Design of engineered slopes in flysch rock mass

Étude et exécution des déblais dans des formations de flysch

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ABSTRACT

The method for the design and realization of systems for ensuring stability of cuts in flysch formations, with an interactive approach based on stress-strain back analyses, is presented. Flysch formations can be regarded as materials belonging in a transitional zone between soft rocks and hard soils. Based on results obtained by laboratory and in-situ investigations in various stages of design and realization of projects, it can be concluded that the strength and deformability parameters for flysch can not accurately be determined by traditional methods, and that it is very difficult to adopt realistic design parameters. An interactive design procedure to be applied during realization of cut support constructions in flysch formations is proposed. The use of proposed methods is presented and illustrated by examples of cuts realized in flysch on the Adriatic motorway route in the vicinity of the town of Rijeka, Croatia. Design procedures used for ensuring stability of cuts are based on results obtained by geotechnical investigations as well as on classifications for heterogeneous rock formations. The system for monitoring behaviour of flysch formations in cuts is established, and flysch formations are classified in open side cuts through geotechnical supervision. Relevant data are used in stress-strain back analyses, so as strain properties of flysch are varied in order to harmonize measured and calculated displacements at cut locations. The results of these analyses either confirm the predictions or require modifying the design support systems in order to ensure cuts stability in flysch formations.

RÉSUMÉ

L'article présente une méthode d'étude et d'exécution d'un système assurant la stabilité des déblais dans des formations de flysch, avec une approche interactive fondée sur l'utilisation des analyses de retour des contraintes-déformations. Les formations de flysch peuvent être considérées comme un matériau appartenant à une zone de transition entre les roches molles et les sols fermes. Suite aux résultats des essais en laboratoire et des travaux de reconnaissance sur le terrain dans différentes phases de l'étude et de l'exécution, l'on peut conclure que les méthodes habituelles des essais ne permettent pas de déterminer exactement les paramètres de résistance et de déformabilité du flysch et qu'il est très difficile de retenir des paramètres réels de projet. L'on propose une procédure d'étude interactive au cours de l'exécution des travaux de stabilisation des déblais dans des formations de flysch. La mise en œuvre des méthodes et des procédures proposées est illustrée par des exemples relevés lors de l'exécution d'un déblai dans les formations de flysch sur le tracé d'un tronçon de l'Autoroute Adriatique, près de Rijeka, Croatie. Les études de stabilité des déblais dans le flysch s'appuient sur les résultats des reconnaissances géotechniques et des classifications retenues des masses rocheuses hétérogènes. Au cours des travaux, un système de mesures et de suivi du comportement du flysch dans les déblais a été mis en place et dans le cadre de la surveillance géotechnique une classification de la masse rocheuse dans les déblais ouverts a été effectuée. Pour obtenir des données pertinentes sur le comportement de la masse rocheuse, il a été procédé à des analyses de retour des contraintes-déformations qui ont permis d'ajuster les déplacements mesurés et calculés dans les déblais, par la variation des propriétés de déformation. Les résultats des analyses ont été utilisés soit pour confirmer soit pour modifier les systèmes de soutènement destinés à assurer la stabilité des déblais dans des formations de flysch.

Keywords : slope stability, flysch, support system, observational methods

1 INTRODUCTION

The geotechnical most challenging section of the Adriatic motorway was constructed in the Draga Valley near the City of Rijeka, Croatia. During period from 2004 to 2006, the section of Adriatic motorway through Draga Valley near Rijeka, Croatia was constructed. The geological fabric of the Draga Valley is very complex. The Cretaceous and the Paleogene limestone are situated on the top of the slope, while the Paleogene flysch crops out at the lower slope, and on the bottom of Draga Valley where the motorway is located. Unlike limestone rocks at the top of the slope, flysch rock mass is completely covered by colluvial deposits, residual soils or breccias.

