Back Analyses of Anchored Retaining Structures

Pavel Žvanut
ZAG Ljubljana, Ljubljana, Slovenia

Janko Logar
University of Ljubljana, Ljubljana, Slovenia

Bojan Majes
University of Ljubljana, Ljubljana, Slovenia

BACK ANALYSES OF ANCHORED RETAINING STRUCTURES

Pavel Žvanut
ZAG Ljubljana
Ljubljana, Slovenia

Janko Logar
University of Ljubljana
Ljubljana, Slovenia

Bojan Majes
University of Ljubljana
Ljubljana, Slovenia

ABSTRACT

Finite element step-by-step back analyses were performed on four typical instrumented test sections of several anchored, bored-pile walls, located on the Vransko - Blagovica section of the Celje - Ljubljana motorway. A sufficiently accurate numerical model was 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 encountered at the end of the construction works. The back analyses were carried out using the computer program Plaxis, assuming the simple Mohr-Coulomb constitutive relationship and a simplified geological structure. The results of these analyses were compared with those obtained using the more sophisticated back analyses performed by Vukadin [2001], which took into account the Hardening Soil model and a more detailed geological structure. It was found that, even though the more sophisticated model provided slightly more accurate results, the results obtained by using the simplified model were very similar, which makes the use of such a model and the observational method very attractive for practicing engineers.

INTRODUCTION

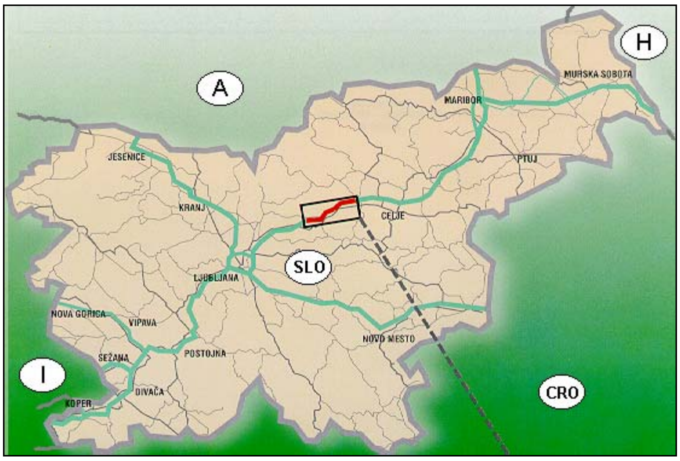
Field monitoring of the performance of retaining structures is necessary in order to confirm the validity of design assumptions. Field data can be collected as a case record, which is then available for improving the numerical model, i.e. the fitting of parameters in order to obtain a representative numerical model. Numerical analysis can help to improve our understanding of the behaviour of deep excavations, and provide guidance for future designs.

A large number of anchored bored-pile walls have been built in Slovenia following the start of the National Motorway Construction Programme. Design and construction did not completely follow the principles of the observational method, but it was nevertheless possible to perform back analyses of the behaviour of structures, and simulation of the observational method.

Four similar retaining structures made using large diameter bored-piles supported by prestressed permanent geotechnical anchors were studied. Two of these structures, the »Trojane East« and »Trojane West« retaining walls, are discussed in detail in this paper. For the other two structures only the final results of the calibration of the numerical model are presented.

PROJECT DESCRIPTION

The retaining structures dealt with in this paper are located on the new Celje - Ljubljana motorway, which is still under construction and passes through a hilly area between Vransko and Blagovica (see Fig. 1).



The Vransko - Blagovica section

Fig. 1. The planned motorway network in the Republic of Slovenia

GEOTECHNICAL CONDITIONS

The complex permo-carboniferous clastic rock stratification in the area of the analysed retaining structures was modelled by means of three characteristic strata: clayey gravel, weathered slate and compact slate. The values of the ground parameters given in the geotechnical investigation reports for the »Trojane East« bored-pile wall are shown in Table 1.

Table 1. Ground properties given in the geotechnical investigation reports for the »Trojane East« pile wall

Ground type	γ (kN/m^3)	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

In the area of the »Trojane West« bored-pile wall a fossil landslide was recorded. At this location the ground properties of the clayey gravel and compact slate were similar to those of the »Trojane East« pile wall (see Table 1), whereas the stratum of weathered slate had lower values of the deformation and strength parameters (E = 10 MPa, c = 0.5 kPa, φ = 24°).

