Observational method for designing high cutting slopes in urban areas

La méthode des observation pour le designe les berges deterreés en surfaces urbaines

Drago Ocepek
Geoinženiring d.o.o., Ljubljana, Slovenia

ABSTRACT

Work for project of permanent supporting measures on high cutting slopes in urban areas consists of geological-geotechnical investigations and analysis of the quality of rocks, soft rocks and hard soils in the construction area. Though the primary goal of these investigations and analysis was the proper selection of the permanent retaining measures for cutting slopes during the phase of the main project, investigations and analysis must be continued through variable conditions during the excavations. Urban areas limited the space for designing cutting slopes in stable inclination without reinforcement. In this paper will be presented designing and excavation works with different reinforcement included monitoring of three high cutting slopes in Slovenia built of heterogeneous mixed hard to soft rock masses (Carboniferous-Permian mixed soft rock, Miocene argillite mixed serial of sandstones with silts stones layers and Clay shales and Eocene flish sediments).

RÉSUMÉ

Les oevres sur les projets des soutiens durables pour les berges deterreés (en surfaces urbaines) présentent les examins de geologie-geotechnologie et les analyses de la qualité des roches, des roches molles et des terres dures aux surface da la construction. L`intetion première de ce projet des examens et des analyses était choisir les soutienes durables pour les berges, mais on a constaté que les examens doivent être prolonger pendant les deterrements si il y a les conditions variables. Les surfaces urbaines sont limitées pour les projets avec l`inclination stable sans renforcement. Cet article presente les modèles et les oevres des deterrements avec les renforcement différents et "monitoring" les trois berges en Slovenie qui sont hétérogènes – les massifs rocheux et molles (Carbon-Perm formation, Miocene argilites et de flysh d`Eocene).

Keywords: geological strength index–GSI, disturbance factor-D, rock mass relaxation, numerical modeling, retaining measures, monitoring, finite element method-FEM, back analyses, strain softening.

1 INTRODUCTION

Permanent reinforcement for high cutting slopes requests the proper selection of the input data for stability and stress–strain analysis of excavation and supporting measures of slopes by the finite element method. Before the start of excavations work and after establishing the retaining measures, the analysis results are checked by monitoring, which will continue in the phase of exploitation of the objects in urban areas. New methods of design include the determination of post peak strength parameters of rock mass after relaxation beside routine measurements. In all cases where discontinuities play a significant role the rock mass structure must be considered included the determination of block geometry and kinematical analyses (Pötsch et al. 2006). In other circumstances, a rock may be uniform and reasonably isotropic by reason of the geometry of discontinuities and their mutual intersections. The suggested method of rock mass characterization allows rock mass classification for different rock quality, from blocky rocks to mixed rock masses. The value range of GSI (Marinos & Hoek 2000) is first determined in the beginning of investigation and later in the excavation phase considering the disturbance factor-D, which expresses disturbances caused by excavation methods and rock mass relaxation (Hoek & Diederisch 2006). The strength and deformability parameters of different rock quality are determined by the generalized Hoek & Brown failure criterion (Hoek et al. 2002) and cheked in construction phase.

Since the cost of these additional investigations and precise analysis with monitoring (Eurocode 7) is negligible in comparison with the costs of the permanent reinforcement if variable geological conditions were not too intensive, we would be able to reduce effectively the investment value of the structure (Ocepek 2005).

2 DESIGNING CUTTING SLOPES UNDER OBSERVATIONAL METHOD (EN 7)

The goal of basic geological-geotechnical investigations and analyses of the quality of rocks, soft rocks and soils for the designing of high cutting slopes is to establish the way and conditions for the excavation works and permanent reinforcement of slopes with proper selection of anti-erosion and retaining measures. With the project there have to be envisaged subsequently required changes and supplements during the performance itself, adapting to the actual geologic-geomechanical conditions. The project has to ensure the geological-geotechnical monitoring which will by means of precise engineering geological measurements give all required data of the area, structure and surface condition of discontinuities, lithological variation, grade of tectonic disturbance or erosion degradation processes and various conditions of excavation damages.

