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Finite Element and Distinct Element Analysis of the Stability of a Large Underground Hydropower Machine Hall in the Himalayas

Rajinder Bhasin* and Thomas Pabst**

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Abstract

Numerical simulations have been performed to assess the stability of a large underground powerhouse in the Himalayas, using both finite element and distinct element approaches. Large convergences (around 250-300 mm) along the 45 m high wall of the Machine Hall have been measured by total station measurements during construction and up to 60 mm in the post construction and operational phase. Displacements are continuing at a reduced rate of about 3 to 6 mm per year. A large number of rock bolts have failed in the powerhouse and the shotcrete liner presents cracks and failure marks, thus questioning the long-term integrity and stability of the existing rock support system. The purpose of the numerical analysis was to back-calculate the prevailing rock mass conditions surrounding the machine hall, thereby gaining a better understanding of the mechanisms responsible for the instability in the cavern. The results from the analysis indicate that there was possibly an underestimation of the rock support requirements needed for the cavern, coupled with a not so good installation (incomplete grouting of the bolts). Both the length and the capacity of the rock bolts were underestimated presumably due to the existence of a high stress regime in the area, which may not have been taken into consideration in the design of rock support. The effect of a possible earthquake, frequent in this area, has also been studied and proves to induce a significant increase of the displacements and the support failure.

Keywords: *rock support system, Q-system, high stress, UDEC, phase*

1. Introduction

Along the past years, several large hydroelectric power plants have been built in the Himalayas. Due to the size of the projects and the specific local constraints, these represent special challenges for rock engineers. In this study, one of these projects, Tala, located on the Wangchu River, in South West Bhutan, was focused on, and especially its Machine Hall, in which large instabilities have been experienced. The Tala hydroelectric project is currently the biggest operating hydropower project in Bhutan. This 1020 MW hydroelectric project is a joint project between India and Bhutan generating 4865 GWh/yr.

The geology of the area around the powerhouse consists of highly deformed and tightly folded bedded sequences of quartzite and amphibolites schist partings. The general foliation trend is N049°E – S49°W with dip in N41°W direction. The Rock Mass Rating (RMR) varies from 19 to 50 and the rock mass quality Q varies between 0.11 and 14 (very poor to good).

The MCT (Main Central Thrust), a major thrust zone which marks the boundary between the Lesser and Higher Himalayas, runs alongside the powerhouse. It is a major tectonic feature and the single largest structure within the Indian plate that has accommodated Indian-Asian convergence. It extends for nearly 2500 km along strike and is a zone of more or less parallel thrust planes along which the rocks of the Central Crystallines have moved southwards against and over the younger sedimentary and metasedimentary rocks. It has not been proven that the thrust was responsible in any way for the bolts failure of the convergence, but it could have an impact on the long-term stability, especially regarding local seismic activity (Naik *et al*., 2011a; Bhasin *et al*., 2013).

In situ stress measurements (hydrofracture method) were carried out by the National Institute of Rock Mechanics (NIRM) in India (Singh *et al*., 2002). They indicated a vertical stress σ_v = 10.9 MPa corresponding to approximately 400 m rock overburden, a minimum horizontal stress σ_h = 9.5 MPa approximately normal to the cavern axis, and a maximum horizontal stress σ_H = 14.2 MPa approximately parallel to the cavern axis. The unconfined compressive strength of the intact rock was reported to be about 63 MPa.

The cavern itself is about 200 m long, 45 m high and 20 m wide (Fig. 1; Naik *et al*., 2011a). The support of the walls is made of 12 m long and 26.5 mm diameter Dywidag rock bolts (1.5 mc/c; Sharma *et al*., 2004) and 200 mm thick shotcrete (Chowdhry, 2007). The yield strength of the bolts is 1033 N/mm^2, i.e. 571 KN for these 26.5 mm diameter rock bolts, and the

*Senior Engineering Geologist, Norwegian Geotechnical Institute, P.O. Box. 3930 Ullevål Stadion, N-0806 Oslo, Norway (Corresponding Author, E-mail: rkb@ngi.no)
**Senior Engineer, Norwegian Geotechnical Institute, P.O. Box. 3930 Ullevål Stadion, N-0806 Oslo, Norway (E-mail: tp@ngi.no)