THE BORED-PILE WALLS

Description of the Structures

The »Trojane East« bored-pile wall was built of bored piles of diameter 100 cm, 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 1.39 cm^2 (Σ = 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 (see Fig. 2).

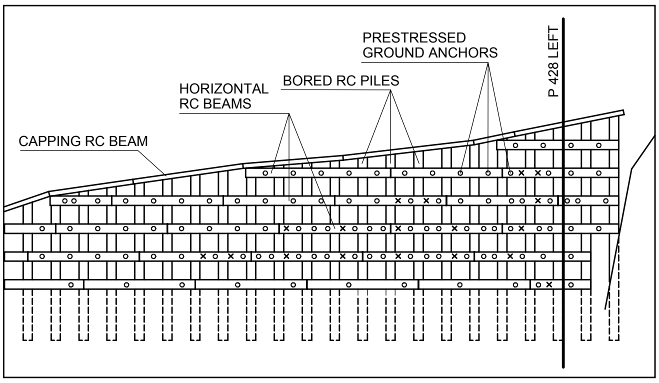


Fig. 2. Front view of the »Trojane East« pile wall

The height of the »Trojane East« 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 »Trojane East« pile wall and anchors

Pile wall			Anchors	
EA (kN/m)	EI (kNm^2/m)	ν (-)	EA (kN)	L_s (m)
2.62 E6	1.64 E5	0.16	1.38 E5	3.0

The »Trojane West« pile wall (see Fig. 3) was made of bored piles of diameter 100 cm, spaced at 1.5 m centre to centre. The pile wall was supported by 2 to 3 rows of ground anchors having declinations of 5° and 30°, and spaced at 1.5 to 3 m centres. The prestressed anchors, which were anchored in the weathered and compact slate, had free lengths of 14 m and 19 m, and fixed lengths of 10 m. The anchors consisted of 4 strands, each having a cross-sectional area of 1.39 cm^2 (Σ = 5.56 cm^2), with a steel quality of f_{py}/f_{pu} = 1570/1770 MPa. The prestressing force in each anchor was 350 kN.

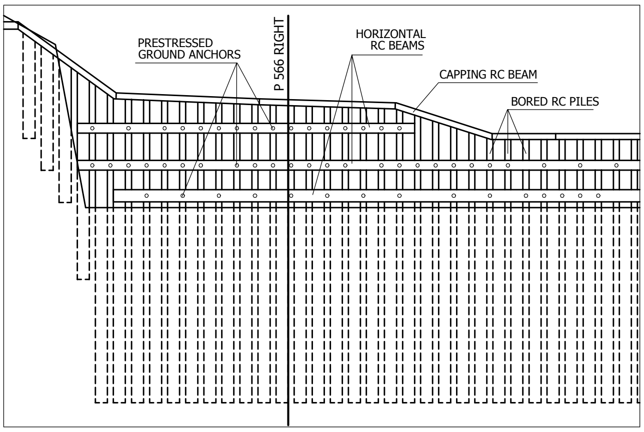


Fig. 3. Front view of the »Trojane West« pile wall

The height of the »Trojane West« pile wall at the investigated cross-section (profile P566-right) was 25.25 m, and the depth of embedment was 16.5 m. At the selected profile three anchor levels were applied. Behind the pile wall a tunnel was executed. Characteristic values of the pile wall and tunnel lining, as well as the parameters corresponding to the anchors, are presented in Table 3.

Table 3. Properties of the »Trojane West« pile wall and anchors

Pile wall, tunnel lining			Anchors	
EA (kN/m)	EI (kNm^2/m)	ν (-)	EA (kN)	L_s (m)
5.24 E6	3.27 E5	0.17	1.10 E5	1.5 and 3.0
3.0 E6	2.25 E4	0.17		

Construction Process

The construction process of the »Trojane East« pile wall 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.-13. Repeat steps 2 and 3 for the 2nd to 6th level of the anchors

The »Trojane West« pile wall was built in 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.-7. Repeat steps 2 and 3 for the 2nd to 3rd level of the anchors

8. Execution of the tunnel behind the pile wall

MONITORING

A monitoring system was constantly in operation during and after the construction of the bored-pile walls. The most important and reliable parameters obtained from this 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.

