Technical Note

Use of the Distinct Element Method as a Tool to Detect Stability Problems in Deep Spillway Excavations

• Eduardo Botero-Jaramillo* • Miguel P. Romo • Bogart Méndez •
Universidad Nacional Autónoma de México
*Autor de correspondencia

• Humberto Marengo •
Comisión Federal de Electricidad

Abstract

Botero-Jaramillo, E., Romo, M. P., Méndez, B., & Marengo, H. (July-August, 2014). Use of the Distinct Element Method as a Tool to Detect Stability Problems in Deep Spillway Excavations. *Water Technology and Sciences* (in Spanish), *5*(4), 187-196.

This paper describes a study to determine the stability of rock excavations in the La Yesca spillway channel using numerical analysis. The results of the analysis led to implementing important changes in the original conception of the spillway (reorientation, channel geometry and length) in order to ensure rock slope stability under static and seismic conditions. This paper describes the 3D numerical modeling of a 280 m high slope (corresponding to the original project) cut in a rock mass having complex geological formations. The modeling was carried out to evaluate both the static and dynamic stability of the projected rock slope. The construction site presented complex geological features such as faults and dikes as well as several geological formations resulting from varying qualities and fracture conditions. Available field data made it possible to incorporate the most important geological and topographical features. The spillway excavation was simulated using four stages. The effect of blast-induced damage and stress relaxation on the rock mass was also taken into account. After the simulation of the excavation process was completed, the seismic motion design for the La Yesca dam was input. These dynamic analysis simulated the three-dimensional behavior of the spillway which enabled identifying possible block instabilities, thereby determining whether to stabilize them or modify the original spillway layout.

Keywords: Distinct element method, seismic analysis, slope stability, spillway problems.

Resumen

Botero-Jaramillo, E., Romo, M. P., Méndez, B., & Marengo, H. (julio-agosto, 2014). El uso del método de los elementos distintos como una herramienta para la detección de problemas de estabilidad en las excavaciones del vertedero profundas. Tecnología y Ciencias del Agua, 5*(4), 187-196.*

Este trabajo describe un estudio para determinar la estabilidad de las excavaciones en roca para el canal del vertedor de La Yesca utilizando análisis numéricos. Los resultados llevaron a la implementación de cambios importantes en la concepción original del vertedor (reorientación, geometría del canal y longitud), con el fin de garantizar la estabilidad de los taludes de roca en condiciones estática y sísmica. Se detalla el modelado numérico 3D de un talud de 280 m (correspondiente al proyecto original) construido en un macizo rocoso que tiene estructuras geológicas complejas. El modelado se llevó a cabo para evaluar la estabilidad estática y dinámica del talud proyectado en roca. El sitio de construcción presenta características geológicas complejas, como fallas y diques, así como varias formaciones geológicas resultantes de diferentes calidades de la roca y condiciones de fracturamiento. Los datos del campo disponibles hicieron posible la incorporación de la mayoría de las características geológicas y topográficas más importantes. La excavación del vertedor se simuló utilizando cuatro etapas. El efecto del daño inducido por las voladuras y la relajación de esfuerzos en la masa de roca también se tuvo en cuenta. Posterior a la simulación del proceso de excavación, se implementó el sismo de diseño de la presa La Yesca. Los análisis dinámicos simularon el comportamiento en tres dimensiones del vertedor, lo cual permitió la identificación de posibles bloques inestables, determinando de este modo si era posible estabilizarlos o modificar el diseño del vertedor original.

Palabras clave: *método de los elementos diferentes, análisis sísmico, estabilidad de taludes, problemas de vertedores.*

Introduction

La Yesca is an important hydroelectric project (750 MW) located in north-western Mexico, over the Santiago River, at the limit between the states of Jalisco and Nayarit. The construction of the spillway channel implied a cut as high as 280 m height (see figure 1) in highly fractured, geologically complex rock mass which was of great concern. The original design of the spillway consisted of a single channel 500 m long and 96 m wide at its base. The main topographical and geological features of the site were captured in a three dimensional discrete element model that takes into account such features as the presence of rock fractures, faults, joints and geological contacts. The representative geological discontinuities were explicitly modeled and massive fracturing in the rock was accounted for by representing these materials as a rock mass, according to the Hoek-Brown criteria (1997). The poor hydraulic behavior of the spillway due to its partial obstruction due to falls of slope rocks possess a great risk to the dam safety. Accordingly, given the great importance spillways have on the safe behavior of dams, it was deemed of most importance to perform detailed numerical analysis to evaluate the slope safety of the high rock cuts. This article presents the analysis carried out for the original design of the spillway of La Yesca Dam and the decisions taken to decrease excavation-associated risks.