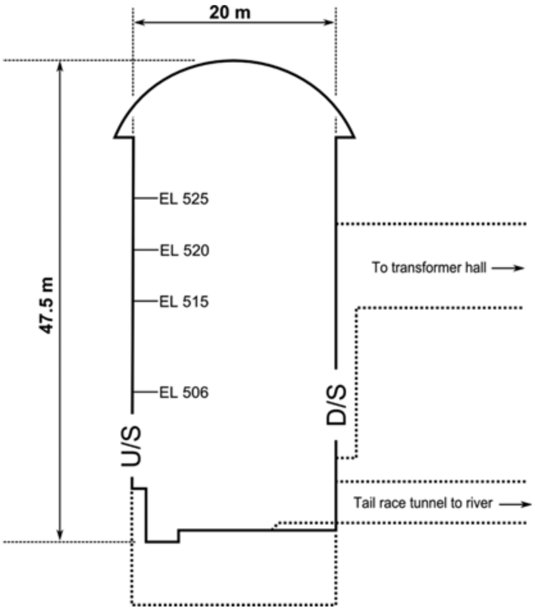

Fig. 1. Section of the Machine Hall Cavern, showing General Geometry (dimensions and elevations expressed in meter) and the Reference Locations for Convergence Measurements (Naik *et al.*, 2011a) (U/S and D/S for upstream and downstream walls).

percentage elongation is 8% (WAPCOS, 2011). The support of the crown is partly different, with 8 m long and slightly stronger bolts, shotcrete and a steel rib.

Total station measurements have monitored large convergence: up to 300 mm during the construction period and up to 60 mm during the post construction phase (Sripad *et al.*, 2003). At the same time, a large number of bolts have started to fail, that is 190 in total in April 2011, or 4% of all the installed bolts (Naik *et al.*, 2011b). Most of the failed bolts (147) have been observed on the upstream wall of the cavern (upstream and downstream walls are referred to as 'U/S' and 'D/S'; also see Fig. 1). The locations of failed rock bolts in the machine hall U/S wall are shown in Fig. 2; it appears that most of the bolts that have failed are located above an elevation of 515 m and that there is a larger number of failed bolts on the second half of the Machine Hall. When these rock bolts broke, they produced a high decibel sound and at times came out of the holes. The length of the broken portions of the rock bolts varied from a few centimetres to a few meters. Yet, the number of failed bolts could be larger than observed, due to the fact that the failure of a fully grouted rock bolt is not always visible since it does not necessarily come out of the hole. Moreover, in addition to the bolts failures, the shotcrete on the cavern walls is also fractured in several places.

Currently, the displacements are still going on, at a rate of about 3 to 6 mm per year (Naik *et al.*, 2011a; 2011b). And if the convergence of upstream and downstream walls is still continuing, this means also that the load on the rock bolts is still increasing due to the movement of the surrounding rock mass. And indeed, during a field visit, in November 2011, it was observed that new rock bolts had been partially shot out of the holes. For now, measures are being taken to prevent further instability and additional support or rehabilitation of the existing one are being studied.

Thus, the objective of this study is to use numerical models in order to simulate what was observed in the machine hall (back analysis) and to use the results to better understand the behaviour of the rock mass and its support. The analysis could as well provide some information on how to prevent further bolts failure and improve general support. An important aspect of this study was also to evaluate the stability of the support, both in its current states and after reinforcement, under dynamic loading, in order to simulate the effect of an earthquake. The main results from this study are presented in this paper.

2. Numerical Simulations and Input Data

Numerical simulations were carried out to better understand the overall behaviour of the rock mass and its support, and possibly explain the reasons why some bolts have failed. Once verified and calibrated, the numerical models may also be used to give recommendations to prevent further instabilities and predict the behaviour of the support in the case of an earthquake. The machine hall cavern is more than 200 m-long; thus, a 2D model is assumed to be realistic enough to catch the general behaviours. This is however a simplification of the reality, because there are actually some differences in the convergences measured along the machine hall (Singh, 2005; also see Fig. 2).

