Three-dimensional numerical modelling of a high slope cut in a rock mass having complex geological formations

La modélisation numérique tridimensionnelle d'une excavation dans une pente de grande hauteur dans une masse de roche ayant des formations géologiques complexes

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ABSTRACT

The paper describes the 3D numerical modelling studies of a 280 m height slope cut in a rock mass having complex geological formations. The modelling was carried out to evaluate both the static and dynamic stability of the projected rock slope, which will be located in northern Mexico. The construction site presents complex geological features like faults and dikes as well as several geological formations from varying qualities and fracture conditions. Available field data made it possible to incorporate the most important geological and topographical features with high degree of detail. The geomechanical model was developed into the commercial three-dimensional distinct element code 3DEC. This code was chosen because it has been widely used for rock mechanics problems and has been evaluated in a number of instances. Also, the code has a built-in programming language (FISH) that allows the user to expand the code's usefulness by using it as a numerical-analysis platform. Data available from field explorations allowed applying the Hoek-Brown and Bieniawski's criteria to estimate mechanical and elastic properties for the rock mass. These properties were consistent with in situ geophysical explorations. Before simulating the construction, an analysis was carried out for the pre-construction conditions under both static and dynamic loading as to validate the model's ability to represent the initially-stable site conditions. During the static analyses of the construction process, the full 3D model was used to simulate this process in four stages. A FISH function was implemented into the code to compute the factor of safety against material failure using the Mohr-Coulomb criteria in each excavation stage. The effect of blast damage and stress relaxation in the factor of safety was also investigated. After the construction simulation was done, a seismic motion was input at the model's base in the slope's normal direction. To substantially reduce the computing time due to the size and degree of detail of the model, dynamic analyses were performed on selected 3D portions (three-dimensional slices) of the model. However, these dynamic analyses simulated the true three-dimensional behavior by applying velocity conditions at the slices' outer boundaries, thus establishing continuity conditions at slices' lateral boundaries. This initial assessment of the rock-slope stability was carried out purposely to anticipate problems that may arise during the construction, and thus take decisions on the possible support measures.

RÉSUMÉ

L'article décrit les études de modélisation numérique tridimensionnelle d'une excavation dans une pente de plus de 280 m de haut dans un massif rocheux ayant des formations géologiques complexes. La modélisation a été effectuée pour évaluer la stabilité statique et dynamique de la pente de roche planifiée, qui sera située au nord du Mexique. Le chantier de construction présente des caractéristiques géologiques complexes comme des défauts et des digues aussi bien que plusieurs formations géologiques de qualités et états variables de rupture. Les données de champ disponibles ont permis l'incorporation des caractéristiques géologiques et topographiques les plus importantes avec un haut degré de détail. Le modèle géomécanique a été développé en utilisant le code tridimensionnel commercial d'élément distinct 3DEC (Three-dimensional Distinct Element Code). Ce code a été choisi parce qu'il a été employé couramment pour des problèmes de mécanique des roches et a été évalué dans un certain nombre de situations. En outre, le code a un langage de programmation intégré (FISH) qui permet à l'utilisateur d'augmenter l'utilité du code en employant le code comme plate-forme d'analyse numérique. Les données fournies par les explorations de champ ont permis l'application des critères de Hoek-Brown et de Bieniawski pour estimer les propriétés mécaniques et élastiques du massif rocheux. Ces propriétés étaient compatibles aux explorations géophysiques faites au chantier. Avant de simuler la construction, une analyse a été effectuée pour les conditions de pré construction sous le chargement statique et dynamique pour valider la capacité du modèle de représenter les conditions initialement stables du site. Pendant les analyses statiques du procédé de construction, le modèle complet en 3D a été employé pour simuler ce processus dans quatre étapes. Une fonction de FISH a été incluse dans le code pour calculer le coefficient de sécurité contre la fracture du matériau en utilisant les critères de Mohr-Coulomb dans chaque étape de l'excavation. L'effet provoqué dans le coefficient de sécurité par les dégâts dus à l'explosion et à la détente des efforts a été également étudié. Après que la simulation de construction a été faite, un mouvement séismique a été provoqué à la base du modèle dans la direction normale de la pente. Pour réduire sensiblement la durée de calcul due à la taille et au degré de détail du modèle, des analyses dynamiques ont été réalisées sur des portions 3D choisies (des tranches tridimensionnelles) du modèle. Cependant, ces analyses dynamiques ont simulé le véritable comportement tridimensionnel en appliquant des états de vitesse aux frontières externes des tranches, ainsi établissant continuité aux frontières latérales des tranches. Cette première évaluation de la stabilité de la pente de la roche a été destinée à être utile pour prévoir les problèmes qui peuvent surgir pendant la construction, et pour prendre des décisions sur les mesures possibles de soutien.