The numerical model was first assessed by evaluating the stability of the rock mass before its excavation and then compared with the observed stable conditions of the rock mass over the time. Afterwards, the rock cut was simulated in four consecutive excavation stages. Stress states, displacement fields and spatial distribution of factors of safety were computed for each step. Finally, the dynamic stability analysis was carried out considering both the Operating Basis Earthquake (OBE) and Maximum Credible Earthquake (MCE), which are two synthetic motions proposed by the International Commission of Large Dams (ICOLD, 2010) representative of the site seismic environment (in this case of the Mexican subduction earthquake-generating mechanism) with 200 and 10 000 years of return period, respectively. On the bases of the analysis results, the risks associated to the spillway original lay out were assessed and decisions were taken.

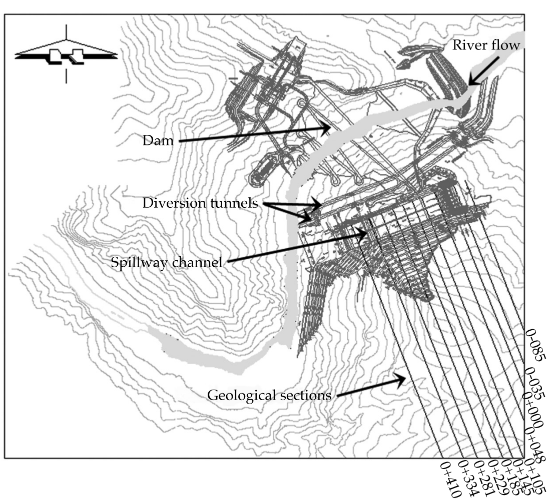


Figure 1. Original project of the spillway channel.

Site exploration

The site geological materials characterization was carried out based on a broad geological and geophysical exploration (CFE, 2006). They are predominantly volcanic, but some alluvial and talus deposits were also found. The igneous rocks are heavily fractured and some dikes are present. The main lithological units include dacites, rhyolites, andesites, breccias and tuffs. Several faults are present in the region, being the Vertedor fault the more important. Figure 2 shows the fractures, faults and the spatial distribution of geomaterials at the main section of the spillway. The trace of the slope excavation is included as a reference, where the stepped line (blue line) depicts the initial excavation perimeter and the continuous line (red line) illustrates the average inclination of the model slope. The circled numbers allude to specific materials, which are presented in table 1. Given the length of the spillway, it is understood that not all of existing materials are visible in the section shown in this figure.

Material properties

Rock mass properties

Triaxial tests were carried out on intact rock. The results were used along with the estimated

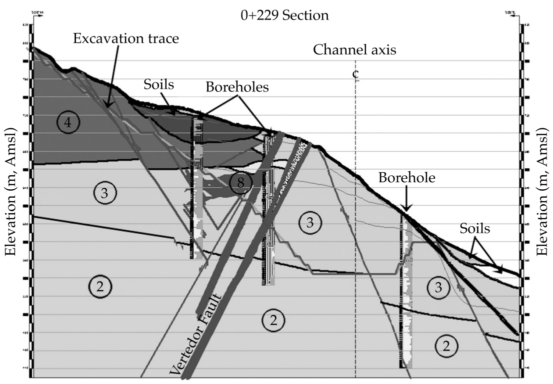


Figure 2. Geological structures at main section of the spillway.