Numerical simulations were also carried out sooner (Venugopala Rao *et al.*, 2003a; 2003b) but were not able to predict the large displacements observed in the machine hall cavern and the failure of so many bolts. Many reasons can explain the discrepancies between numerical results and field observation, from the choice of the code to the values of some input parameters. But today, thanks to field observations and displacements measurements, it becomes possible to calibrate the models and to better simulate

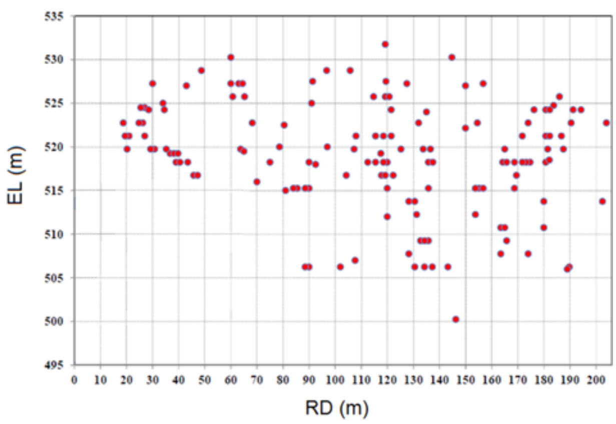

Fig. 2. Location (Red Dots) of Failed Rock Bolts on the Upstream (U/S) Wall of the Machine Hall Cavern (Naik *et al.*, 2011a). EL: Elevation (m), RD: Position Along the Cavern (approximately 200 m long)

Table 1. Rock Mass and Joints Properties used as Input Parameters in Phase2 and UDEC Models

Intact rock mass (Singh *et al*., 2002)	
Density	2740 kg/m^3
Young's modulus	30 GPa
Poisson's ratio	0,20
Cohesion	6 MPa
Friction angle	52°
Joints properties (Singh *et al*., 2002)	
Shear stiffness JK_s	1 GPa/m
Normal stiffness JK_n	25 GPa/m
Cohesion	0 MPa
Friction	25°
Fractured rock mass (Venugopala Rao *et al*., 2003a; 2003b)	
Density	2650 kg/m^3
Young's modulus	6,4 GPa
Poisson's ratio	0,355
Cohesion	3,41 MPa
Friction angle	26,2°

the general behaviour inside the cavern.

In this study, two numerical approaches were used to simulate the powerhouse machine hall and the rock support. Phase^2 (Rocscience Inc.) is a finite element code commonly used for 2D numerical analysis of rock support (Kveldsvik *et al*., 2011). UDEC (Universal Distinct Element Code) is a distinct element model used to simulate blocky rock structures where mechanical discontinuities control the overall deformation (Bhasin and Høeg, 1997, 1998).

The rock mass and the joints properties were obtained from the numerous articles published since 2003 about the Tala project (Singh and Goyal, 2005; Singh and Sthapak, 2007). Table 1 summarized the main parameters input in the numerical models. The rock and joints characteristics, together with the regional stresses, were measured at the beginning of the project and implemented in the models. The Mohr-Coulomb failure criterion has been chosen to simulate both the rock mass (Phase^2) and the joints (UDEC), mainly based on the previous numerical simulations carried out by Venugopala Rao *et al.* (2003a; 2003b). The remaining uncertainties like the precise joints sets configurations, the lengths of joints or the relaxation amplitude, were partly overcome by the partial calibration of the models, based on the convergence measurements at elevations 506, 515, 520 and 525 (see Fig. 1 for the locations).

In UDEC however, the rock mass is simulated as a group of deformable blocks and the joint properties in the model control how the blocks interact together. Therefore are the joint sets data critical to carry out realistic simulations. Singh *et al.* (2002) have reported the major discontinuities in the machine hall cavern. A total of five joint sets (plus the foliation) have been observed, but it appears that they can be represented by four planes (Gupta *et al.*, 2007). In general, the rock mass is considered as "moderately jointed", which, according to Palmström (1995), corresponds to a volumetric joint count of 3 to 10 joints per cubic meter, resulting in blocks of approximately 0.03 to 1 m^3. Similar observations have been made around the desilting chamber (not simulated here; Venugopala Rao *et al*., 2007). The models used in this study are approximately 170 m wide and 200 m high, to prevent any side effects. This means that it was not realistic to simulate all the joints with their actual spacing, otherwise the size of the model would have been too large and so the risk of numerical instabilities would have drastically increased. Moreover, the continuity of the joints was ensured only on a few meters and orientation and spacing could vary a lot (Singh *et al*., 2002), making it difficult to reproduce exactly what was observed in the cavern. Consequently, four zones were defined around the cavern. In the first one, 5 m around the cavern, joints spacing was set at 2 m, resulting in a moderately jointed area, as observed *in-situ*. The next zones, 10, 20 and 75 m around the cavern, had respectively 4, 8 and 20 m joints spacing. The maximum mesh size is 10 m.

