Interactive design for deep excavations

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ABSTRACT
The paper presents the advantages of the use of interactive design, especially for construction in the rock mass. The rock mass deformability and strength characteristics are determined from the rock classification, and the characteristics of the supporting system for deep excavations is determined from rockbolt pull-out tests. This does not provide sufficient knowledge on the behavior of the rock mass and the supporting system during construction. In order to improve the safety of deep excavations in the rock mass it is very advantageous to use the interactive design, where in situ measurements of the rock mass displacements are made and compared to the design ones. If discrepancies between these displacements occur, it is possible to use contingency measures to assure the excavation stability. Back-analysis in the early excavation stages are also very helpful for the determination of the safety of the design geometry and supporting system. They also provide valuable information on the actual rock mass and supporting system characteristics.

Keywords: interactive design, deep excavation, rockbolt

1 INTRODUCTION
When excavations are made in the rock mass for the construction of roads and buildings in urban areas, the only parameter that can be controlled is the excavation slope. Generally, the excavation slope depends on the rock conditions and the chosen support system for the excavation stability. In urban areas excavations sometimes have to be made vertically with safe and demanding support systems, which require strict technical construction of the support system.

The deformability and strength characteristics of the rock mass are determined from geotechnical investigation and the use of the rock mass classification system. It is then possible to make the geotechnical model for the rock mass and perform the stability and stress-strain analyses. It is first assumed that the rock mass slope is unsupported during excavation, which results in the initial value of the factor of safety. If a low initial factor of safety is obtained, the stability analysis should include a support system. The design support system will thus result from the stability analysis, which provides a satisfactory factor of safety during all phases of excavation. Due to the uncertainties regarding the rock mass and the supporting system characteristics that are included in the described design process, it is necessary, especially for demanding geotechnical structures, to use additional methods in order to secure the structure stability.

The interactive design methods for cuts in the rock mass are presented by Hoek and Bray (1977) and Hoek and Brown (1980). The interactive design for deep excavations is applied throughout excavation and construction of the support system and includes extensive monitoring (Nicholson et al., 1999; Kovačević et al., 2002; Kovačević, 2003; Arbanas, 2002). The selection of the support systems during interactive design is presented by Windsor and Thompson (1992) and the selection of corresponding rockbolts by Stillborg (1994). According to the suggested procedures, a new design of the excavation and/or the application of additional support measures are required when instability of the excavation, or insufficient stability, is detected during construction. If additional support measures are necessary, they usually consist of modifications or optimization of the design support system (Windsor and Thompson, 1992). Stillborg (1994) suggests monitoring of the excavation throughout construction and also
when it is completed, as a part of the whole design process. This process, which includes field investigation, initial design, construction, monitoring and the resulting contingency measures, should be handled by the designer and the supervising engineer.

The paper describes the whole process of interactive design of deep excavations. It starts with engineering geology and field investigation, and proceeds with the classification of rock samples and laboratory determination of rock characteristics, supported by additional rock strength determination during excavation. It then includes extensive monitoring in order to get sufficient knowledge on the actual behavior of the rock mass with the support system during excavation and construction, back-analyses, and contingency measures. The contingency measures consist of design modifications and/or additional support elements in case when monitoring results and back-analyses show that the excavation safety is uncertain.

The interactive design is still not used often enough, even though its advantages are quite obvious. The stress-strain analyses are mostly used only for the determination of limiting values of the allowed rock mass deformations during excavation for the initial design, whereas stress-strain back-analyses are seldom used during excavation, only for cases of unexpected events or, even worse, rock mass failure (Sonmez et al., 1998). The least used are additional stability analyses with the actual rock mass deformability characteristics and rockbolt forces, which provide the best way of determining the actual stability of the excavation in progress.

2 INTERACTIVE DESIGN

2.1 Engineering geology mapping

The engineering geology mapping of the location for excavation is the first step in the process of interactive design. The geologic structure of the rock mass, including the rock mass type and the discontinuities that it contains, is one of the key factors which influence the stability of the excavation.

Surface mapping is combined with the mapping of the open excavation and the analysis of core samples from investigation boreholes. It is, thus, possible also to determine weaker zones at greater depths in the rock mass. When deep excavations are made in very fractured rock mass, the rock blocks are relatively small compared to the excavation depth, so that the influence of discontinuities on the excavation stability has to be considered with respect to the excavation depth (Sjoberg, 1996).

2.2 Rock classification

The rock classification is one of the main requirements for the excavation design. It also provides information from which correlations can be made with the rock mass deformability and strength characteristics. This, in turn, makes it possible to determine the appropriate support system (Hoek, 2000).

