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A Numerical Modelling Approach to Assess Deformations of Horseshoe Cavern on Account of Rock Mass Characteristics and Discontinuities

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ABSTRACT

Caverns are massive underground openings excavated for purposes like defense installations and nuclear waste disposal which becomes challenging for weak strata consisting of fractured rock masses and may result in future calamities. This study is dedicated to ascertain stability of a horseshoe cavern in different types of granitic rock masses as well as fractured rocks. Two different types of granitic formations are accounted and displacements obtained along cavern periphery have been illustrated in the preliminary part of this study. An increment in vertical displacement at the crown of 260% and lateral displacement of almost 170% for both walls were observed for moderately weathered rock. Further, implications due to orientation and frequency of joint sets on the displacements incurred has also been explored. This study acquires its novelty by considering combinations of joint sets with varying spacings for investigating their implications on cavern walls. Presence of discontinuities depicted that horizontal joint spaced closely increased the deformation magnitude which reduced with decrement in joint frequency. Subsequently, along with horizontal joints at 4m interval, vertical and oblique joints sets were also incorporated at different frequencies. Consideration of vertical joints at 2m spacing with horizontal joints resulted in 313.2% increase in vertical displacement at cavern crown as well as 340% and 363% increase in lateral deformation at the left and right wall, respectively in comparison to intact rock. In case of oblique joints spaced at 2m with horizontal joints, increment in vertical deformation at the crown proliferated to 329% in comparison to intact rock.

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1. INTRODUCTION

The scope of better mechanisms related to ground control and advancements in the field of numerical modelling techniques has allowed us to assess the stability of the walls of subterranean structures such as large underground caverns. A cavern is a hollow passage beneath the earth, which has one of its openings to the surface of earth. The main concern is to ensure longstanding stability of these structures, which notifies us for everlasting operational necessities. One example of such debacle pertaining to underground structures include subsidence of the Seoul subway tunnel in South Korea [1].

The Hoek-Brown empirical failure criteria have been extensively utilized for asserting rock-mass parameters [2]. Other popular empirical approaches pertaining to behaviour of rock mass have also been bestowed by several researchers [3, 4]. Stability assessment of specific underground projects with the usage of various numerical modelling tools has been explored over the past decades. A parametric study performed using Universal Distinct Element Code (UDEC) concluded that some parameters of faults were really crucial for asserting the stability of these structures [5]. Research study pertaining to the assessment of stress variations between a slope and tunnel was carried out for both single as well as multiple tunnel scenarios [6]. Three-dimensional numerical modelling code (3DEC) has also been utilized by researchers to assess the promulgation of cracks along the walls of underground structures as well as asserting their responses under the dynamic loads [7, 8]. A research

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study utilized Intelligent Committee Machines for forecasting the Peak Particle Velocity (PPV) generated due to bench blasting on rock slopes [9]. The stability aspect due to different extreme loading conditions has been given a lot of importance over the past decades. However, the depletion of static stability on account of poor geological formations along with presence of joints still needs in-depth assessments for mitigating future catastrophic failures. A jointed rocky medium is an accumulation of intact rock separated by the presence of discontinuities. The presence of discontinuities substantially weakens the in-situ rock mass. Researchers had adopted discrete element method in order to evaluate the implications of existing joints to ascertain the hydro-mechanical response of an underground storage facility [10]. However, the static response of any underground structures constructed under jointed geological formations is also crucial to investigate. The deleterious implication of underground openings substantially increases when the existing geological formations comprises of weak rock types. This study has shed light into the response of an underground cavern under different types of rock formations along with various joint sets. Studies have also been extended to analyze the behaviour of rocks under nonlinear loading which forecasted increment of dynamic Young's Modulus with amplitudes [11]. A study highlighted the behaviour of jointed rock mass under different types of loads by proposing a failure criterion which accounts for major principal strain as it was observed that the state of strain gains equal importance to the stress state [12]. A research study looked into the extent of ground subsidence due to the construction of tunnels [13]. Assessment of tunnel stability has also been carried out by various researchers [14, 15]. Researchers have also looked into implications of tunnel stability in liquified soil conditions [16]. All the aforementioned literatures convey the stability aspect of underground structures under various scenarios but fails to dispatch the quantitative responses of underground structure peripheries which is highly linked to the type of surrounding rock masses as well as presence of discontinuities.