values of the Geological Strength Index (GSI), obtained from field observations, to determinate strength and deformability properties for the geomateriales using the Hoek and Brown failure criterion for jointed rock masses (Hoek & Brown, 1997; Hoek, Carranza-Torres, & Corkum, 2002). The elasticity modulus E_m was estimated for two construction rock conditions: zero damage, D = 1 and D = 0.7, which is related to a moderate damage, induced by an adequate and controlled excavation process (Brady & Brown, 2004). The compression wave velocity for the constitutive materials, V_p, was measured from geophysical explorations (see table 1). The Hoek and Brown failure criterion was used for all materials and it was related with Coulomb's failure criterion to estimating an equivalent friction angle, ϕ', and a cohesive strength, c', according to equations (1) to (3):

$$\sin \phi = \frac{k-1}{k+1} \quad (1)$$

$$c' = \frac{\sigma_{cm}}{2\sqrt{k}} \quad (2)$$

$$\sigma_{cm} = \sigma_{ci} s^{a} \quad (3)$$

Where k is the slope of the line relating the major and minor principal stresses σ'_1 and σ'_3; σ_{cm} and σ_{ci} are the uniaxial compressive strengths of the rock mass and intact rock, respectively; s and a are constants which depend upon the rock mass characteristics. The variation of ϕ' and c' were obtained as a function of σ'_3, through a fitting process (Hoek & Brown, 1997):

$$\sin \phi = \frac{6\, a\, m_b \left(s + m_b\, \sigma'_{3n}\right)^{a-1}}{2(1+a)(2+a) + 6\, a\, m_b \left(s + m_b\, \sigma'_{3n}\right)^{a-1}} \quad (4)$$

$$c' = \sigma_{ci} \cdot \frac{\left[(1+2\,a)\, s + (1-a)\, m_b\, \sigma'_{3n}\right]\left(s + m_b\, \sigma'_{3n}\right)^{a-1}}{(1+a)(2+a)\sqrt{1 + \left[6\, a\, m_b \left(s + m_b \sigma'_{3n}\right)^{a-1}\right] / \left[(1+a)(2+a)\right]}} \quad (5)$$

Table 1. Material properties.

Material	ρ (kg/m³)	ν	m_b
1. Dacite V_p = 3.8 km/s	2 500	0.35	6.25
2. Dacite V_p = 3.2 km/s	2 500	0.35	6.71
3. Dacite V_p = 2.7 km/s	2 500	0.35	4.69
4. Fractured breccia V_p = 2.5 km/s	2 500	0.35	3.34
5. Uncompressed dacite	2 500	0.35	2.37
6. Uncompressed breccia	2 500	0.35	1.78
7. Dacite-rhyolite V_p = 1.7 km/s	2 500	0.35	1.64
8. Dyke (andesite)	1 680	0.35	0.80
9. Vertedor fault	2 500	0.35	0.93
10. Vitreous tuff	2 500	0.35	1.19

Where m_b is the value of the constant m (see table 1) for the rock mass and $\sigma'_3 = \sigma'_{3máx}/\sigma_{ci}$ is the upper limit of confining stress over which the relationship between the Hoek and Brown and the Mohr-Coulomb criteria are considered. Its value was determined from the theory of elasticity, where the stress ratio σ'_3/σ'_1 for the k_0 condition is given by:

$$\frac{\sigma'_3}{\sigma'_1} = k_0 = \frac{\nu}{1-\nu} \qquad (6)$$

The in situ σ'_1 stresses were determined from a geostatic stress field. Accordingly, σ'_{3max} was computed using eq. (6) and the Poisson ratios, ν, given in table 1. The values of c' and ϕ' (obtained from equations (4) and (5), respectively), as well as other strength parameters, computed for each material in the range $0 < \sigma'_3 < \sigma'_{3max}$ are given in table 2.

Rock blocks contact properties

The numerical method used for the analysis has a soft contact formulation, which uses normal, k_n, and shear, k_s, stiffnesses and a yield criterion to simulate joint behavior. The Mohr-Coulomb joint model was used given its simplicity and its proven applicability to complex friction problems. The friction resistance τ' (as a function of σ'_n) between rocks blocks considered was $\tau' = 0.85\,\sigma'_n$ for $\sigma'_n < 200$ MPa and $\tau' = 0.50 + 0.60\,\sigma'_n$ for $\sigma'_n > 200$ MPa (Byerlee, 1978). It is worth mentioning that the maximum principal stress value computed in the numerical model was much lower than 200 MPa which in accordance with Byerlee (1978) would yield a friction coefficient of 0.85 (ϕ' approximately equal to 40°). Given the many uncertainties involved in the rock-rock friction problem, it was judged convenient to assume a conservative maximum value of 36^0. The minimum value was assumed 25°, which corresponds to the minimum value obtained through the Hoek-Brown criterion (see table 2). Table 3 shows the actual values used for each material contact. It is important to stress the fact that when two different materials were in contact, the lowest friction angle was considered.