The sequence of the simulations, both with Phase^2 and UDEC, is the usual one. First, the simulations are solved without excavation, in order to let the model stabilize (initialization). The cavern is then excavated, and relaxation is simulated by allowing a deformation of 10% of maximum total displacement in UDEC, and 20% of the stresses in Phase^2. Finally, the support is installed and the simulations are carried out until equilibrium, i.e. until convergence is reached in the models, assuming a tolerance of 0,0011 in Phase^2, and a solve ratio of 10^{-5} in UDEC. Dynamic conditions are applied from this last state.

3. Results and Discussion

Figure 3 presents the results obtained from the simulations carried out with Phase^2, showing the total displacements and the bolts failure. The model indicate a total maximum displacement of around 12 cm after equilibrium is reached. The convergence of the walls seems rather symmetric, and displacements along the U/S wall are only slightly larger due to a higher elevation. Quite a large number of bolts fail in the model, especially on the top and on the bottom of each wall. The liner is also altered at the

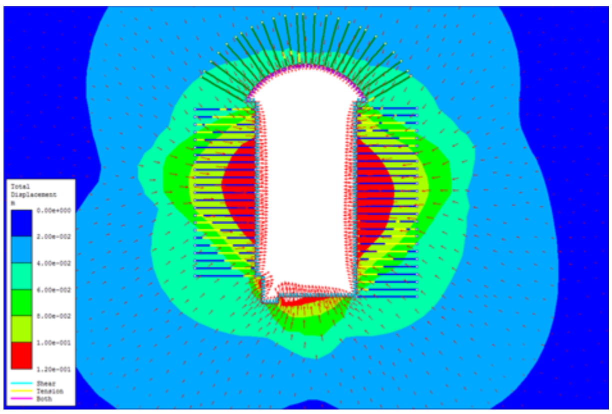

Fig. 3. Total Maximum Displacements and Bolt Failures around Cavern Hall

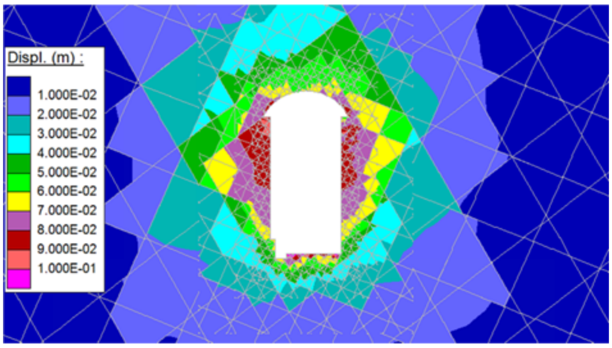

Fig. 4. Total Maximum Displacement (m) around the Cavern Hall, simulated with UDEC (blue: minimum displacements; red/purple: maximum displacements up to 10 cm)