Application of distinct element code to ascertain the stability of underground caverns have gained an impetus over the past years due to its robustness in handling large discontinuities. In recent years, many studies have been conducted to ascertain the stability of underground openings using 3DEC, which is a distinct element code [17-19]. An investigation on predicting lateral displacement of rock mass at locations situated away from cavern walls using distinct element code in interconnected medium has also been performed with in-depth insight into the squeezing action of cavern walls [20]. However, the aforementioned study negated the aspect of surrounding geological rock types and conveyed the lateral deformations at various locations located transverse to the cavern walls. Stability analysis of large underground cavern has also been performed via FEM which aided in obtaining significant insights regarding the stresses of the neighboring rocks as well as rock supports [21]. Predictive modelling study has also been performed via Artificial Neural Network (ANN) for proper assessment of underground opening and surrounding soil interaction on the settlement of surface and subsurface soil layers [22]. Stability analysis on tunnels were also performed using a discontinuum model generated by 3DEC numerical code [23]. Significant insights were attained through the aforementioned studies; however, the quantitative assessments of deformations of underground openings due to jointing as well as type of geological formations were not emphasized till date. The present study has been focused on attaining quantitative estimates of deformations along cavern periphery and provides a holistic insight regarding its stability under various jointed geological formations. When underground excavations are carried out, the displacements due to overburden are found to occur at the crown and side walls of the cavern. Due to such opening, the equilibrium of stress is disturbed and it adjusts to achieve a new state of equilibrium by undergoing deformations resulting in sagging of roof as well as inward movement of side walls. Based on the aforementioned literatures presented, it has been observed that, there persists scanty studies to assess the displacements of cavern walls in different types of rocky formations as well as caverns constructed in fractured rocks. This study emphasizes on the assessment of underground cavern's response in terms of peripheral displacement by incorporating joints as well as numerous joint sets in the rock mass with the aid of 3DEC. The existing geological formations as well as presence of discontinuities are one of the crucial aspects which needs utmost supervision before the construction of any underground structures. The presence of fractured rock mass substantially weakens the neighboring rock strata which proliferates drastically when the strength of the surrounding rock mass is even less. The novelty of this study has been acquired by considering two different types of geological formations as well as different types of joint sets with varying frequencies which are quite prevalent at different places globally and the deformations encountered along the walls of horseshoe cavern due to the aforementioned aspects have been delineated in this study. The following subsections provides insight into the numerical modeling aspect via 3DEC software followed by the modelling details which has been adhered in this study. The second section of this article conveys the utilized rock mass parameters along with properties of discontinuities as well as sheds light into the application of in-situ stresses in the generated model. Finally, both the lateral as well as vertical displacements has been procured along the cavern periphery due to different types of geological formations as well as various joint sets which has been incorporated in the model. The terminating part of this article presents the significant insights via concluding remarks attained through this numerical modelling study.

1. 1. Numerical Modelling Stability analysis of a horseshoe cavern was conducted under two different types of ground conditions having intact rock of different rock strength. Spacing of discontinuities and inclusion of joint sets has also been varied in this study to ascertain the change in displacements along the cavern walls. The entire cavern has been modelled using two types of geological rock formation with the usage of discontinuum 3D numerical models i.e., 3DEC. 3DEC is a three-dimensional modelling tool based on Distinct Element Method mainly utilized for modelling discontinuum. Discontinuities are regarded as boundary conditions between blocks and vast displacements along discontinuities as well as rotation of blocks are permitted[1]. The applicability of FEM in the simulation of large deformations is quite cumbersome, whereas, Distinct Element Method (DEM) models every particle as an individual entity and represent granular material as an idealized assembly of particles. This aspect conveys that the DEM approaches are quite suitable for investigating the phenomena occurring at the length scale of particle diameter and simulating the bulk behavior of particles. In case of 3DEC, the independent blocks act either as a rigid or deformable material. Deformable blocks are further segregated into a mesh of finite difference elements, and individual element reacts according to a specified linear or nonlinear stress-strain law.