Keywords :Numerical modeling, Rock slope, Stability

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1 INTRODUCTION

An important hydroelectric project is to be constructed in northern Mexico. In order to build its spillway channel, a cut of 280 m height (at the maximum section) had to be made in a highly fractured, geologically complex rock mass. The spillway channel is 500 m long and 96 m wide at its base. To capture the most important topographical and geological features of the site, a three dimensional discrete element model was carried out. This method was used to account for the presence of rock fractures, faults and geological contacts prevailing on site. The numerical simulation was performed to investigate both static and dynamic stability of the rock cut. The model was built on the basis of geological, geophysical and topographical field survey results.

Information gathered from field explorations allowed applying both the Hoek-Brown and Bieniawski criteria to estimate mechanical and elastic properties for the rock mass. These properties were consistent with *in situ* geophysical explorations.

The stress relaxation and induced blast damage was accounted for through the damage index (Brady and Brown, 2004).

The model was validated through the simulation of the natural state of the rock mass before construction, by analyzing the factors of safety for this condition under Mohr-Coulomb failure criterion. Afterwards, the rock cut construction process was simulated in for consecutives excavation stages. Stress states, displacement fields and spatial distribution of factors of safety were computed for each stage.

The dynamic analysis was carried out considering both the design and the maximum credible earthquakes, which consisted in two synthetic motions (representative of the Mexican subduction earthquake-generating mechanism) with 200 and 10,000 years of return period, respectively, acting at the model's base.

2 NUMERICAL MODEL

Figure 1 depicts the geometry of the numerical model. It may be seen that the three dimensional topography of the site was fully accounted for, thus the excavation zone being analyzed was free from any boundary condition potential effects. The model consisted of 225,955 tetrahedral solid elements of constant strain, and 88,655 nodes.

The model was developed under the commercial discrete element code 3DEC (Itasca, 1998). The code was used as a numerical platform, as in-house sub-routines were coded into 3DEC's programming language, FISH, to account for contact properties set up, factor of safety computation, computation and plotting of relative displacement vectors during seismic analyses.

The code uses a time marching solving procedure and allows to explicitly modeling contacts and discontinuities between blocks. The interaction between blocks is modeled through stress – displacement relations by means of normal, Kn, and shear, Ks, stiffnesses for each contact. Internal stresses in each block are computed through finite difference method. The most important geological discontinuities and faults were included explicitly in the model, while the minor rock fractures interacting along the major discontinuities were taken into account considering the fractured rocks as a rock mass, according with the Hoek-Brown, and Bieniawski criteria. Figure 2 shows the spatial distribution of geological materials before the excavations, and figure 3 depicts the maximum section of rock cut, which will be used from here on to present some of the obtained results.