Flysch formations can be regarded as materials belonging in a transitional zone between soft rocks and hard soil. Based on results obtained by laboratory and in-situ investigations in various stages of design and realization of projects, it can be concluded that the strength and deformability parameters for flysch can not accurately be determined by traditional methods, and that it is very difficult to adopt realistic design parameters.

The major part of the motorway was constructed by cutting in flysch rock mass. On this section, the motorway was designed and built by making side cuts, by defining support work, and by ensuring stability of side cuts in flysch, up to 20 m in side-cut height. Interactive design of rock mass cutting, based on the observational methods, was introduced during the construction. The work for ensuring stability of side cuts in flysch was conducted in accordance with the procedure recommended for the second phase of interactive design during realization of the works. The initial design was done based on the soil and rock parameters, obtained from GSI classification of flysch rock mass and laboratory testing of rocks and soils. The appropriate measured equipment was installed before and during the construction–vertical inclinometers, horizontal

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-2127

deformeters, piezometers and geodetic surveying and flysch formations are classified in open side cuts through geotechnical monitoring and supervision. Relevant data about flysch displacement, data about rock mass quality in side cuts, and test data for anchors as vital portions of support systems, are used in stress and strain back analyses, and strain properties of flysch are varied in order to harmonize measured and calculated displacements at side cut locations. The results of these analyses either confirm the predictions or point to the need to modify the design support systems in order to ensure stability of side cuts in flysch formations.The measured values and the back analysis enabled establishing real rock mass strength parameters and deformation modulus. In the paper we are presenting our experience with designing and construction of various support constructions and with the applying observational method during the construction of the engineered slopes in flysch rock mass.

2 GEOTECHNICAL PROPERTIES OF FLYSCH ROCK MASS IN DRAGA VALLEY

The geological fabric of steep slopes of Draga Valley is made of limestone rock mass. At the bottom of the valley, there are deposits of Paleogene flysch mainly made of siltstones with rare layers of sand, marl, and breccia. Flysch rock mass is covered with slope formations, which tend to slide and denude (Arbanas et al. 1994). Usual geotechnical cross section consists of three layers: clay cover made after disintegration of flysch rock mass (residual soil) or brought by gravitation from hypsometrically higher parts of the slope, layer of weathered flysch deposits with variable characteristics of weathering decreasing with depth, and fresh flysch zone. Because of reasons how Draga Valley had become, and geomorphologic processes which influenced at current relief, changes in geotechnical profile are often and sudden (Arbanas et al. 2007a).

The rock mass is mainly made of siltstones which exhibit visual transfer from completely weathered (CW) zone with yellow color through highly weathered (HW), moderately weathered (MW) and slightly weathered (SW) deposits all the way to fresh rock mass (F) colored grey to blue (ISRM 1981a). In the zone of the completely weathered siltstones, the rock mass is completely disintegrated, but original structure of the rock mass stayed intact (ISRM 1981a, b). The layers of fresh siltstones have no visible weathering marks, except color change on the main discontinuity surfaces. During decomposition of singular weathering zones of the flysch rock mass, along with visual check of the material from boreholes, significant contribution came from results of geophysical measurements using surface seismic refraction methods and down-hole method (Arbanas et al. 2007a).