1. 2. Model Details The horseshoe cavern adopted for this study has a length of 1050m, width of 25m and 40m height. Cavern roof was modelled as an arch with 5m rise. Cavern considered for this study was assumed to be situated at 50m below ground level. To reduce the influence of artificial boundaries, a span of 5D was provided (where "D" refers to cavern diameter) at the sides in transverse direction and from cavern base to the model bottom. Further, different models were generated by changing the frequency of horizontal joints for a single type of rock formation and these models were analyzed to assess the cavern stability. Numerous combinations of joint sets were also incorporated in the model in similar type of rock formation for analyzing the effect of jointing.

The extent of area where discontinuities were invoked into the model along with the excavated opening as well as the sequence for initiating the excavated portion of the opening is illustrated in Figure 1. Discontinuities invoked into the model comprises of the following:

a. Horizontal joints at spacing of 2m, 4m and 6m.

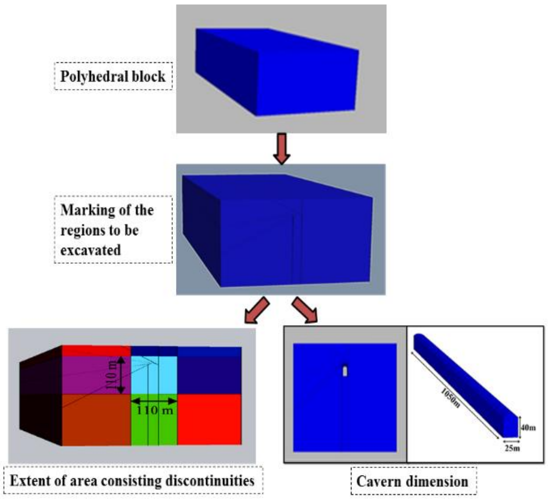

Figure 1. Generation of the model depicting cavern dimensions and extent of discontinuities

b. Horizontal joints at 4m spacing along with vertical joints at spacing of 2m, 4m and 6m.

c. Horizontal joints at 4m spacing along with oblique joints at spacing of 2m, 4m and 6m.

The aforementioned extent of discontinuities invoked into the model has been explored for the first time in terms of delineating the stability of horseshoe cavern. The entire domain of the generated model was divided into deformable blocks with the help of 'gen edge' command, with each block further discretized into tetrahedrons with predominant geometrical/geological features forming boundaries of different blocks. Regions lying close to excavation were meshed with smaller size and coarser mesh sizes were adopted for locations away from the cavern. The authors would like to highlight that the process of generating the model as presented in this study has been kept exactly the same as per previous published studies [8, 20]. A flowchart of the adopted research methodology is presented in Figure 2 delineating every step which have been undergone in this study for extracting the deformations along cavern periphery. Preliminary parametric assessments include assessing the cavern stability without joint sets in two different types of rock formations. Both values of horizontal and vertical displacement were noted at intervals of 210m along the length of cavern and the maximum procured displacements have been reported in this study. Later part of this study embraces inclusion of horizontal joint sets as well as horizontal joint set along with vertical or oblique joint sets at different spacings and subsequently maximum displacements in both directions have been considered as the displacements occurring along the walls of cavern.