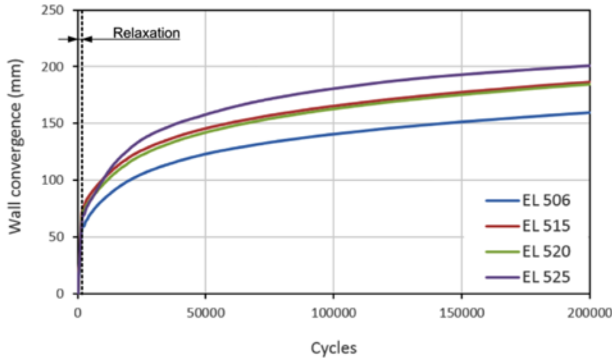

Fig. 6. Convergence simulated with UDEC for Different Elevations

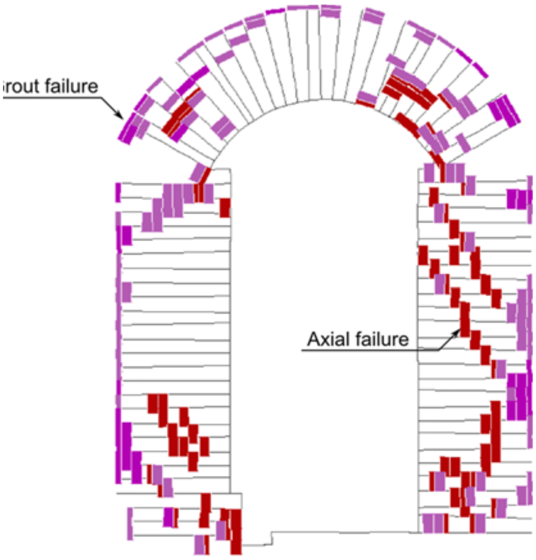

Fig. 5. Bolt Failure around the Machine Hall simulated with UDEC

same places, plus on the crown where the simulation indicates its extended failure, which is partially confirmed by observations made by Chowdhry (2007). The floor of the cavern in the model is also uplifted by more than 12 cm, which is higher than the 15 mm measured in-situ (Singh, 2005). The peculiar geometry of the invert is assumed to be responsible to the higher displacements observed in the models.

Figure 4 presents the same results as Fig. 3 but obtained with UDEC. The bolts failure is shown in Fig. 5. The displacements simulated in UDEC are comparable to those in Phase^2, with a total maximum displacement of approximately 10 cm. In the continuous model, the displacements were concentrated in the middle of the walls, while in UDEC, they increase with the elevation. The D/S wall seems slightly more affected by the displacements. In Fig. 5, it appears that the failed bots along the wall are located at approximately the same place as in Phase^2, that is on the top and the bottom of each wall. However, more bolts fail in the UDEC model. It can also be noted that the bolts in the crown are significantly more unstable than in Phase^2. Overall however, the general behaviour of the cavern seems to be similar in the two numerical approaches.

In both Figs. 3 and 5, the number of bolts failing is much larger than the 4% observed in the cavern (Naik *et al*., 2011b). However, previous 3D simulations (Naik *et al*., 2011a) have shown that the proportion of failed bolts could actually be around 25%, which is closer to the results of the simulations in this study. It should also be remembered that displacements are continuing and that not all the failed bolts are necessarily observed, as long as they are not expulsed.

The simulations carried out with UDEC are not completely stabilized after 200,000 cycles (which is a significant number) as can be seen in Fig. 6 and displacements do continue. However, the rate of displacement is significantly decreased compared to what was observed right after the excavation. This behaviour is very similar to the field observations, where after a period of fast and large displacements, i.e. more than 30 cm in a couple of months, movement has slowed down to an average of 3 mm/y. However, the "time" or number of cycles simulated in UDEC models is essentially numerical time and does not correlate directly to real time; consequently, the "time" dependent results are presented mainly to show a trend and indicate how the displacements tend to stabilize but cannot be easily compared to the actual rate of displacements in the field. A more thorough calibration of the models is however planned to try to link the experimental and the numerical results.

The displacements measured at several elevations inside the cavern hall (Sripad *et al*., 2003; Singh, 2005; Naik *et al*., 2011b) were compared to the displacements simulated with Phase^2 and UDEC. Results are presented in terms of convergence in Fig. 7. Multiple convergence measurements were taken for each elevation at different location along the cavern and are indicated with error bars. Convergence in the UDEC model was estimated after 200,000 cycles. It appears that the results between the measurements in the cavern and the simulations do not significantly differ. Both model do overestimate the displacement towards the base of the cavern (EL 506) while they are much closer to the field measurements higher up.

Reports and studies dealing with the stability of the cavern have previously put forth the hypothesis that failure and high convergence may be due to bolts failures, due themselves to bad

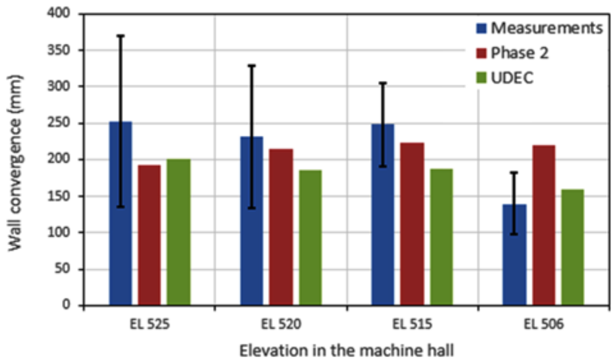

Fig. 7. Comparison of Convergences of the Walls of the Machine Hall using Continuum and Discontinuum Code

