the back-calculated cross-section (Fig. 4).

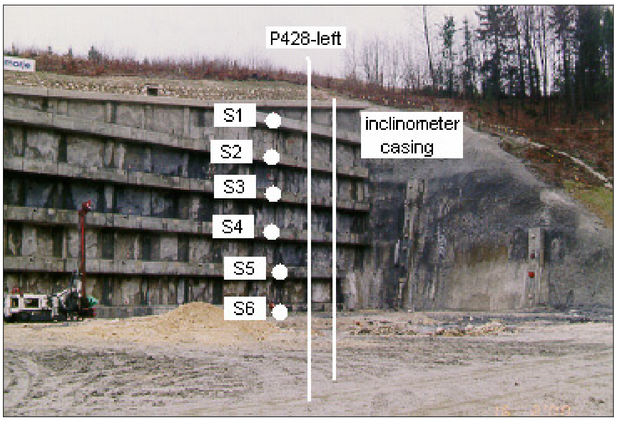


Figure 4. The established monitoring system at the investigated cross-section of the »Back-analysed« pile wall

The lengths of the casings in the »Predicted« pile wall were between 6.0 and 19.5 m. The anchor load cells were installed at three of four anchor levels of the studied cross-section (Fig. 5).

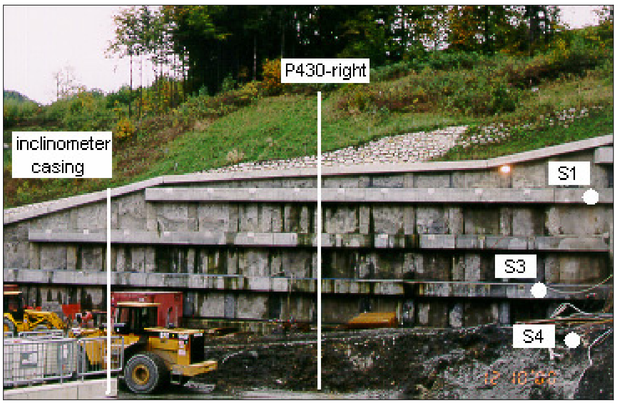


Figure 5. The established monitoring system at the investigated cross-section of the »Predicted« pile wall

Because there were no structures on the slopes behind the pile walls, vertical displacements of the ground behind the retaining walls were not measured, and a simple numerical model was used.

5 FINITE ELEMENT ANALYSES

The finite element analyses which were performed for the instrumented cross-sections were carried out using the well-known computer program Plaxis. The calculations were performed assuming plane-strain conditions, with 15-node elements. A simplified geological structure was used in the numerical model. Non-linear soil and rock behaviour was modelled by taking into account the simple Mohr-Coulomb (MC) constitutive relationship. The construction process previously described was simulated in the back-analyses of the profile P428-left and in the predictions of the profile P430-right.

Figures 6 and 7 show the geometrical data and the generated mesh of finite elements.

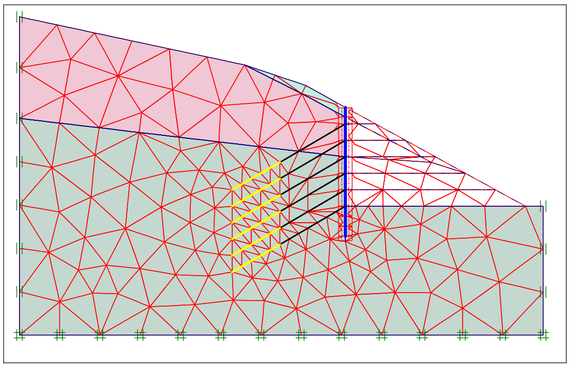


Figure 6. Profile P428-left of the »Back-analysed« pile wall

The results for »Back-analysed« pile wall were compared with those obtained using more sophisticated back analyses performed by Vukadin (2001), taking into account the Hardening Soil (HS) model and a more detailed geological structure.