Determination of geotechnical properties of the flysch rock mass, during geotechnical examination works, was disabled because of the flysch rock mass behavior. During boring, it was difficult to get undisturbed samples, because of rock mass disintegration in highly (HW) to moderate weathered (MW) siltstones. The significant is also a sudden degradation and disintegration of slightly weathered (SW) to fresh (F) siltstones after removing of geostatic loads and exposing to air and water during boring. The consequence of these processes in fresh (F) siltstones was very small number of undisturbed samples for laboratory uniaxial strength tests. The uniaxial strength of slightly weathered (SW) to fresh (F) siltstones obtained from laboratory uniaxial test varied from 8 to 32 MPa (Arbanas et al. 2008). Obtaining of the undisturbed samples in completely (CW) to moderately weathered (MW) was not possible. The main test comprised of was Point Load Test (PLT), where samples, obtained by boring, were used without further processing and almost immediately after sampling (ISRM 1985). Disadvantage of Point Load Test is surely large dispersion of the results, which especially occur with weak rock masses like flysch. But, regardless of given disadvantages, use of Point Load Test method is recommended in case of lack of more reliable testing, lack of appropriate representative samples, and in combination with detailed description of tested samples of flysch rock mass. Test results of PLT on fresh (F) siltstone samples showed that corresponded uniaxial strength of these materials is from 10 to 15 MPa, and in extreme cases to 20 MPa. The corresponded uniaxial strength of moderate (MW) to slightly weathered (SW) samples showed values <2 MPa, and these values obtained from PLT are unconfident and unacceptable for engineering analyses without adequate precautions (Arbanas et al. 2008).

Determination of the shear strength criteria and deformation modulus of flysch rock mass was based on the Geological Strength Index (GSI) concept (Hoek 1994; Hoek et al. 1995; Hoek et al. 1998; Marinos & Hoek 2000; Marinos & Hoek 2001, Marinos et al. 2005). Based on recommendations from Marinos and Hoek (2001), fresh (F) siltstone flysch rock mass is placed in group E to H, with GSI values from 30 to 10 (Arbanas et al. 2008; Brunčić 2008).

For determination of flysch rock mass strength, the Hoek-Brown failure criterion is used (Hoek et al. 2002) with uniaxial strength value (σ_c) of fresh (F) siltstone rock mass of 10 MPa and disturbance factor (D) of 0.7, which corresponds to machine excavation. In completely weathered (CW) flysch rock mass on the contact with clayey cover the Mohr-Coulomb criterion is adopted with strength parameters equal the parameters in the colluvial deposits and residuals soils ($\phi=26^o$, c=6 kPa) (Arbanas et al. 2008a; 2008b; Brunčić 2008).

Deformation characteristics of siltstone and other flysch components are even harder to determine than strength parameters. Since the stress-strain analyses are performed for the control of the behavior of the cuts in flysch rock mass based upon GSI concept of the rock mass, the determination of the deformation properties of the rock mass was performed by the use of the expression of Hoek, Carrranza-Torres and Corkum (Hoek et al., 2002; Hoek & Diederichs 2005). The proposed expression still shows the considerable deviations of the values of deformability modulus as compared to measured values during the cut excavation in the flysch rock mass. Based upon the previous cognitions, in the case of the behavior of the rock mass cut on the section of the Adriatic motorway was constructed in the Draga Valley, the proposed values are reduced by factor A, so the stress-strain analyses are performed by the use of expression (1):

$$E_m = A \cdot \left(1 - \frac{D}{2}\right)\sqrt{\frac{\sigma_c}{100}}10^{\frac{GSI-10}{40}} \qquad (1)$$

The values of the correction factor A vary from 0.05 to 0.09 (Brunčić 2008) The measurements performed by the use of measuring equipment during the excavations showed the relatively good agreement of the measured and proposed deformation strengths using mean value of A = 0.07 (Arbanas et al. 2008). Deformation modulus of flysch rock mass, obtained from back stress-strain analysis based on *in situ* measurement results show values of elastic modulus (E_m) of fresh (F) siltstones, which ranges form 80 to 200 MPa (Arbanas et al. 2007a).

3 SUPPORT SYSTEMS AND STABILIZATION OF CUTS IN FLYSCH ROCK MASS

During the construction of the described section of Adriatic motorway, on the major part of the road, the cutting in flysch slopes is designed and executed. To ensure stability of the cuts, the different types of support structure were adopted depending on the geological condition of analyzed location. On the locations with deep clayey cover the first choice is flattening or benching the slope of the cut, but because of strictness of motorway corridor, this method was uncommonly applicable. Stabilization the most of cuts in deep clayey cover were ensured with buttressing technique. Buttressing technique is used to offset or counter the driving forces of a slope by rock fill in the toe of the cut that increase the resisting force. The other role of the rock fill is to lowering the ground water level in the slope and moves the ground water table in the deep of the slope.