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[1] https://usermanual.wiki/Document/Manualof3DECV410.1356105871.pdf

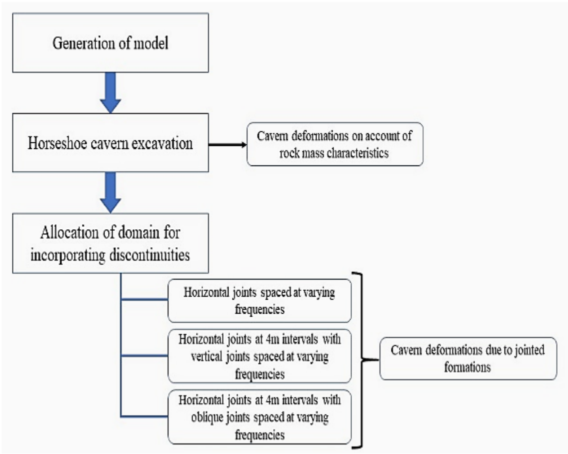


Figure 2. Flowchart of the adopted research methodology pertaining to this study

2. ROCK MASS PARAMETERS

Granitic formations with two different RMR values have been considered in this study with an overburden of 50m. The rock formations were classified into hard and moderately hard rock with RMR value of 65 and 54 respectively. Physico-mechanical properties of different materials utilized in model generation are presented in Table 1 and the joint properties are summarized in Table 2.

Material properties were introduced in the model using 'prop mat' command. Subsequently, with the usage of 'change mat' command, rock properties were assigned to the corresponding blocks. Joint properties were assigned with the help of 'change joint' command. For both ends of the generated model, displacements in x and z directions were restrained, and displacements in three different directions were restricted at the model base.

2. 1. In-situ Stress The vertical in-situ stress of 8.12MPa and 7.25MPa were introduced by considering the density of rock mass as per Table 1. Orientation of cavern has been attained in a way such that maximum stress in horizontal direction of magnitude 12.18MPa and 10.88MPa is experienced along the cavern length and minimum horizontal stress magnitude of 8.932MPa and 7.98MPa is addressed normal to axis of cavern.

K_H (maximum horizontal stress/Vertical stress): 1.5

K_h (Minimum horizontal stress/Vertical stress): 1.1

Due to the existence of numerous discontinuities in the generated model, the estimation of existing stresses is very difficult via both analytical computations as well as field measurement. A research study delineated that for complex geological formations, application of proper boundary stresses should be performed for attaining the existing stresses in the generated model which has been adhered in this study also [24, 25]. The existing stress conditions were ascertained in the generated model with the usage of 'In situ' command and incorporation of gravity loading was attained with the usage of 'gravity' command. Automatic damping was used to dampen the equations of motion under applied initial as well as induced conditions and this was achieved with 'damp auto' command. Subsequently, analysis was performed in multiple stages involving in-situ equilibrium, arched roof excavation as well as excavation of cavern body both in non-fractured and fractured medium as illustrated in Figures 3 to 6.

TABLE 1. Physico-Mechanical properties of rocks

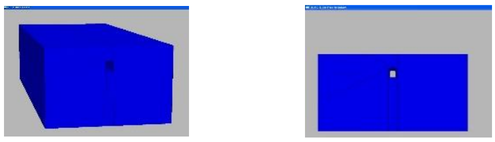
RMR	Elastic modulus (Pa)	Shear modulus (Pa)	Cohesion (Pa)	Friction angle (Deg.)	Density (kg/m^3)
65	17.3e9	10.4e9	1.2e6	70	2.8e3
54	3.8e9	2.3e9	0.56e6	60	2.5e3

TABLE 2. Input properties of joints and joint sets

Normal stiffness (Pa)	Shear stiffness (Pa)	Friction angle (Deg.)
9.0e9	0.9e9	42

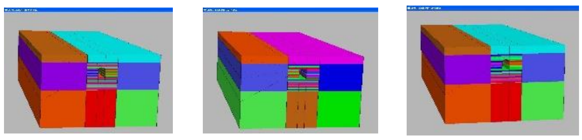
3. RESULTS AND DISCUSSION

The model was analyzed in two types of rock formation and the maximum displacements in both directions were procured at the observation points denoted on the cavern profile as per Figure 7. Later, joint sets were included in the model by considering only hard rock properties.