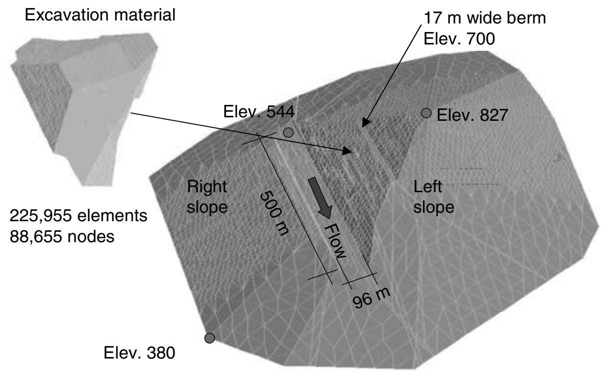


Figure 1. Numerical model

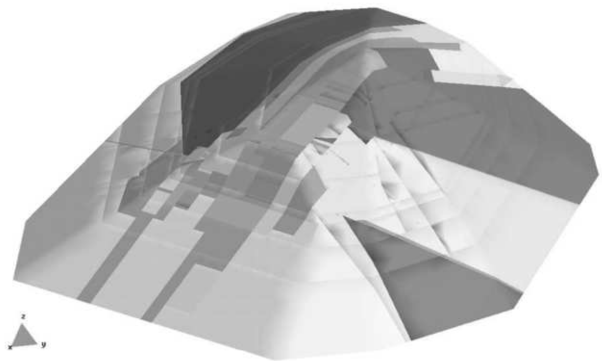


Figure 2. Spatial distribution of geological materials

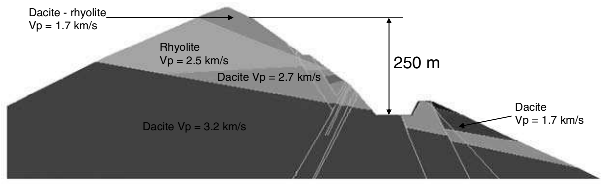


Figure 3. Maximum section of the slope

To obtain the mechanical and deformability properties of the rock mass, Hoek-Brown and Bieniawski criteria were used. To this end, RQD calculations for rock in situ were performed, as well as compression resistance for intact rock from boring samples were obtained. The state of discontinuities in the rock mass (separation, longitude, opening, roughness, filling, humidity, etc) was also investigated to fulfill the requisites of both geomechanical criteria. The corresponding properties of rock mass are shown in Table 1.

Table 1. Rock mass properties

Material	Em (MPa)	ν	ρ (kg/m^3)	V_s (m/s)	V_p (m/s)	C (MPa)	ϕ
Dyke (andesite)	841	0.35	2500	353	735	0.03	25
Vertedor fault	1000	0.35	2500	385	801	0.15	26
Dacite-rhyolite Vp = 1.7 km/s	4500	0.35	2500	816	1700	0.34	34
Vitreous tuff	1679	0.35	2500	499	1038	0.28	33
Brecha decomprimida	2512	0.35	2500	610	1270	0.91	39
Uncompressed dacite	3981	0.35	2500	768	1599	1.01	41
Fractured breccia Vp = 2.5 km/s	9700	0.35	2500	1199	2495	1.68	44
Dacite Vp = 2.7 km/s	11300	0.35	2500	1294	2693	2.41	47
Dacite Vp = 3.2 km/s	17783	0.35	2500	1623	3379	4.36	49
Dacite Vp = 3.8 km/s	22500	0.35	2500	1826	3801	2.84	49

Discontinuities normal and shear stiffnesses were estimated from the Young and shear rock mass modulus, as well as from field data (Brady and Brown, 2004). All contacts were considered entirely frictional (zero cohesion). The static friction angle for each discontinuity was selected based in reported experiences by Byerlee (1978). Dynamic friction angle was taken equal to the static value. Table 2 shows discontinuities properties for each material.

Table 2. Discontinuities properties

Material	K_n (Mpa/m)	K_s (Mpa/m)
Dyke zone	252	93
Vertedor fault	300	111
Vitreous tuff	504	187
Uncompressed breccia	754	279
Uncompressed dacite	1194	442
Dacite-rhyolite Vp = 1.7 km/s	1350	500
Fractured breccia Vp = 2.5 km/s	871	323
Dacite Vp = 2.7 km/s	994	368
Dacite Vp = 3.2 km/s	1090	404
Dacite Vp = 3.8 km/s	1133	420

3 SITE ANALYSIS BEFORE EXCAVATION

Before the excavation process was simulated, the site was analyzed under its original configuration for static and dynamic conditions. The resulting factor of safety distribution indicates that the slope is stable for the initial stress state (figure 4). Seismic analyses results are presented in the corresponding section further down in the paper.