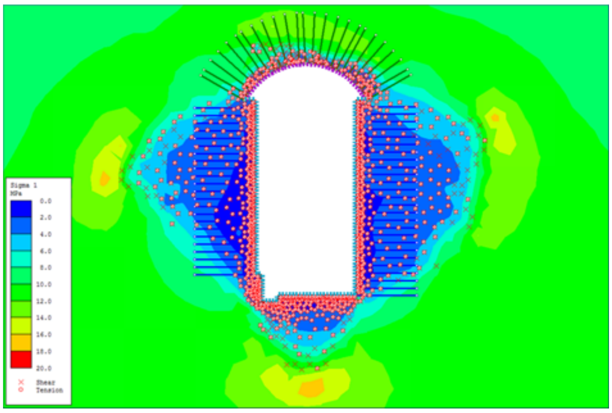

Fig. 8. Major Stresses around the Excavation together with the Yielded Elements

grouting quality. Additional numerical simulations with UDEC (not shown here) shows that it may be partially true, but not completely. If the bolts were all badly grouted, the displacements would be even larger and would eventually result in the collapse of the cavern. It consequently appears that the capacity of the bolts war somewhat underestimated. Another reason, according to the results obtained in this study, could be that the bolts may not be long enough to encompass all the area affected by the excavation. Fig. 8 presents the distribution of the major stresses around the excavation together with the yielded elements (Phase^2 simulations). It clearly shows that the affected area along the walls reach a distance of at least 20 m on each side of the cavern, especially at mid-elevation of the machine hall. Fig. 9 shows the displacements on each side of the cavern simulated at different elevations (Phase^2). Again, it appears that the displacements largely increase from a distance of approximately 22 m from each wall. Therefore it seems necessary to at least add a few bolts that could reach such distances. In the field reports, 20 m is also the recommended distance the bolts should reach to assure stability. Moreover, the extensometers show that about 80% of the total deformation occurs in the first 20 m from the wall, which is exactly what is simulated with Phase^2 where a maximum of 2 cm displacement is observed farther than 20 m, for a total

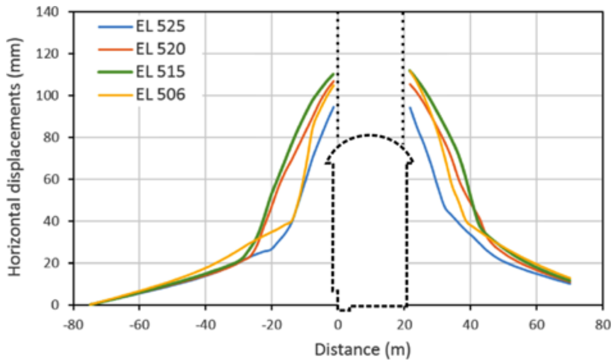

Fig. 9. Horizontal Displacements around the Excavation with Dashed Lines Indicating the Position of U/S and D/S Walls as Reference

displacement of around 10 cm (Fig. 9).

4. Additional Reinforcement

Recommendations for stabilizing the instability experienced in the powerhouse were proposed, based on preliminary assessment, but it was mentioned that it may need to be altered as more detailed analysis and information is obtained. An energy-absorbent support system was recommended for the rehabilitation of the sidewalls of the caverns, made of three layers: a chain mesh and lacing, then yieldable D-bolts (Li, 2010) and finally de-bonded cable bolts. The D-bolts would take care of the fractures zones at 1 m and 7 m depths, while the cable bolts would secure the fracture zone at 12 m depth. Mesh and lacing would provide surface containment to the sidewalls. The precise length and capacity of the bolts was not specified. The previous numerical models were therefore used to give some recommendations for the new reinforcement.