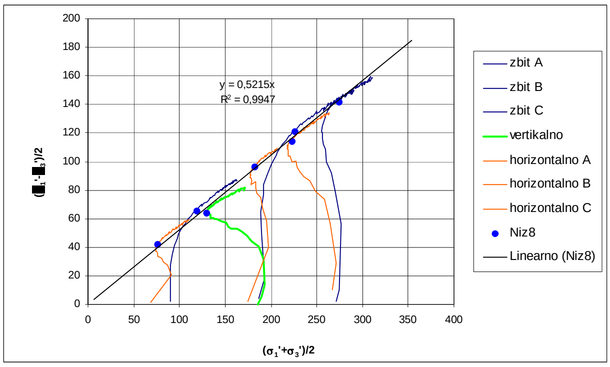
Generally the monitoring comprises the measurements of anchor forces, geodetic points built-in by the edges of slopes, measurements of deformations with the depth and groundwater level in built-in inclinometers. According to need also displacements of critical discontinuities are measured and spatial stress state with especially built-in cells (CSIRO). The monitoring has to be continued also in the phase of exploitation of structures, carefully observing all changes and consequently perform supplementary reinforcement of slope.

3 CASES OF DESIGNING THE PERMANENT PROTECTION OF HIGH CUTTING SLOPES UNDER THE MONITORING METHOD EN 7

3.1 *Permanent reinforcement of slopes in the construction area for oil tanks in Ortnek*

In the phase of investigations during the construction the slope was additionally engineering-geologically mapped already during the excavation works. Precise measurements of discontinuities were made and geological strength index GSI was established at the same time. Samples were taken from the cutting slope for triaxial shear and oedometric tests, mainly for the purpose of establishing the coefficient of rock permeability. For determination of deformation parameters the pressuremeter tests were performed in the anchored borehole.

The results of triaxial shear tests in addition to value range of GSI were included in the calculation of the generalized Hoek&Brown failure criterion. On the basis of established joint intersection system with planes of slopes the global spatial stability analysis was performed included the designed seismic acceleration. In addition the precise stage construction stress-strain analysis of all six excavation phases and built-in retaining measures were carried out as well as the analyses of the last phase of foundation of the oil tank. The stability of the entire excavation was established by hybrid analysis according to FEM (Geoslope, Sigma/W-Slope/W).



Picture 1: Stress paths of triaxial shear tests of seven samples of clay shale taken during the slope excavation with determined shear straight line.

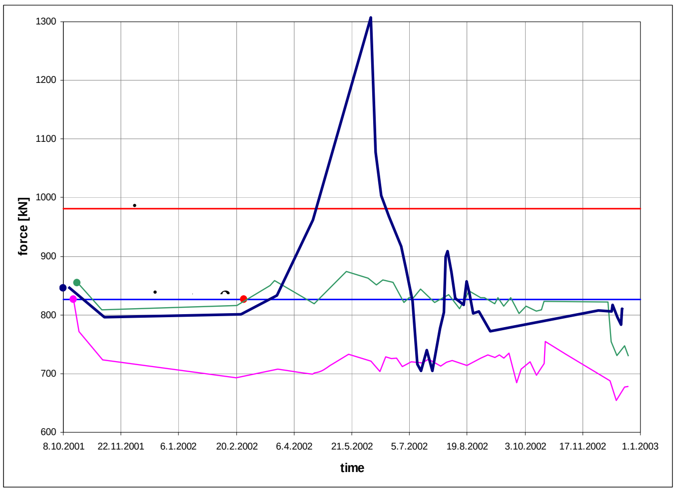
The investigation was carried out by Department of Soil mechanics with laboratory-FGG–University in Ljubljana. The results of investigation served for the numerical analyses of stress strain state during of the excavation and supporting measures.

Picture 2: The picture shows permanent reinforcement of the slope before the construction of oil-tanks. The protection is performed by five armored concrete beams tied up with permanent prestressed geotechnical anchors. Immediately after the excavation the slope was simultaneously sprayed with shotcrete in thickness d ≈ 0,2 m over heavy reinforcement meshes.

3.1.1 *Measurements of anchor forces*

Immediately after the testing and wedging of anchors on the designed force 834 kN (Fig. 3, horizontal blue line) of the anchors we began with measurements of anchor forces by means of electronic measuring devices. Measurements show changes of force with water pressures increase during strong rain (autumn-winter-spring) period and decrease of force after rock mass relaxation at the toe of the slope. The increase of force at the crest of slope is attributed to deformations as the consequence of discharge force after excavation; these deformations are predicted with the numerical model.