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

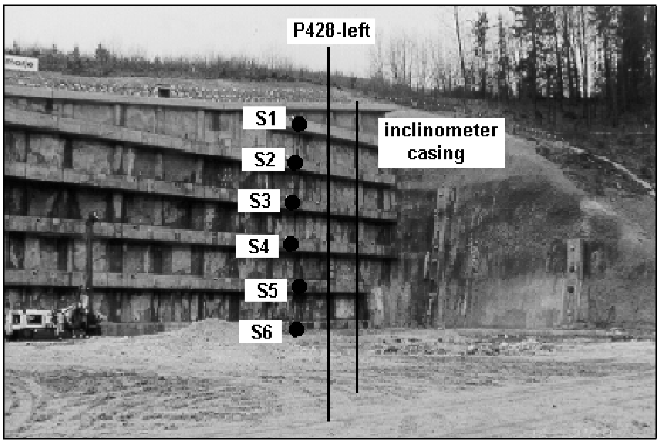


Fig. 4. The established monitoring system at the investigated cross-section of the »Trojane East« pile wall

The lengths of the casings in the »Trojane West« pile wall were between 11.5 and 26.0 meters. Three anchor load cells were installed at all anchor levels of the studied cross-section (see Fig. 5).

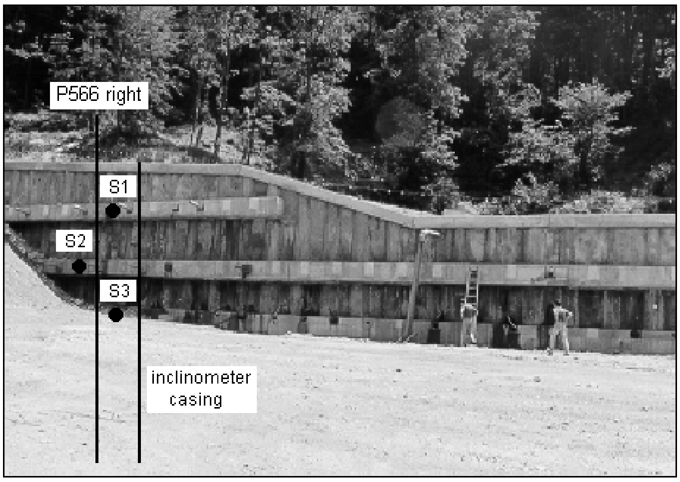


Fig. 5. The monitoring system at the discussed cross-section of the »Trojane West« pile wall

BACK-ANALYSES

The finite element analyses, which were performed for the instrumented cross-sections, were carried out using the well-known computer program Plaxis, version 7.11. 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 ground parameters for the MC model were available, whereas there was not enough geotechnical data for the more sophisticated models. The bored pile-walls were modelled as structural elements. Interface elements were introduced between these structural elements and the rock layers. The free lengths of the anchors were modelled by node-to-node anchor elements, whereas the bonded lengths of the anchors were modelled by geotextile elements. The construction process previously described was simulated in the analyses of the profiles P428-left and P566-right.

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

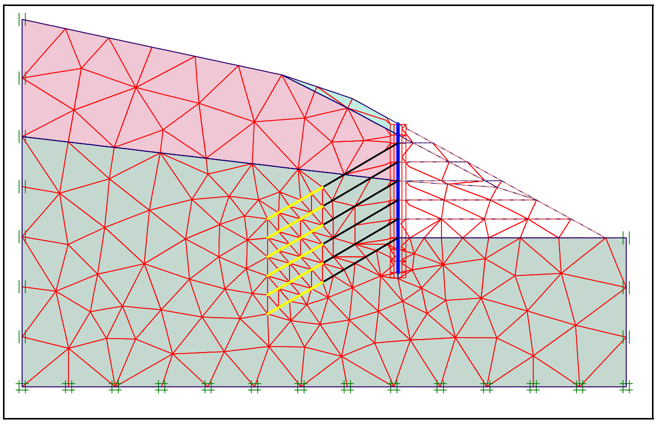


Fig. 6. The geometrical data and the generated FE mesh for the profile P428-left of the »Trojane East« pile wall