Increasing the length (from 12 to 20 m) or the capacity (from 570 to 620 kN) of the bolts in the models carried out with Phase^2 and UDEC gives varying results (Fig. 10), even if the previous results were fairly similar (Fig. 7). It appears that the length of the bolts has no significant effect on the displacements in Phase^2,

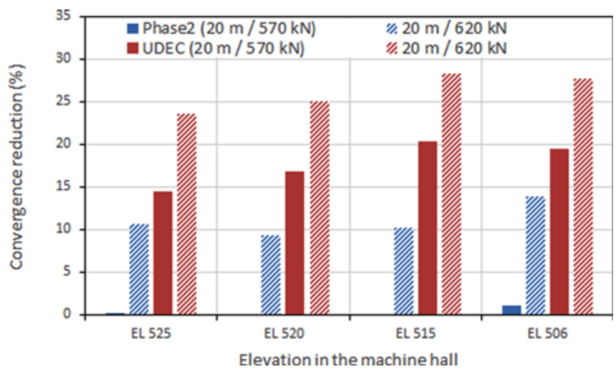

Fig. 10. Convergence Reduction with Longer and Stronger Bolts in Continuum and Discontinuum Models

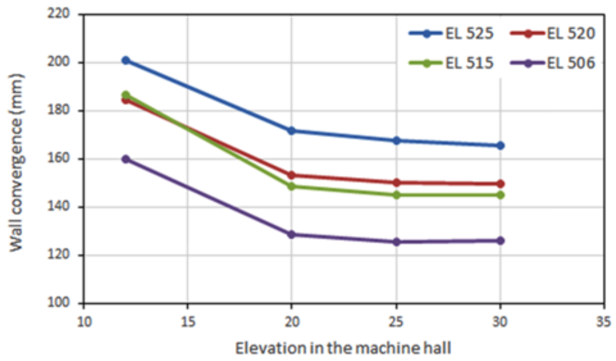

Fig. 11. Simulated Convergence at Different Elevations for Different Bolts Lengths (UDEC, bolts capacity = 570 kN)

while an increase in the capacity (+230 kN) allows to reduce the convergence by approximately 10%. The opposite phenomenon is observed with UDEC, where the increase in capacity has very little effect, while 8 m-longer bolts decrease the convergence by up to 20%. It appears that stronger bolts help better accommodate the plastic deformation of the whole rock mass (Phase^2), while longer bolts better prevent Displacements Along The Joint Plans (UDEC). A sensitivity analysis on the length of the bolts was carried out with UDEC (Fig. 11). It shows that above a certain length, there is not significant improvement of the stability.

A conclusion from this study is therefore that it may be necessary to use both stronger and longer bolts in order to efficiently reinforce the machine hall cavern.

5. Dynamic Loading

A dynamic analysis appears somehow necessary, considering the area where the powerhouse is built. According to the IS (Indian Standards) code, the area lies in zone IV, which means it is highly seismic and has endured several earthquakes in the last years. The numerical simulation of an earthquake is carried out by applying a dynamic loading to the model. The initial state is the nearly stabilized model presented previously. Boundary conditions are modified to viscous boundary (or free-field motion) so the seismic waves are not reflected on the sides of the models but absorbed as if they propagated through an infinite field. The acceleration time history of a real earthquake looks like a random signatures, with many cycles of motions and a wide spectrum of frequencies. In this study, since the objective is a general assessment of the effect of an earthquake, the signal was simplified to a sinusoidal function. Based on literature and previous simulations carried out in the area (Pal *et al.*, 2011), a shear sinusoidal wave of frequency 3 Hz was applied at the base of the model for 3 s, and let propagate upwards. The Peak Ground Acceleration (PGA) is assumed to be approximately 0,24 m/s^2, based on the zone IV factor in the IS Code 1893-2002, which is quite typical for such region. The value of the PGA should sometimes be decreased, depending on the depth of the tunnel. According to Hashash *et al.*, 2001, for a tunnel deeper than 30 m, the PGA should be decreased to 70% of its value. The value of 0,24 was nevertheless kept in order to be a little bit more conservative. The maximum ground velocity V_{max} was then calculated by:

$$V_{max} = \frac{PGA}{2\pi f} \quad (1)$$

This shear stress t_s applied at the base of the model was calculated as (Bhasin and Kaynia, 2004):

$$\tau_s = V_s \cdot \rho \cdot V_{max} \quad (2)$$

where, ρ is the rock mass relative density and V_s is the shear wave velocity given by the following equation (Bhasin and Kaynia, 2004):

$$V_s = \sqrt{\frac{G}{\rho}} \quad (3)$$

where, G is the shear modulus. In order to compensate for the viscous bottom boundary, the applied shear stress was doubled, giving a boundary shear stress of 60 kPa.