In the anchor, built-in in the second line of anchors in the area of about 20 m wide tectonic disturbed zone of intensively folded and sheared clay shale with layers of siltstone, the force osculates heavily (dark blue line). The force exceeded maximum numerical predicted (980 kN-red line). After the building-in of data logger, the measurements showed oscillating of anchor forces of the size range from 10 % to 25 % of the value of wedging force.



Picture 3: Diagram of anchor force vs. time of four measuring cells.

The comparison of monitoring results with predictions of numerical analyses indicates that the results are in satisfactory conformity. With the use of Mohr-Coulomb material models the predicted deformations and calculation forces in anchors are overestimated. The results of the whole monitoring in time period of five years show that the selected retaining measures ensure permanent global stability.

3.2 *The design and performance of permanent reinforcement of high cutting slopes in the area of the border - crossing Gruškovje*

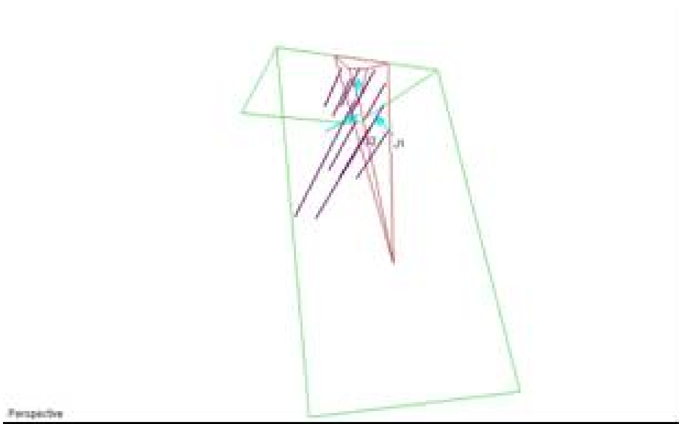
The project of retaining measures on high cutting slopes was done for the requirements of construction of international border-crossing Gruškovje. Prior to this, precise geological-geotechnical investigations and measurements had been carried out.

The main fault in this area crosses the valley of the stream "Maceljčica" in direction NW–SE and across both slopes and affects variously directed joint systems. Shear characteristics of joints were determined on the basis of evaluation of joint roughness coefficient JRC, joint compressive strength JCS, uniaxial compressive strength and basic friction angle of rock mass. Strength parameters of weathered and compact rock were obtained on the basis of simulation »large scale triaxial in situ test«. For the input data there were used a series of uniaxial compressive tests of the specimens taken from the bore-hole performed on the slope by means of diamante double core drilling included pressuremeter tests. GSI was established during detailed engineering geological mapping of the existing cutting slopes, additionally performed trial tits and during the core logging.

The stability of the cutting slope was established on characteristics profiles, where the cutting slopes reach the maximum height 63,5 m.

3.2.1 *Geological and geotechnical investigations in the construction phase*

The engineering geological works during the excavation of slopes included the measurements of surface condition of the newly excavated rock mass immediately after performed mechanical excavation and pre splitting. The lythological and structure variations, GSI and precise measurements of discontinuities were carried out.



Picture 4: 3 D wedge stability analysis by determination of retaining measures performed during the construction phase.

Spatial statistic analyses of discontinuity measurements and stability analyses of the critical intersection planes forming wedges were performed by the program – DIPS and SWEDGE (Rocscience).

Picture 5: Finale structure and protection of slopes.

The safety factor F = 1,25 was determined for permanent stability of the cutting slope in conformity with standards EN 7 (projecting in variable geotechnical conditions). The cutting slope has to be protected by mesh and sprayed concrete, reinforced by passive anchors, in the area of rupture zone of compressed slate siltstone in the lower part by the road also by anchored armored concrete columns.

3.2.2 *Numerical analysis of excavation and retaining measures*

Stress-strain analyses by FEM were performed by program packet Geoslope (SIGMA/W-SLOPE/W, version 5.15). The analyses comprised the initial stress state and stage construction phases of excavation and performance of retaining measures. Finally stability analyses were made by taking into consideration the changes of stress strain state. For the stress strain analysis the strain softening constitutive model was used for weathered and compact mixed Miocene rock mass

3.2.3 *Monitoring and servicing*

The monitoring has been carried out already during the construction works and is continuing in the phase of exploitation of the structure. It comprises measurements of deep deformations in four inclinometers, simultaneously with the measurements of groundwater level. Sixty measurement points are placed on the surface of slopes for displacements measurements. In addition, also the measurements of anchor forces are carried out on in-builed measurement cells. The project recommends four measurements per year in the phase of guarantee period, two measurements per year after this period and engineering-geologic supervisions once per year. Servicing require regular cleaning of weathered material from behind the anti-erosion meshes and regular cleaning of drain sewers on benches and outlets of deeply bored-in horizontal drains.