There are several rock classification systems in use. The geotechnical RMR classification (Rock Mass Rating System) was developed by Bieniawski in early seventies of the last century (Bieniawski, 1976). It was further elaborated according to the results of its application and verification at numerous underground construction sites in different geologic conditions (Bieniawski, 1979). The final version of the RMR classification was also developed by Bieniawski (1989) on the basis of gathered experience in the construction of tunnels, underground structures, quarries, mines, cuts and foundations. It takes into account the following parameters: the uniaxial compressive rock strength, the RQD index (Rock Quality Designation), the spacing, state and orientation of discontinuities, and the underground water conditions.

The rock classification is completed by the use of strength parameters (Bieniawski, 1989). The Point Load Test (ISRM, 1981) is usually performed on rock samples in order to determine their compressive strength. The classification is then used for the final determination of the deformation modulus (Bieniawski, 1979; Serafim and Pereira, 1983; Hoek and Brown, 1997; Hoek, 2004) and strength parameters of the rock mass (Hoek, 1994; Hoek et al., 1995; Hoek et al., 2002) for the stability analysis and the design. Engineering judgment has to be used along with the rock classification system.

2.3 Monitoring

The design factor of safety for deep excavations obtained from the stability analysis based on correlations with the rock classification system may not be realistic due to uncertainties related to the
lack of knowledge on the real behavior of the rock mass. It has also been shown that the rock mass deformations during construction in the rock mass are generally much larger than those predicted by the stress-strain analysis based on correlations with the rock classification system (Kovačević et al., 2005). It is, thus, necessary to use additional methods in order to get sufficient knowledge on the behavior of the rock mass in the process of excavation and construction of the support system for deep excavations.

This is possible when interactive design is used. One of the main elements of interactive design is monitoring during excavation and construction of the support system, which includes surveying of a net of benchmarks, and measurements of the rock mass displacements by inclinometers and extensometers-deformeters. The inclinometers, placed in the vertical borehole, measure horizontal displacements of the rock mass from the surface (Amstad et al., 1988) and the extensometers (deformeters and sliding micrometers) are used for measuring displacements along the borehole (Kovari et al., 1987; Amstad et al., 1988). These measurements make it possible to determine the accurate values of the deformation modulus of the rock mass through stress-strain back-analyses in which measured and calculated displacements are matched to the level of engineering acceptable accuracy (Arbanas, 2002; 2003; 2004; Arbanas et al., 2003; 2004).

The stiffness of the rockbolts within the range of the design rockbolt forces is determined from the rockbolt testing (ISRM, 1981). The forces in the rockbolts can be determined from measurements performed in all excavation stages. The most favorable measuring methods are the installation of the measuring device on the rockbolt (Farmer, 1975), and the use of extensometers right next to the rockbolt (Thompson et al., 1995), but these methods are rarely used because of their high cost.

The rockbolt bearing capacity is controlled by performing in situ pull-out tests (ISRM, 1981). According to the ISRM standard, at least 5% of all installed rockbolts are tested, which is not sufficient for a reliable stability analysis. In addition, the tested rockbolts have to be rejected and can no longer be used for reinforcing the rock mass. A much more reliable stability analysis can be performed if the rockbolt bearing capacity is determined by in situ acoustic emission tests (Arbanas et al., 2005). These tests can be performed, if necessary, on all the installed rockbolts and still maintain their rock reinforcing function.

2.4 Back-analyses and contingency measures

The monitoring results make it possible to perform back-analyses of the supported rock mass behavior for every excavation stage. The stress-strain analyses, with measured activated forces in installed rockbolts, result in more accurate values of the rock mass deformation modulus. These back-analyses provide the values of the deformation modulus which usually turn to be quite different from the one obtained through correlations using the rock classification system. The new stability analysis can also be performed, usually by the method of limiting equilibrium, by using the measured bearing capacity of installed rockbolts. The obtained factor of safety is, thus, much more reliable than the one obtained prior to design, because it is now based on the actual rock mass and support system behavior in the excavation and the actual rock and rockbolt properties.

If the back-analyses show that the original design is not safe enough, contingency measures can be taken. They consist of prestressing the rockbolts, installing additional rockbolts in the excavated rock mass and/or changes of the excavation geometry for the next excavation stages.

Stillborg (1994) suggests that the design should be regarded as a process, combining the original design, extensive monitoring during construction and exploitation, which is all included in the interactive design. The best approach to interactive design is to include monitoring and possible contingency measures in the original design.

