Interactive design – Croatian experience

M. S. Kovačević, V. Szavits-Nossan
Faculty of Civil Engineering, University of Zagreb, Croatia

ABSTRACT
The Croatian experience with the application of the interactive geotechnical design is presented. The interactive design includes extensive in situ monitoring during construction, which was performed on several deep excavations supported by rock bolts, particularly in urban areas, and also in installed piles during the construction of a highway viaduct. According to the interactive design, contingency measures are taken when the stability of the structure is endangered, and the original design is changed, if necessary, for the subsequent construction stages. The in situ measurements provide a valuable data base for the study of the soil and rock behaviour in general. The procedure of grouted rock bolt pull-out testing with the simultaneous use of acoustic emission is also presented. This procedure is a very valuable addition to the interactive design and it can be recommended for in situ quality control of rock bolts.

Keywords: interactive design, deep excavation, rock bolt, acoustic emission, pile testing

1 INTRODUCTION

The interactive geotechnical design (Kovačević, 2003) has been used on numerous projects in Croatia. It consists of making the design for a geotechnical structure with provisions for extensive in situ monitoring during construction. The monitoring results make it possible to verify whether the soil or rock and the structure are behaving in the way predicted by the project, and also to carry out numerical back analyses in order to match numerical and measurement results to the level of engineering acceptable accuracy (Arbanas, 2002; 2003; 2004; Arbanas et al., 2003; 2004). These numerical analyses enable the determination of the real soil or rock stiffness, the suitability of the supporting system in cases of deep excavations and tunnelling, and also the real factor of safety. When the monitoring and the numerical results show that there might be problems with the safety of the geotechnical structure, it is then possible to take contingency measures either on the constructed part of the structure or for the subsequent construction stages.

This paper describes geotechnical projects undertaken in Croatia where the interactive design was used. Besides the provision for ensuring the safety of the structure, the monitoring results made it possible to attain a valuable data base on the soil and rock behaviour, which, in turn, allows for the use of sophisticated constitutive relationships for modelling the real soil and rock behaviour. The commercially available computer programs for solving geotechnical problems permit the implementation of new constitutive models, so that the in situ results with the numerical modelling provide a powerful tool for getting better acquainted with the soil and rock behaviour in general.

The interactive geotechnical design was used for ensuring the stability of several deep excavations supported by rock bolts in urban areas (Kovačević et al., 2005). The bearing capacity of rock bolts is determined by pull-out tests. Trial pull-out tests are performed in-situ to check the design rock bolt bearing capacity (ISRM, 1981). According to the ISRM standard, at least 5% of the installed rock bolts are checked and then rejected. The laboratory pull-out tests with the simultaneous use of the acoustic emission make it possible to determine the limit load, close to the rock bolt bearing capacity, at which the test can be stopped and the rock bolt can still be used for supporting the rock mass (Arbanas et al., 2005). These test results are very promising for in situ use. The use of the acoustic emission in situ would make it possible to determine the rock bolt limit load for a much larger number of rock bolts than by the standard pull-out test, and leave the rock bolts in place for reinforcing the rock mass.

The interactive design was also used for checking the deformations of piles and the foundation soil, as well as their bearing capacity. The measuring devices were installed in the pile in order to determine whether additional measures, such as jet grouting the soil under the pile, were necessary for ensuring the design pile bearing capacity.

2 DEEP EXCAVATIONS

The ever larger structures that are being constructed, particularly in urban areas, require detailed soil-structure interaction analyses and the accurate determination of soil stiffness. Rock mechanics engineers have developed correlations between the rock stiffness and various rock classification characteristics such as the Rock Mass Rating (RMR) index or the Geological Strength Index (GSI) (Hoek & Brown, 1997; Serafim & Pereira, 1983). These correlations are based on the value of the deformation modulus determined through the linear elastic back analyses matching the calculated and measured displacements.