The magnitude of k_n is computed through k_s, assuming an elastic relation between them (Kulhawy, 1975):

$$k_s = \frac{k_n}{2(1+\nu)}; \quad k_n = 2\,k_s\left(1+\upsilon\right) \qquad (7)$$

Where ν the joint material Poisson's ratio, and k_s is the shear stiffnesses included in table (3).

Table 2. Strength parameters of rock material.

Material	c' (MPa)	ϕ'	σ_{cm} (MPa)
1. Dacite $V_p = 3.8$ km/s	2.84	49	8.60
2. Dacite $V_p = 3.2$ km/s	4.36	49	14.13
3. Dacite $V_p = 2.7$ km/s	2.41	47	5.42
4. Fractured breccia $V_p = 2.5$ km/s	1.68	44	3.33
5. Uncompressed dacite	1.01	41	1.13
6. Uncompressed breccia	0.91	39	0.64
7. Dacite-rhyolite $V_p = 1.7$ km/s	0.34	34	0.39
8. Dyke (andesite)	0.03	25	0.14
9. Vertedor fault	0.15	26	0.22
10. Vitreous tuff	0.28	33	0.28

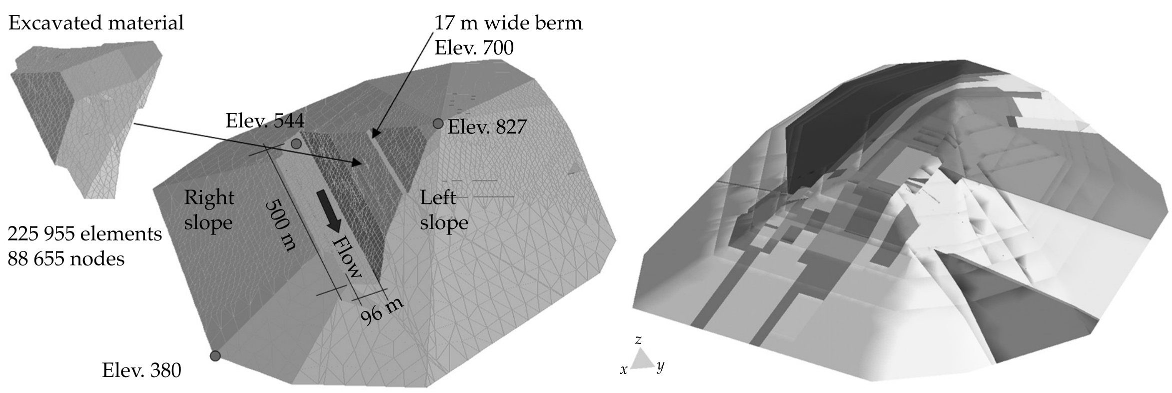
Table 3. Contact properties.

Material	ϕ'	τ' (MPa)	U_c (m)	k_n (MPa/m)	k_s (MPa/m)
1. Dacite V_p = 3.8 km/s	36	1.73	0.004	1 168	433
2. Dacite V_p = 3.2 km/s	36	1.62	0.004	1 093	405
3. Dacite V_p = 2.7 km/s	36	1.80	0.005	972	360
4. Fractured breccia V_p = 2.5 km/s	30	1.94	0.006	872	323
5. Uncompressed dacite	30	2.07	0.006	934	346
6. Uncompressed breccia	30	2.13	0.007	820	304
7. Dacite-rhyolite V_p = 1.7 km/s	30	2.22	0.007	854	316
8. Dyke (andesite)	25	2.33	0.015	420	155
9. Vertedor fault	25	2.31	0.015	416	154
10 Vitreous tuff	27	2.28	0.015	410	152

Numerical model

The numerical model was properly designed so that its boundary conditions would not affect the results of the excavation process (figure 3). The model consisted of 225 955 tetrahedral solid elements of constant strain, and 88 655 nodes. The model was built from 11 geological sections roughly spaced every 50 m along the spillway channel (see figure 1). From elevation 544 to 624 amsl (above mean sea level), the left slope of the excavation was modeled with an inclination of 0.88:1 (H:V); from 624 to 700 amsl the slope inclination was 1.40:1; and from 700 amsl to the top of the slope, the inclination was 1.33:1. The right slope of the spillway channel had a constant inclination along its height (elevation 544 to 580 amsl) of 0.54:1.