Table 1: Maximum sizes of vectors of deep displacements in inclinometers with depth

Inclinometer	Vector displacements	Depth
IPA- 1	2 cm	12 m
IPL-1	3,5 cm	12,5 m
IPL-2	1,2 cm	27 m
IPL-3	~3,7 cm	16 m

The monitoring results of deep movements in inclinometers match quite well with the numerical predicted deformations (FEM by using strain softening material model for weathered and compact mixed Miocene rock mass).

3.3 *Designing with monitoring of cutting slope of the blocks of flats “Semedela Bellevue”*

Engineering geologic mapping and boreholes equipped as inclinometers indicated that flysch layers are variably weathered in depth being at some places slightly folded and tectonically disturbed. The layers fall in under gentle inclinations into slope of designed structures entrenched into backside slope and the depth of two cellar floors. According to data of core logging the rock is weathered up to 7,0 m depth.

3.3.1 *GSI and pressuremeter tests*

On the basis of detailed core logging the rock mass was divided in three types. The following values of geological strength index with parallel results of measurements by pressuremeter are in next table:

Table 2

Surface quality	GSI	Pressuremeter modulus Ep1 (MPa)
Highly weathered flysh	23-27	-
Moderately weathered flysh	25-30	180 - 350
Slightly weathered flysh	40-43	450 - 750

3.3.2 *Laboratory tests*

Laboratory tests were performed in the laboratory for geomechanics, Geoinženiring d.o.o. In direct shear apparatus two intact specimen of soft rock were investigated. Two pieces of rock core were separately worked upon by diamante saw for uniaxial comprehensive strength tests with measurements of deformations, while thirty-nine pieces of rock were determined point strength index. The results of investigations are given in the following table:

Table 3

Material	φ_{dir} (°)	C kPa	σ_{max} MPa	Ei_{50} MPa	E_{ap*} MPa
Silt stone	20,8	9,4	0,8	100	10
Sandstone	19,6	35,1	13,6	-	-

*ap – after peak strength modulus of intact specimen

3.3.3 *Generalized Hoek & Brown failure criterion*

Generalized Hoek and Brown failure criterion (Hoek et all 2002 and Hoek, Diederisch 2006) was used for determining strength deformability parameters of mixed soft rock mass. The computer program Rocklab 1.21 enabled determination of deformability modulus after relaxation of rock mass. The following strength deformability parameters were determined:

Table 4

Rock Mass Type	φ_{rm} (°)	C (kPa)	Ei (MPa)
Moderately weathered flysh	25,77	35	458,72
Slightly weathered flysh	30,75	68	873,45

3.3.4 *Numerical analyses*

Numerical analyses were performed in the main project phase by program Geostudio (version 6.20). The analyses comprised the excavation performance and protection of permanent cutting slope at phases from behind the designed structures and excavation and slope protection of the construction pit (2 floors). At the same time the stability analyses of intermediate and final phase of excavation was calculated. The strain softening material model was used. The protection of slope was designed by means of anchoring with self-boring injection anchors, while for the protection of slope of construction pit the primary lining up to the level of block foundation was designed, reinforced by self-boring anchors.

3.3.5 *The performance of excavation and retaining measures under monitoring method EN 7*