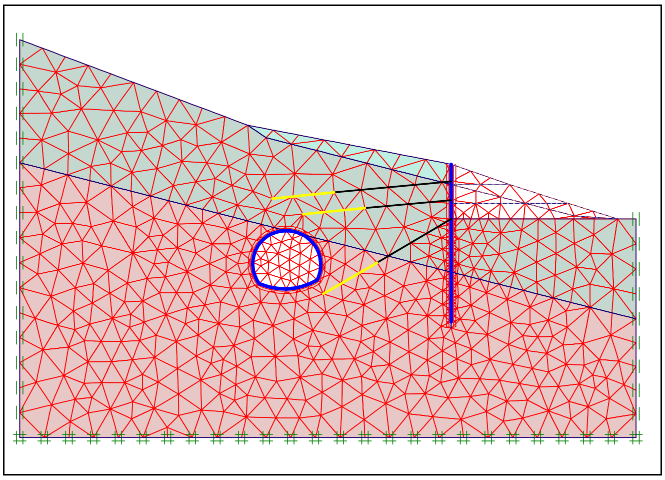


Fig. 7. The geometrical data and the generated FE mesh for the profile P566-right of the »Trojane West« pile wall

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

RESULTS

Step-by-Step Back Analyses

It was observed that a sufficiently accurate numerical model, i.e. the 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 (compare "Calculated stage" with total "Number of Stages" in Table 4). Taking into account the fact that the critical stages of anchored pile wall construction are the last steps of the excavation works, an accurate model for these stages can be obtained during the first half of the construction sequence.

Table 4. Review of the step-by-step back analyses of the investigated retaining structures

Bored-pile wall	Profile	No. of Strata	No. of Anchors	No. of Stages	Calc. stage
A	576-left	3	4	10	5
B (West)	566-right	3	3	8	4
C (East)	428-left	3	6	13	6
D	430-right	3	4	9	5

Back-Calculated Ground Properties

The final back-calculated ground properties of the three characteristic strata, in the area of the »Trojane East« anchored bored-pile wall, are presented in Table 5 (compare with the original data from Table 1).

Table 5. 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

Horizontal Displacements of the Top of the Pile Walls

Figures 8 and 9 show the measured and back-calculated horizontal displacements of the top of the »Trojane East« and »Trojane West« pile walls at the investigated cross-sections, 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.

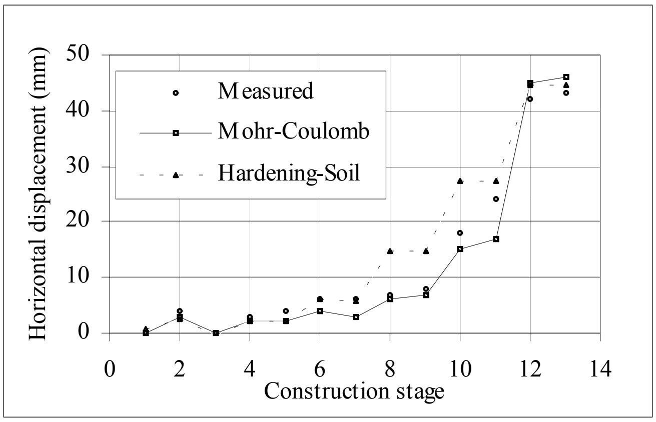


Fig. 8. Measured and calculated horizontal displacements, at various stages of the construction sequence, at the top of the »Trojane East« pile wall, at profile P428-left

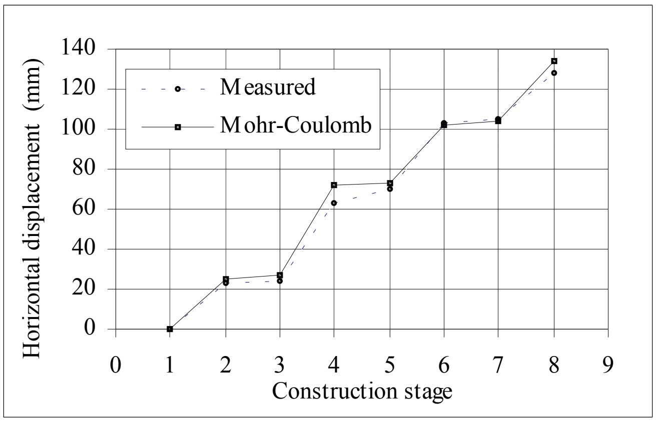


Fig. 9. Measured and calculated horizontal displacements, at various stages of the construction sequence, at the top of the »Trojane West« pile wall, at profile P566-right

<u>Horizontal Displacements of the »Trojane West« Pile Wall during the Construction Sequence</u>

Figure 10 shows the measured horizontal displacements of the »Trojane West« pile wall during the construction sequence at profile P566-right, and the back-calculated horizontal displacements after the execution of the tunnel.