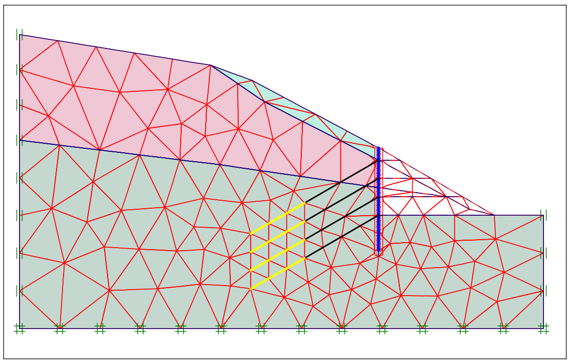


Figure 7. Profile P430-right of the »Predicted« pile wall

6 RESULTS

6.1 *Step-by-Step Back Analyses*

It was observed that a sufficiently accurate numerical model, i.e. a simple MC model, together with a simplified geological structure and back-calculated ground properties, could be obtained during the first half of the construction sequence. The final back-calculated ground properties of the three characteristic strata, in the area of the »Back-analysed« anchored bored-pile wall, are presented in Table 3 (compare with the original data from Table 1).

Table 3. Back-calculated ground properties

Ground type	γ (kN/m^3)	ν (-)	E (MPa)	c (kPa)	φ (°)
Clayey gravel	21	0.33	15	5	24
Weathered slate	24	0.33	55	15	23
Compact slate	24	0.33	100	40	30

The parameters obtained by performing back analyses of the four bored-pile walls were used to predict the behaviour of another similar retaining structure, on the same motorway section, in similar ground conditions. Due to the high degree of tectonisation and weathering and due to differences in the lithology of the permo-carboniferous clastic rock, a classification of the soft rock formations was needed. For this purpose, a set of material parameters was determined by the above mentioned back analyses (Tab. 4).

Table 4. General classification of the materials

Ground type	γ (kN/m^3)	ν (-)	E (MPa)	c (kPa)	φ (°)
Clayey gravel	21	0.33	11-15	5	24
Weathered slate	24	0.33	45-55	15-20	23
Compact slate	24	0.33	65-120	28-40	26-32

6.2 *Horizontal Displacements*

Figure 8 shows the measured and back-calculated horizontal displacements of the top of the »Back-analysed« pile wall at the investigated cross-section, taking into account the actual construction sequence. It can be seen that the measured results and the corresponding back-calculated values (MC, HS) are in good agreement.

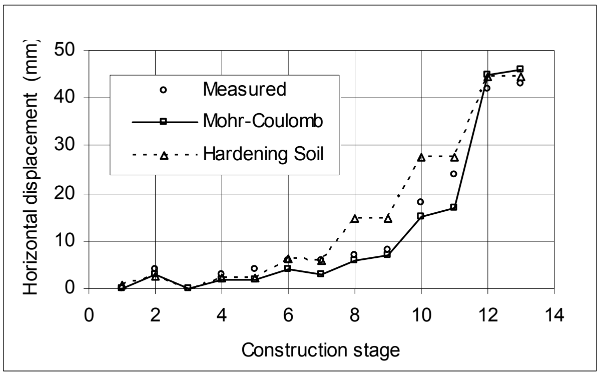


Figure 8. Horizontal displacements at the top of the »Back-analysed« pile wall, at profile P428-left

Figure 9 shows the predicted and measured horizontal displacements of the top of the »Predicted« pile wall. The predicted results (MC) are in very good agreement with the corresponding measured values.

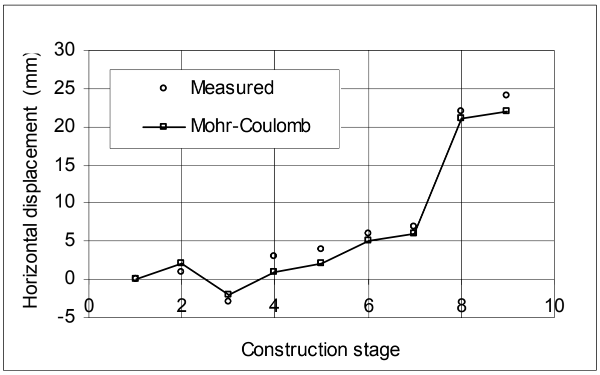


Figure 9. Horizontal displacements at the top of the »Predicted« pile wall, at profile P430-right

Figure 10 shows the horizontal displacements of the »Predicted« pile wall at the last stage of the construction sequence. The deformation curves corresponding to the predicted and actually obtained values are in good agreement. There is a small difference at the upper five metres of the pile wall – the measured displacements are a little larger than the predicted ones – and at the lower part, where the opposite situation occurs.