The same approach was adopted for several deep excavations performed in very hard fissured and jointed soils and rocks in Croatia (Kovačević et al., 2005). Measurements of linear deformations of the soil and rock mass were taken throughout construction. A sliding deformeter measured relative displacements between benchmarks placed at the distance of one meter along boreholes to an accuracy of 30 microns. The use of this device was described in Kovačević (2003) and Kovačević et al. (2002). Horizontal deformeters and vertical inclinometer-deformeters were used for monitoring during the construction of all these deep excavations.

The comparison between the results of numerical analyses, which simulated construction stages for the deep excavations, and the measured deformations, clearly showed that the existing correlations based on rock classification characteristics significantly underestimate the values of deformations (Kovačević et al., 2005). Additional measures along the lines of interactive design had to be taken in order to ensure the excavation stability in all the cases.

One of the examples of these deep excavations, where the interactive geotechnical design was used, is shown in Figure 1.

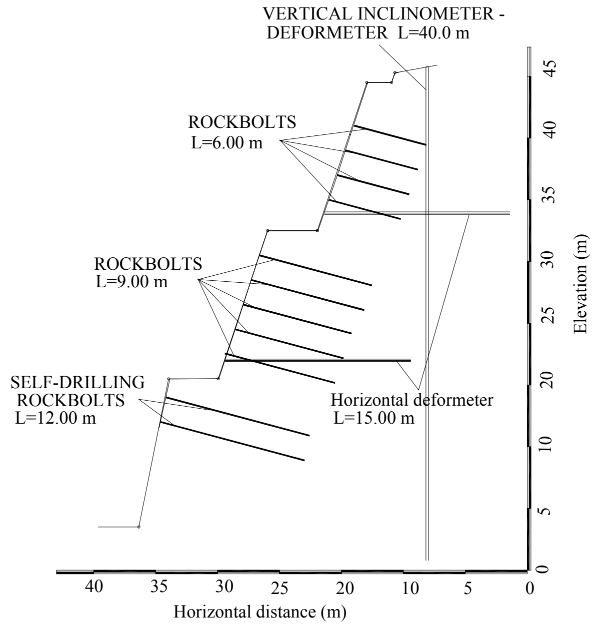

Figure 1. Lenac excavation support system and measuring devices (Kovačević et al., 2005)

A 35 m to 55 m deep cut was made in limestone over a period of 8 months in 2002 for the construction of a shipyard platform Lenac in Rijeka. The berms were 4 m wide, and they were made at each 12 m of the cut depth. The slope inclination was 3:1. The cut was made in sections of 4 m, and it was supported by multilayered reinforced shotcrete and rock bolts.

The measured deformations were much larger than the ones predicted by the design, so that contingency measures had to be taken. When the excavation was 12 m deep, the rock bolts had to be prestressed and additional rock bolts were installed. The numerical back analyses, in which the stiffness of the rock mass had to be adapted to the measured displacements, showed that it was necessary to intervene also in the original design. The subsequent section lengths were, thus, restricted to 50 m. For the last 12 m of excavation, the height of sections was lowered to 2 m, and the section lengths were restricted to 20 m.

3 ACOUSTIC EMISSION

Despite the interactive geotechnical design, which makes it possible to get a better knowledge on the soil and rock mass behaviours, the behaviour of the rock bolts, which reinforce the rock mass, is still not known well enough. The low percentage of rock bolts tested in situ by pull-out tests do not guarantee that their bearing capacity is accurately determined, due to the heterogeneity of the rock mass. More rock bolts are usually not tested because of the cost of the whole process of drilling, rock bolt installation, grouting and testing, after which the rock bolts have to be rejected.

Along with the interactive geotechnical design, a better knowledge of the limit load in the rock bolts would contribute to the safety and better stability of geotechnical structures where they are used. The effectiveness of rock bolts depends, not only on its bearing capacity, but also on the grouting mixture and the way the grouting is applied.