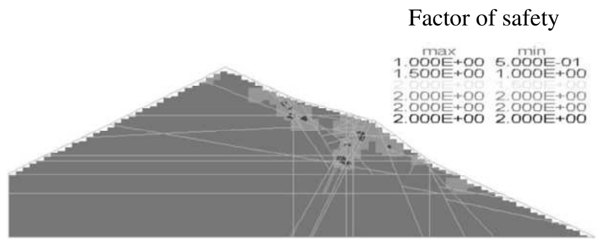
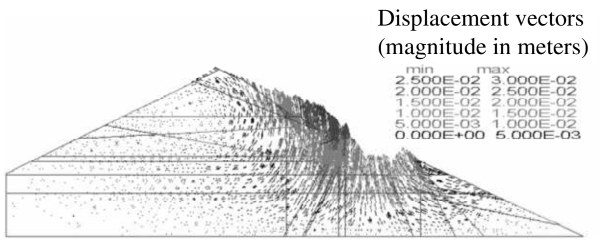


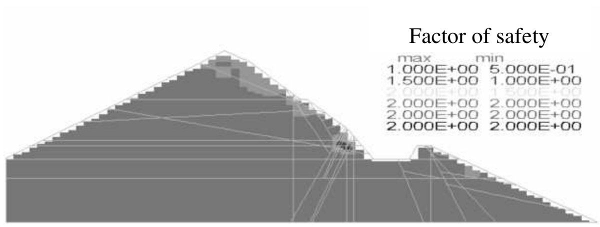
Figure 4. Security factor before excavation in maximum section

4 EXCAVATION PROCESS SIMULATION

The excavation process from elevation 824 to 544 was simulated in four stages. Displacements and factors of safety were computed for each stage to evaluate any potential sliding in the slope. The results indicated that after the excavation process the displacement field was due to expansions in the rocks caused by stress relaxation, as shown in figure 5. The factor of safety distribution was considered adequate to maintain slope stability, as seen in figure 6.



4.1 *Figrue 5. Displacement vectors at maximum slope section*



Figrue 6. Security factor at maximum slope section

5 EFFECT OF EXCAVATION PROCESS IN THE ROCK MASS AND ITS IMPLICATION IN THE SECURITY FACTOR

The damage induced to the rock during blasting and excavation activities was evaluated using the Hoek-Brown criterion. According to Brady and Brown (2004), if the excavation process is executed with high quality, the induced damage to the rock is about 30 %. This damage level is represented through the damage index, D (Brady and Brown, 2004), which varies from 1 (100 % damage) to 0 (0% damage). Figure 7 presents the Hoek-Brown failure envelopes for one of the geological materials considered. These envelopes were computed for damage conditions of 50% and 70%. Results of factors of safety for the 70% damage condition are presented in figure 8, where it is seen that a zone of low factor of safety develops in the higher zone of the slope. According to filed surveys, the rock in that area is highly fractured, thus it is likely that the excavation process will induce damage to it, and possibly be the cause of rock falls during the construction process. Thus care must be taken to control them as the excavation proceeds.