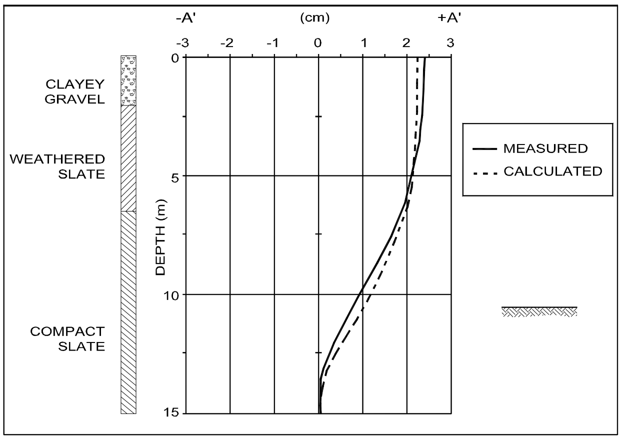


Figure 10. Horizontal displacements of the »Predicted« pile wall at the last stage of the construction sequence

6.3 *Anchor Forces*

The measured anchor forces and the corresponding back-calculated values (MC, HS) at the six anchor levels (S1 to S6) at the investigated cross-section P428-left of the »Back-analysed« pile wall during the construction process are shown, for all stages of the loading, in Table 5.

Table 5. Measured and back-calculated anchor forces (in kN)

Stage	Measured					
	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
	Back-calculated (MC)					
3	600					
5	604	600				
7	615	617	600			
9	620	633	629	600		
11	627	646	652	639	600	
13	678	688	713	724	692	600
	Back-calculated (HS)					
3	600					
5	624	600				
7	660	633	600			
9	720	699	654	600		
11	762	696	696	664	600	
13	822	741	759	764	708	600

* The prestressing force was 350 kN instead of 600 kN

It was found that the measured values were somewhat higher than the calculated ones obtained using the MC model, and very close to those calculated using the HS model. In both cases the exception is the uppermost anchor. The difference between the measured and back-calculated anchor forces can be partly attributed to the fact that the anchor at the fourth level was prestressed to a lower force and partly to the fact that the MC model is not the most appropriate for the accurate modelling of the displacements which directly govern the anchor forces. The measurements show a significant increase in the anchor forces (at three of the anchor load cells, by more than 150 kN).

The predicted anchor forces and the corresponding measured values (MC) at the four anchor levels (S1 to S4) at the investigated cross-section P430-right of the »Predicted« pile wall during the construction process are shown, for all stages of the loading, in Table 6.

Table 6. Measured and predicted anchor forces (in kN)

Stage	Predicted				Measured			
	S1	S2	S3	S4	S1	S2	S3	S4
3	600				600			
5	610	600			624	/		
7	629	625	600		635	/	609	
9	654	663	667	600	700	/	668	612

The 2nd anchor level did not have a measuring anchor.

It was found that the measured values are in good agreement with those obtained by using the MC model.

7 CONCLUSIONS

Four large-diameter bored-pile walls, constructed in soft permo-carboniferous clastic rock and supported by prestressed permanent geotechnical anchors, were studied. Step-by-step back analyses were performed and it was observed that a sufficiently accurate numerical model could be obtained in the early stages of the construction sequence, so that it was possible to predict with confidence in advance the critical stages which were actually encountered at the end of the construction works.

A simple MC constitutive relationship, which needs only four easily-accessible ground parameters, making it easy to calibrate the numerical model, together with a simplified geological structure, was first used in the back analyses. Secondly a more elaborate HS model was used in the back analyses to obtain reliable material parameters for the model. It was shown that the results obtained by using both models were very similar, which makes even the use of the simple MC model and the observational method very attractive for practicing engineers.

The parameters obtained by performing these back analyses were used to predict the behaviour of another similar retaining structure in similar ground conditions. Due to the high degree of tectonisation and weathering, as well as differences in the lithology of the permo-carboniferous clastic rock, a classification of soft rock formations was needed. For this purpose, a set of material parameters was determined by performing back analyses. FEM prediction of the behaviour of the additional retaining structure using suitable material parameters from the back analyses, according to the proposed classification scheme, was in good agreement with observed behaviour.

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