In Arbanas et al. (2005) laboratory pull-out tests on rock bolts with 48 different grout mixtures, and simultaneous acoustic emission measurements are described. It is shown that this new testing procedure can reliably be used for the quality control of rock bolts. Contrary to the standard pull-out test, where rock bolts can no longer be used after the test, the acoustic emission can be used for the determination of the load in vicinity of the failure load, so that the rock bolts can subsequently be used for reinforcing the rock.

Different materials and structures can be tested by the procedure which uses acoustic emission (Pollock, 1989). When cracks are formed in the material, as plastic deformations occur during loading, the released energy induces waves which are registered by a sensor, digitally and by sound, called the acoustic emission counts.

The sensor was placed at the rock bolt free end during the application of tensile load for tests described by Arbanas et al. (2005). The development of plastic deformations indicates the beginning of rupture of the bonds between the rock bolt and the surrounding grout mixture, as well as of the bonds in the mixture itself. This development can clearly be detected when rock bolts are tested by the acoustic emission. Contrary to the standard pull-out tests, where there is no clear sign of plastic deformations, the tests in which acoustic emission is used can be stopped at the limit load close to the rock bolt bearing capacity, when the number of acoustic emission counts suddenly increases.

The testing equipment for these pull-out tests with the measurements of acoustic emission counts is shown in Figure 2. By connecting the system for measuring the acoustic emission counts with the systems for measuring the tensile force and displacements, all three values are registered at the same time.

Figure 2. Equipment for pull-out tests with acoustic emission (Arbanas et al., 2005)

The results of testing rock bolts with 48 different grout mixtures by applying the tensile load and measuring the displacements as well as the acoustic emission counts, showed that this testing procedure is very promising for the determination of the rock bolt limit load. It can, thus, be recommended for in situ quality control of installed rock bolts.

4 PILE TESTING

The interactive geotechnical design was applied for the construction of foundations for the viaduct Krapinčica on the highway Zagreb-Macelj. The foundation soil consisted of poorly graded sand with clay and clay of low plasticity. The design included the pile raft foundations. The piles were 1.2 m in diameter and 9 to 11 m long. The dynamic testing of the bearing capacity of piles installed in the first stage of construction showed that the pile bearing capacity was unexpectedly low. This indicated that the pile bearing capacity predicted in the design was overestimated. In order to prevent too large viaduct deformations and the foundation soil failure, the soil under the piles was improved by jet grouted columns, 1.2 m in diameter and 3.5 m to 4 m long, which significantly increased the stiffness and bearing capacity of the foundation soil.

In the second stage of pile installation, measuring devices were installed in the piles in order to monitor the vertical deformations of the piles and the foundation soil. Sliding deformeters were used for measuring the relative vertical deformations, and the total displacements were measured by surveying. This monitoring program was undertaken to check whether the foundation soil was sufficiently stiff to prevent excessive displacements of the piles, and also to check the pile bearing capacity.

The maximum vertical displacement measured in the piles during the viaduct construction was 0.55 mm. The calculated pile bearing capacity was 1.47 to 1.72 times greater than the actual load on the piles. The monitoring results showed that the tested piles were behaving according to the design and no contingency measures were necessary.

The use of monitoring, as the most important part of interactive geotechnical design, proved that the piles in the second stage of construction were safe as designed. Those in the first stage of construction required contingency measures in terms of jet grouting. In any case, whether contingency measures are required or not, the interactive design brings additional assurance that the geotechnical structure will behave in the desired way.

5 CONCLUSIONS

The application of the interactive geotechnical design in Croatia was illustrated on an example of deep excavation, where contingency measures had to be undertaken and the original design changed in order to provide the cut stability.