The numerical model is based on a time marching solving procedure finite difference which allows to explicitly simulating the contacts and discontinuities between blocks. The interaction between blocks is accounted for through stress-displacement relationships for each contact. Internal stresses in each block are computed through the finite difference method.



(a) (b)

Figure 3. 3D geometry of the numerical model.

The most important geological discontinuities and faults were included 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 (Hoek & Brown, 1997).

Site initial conditions

The results of the static and seismic (OBE and MCE seismic conditions) calculations of the site initial conditions showed no indication of any instability, which agrees with the historical stability of the rock mass.

Excavation process simulation

The excavation process from elevation 827 to 544 amsl was simulated in four stages. Displacements and factors of safety were computed for each stage to evaluate any potential slope sliding during the excavation process. The results indicate that after the excavation was completed, the displacement field was mainly due to expansion of the rocks caused by stress relaxation, as shown in figure 4(a) through 4(d). The analysis show that the excavation process most likely will not induce massive rock falls. However, in figure 5(a) through 5(d) it is seen that the safety factor in some areas of the slope indicates that instabilities are likely to occur during the construction process. Accordingly, it was considered that important amounts of debris could fall down hill, jeopardizing the stable construction of the spillway slopes.

Effect of excavation process in the rock mass and its implication in the factor of safety

Due to the excavation process the rock mass suffers some damage causing strength reductions mainly near to the slope surface. Accordingly, a damage factor of 0.7 was considered, which corresponds to a good quality excavation process (Brady & Brown, 2004). Figure 5d shows the factor of safety distribution in the maximum slope section for this damaged condition. It is noticeable that a zone of low factor of safety develops at the top of the slope. These results suggest that potential rock instabilities are likely to unfold during the construction process, thus indicating that the excavation should be properly monitored to

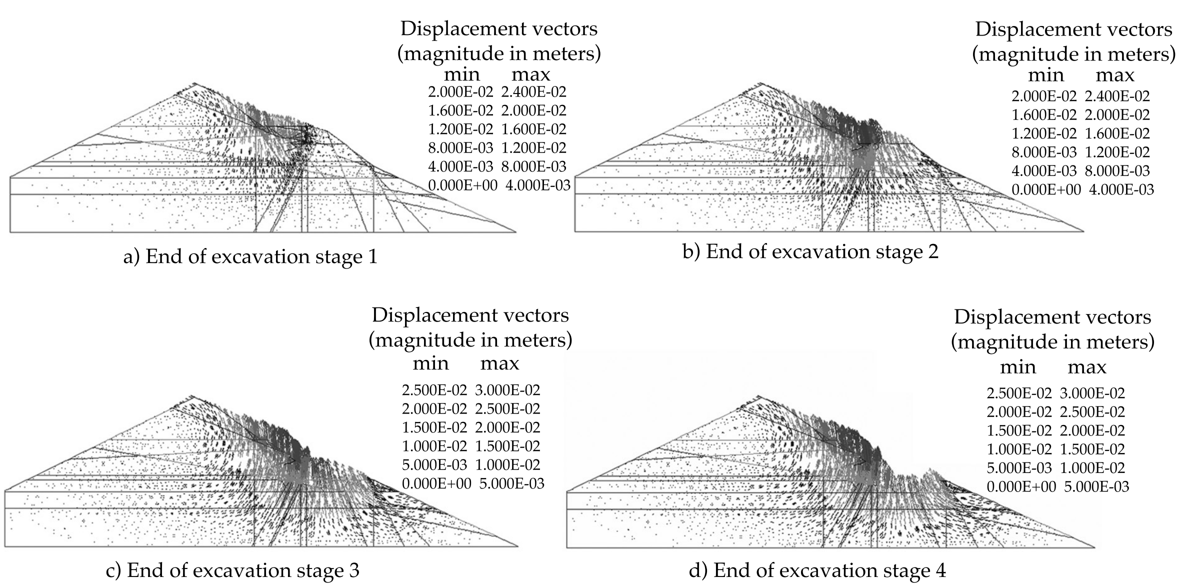


Figure 4. Resultant displacement field due to excavation process.