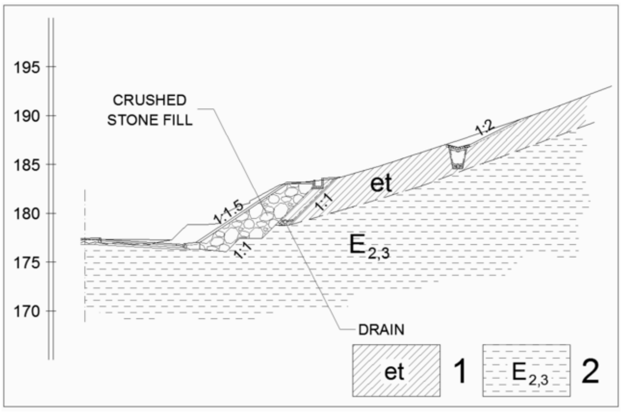

Figure 1. Buttressing on the slope in clayey cover (1.Clayey cover; 2.Flysch rock bedock).

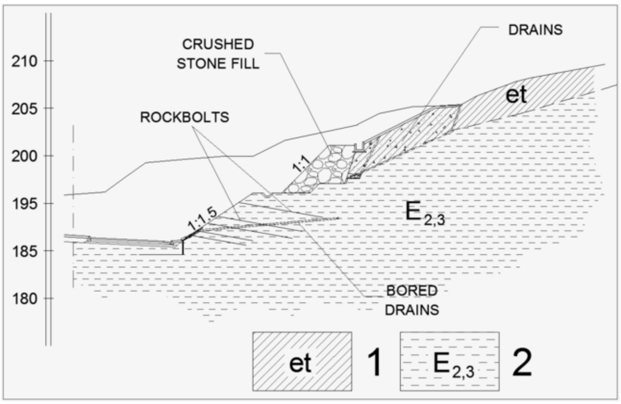

Figure 2. Buttressing on the slope partially in clayey cover (1.Clayey cover; 2.Flysch bedrock).

The buttressing techniques were adopted on the position where the cuts are completely in clayey formations (Figure 1) so as on location where the cuttings partially reach flysch bedrock (Figure 2, 3). The trenches in the outback of the rock fill were installed to decrease ground water level in the upper parts of the slope so as to scale up resistance of deposits.

Figure 3. Photo of buttressing on the slope partially in clayey cover.

The cut stability in the flysch rock mass was ensured by reinforcing of the cuts by rockbolts and appropriate supporting system. Because of steep slopes it wasn't possible to select a stable geometry on the most cuts in the flysch rock mass without additional reinforcement or support system. The support system was designed in two phases. The first phase was predicted rockbolt reinforcement system with multilayer sprayed concrete to enable stable excavation of the cuts with relatively low factors of safety. In the second phase, stiff concrete retaining construction was applied to fix relatively soft primary reinforcement system (Figure 4). On some locations, where this system can't ensure satisfying stability, the additional reinforced concrete grid construction with rock anchors was adopted.

The primary reinforcement systems were performed by excavation in the working stages, in longitudinal stories of 3.0 m height and a successive construction of a three-layered sprayed concrete support system reinforced by a self-boring rockbolts from top to bottom of the excavation. The stability of the cut in the flysch rock mass without applied support system is time dependent. The working stages are relative very short: excavation in one day, first layer of sprayed concrete and rockbolts installation in next two days, and additional two layers of sprayed concrete in next two days. Simultaneously with reinforcement support system deep drainage boreholes were drilled to allow dissipation of pore pressure and lowering of ground water in the cuts.