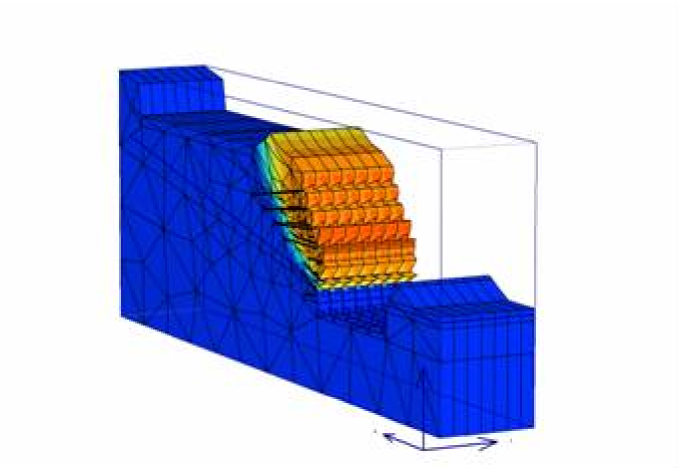
For the construction of designed terrace blocks up to 12 m high cuttings were performed into backside slope and up to 10 m deep excavations for the construction of underground garages. The construction is being carried out under monitoring method by means of monitoring device which includes the monitoring of excavation (simultaneous determination of GSI), measurements of deep displacements, ground water levels and measuring points. In the same way the condition of nearby structures is being observed (terrace arranged serial houses down to the bottom of the slope). The measurements are performed twice per month during the phase of construction works.

The construction is being performed under constant projecting geotechnical supervision, adapting the retaining measures to the actual geological-geomechanical conditions. The supervision showed that in left part of excavated pit appeared about 6 m wide tectonic zone with sub vertical discontinuities in sandstone and intermediate marl clay (alterated clay due to suction). By tectonic zone the layers direct up to 20° along the slope of construction pit, while at the same time small quantities of water leak out of the cracks in sandstone. Thus, a little too expeditious excavation under not-yet injected anchors brought about wedge failure of rock (about 40 m^3). The improvement of the slope was performed by the lining (heavy meshes and sprayed shotcrete d = 0,1 m) reinforced by self-boring injecting anchors of the length L = 6 m to12 m in a span of 1m.

In the central, not yet excavated part of the slope and construction pit at a distance of 12 m there appear three underground water-tanks for water supply of the town Koper, built in seventies and nineties in the former century. The most rigorous retaining measures were designed here: the protection of the 12 m height upper permanent slope in inclination 55° with self-boring injecting anchors Ø 38 mm of the length L = 8–14 m, in 2 m horizontal span and the performance of excavations in maximum floor height h = 2,5 m (4 floors). The backside of the 10 m height slope of the construction pit in inclination 80° shall have to be protected by primary lining (heavy meshes and sprayed shotcrete d = 0,1 m) reinforced by anchors of the length L = 6 m to 12 m, in 1,5 m horizontal span (4 floors).

The retaining measures were established by numerical analysis with the program Plaxis 3 D (version 2). The rock mass of this area was divided into three categories: moderately weathered flysch, weathered flysch and tectonically weakened flysch (additionally disturbated due to mining with performance of old water - tanks). This rock zone was performed within analysis by rock mass relaxation by means of disturbance factor D = 1 in Hoek & Brown failure criterion for slopes (Hoek, Diderisch, 2006).

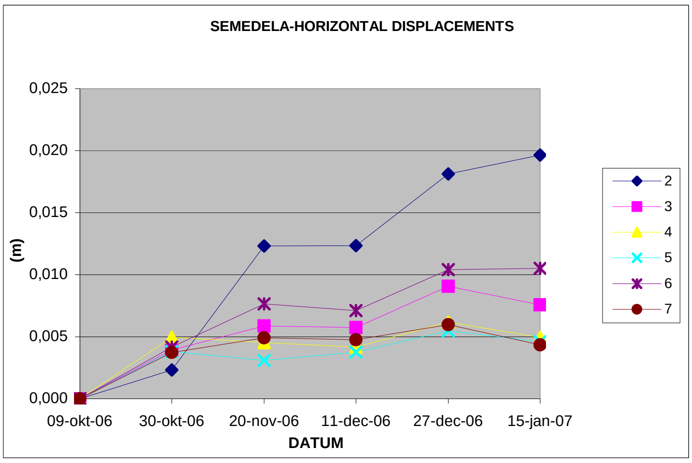
The next picture shows 3 D numerical model of excavation and slope protection to the bottom of the construction pit, with total deformations 2,2 cm.



Picture 8: Final stage after the excavation works and slope protection to the bottom of the construction pit, with total deformations amounting to u_{tot} = 2,2 cm.

Safety factor of permanent slope from behind the designed structures is F = 1,332, while safety factor during the excavation down to the bottom of construction pit is (temporary slope) F = 1,105 (Partial safety factors for projecting in variable geotechnical conditions EN7).