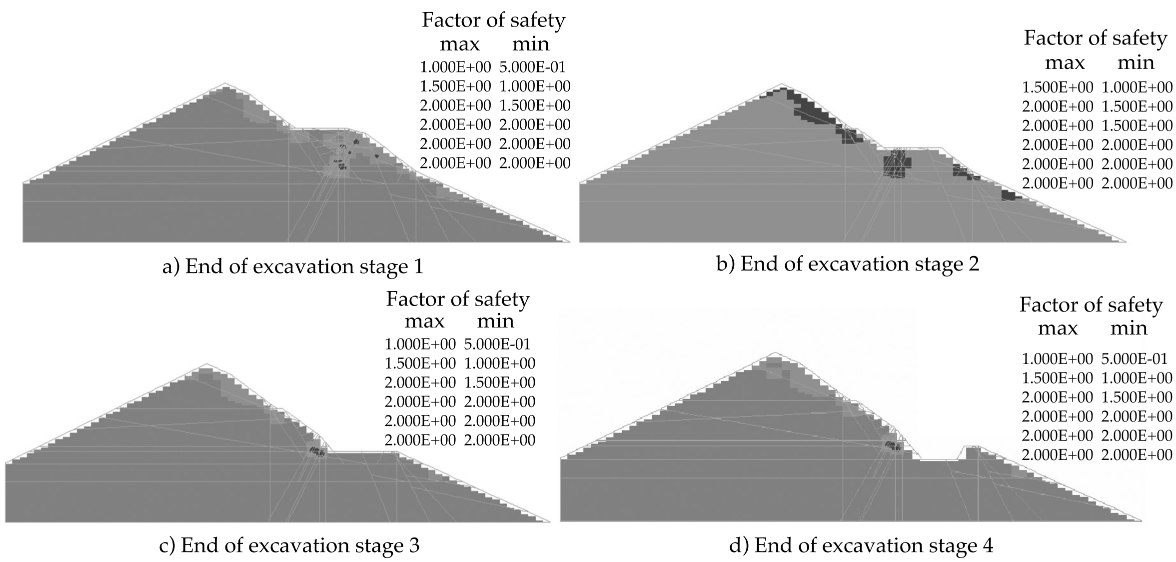


Figure 5. Evolution of safety factor due to excavation process.

detect any sign of rock movements and proceed to stabilize the area as required.

Seismic analysis

Despite the effect of transient loads can affect noticeably the behavior of rock masses, the physics of the phenomenon is poorly understood (Jing, 2003). Henceforth, linear elastic rock models are widely accepted for analyzing seismic rock mass responses. The dynamic response of the slope was computed for both the OBE and the MCE according to the design criteria used for La Yesca dam (ICOLD, 2010). Synthetic earthquakes were developed to obtain the OBE and MCE time series. The input motions computed were representative of the Mexican subduction (Cocos plate) earthquake-generating mechanism.

The seismic response of the slope at the end of the excavation for the OBE earthquake is shown in figure 6, where it is seen that displacements up to 40 cm of were developed at the top of the slope. This indicates that

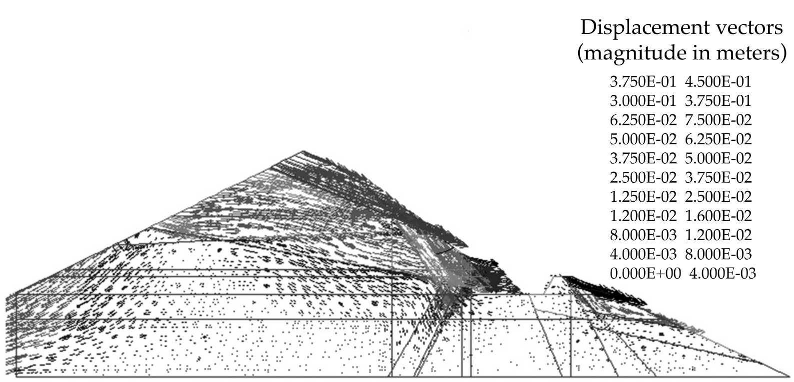


Figure 6. Resultant displacements at the end of the excavation.

instabilities can occur over that area, which in case of rock debris sliding towards the spillway channel, could lead to its obstruction or to a malfunction of it, endangering the dam itself. Also, the results show that a potentially unstable block can develop at the toe of the slope.