Laboratory pull-out tests on grouted rock bolts, with the simultaneous measurement of the acoustic emission counts provide a very efficient method for the quality control of rock bolts, which is a valuable addition to the interactive design. The results of these tests show that it is possible to detect the limit load, close to the rock bolt bearing capacity, when the number of acoustic emission counts suddenly increases. The test can be stopped at this load and the rock bolt can remain in use for reinforcing the soil mass. This could be a powerful tool for in situ testing of rock bolts.

The application of the interactive design was also shown on pile testing, where vertical displacements of the piles and the foundation soil were measured, and the pile bearing capacity was determined.

Even though the interactive design is not used as often as it should be, it provides, not only a safe and economic solution for the geotechnical structure, but also important additional knowledge on the soil and rock behaviour in general.

REFERENCES

Ž. Arbanas, The influence of rock bolts on the rock mass behavior during excavation of deep cuts, MS Thesis, Faculty of Civil Engineering, University of Zagreb (in Croatian), 2002.

Ž. Arbanas, Construction of open pit Zagrad in Rijeka, Građevinar, Vol. 55, No. 10, 591-597 (in Croatian), 2003.

Ž. Arbanas, Prediction of supported rock mass behavior by analyzing results of monitoring of constructed structures, Ph.D. Thesis, Faculty of Civil Engineering, University of Zagreb (in Croatian), 2004.

Ž. Arbanas, B. Jardas, M. S. Kovačević, Reinforcement Systems in Construction of Open Pit Zagrad in Rijeka, Croatia, Proc. 13th. European Conf. on Soil Mech. and Geotech. Eng., Geotechnical Problems with Man-made and Man Influenced Grounds, Prague, Czech Republik, (Eds. I. Vaniček, R. Barvinek, J. Bohač, J. Jettmar, D. Jirasko and J. Salak), August 25-28, Vol. 2, 23-28, 2003.

Ž. Arbanas, B. Jardas, M. S. Kovačević, Excavation of Open Pit Zagrad in Rijeka, Croatia-A case history, Proc. 5th Int. Conf. on Case Histories in Geotech. Eng., New York, NY, USA, April 13-17, 5.64.1-5.64.6, 2004.

Ž. Arbanas, M. S. Kovačević, V. Szavits-Nossan, Quality control of rock bolts, Građevinar, Vol. 57, No. 11, 859-867 (in Croatian), 2005.

E. Hoek, E. T. Brown, Practical Estimates of Rock Strenght, Int. J. Rock Mech. & Mining Sci. & Geomechanics Abstracts, Vol. 34, No. 8, 1165-1187, 1997.

ISRM, Commission on Standardization of Laboratory and Field Test, ISRM Suggested Methods for Rock bolt Testing, Oxford: Pergamon Press, 161-168, 1981.

M. S. Kovačević, The Observational Method and the Use of Geotechnical Measurements, Geotechnical problems with man–made and man influenced grounds, Proc. 13th Europ. Conf. on Soil Mech. and Geotech. Eng., Prague, Czech Republic, August 25-28, Vol. 3, 575-582, 2003.

M. S. Kovačević, I. Jašarević, Ž. Lebo, Experiences obtained by execution of high pre-cuttings and tunnels in rock of the HSSR type in Croatia, 6th Int. symposium on tunnel construction and underground structures, 25-27 September 2002, Ljubljana, Slovenia, 217-229, 2002.

M. S. Kovačević, Ž. Skazlić, V. Szavits-Nossan, Case Histories of Very Hard Fissured Soils Stiffness Determination, Geotechnology in Harmony with the Global Environment, Adachi, T. (ed.), Osaka, Millpress Rotterdam, 703-706, 2005.

A. A. Pollock, Acoustic Emmision Inspection, Metals Handbook, Ninth Ed., ASM International, Vol. 17, 278-294, 1989.

J. L. Serafim, J. P. Pereira, Consideration of the Geomechanical Classification of Bieniawski, Proc. Int. Symp. on Engineering Geology and Underground Construction, Lisbon, Vol. 1, II.33-II.42, 1983.