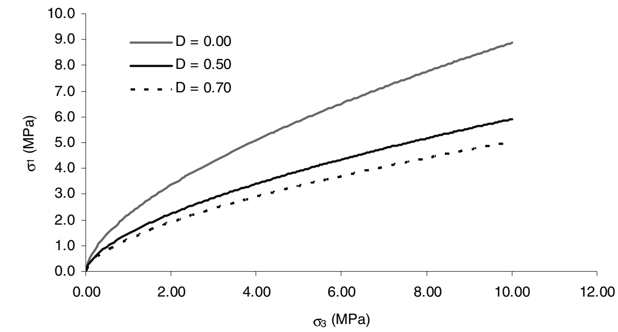


Figure 7. Hoek and Brown failure envelopes for rock mass damage

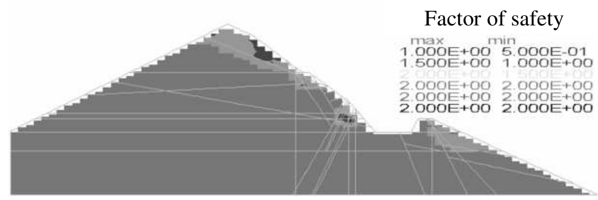


Figure 8. Factor of safety affected by damage index

6 SEISMIC ANALYSES

To avoid excessively large computing time, seismic analyses were performed individually for several portions of the full 3D model. Each portion was kept three-dimensional but considering that no normal strain developed on the lateral boundaries.

The dynamic response of the slope was computed for the design earthquake, as well as for the maximum credible earthquake. The design earthquake had a return period of 200 years (Tr200), and the maximum credible earthquake had a return period of 10,000 years (Tr10000). These two motions were input at the base of a numerical model that included the valley and the dam body of the hydroelectric project (Romo *et. al.*, 2006). The dynamic response at the spillway zone was monitored in the slope's transverse direction and the corresponding signal was used as the input motion of the spillway numerical model (figure 1) to compute the slope's earthquake response.

6.1 *Design earthquake*

First, the seismic analysis of the whole model, before the excavation process, was carried out to study site's initial conditions. Figure 9 shows the relative displacement vectors at the end of the Tr200 earthquake. The results indicate small displacement of the order of 3 cm. These movements are not relevant for the overall slope stability.

Figure 10 shows the relative displacements at the end of the design (Tr200) earthquake. It is seen in this figure that the material at slope's top has up to 40 cm of displacement. This displacement is important and measures should be taken to stabilize that area.