In the two upper strata a gradual increase in the displacements was observed during the construction sequence. The deformation curves, corresponding to the actually obtained and the back-calculated results (stage 8), are in good agreement.

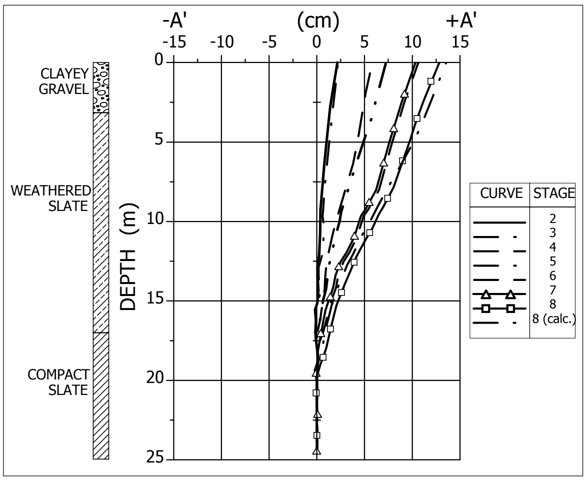


Fig. 10. Measured horizontal displacements of the »Trojane West« pile wall during the construction sequence, and the calculated displacements for stage 8

<u>Anchor Forces</u>

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 »Trojane East« pile wall during the construction process are shown, for all stages of the loading, in Table 6.

Table 6. 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

* The prestressing force was 350 kN instead of the design value of 600 kN.

Stage	Back-calculated (Mohr-Coulomb)					
	S1	S2	S3	S4	S5	S6
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

Stage	Back-calculated (Hardening Soil)					
	S1	S2	S3	S4	S5	S6
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 measurements show a significant increase in the anchor forces (at three of the anchor load cells, by more than 150 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 pre-stressed 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 to the anchor forces.

Figure 11 shows the differences between the measured anchor forces and the corresponding calculated values (MC, HS) in the second uppermost anchor at the investigated cross-section, taking into account the actual construction sequence. The measured values are in excellent agreement with the values obtained when using the HS model, and are also still in good agreement with those obtained by using the MC model.

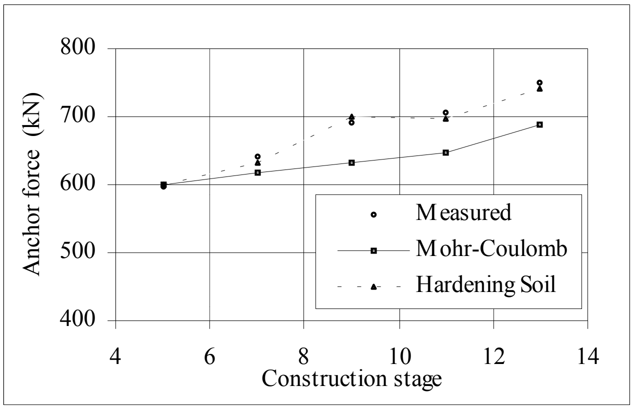


Fig. 11. Measured and back-calculated anchor forces in the second level anchor at profile P428-left

The differences between the measured anchor forces and the corresponding back-calculated values (MC) in the uppermost anchor of the »Trojane West« pile wall at the studied cross-section are shown in Fig. 12. The forces which were measured in the uppermost anchor are in very good agreement with the calculated values, which were in general a little higher. In the case of the other two anchor load cells the measured forces were a little bit larger than the calculated values.