3 EXAMPLE

A deep excavation was made in Rijeka, Croatia, in 2001, over a period of 9 months, for the construction of underground garages and a high storey building (Arbanas, 2003; Arbanas et al., 2003; 2004). The construction location was situated between a railway at its southern side and Pomerio Street at the North, on the area of 90 m x 60 m. The deepest and most complex part of the excavation was at the northern side of the construction site, close to Pomerio Street and the surrounding buildings. This part of excavation, almost vertical, was 21 m deep, and a stone wall of 7 m was made to support the excavation (Figs. 1 and 2).
After geologic mapping and geotechnical investigation it was determined that the rock mass was composed partly of limestone and partly of flysh layers. The RMR classification was made for both rock types, and deformability and strength characteristics of the rock mass were determined accordingly.

The stability analysis showed that a reinforced concrete girder with self-drilling rockbolts at the crossings of the girder beams has to be used to support the excavation. The stress-strain analysis for the chosen excavation geometry and the selected support system gave the expected rock mass displacements.

The monitoring of the excavation progress at its northern side was carried out with a horizontal deformeter 16 m long, and a vertical inclinometer 25 m long (Fig. 3). The excavation was made in stages, each 2 m high, according to the vertical spacing of the girder beams. The displacement measurements were taken after each excavation stage was completed, and 15 days upon its completion.

The stress strain back-analyses started with the design deformability characteristics of the rock mass based on the RMR classification and the rockbolt stiffness was determined form in situ control pull-out tests (ISRM, 1981). The resulting displacements, of up to 0.50 mm, were close to the design ones, but much smaller than those measured in situ, which were up to 7 mm (Fig. 4). In order to match calculated and measured displacements it was necessary to decrease the rock mass modulus of elasticity by a factor of 20 in subsequent back-analysis.

The final stress-strain analysis gave the stress state in the rock mass and activated forces in rockbolts. By applying the appropriate factor of safety to these forces it was possible to determine the rockbolt parameters required for the stability analysis. The stability analysis showed that the design excavation geometry was safe.

However, due to much larger in situ displacements compared to the design ones, after excavating the first three stages, it was necessary to prestrain the rockbolts and to install additional rockbolts between the girder crossings. The in situ measurements also indicated that the rock mass was losing stability if left unsupported for longer than 12 hours, thus endangering the surrounding street and buildings, so that a time limit was imposed on the construction of the support system for lower excavation stages.
4 CONCLUSIONS

Because the rock mass strength and deformability characteristics, which are for design determined from correlations with the rock classification system, do not provide reliable enough information on the rock mass behavior during construction of demanding geotechnical structures, it is necessary to provide additional means for securing the structure. For deep excavations in the rock mass it is also necessary to have additional knowledge on the characteristics of the supporting system, especially on the actual forces in the rockbolts.

The interactive design provides all the tools which are required for safe construction in the rock mass. The main advantage of interactive design is the monitoring of the structure during construction that it includes. The displacement measurements of the supported rock mass, which result from the monitoring, make it possible, first, to detect any discrepancies with the design displacements and to make in situ provisions for securing the structure. They also provide valuable data for carrying out stress-strain and stability back-analyses. The stress-strain back-analyses are carried out in the early stages of the excavation, until the calculated and measured displacements of the rock mass are matched to the engineering acceptable accuracy.

The final back-analysis gives the appropriate rock mass deformability characteristics, which usually turn out to be very much different form the ones determined through the rock classification system for the original design. It also gives the actual forces in rockbolts, which are, after applying the required factors of safety, then used in the new stability analysis. This analysis is very useful because it can, more reliably than in the original calculation, determine the excavation factor of safety. In case when the new factor of safety is lower than required, the progress of excavation can be changed in the original design.

Any changes on the structure, as compared to the original design, represent the contingency measures. They can consist of changes in the supporting system, like prestressing the rockbolts and installing additional ones, changes of the excavation geometry, and/or changes in the time schedule of excavating.

In the presented example of the use of interactive design for a deep excavation in Rijeka, Croatia, where extensive monitoring and back-analyses were performed, it was necessary to prestress the rockbolts, install additional ones, and change the time schedule for the consecutive excavation stages.

Even though the advantages of interactive design are quite obvious, it is still not very much in use. The back-analyses are particularly seldom used. The paper is intended for advancing the use of interactive design, to make sure that monitoring is included in the projects for demanding geotechnical structures in the rock mass, and to emphasize the need for including possible contingency measures in the original design.

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