The MCE is a highly severe seismic event. The resultant slope displacements by action of this earthquake increase dramatically with respect to the OBE earthquake. At the top of the slope the displacements indicate the failure in this zone of the rock cut (figure 7). Displacements at the toe of the slope also increase strongly. Displacement magnitudes at the slope toe reach about 40 cm, thus indicating possible block detachments under the action of the maximum credible earthquake. That could lead to a major slope slide towards the spillway channel.

Corrective actions

The analysis results show the potential instabilities of the spillway slopes and hence impairing its correct operation. Accordingly it was decided to modify both its initial lay out and geometrical design. To this end The Federal Commission of Electricity (owner of the project) implemented important changes observed when comparing figure 8 (original design) with figures 9 and 10 (final design). The main modification on the spillway lay out was changing the orientation (with respect to the original) in 28° to the southeast which reduced the slope maximum height by 15 m. This had a benefic effect in decreasing excavation volumes and lessening the hazard of falling rock blocks into the spillway channel that could likely impair its proper operation or even clog it, putting at a high risk the dam safety. Regarding the modification of the original spillway consisted in dividing the one channel section into a three channel section, which in addition to increasing the overall stability of the spillway slopes, the material volume excavation was decreased. Picture10 depict a view of the final configuration of the La Yesca dam spillway.

Conclusions

- From the analysis performed, it can be concluded that numerical modeling is an important tool in the assessment of geotechnical projects. Results from such analysis allow forestalling possible problems that can arise during project execution. Also, numerical modeling 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

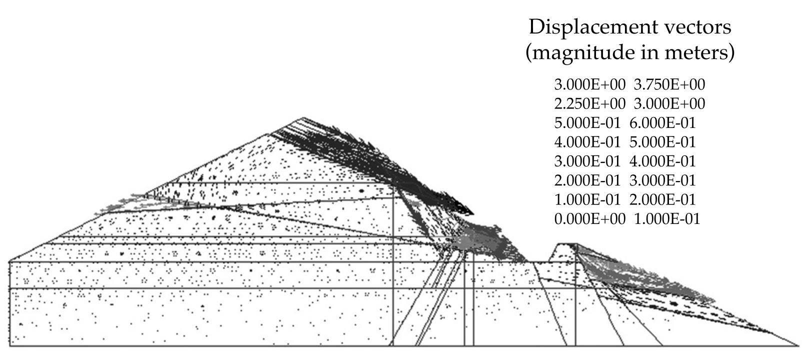


Figure 7. Resultant slope displacements by action of MCE.

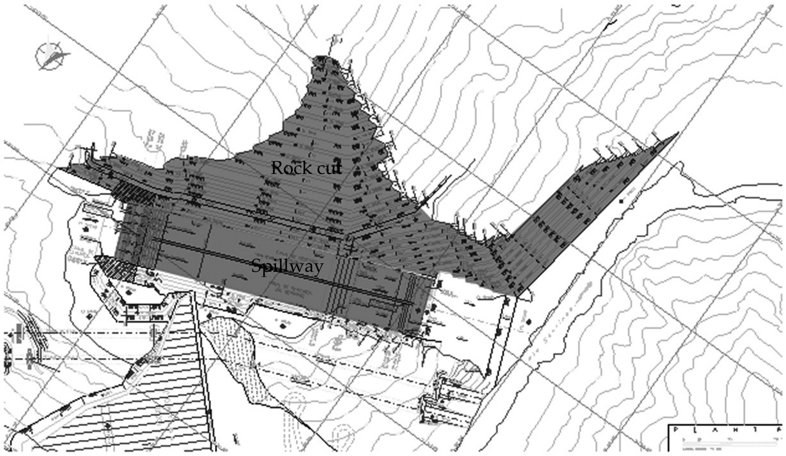


Figure 8. Original conception of the spillway.