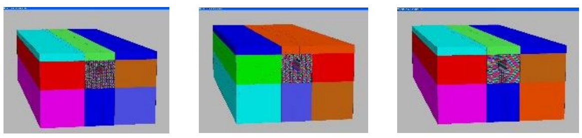
(a) (b)

Figure 3. Cavern created within the block



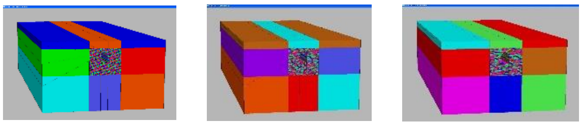
(a) (b) (c)

Figure 4. Cavern created within horizontal joints at spacing (a) 2m, (b) 4m and (c) 6m



(a) (b) (c)

Figure 5. Cavern created with horizontal joints (4m) and vertical joints at (a) 2m, (b) 4m and (c) 6m spacings



(a) (b) (c)

Figure 6. Cavern created with horizontal joints (4m) and oblique joints at (a) 2m, (b) 4m and (c) 6m spacings

Displacements at these corresponding points were found out varying the spacing of joint sets.

Stage 1: Investigations were performed in intact rock mass having two different types of rock properties. The displacements reported hereafter includes the direction of displacement which has been denoted with proper sign. For vertical displacements, displacements occurring in the downward direction is presented with a negative sign whereas along the cavern walls, positive displacements indicate displacements towards the right side and negative displacements indicates displacement are occurring towards the left side. Figure 8 shows the displacement at the cavern crown for both rock formations. Table 3 depicts the maximum displacements in both directions at the left wall.

The maximum vertical displacement procured at the right wall of cavern has also been assessed and the magnitudes are depicted in Table 4. It can be observed that magnitude of increase in lateral displacements along the side walls was significantly higher as compared to displacements in vertical direction.

The vertical displacement was found to be -1.89mm at the crown in case of hard rock, which increased to -6.84mm for moderately hard rock. Similar trend of

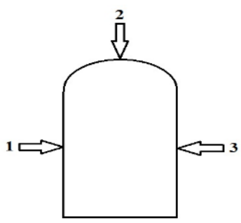


Figure 7. Observation points of cavern

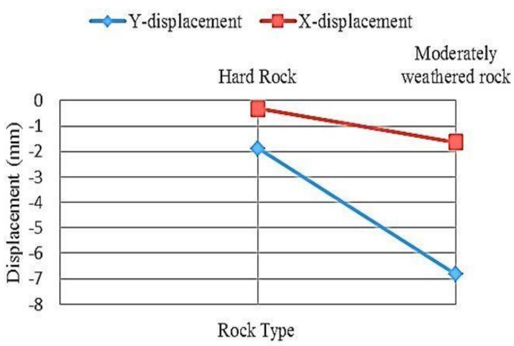


Figure 8. Displacements at the crown of cavern for two types of rock formation

TABLE 3. Displacements at left wall for both rock formations

Maximum Displacement (mm)	Hard rock	Moderately weathered rock
Vertical	-0.123	-0.854
Horizontal	9.17	24.7

TABLE 4. Displacements at right wall for both rock formations

Maximum Displacement (mm)	Hard rock	Moderately weathered rock
Vertical	-0.213	-0.735
Horizontal	-10.8	-29.2

increase in horizontal displacement was found while carrying out the analysis in both rock formations. The horizontal displacement at cavern crown was found to be -0.324mm in case of hard rock, which increased to -1.64mm in case of moderately hard rock. This aspect depicted that vertical displacement at the cavern crown is the predominant one which increased drastically in case of moderately weathered rock.

In case horizontal displacements at the side walls, similar trend of increment in the deformation magnitude has been observed for moderately weathered rock. The maximum horizontal displacement at the left wall observed to be 9.17mm for hard rock condition which substantially increased to 24.7mm in case of moderately weathered rock. The maximum horizontal displacement at the right wall was higher in moderately hard rock formation with a value of -29.2mm as compared to -10.8mm in hard rock formation. It can be observed that magnitude of increase in lateral displacements along the side walls was significantly higher as compared to displacements in vertical direction.