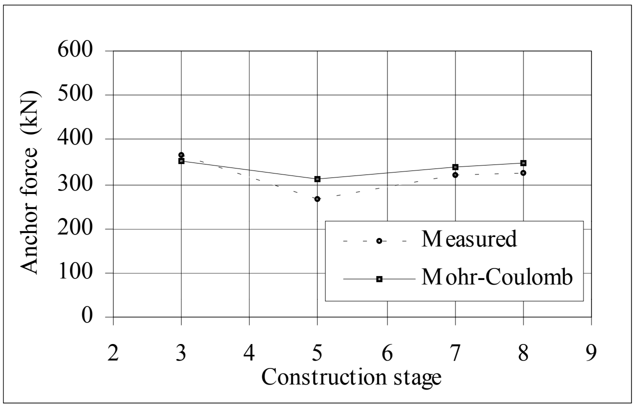


Fig. 12. Measured and back-calculated anchor forces in the uppermost level anchor at profile P566-right

Total Displacements at the Final Stage

Figure 13 shows the back-calculated (MC) total displacements of the ground around the »Trojane East« pile wall at profile P428-left, at the final stage.

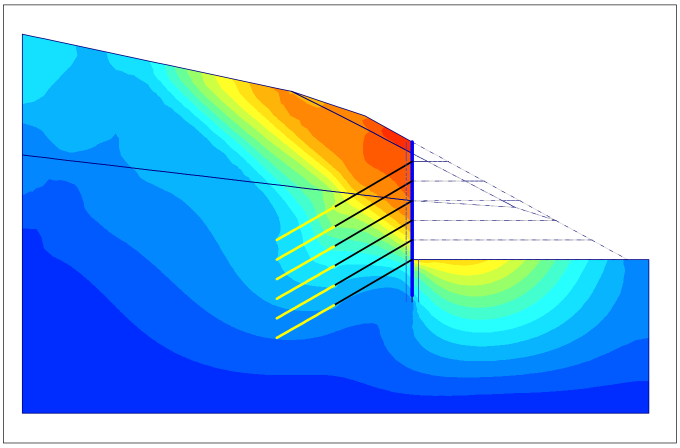


Fig. 13. Total ground displacements

It is clear that the largest displacements appear behind the upper part of the pile wall. Somewhat smaller displacements occur at the bottom of the excavation close to the pile wall, which is a consequence of the heave caused by the unloading.

CONCLUSIONS

Four similar retaining structures, built using large diameter bored-piles constructed in soft permo-carboniferous rock 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. The critical stages at the end of the construction works can be verified with confidence well in advance.

A simple MC model, which needs only four easily-accessible ground parameters, making it easy to calibrate the numerical model, was used, together with a simplified geological structure, in the analyses. The results were compared with those obtained using more sophisticated back analyses, as performed by Vukadin [2001], taking into account a HS model, which needs much more expensive investigations, and more details about the geological structure. It was shown that even with the use of the simplified numerical model the final results are very similar, which makes the use of back analyses and the observational method even more attractive for practicing engineers.

REFERENCES

Brandl, H. [1999]. "Design of slope retaining structures based on the observational method". *Proc. of 3rd Meeting of the Slovenian Geotechnical Society*, Portorož, Slovenia, 2nd Book, pp. 3-14.

Brinkgreve, R.B.J., Vermeer, P.A. [1998]. "*PLAXIS – Finite element code for soil and rock analyses: version 7*", Balkema, Rotterdam.

Majes, B., J. Logar, and B. Pulko [2000]. "Geotechnical constructions in permo-carboniferous clastic rock". *Proc. of the Faculty of Civil and Geodetic Engineering on the Doorstep of the Millennium*, University of Ljubljana, Slovenia, pp. 127-139.

Vukadin, V. [2001]. "*The use of different constitutive models for back analyses of retaining structures*". Master's Thesis, University of Ljubljana, Slovenia (in Slovenian).

Žvanut, P. [2002]. "Elasto-plastic finite element analysis of an anchored bored-pile wall". *Proc. 2nd Canad. Spec. Conf. on Computer Applications in Geotechnique*, Winnipeg, Canada, CD-ROM, pp. 33-37.

Žvanut, P. [2002]. "*Design, construction and monitoring of embedded retaining structures*". Master's Thesis, University of Ljubljana, Slovenia (in Slovenian).

Žvanut, P. [2002]. "Finite element analysis and the observed performance of an anchored bored-pile wall". *Proc. 5th European Conf. on Numerical Methods in Geotech. Engrg.*, Paris, France, pp. 655-660.

Žvanut, P., B. Majes and J. Logar [2003]. "Back analyses of high retaining structures within the framework of the observational method", *Proc. 13th European Conf. on Soil Mech. and Geotech. Engrg.*, Prague, Czech Republic, Vol. 2, pp. 933-938.