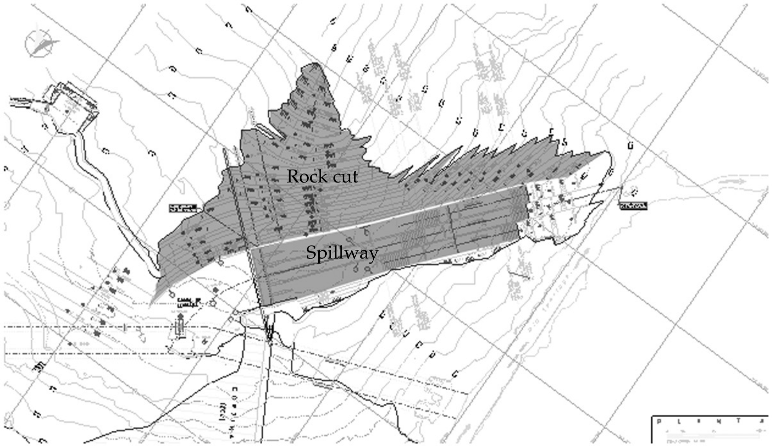


Figure 9. Final spillway design.

Figure 10. Final spillway conformation (Modified www.cfe.gob.mx).

results. When material properties are not known properly, parametric studies should be carried out to evaluate the influence of the various parameters. It is worth mentioning that the spillway, along its new trace and the geometry changes mentioned, was executed without any major problems. It is worth mentioning that numerical analysis allow determination of "hidden" problems, which with other procedures may not be detected. Accordingly, numerical methods are powerful tools that provide clues for taking educated design decisions and consequently improve structural security and help lowering risk levels.

- The implemented changes were very important, and the visualization of the potential problems only was possible with the 3D numerical study.

Posted: 16/04/13
Accepted: 11/04/13

References

Brady, B. H. G., & Brown, E. T. (2004). *Rock Mechanics for Underground Mining* (3rd edition). Boston: Kluwer Academic Publishers.

Byerlee, J. (1978). Friction of Rocks. *Pageoph*, *16*, 615-26.

CFE (2006). *Geological Survey Report for the Spillway Channel, La Yesca Hydroelectrical Project*. México, DF: CFE.

Hoek, E., & Brown, E. T. (1997). Practical Estimates of Rock Mass Strength. *International Journal of Rock Mechanics & Mining Sciences*, *34*(8), 1165-86.

Hoek, E., Carranza-Torres, C., & Corkum, B. (2002). Hoek-Brown Failure Criterion – 2002 Edition. Mining and Tunnelling Innovation and Opportunity. In R. Hammah, W. Bawden, J. Curran, & M. Telesnicki (Eds.), *Proc. 5th North Am. Rock Mech. Symp. & 17th Tunn. Assn. Can. Conf.* (pp. 267-273), University of Toronto.

ICOLD (2010). Concrete Face Rockfill Dams: Concepts for Design and Construction. *Bulletin*, *141*, 108.

Jing, L. (2003). A Review of Techniques, Advances and Outstanding Issues in Numerical Modelling for Rock Mechanics and Rock Engineering. *International Journal of Rock Mechanics & Mining Sciences*, *40*(3), 283-353.

Kulhawy, F. H. (1975). Stress Deformation Properties of Rock and Rock Discontinuities. *Journal of Engineering Geology*, *9*(4), 327-50.

Institutional address of authors

Dr. Eduardo Botero Jaramillo
Dr. Miguel P. Romo
Dr. Bogart Méndez

Instituto de Ingeniería
Universidad Nacional Autónoma de México
Ed. 4-217 Ciudad Universitaria, Delegación Coyoacán
04510 México, D.F., México
Telephone: +52 (55) 56233 600, ext. 8462, 3648
eboj@pumas.iingen.unam.mx
mromo@pumas.iingen.unam.mx
bmendezu@iingen.unam.mx

Dr. Humberto Marengo

Comisión Federal de Electricidad
Río Mississippi 71, Colonia Cuauhtémoc
Tecoyotitla 262-3
06500 México, D.F., México
Telephone: +52 (55) 5229 4400
Fax: +52 (55) 5207 0287
humberto.marengo@cfe.gob.mx