Stage 2: The later part of this study comprises of asserting the stability of cavern under the influence of different types of discontinuities. Horizontal (H) joint sets were incorporated in the model with different joint spacings. Three different frequencies of horizontal joint spacing have been explored in this study in order to attain comprehensive insight regarding the displacements incurred along the cavern periphery with respect to the joint spacings. Displacements in both directions were extracted at the observation points at different intervals along the cavern length and the maximum displacement has been reported hereafter.

The crown of cavern incurred maximum vertical displacement after the incorporation of horizontal joints. In case of intact rock mass, maximum displacements in vertical and horizontal direction were observed to be -1.89mm and -0.32mm, respectively; which increased considerably after the inclusion of horizontal joints. After the inclusion of horizontal joints at a spacing of 2m, the maximum vertical and horizontal displacements showed considerable increase with values of -4.14mm and -

0.955mm, respectively. This suggests that presence of discontinuities significantly proliferated the vertical displacement at cavern roof. Maximum vertical and horizontal displacements were found to be -3.48mm and -0.513mm, respectively when the spacing of joints increased to 4m. When the joint spacing was further increased to 6m, the maximum vertical and horizontal displacements were found to be -1.96mm and -0.389mm, respectively. The frequencies of the joint sets are quite a significant parameter in terms of asserting the displacements along the cavern periphery. Higher spacing of horizontal joint sets depicted less increment in both horizontal and vertical displacements at the cavern peripheries which increased drastically with the reduction of spacing of the horizontal joints. The maximum displacements at crown under horizontal jointing are depicted in Table 5. Tables 6 and 7 depicts the displacements at the left and right wall of cavern, respectively.

The presence of horizontal joints increased the magnitudes of horizontal displacements along the cavern walls as compared to intact rock mass. In the later part, along with horizontal joint sets, two different types of joint sets i.e., vertical and oblique joint sets, have also been incorporated in the model having hard rock properties. The displacements in both directions were analyzed along the periphery of cavern. The spacing of the horizontal joints has been kept as constant i.e., 4m, so that significant insights can be attained due to incorporation of other joint sets as well as variations in their frequencies. The joint sets incorporated in the model are as follows:

1. Horizontal joints and vertical joints at 4m and 2m spacing, respectively.
2. Horizontal joints along with vertical joints both at 4m spacing.
3. Horizontal joints and vertical joints at 4m and 6m spacing, respectively.
4. Horizontal joints at 4m spacing and oblique joints at 2m spacing.
5. Horizontal joints and oblique joints at 4m spacing.
6. Horizontal joints at 4m spacing along with oblique joints at 6m spacing.

TABLE 5. Displacements observed at cavern crown

Max. Displacement (mm)	**No joints**	**H joints at 2m**	**H joints at 4m**	**H joints at 6m**
Vertical	-1.89	-4.14	-3.48	-1.96
Horizontal	-0.32	-0.955	-0.513	-0.389

TABLE 6. Displacements obtained at the left wall

Maximum Displacement (mm)	**No joints**	**H joints at 2m**	**H joints at 4m**	**H joints at 6m**
Vertical	-0.12	-0.703	-0.484	-0.229
Horizontal	9.17	12.6	11.8	11.2

TABLE 7. Displacements obtained at the right wall

Maximum Displacement (mm)	**No joints**	**H joints at 2m**	**H joints at 4m**	**H joints at 6m**
Vertical	-0.21	-0.94	-0.37	-0.32
Horizontal	-10.8	-13.4	-12.6	-11.4

Figure 9 depicts that the maximum displacements procured in vertical direction at the cavern crown were -7.81mm, -6.26mm and -5.59mm with an increase in spacing of vertical joints. The maximum horizontal displacements observed at the crown were -0.682mm, -0.427mm and -0.373mm, respectively with an increase in spacing of vertical joints. This suggests that incorporation of multiple joint sets increased the vertical displacement at the cavern crown significantly, whereas, the change in horizontal displacement at the cavern crown were observed to be insignificant. Moreover, as the vertical joint spacing was increased, reduction of vertical displacement at the cavern crown was also observed.