The next picture shows geodetic measurements of points on the crest of the excavated slope. The measurements conform quite well to the prediction of 3 D model, for which the material model with kinematical hardening was used for all three types of rock (Hardening soil–HS). This model proved to be optimal with projecting of retaining measures and predicted deformations in mixed soft rock masses.



Picture 8: Picture shows the geodetic measurements of points. Maximum deformations are at point 2 on the crest of the slope.

4 CONCLUSION

In addition to properly performed geological-geotechnical investigations and analyses in the phase of designing, the projecting of deep cuts displayed the need for thorough design of geologic-geotechnical monitoring of the construction. In this way the designed solution of protection of high cutting slopes will be optimally placed into given geologic-geotechnical situation. Thus, along with monitoring, the required safety is ensured during the excavation works with rational way of projecting as well. Immediately after each completed construction phase the monitoring has to be restored as to ensure the possibility of comparing the predicted deformations with actually calculated ones and to perform any additional retaining measures required. The usage of partial safety factors in conformity with geotechnical standard Eurocode 7 for variable geological-geomechanical conditions enables the adaptation to natural conditions.

With major deviations from the changes envisaged with the project, the supplementary geological-geomechanical investigations and analyses have to be done. In some cases the results of analyses enable optimal solution of retaining measures which brings to the lowering of the investment cost; however the changes that may appear during the works require reinforcing of the retaining measures, increasing the investment costs. In view of this the projecting in given geologic structure has to envisage the worst possible geomechanical conditions in particular if the basic geological-geomechanical investigations are not performed in satisfactory extent.

REFERENCES

Barton, N.R., Bandis, S.C. (1990) Rewiew of predictive capabilities of JRC-JCS model in Engineering practise. In Rock Joints, proc. Int. Symp. On rock joints. Leon. Norway. Editors: N. Barton and O. Stephansson, Rotterdam, Balkema.

Brinkgreve, R.B.J., Broere, W. (2004). PLAXIS – 3 D, TUNNEL, Version 2, 2600 An Delft, ISBN 90-808079-4-X

Crowder, J. J., Bawden, W. F. (2004). Review of Post-Peak Parameters and Behaviour of Rock Masses: Current Trends and Research. Rock News, October 2004, Lassonde Institute, University of Toronto, Toronto.

Hoek, E., Carranza–Torres, C. T., Cokum, B. (2002). Hoek & Brown failure criterion – 2002 edition. Proc. North American Rock Mechanics Society meeting in July 2002, Toronto.

Hoek. E, Diederisch M.S., Empirical estimation of rock mass modulus, International Journal of Rock Mechanics&Mining Sciences 43, 2006, 203 – 215.

Hoek E., Marinos, P. G, Marinos, V.P. (2005). Characterization and engineering properties of tectonically undisturbed but lithologically varied sedimentary rock masses. International Journal of Rock Mechanics & Mining Sciences 42, 277 – 285.

Kavvadas, M. J. (1998). Modelling the soil behaviour-Selection of soil parameters, Proceedings of the Second Int. Symp. on Hard Soils–Soft Rocks 1998. A. Evangelista, L. Picarelli: Balkema/Rotterdam/Brookfield, Vol 3, 1441–1461.

Marinos, P., Hoek, E. (2000). GSI: A geologically friendly tool for rock mass strength estimation. Int. Conference on Geotechnical and Geological Engineering, Geoeng 2000, Melbourne, Technomic Publishing Company, Inc. U. S. A., 1422 – 1440.

Ocepek, D., Vogrinčič, G. (2000). Critical State Approach to Stability of Clay Shale Designed Structures of the Motorway Trojane Blagovica. Int. Conference on Geotechnical and Geological Engineering, Geoeng 2000, Melbourne, Technomic Publishing Company, Inc. U. S. A.

Ocepek, D., (2005) New Trends in Rock Mass Characterization for Designing Geotechnical Structures, Acta Geotechnica Slovenica, L. Trauner, Univ. of Maribor, ISSN: 1854-0171

Pötsch, M., Schubert, W., Gaich, A., (2006), Kinematical analysis of rock blocks supported by 3 D imaging. In Proceedings of the 41st U.S. Rock Mechanics Symposium – Golden Rocks 2006, Paper No. 06-1079, under preparation.