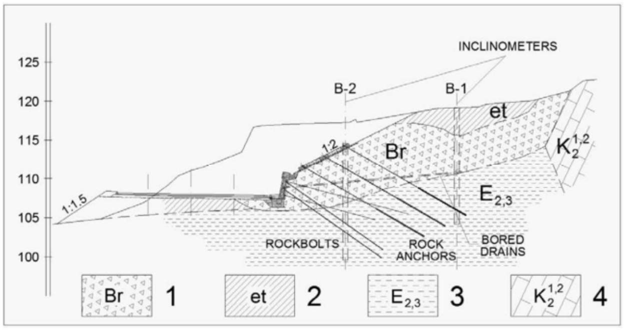

Figure 4. Reinforced cut in flysch formation (1.Breccia; 2.Clayey cover; 3.Flysch bedrock; 4.Limestone rocks).

During the cut construction a monitoring system was established. The monitoring system included measuring of deformation in horizontal deformeters and vertical inclinometers, geodetic surveying, so as measuring of the force rockbolts by installed load cells. The measured data enabled the control stress-strain back analysis to confirm parameters for describing the real behaviour of excavated and reinforced rock mass. Based on the results of these back analysis an active design procedure was established (Arbanas 2004; Arbanas et al. 2006; Kovačević 2003) which made possible the required changes in the rock mass reinforcement system in cuts if the observations indicates on unacceptable deformations.

4 STABILITY ANALYSIS OF CUTS IN FLYSCH ROCK MASS

To confirm the stability of the reinforced flysch rock mass cuts, limit state slope stability analyses and stress-strain analyses were carried out. Combination of these methods enables the understanding of reinforcement system behaviour (Arbanas 2004; Arbanas et al. 2006; 2007a; 2007b). Geotechnical model was established from prognosis engineering-geological cross-sections and appropriate classifications of rock flysch mass.

Stress-strain analyses were carried out with Sigma/W (Geo-Slope 1998) using finite elements method. Behaviour of the rock mass layers and soil (residual soil in slope formations) is reproduced with elastic-plastic model (Arbanas et al. 2008; Brunčić 2008).

An interactive rock mass excavation cut design, based on the observational method (Nicholson et al. 1999; Kovačević & Szavits-Nossan 2006; Arbanas et al. 2006) was introduced in the phase of the construction. Rock mass cut design methodologies were shown by Hoek and Bray (1977; Wyllie & Mah 2004) and have been amended to include the selection of support structures (Kovačević 2003; Arbanas et al. 2006) and the appropriate rockbolts.

Measured strain in the vertical inclinometers-extensometers (deformeters) and horizontal extensometers (deformeters) showed a good match with the predicted calculated strain for all excavation stages. To confirm designed support system, measured and calculated deformations of the slope are compared on the positions of the vertical and inclinometers and horizontal deformeters. The differences between measured and calculated displacement values were less than 4.0 mm during all stages of construction. Changes in reinforcement systems were rare and mostly caused with differences between predicted and actual geological conditions.

During the monitoring of cuts behavior in period of 2 years after construction, the long term deformations are observed. The analyses were indicated that the values of long term deformations in reinforced flysch rock cuts are significant in relation to the measured values of deformations during construction.

5 CONCLUSIONS

Significant properties of flysch formations, describing realistic values of strength and deformability parameters, were obtained based on preliminary investigations; experience gained during cut stabilization procedures in flysch rock mass, and during measurements and monitoring on installed equipment, and also based on back stress-strain analyses. The range of classification values for local flysch rock mass was defined more accurately in the scope of classification systems pertaining to heterogeneous rock materials. The analysis and construction of different support structures to ensure stability of cuts in flysch slopes are described. During the cut construction a monitoring system was established. The measured data enabled the control stress-strain back analysis to confirm parameters for describing the real behaviour of excavated and reinforced rock mass. Based on the results of these back analysis an active design procedure was established which made possible the required changes in the rock mass support systems if the observations indicates on unacceptable deformations.

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