Figures 12 and 13 present the main results for the dynamic analysis, that is respectively the convergence of the walls varying with time and a more general view of the displacements around the machine hall. Results show that if the movement was limited to less than 10 cm under static conditions, it could largely excess

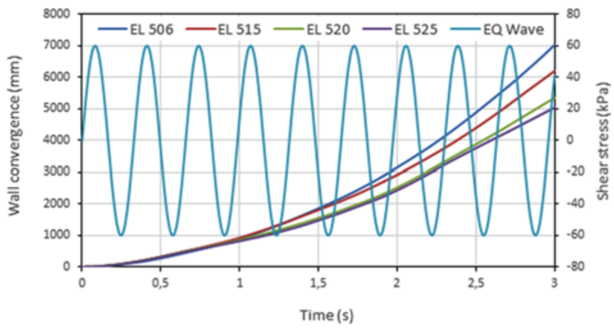

Fig. 12. Additional Convergence induced by an Earthquake showing the Input Sinusoidal Shear Stress

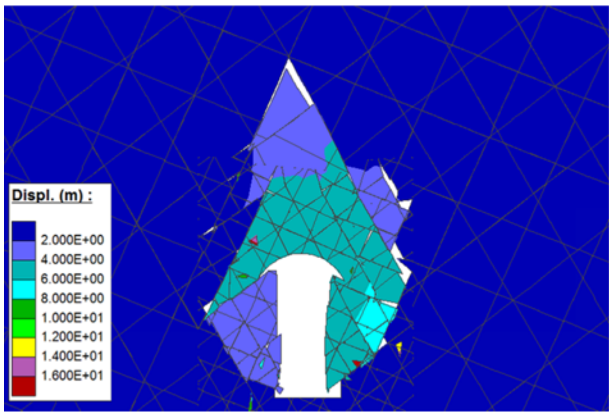

Fig. 13. Collapse of the Machine Hall Cavern under a Dynamic Loading simulated with UDEC

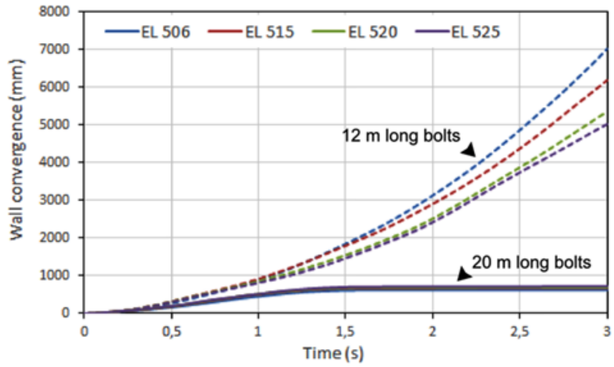

Fig. 14. Convergence induced by an Earthquake simulated with UDEC at Different Elevations and for 12 m- and 20 m-long Bolts

several meters in case of an earthquake. Maximum displacement occurs during the first second of the earthquake. A large zone is mobilized by such earthquake and the cavern seems to completely collapse. The amplitude of the dynamic loading is however rather high and these results may consequently be conservative.

The same models were simulated including this time longer bolts (20 m) to evaluate the impact on the proposed reinforcement system in the case of an earthquake. Results (Fig. 14) show that even if the displacements remain large (XXX mm), they are significantly reduced.

6. Conclusions

A certain number of instabilities were observed during and after construction of the machine hall of the Tala hydroelectric power house. Approximately 4% of the bolts in the powerhouse are reported to have failed and the walls of the cavern are continuing to converge, at a slow rate. Plans are underway to stabilize this important underground structure. Numerical simulations, based on two codes, have confirmed what was observed in situ. Convergences have been fairly well reproduced and some information was obtained regarding bolts failures. Observations in the cavern show that the expulsed bolts were free of grouting, indicating that maybe the reason of these failures may be the not so good installation. Numerical simulations also show that the bolts should be longer in order to be more efficient and that their capacity may have slightly been underestimated. Dynamic simulations have also shown that the cavern stability is highly susceptible to earthquake, and that large displacements (and possibly collapse) could occur under dynamic loading.

Based on this study, recommendations have been proposed to stabilize the walls of the cavern. Complementary 3D simulations are intended to be carried out to improve these results.

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