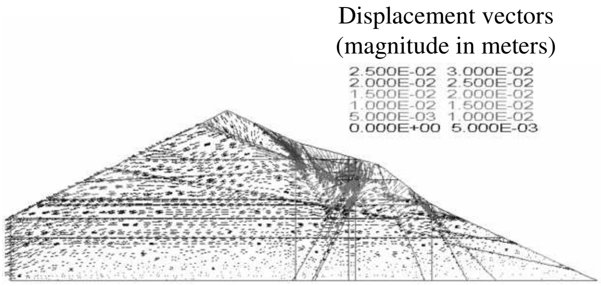


Figure 9. Resultant displacement at initial slope conformation

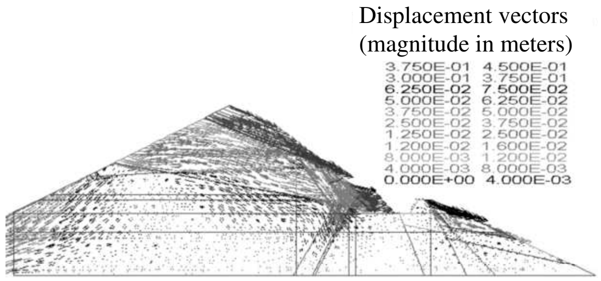


Figure 10. Relative displacements at the end of design earthquake

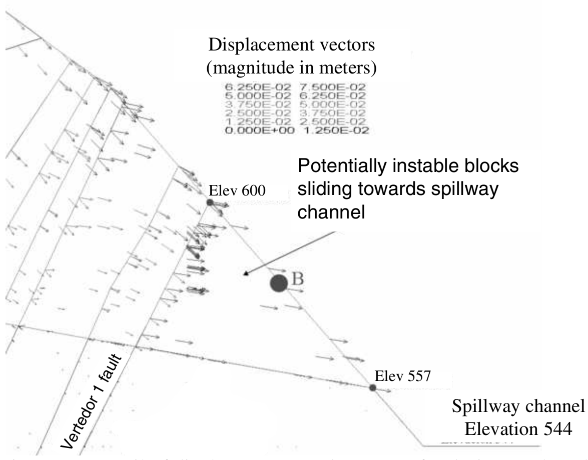


Figure 11. Detail of displacements at slope's toe for design earthquake

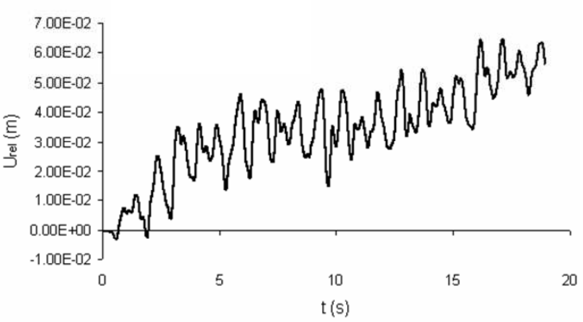


Figure 12. Displacement evolution at point B during design earthquake

A detail of slope's displacements at its toe is shown in figure 11. It is seen here that there exists potentially instable blocks sliding towards the spillway channel. The computed displacements are around 6 cm. Figure 12 depicts the displacement evolution at point B during the earthquake. These areas should be stabilized to avoid excessive rock debris during seismic events, and to augment slope's stability during earthquake episodes.

6.2 *Maximum credible earthquake*

The maximum credible earthquake is a very severe seismic event, with a 10,000 years return period. Slope displacements at the end of this earthquake increase dramatically with respect to the design earthquake. At slope's top the displacements are excessively large, thus indicating failure on this zone of the slope. The ideal solution to this problem would be to remove the material at slope top. Displacements at slope's toe also increase strongly, as shown in figure 14. Displacement magnitudes in the toe reach about 40 cm, thus indicating possible block detachments under the action of the maximum credible earthquake. Since this is a local failure it could be stabilized mechanically to avoid stability problems.

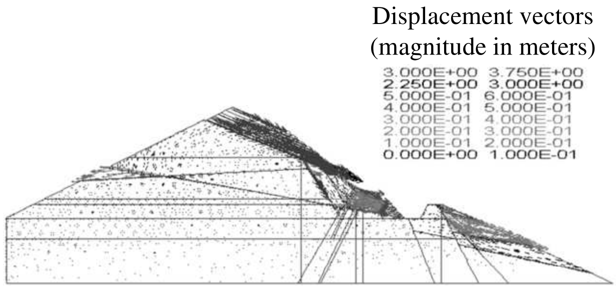


Figure 13. Relative displacements at the end of Tr10000 earthquake

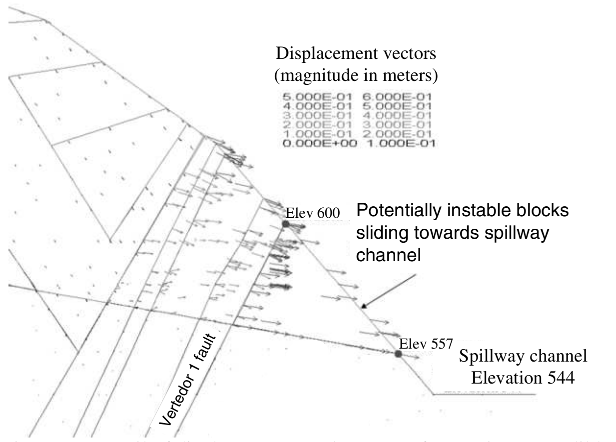


Figure 14. Detail of displacements at slope's toe for maximum credible earthquake (Tr10000)

7 CONCLUSIONS

From the analyses performed, it can be concluded that numerical modelling is an important tool in the assessment of geomechanical projects. Results from such analyses allow forestalling possible problems that may arise during the project execution. Also, numerical modelling is a helpful tool for selecting the zones where detailed monitoring should be carried out. However, the numerical models, as it is well known, should be fed with realistic material properties obtained from laboratory and/or field tests in order to obtain meaningful results. The project is being executed without any major problems so far, in accordance with numerical results for the excavation stage.

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