Figure 10 shows the highlights of the displacement at the left wall of cavern. The lateral displacement procured at the left wall was significantly higher due to the inclusion of multiple joint sets. With the increment in spacing of vertical joints, maximum vertical displacements procured at left cavern were -0.802 mm, -0.696 mm and -0.494 mm, respectively; showing a decrement in the vertical displacement magnitude with increase in vertical joint spacing. Incorporating vertical joints at 2m interval along with horizontal joints spaced at 4m interval induced a lateral displacement of 40.3mm, which drastically reduced to 23.8mm in case of vertical joints spaced at 6m intervals along with horizontal joints at 4m spacing.

Further, oblique (O) joint sets at different spacings i.e., 2m, 4m and 6m, respectively, were incorporated in the model along with horizontal (H) joint set spaced at 4m interval and the displacements at cavern crown have been reported in Table 8 and displacement at the right wall has been illustrated in Figure 11.

The maximum displacements in vertical direction observed at the cavern crown after inclusion of oblique

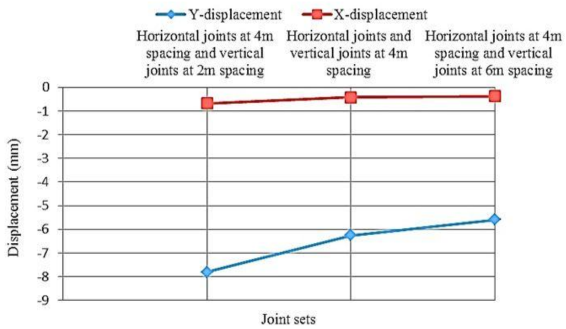


Figure 9. Displacements at cavern crown after vertical joint set inclusion

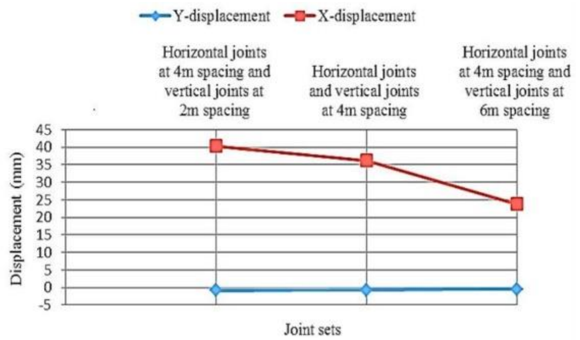


Figure 10. Displacements at left wall of cavern after vertical joint set inclusion

TABLE 8. Displacements with horizontal and oblique joints at cavern crown

Maximum Displacement (mm)	H joints (4m) with O joints (2m)	H joints and O joints (4m)	H joints (4m) with O joints (6m)
Vertical	-8.10	-7.40	-7.17
Horizontal	-1.47	-1.21	-1.19

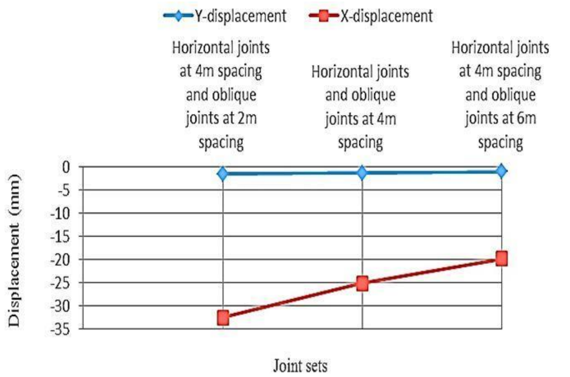


Figure 11. Displacements at right wall of cavern after inclusion of oblique joint set

joint sets were -8.1mm, -7.40mm and -7.17mm. Similar trend of decrement in the magnitude of vertical displacement was procured for the cavern roof with the increment in the spacing of the oblique joint set. Maximum displacement in the horizontal direction also reduced with the increment in spacing of oblique joints. At the right wall of cavern, maximum vertical displacements observed were -1.48mm, -1.27mm and -1.03mm comprising of horizontal joints at 4m intervals along with oblique joints spaced at 2m, 4m and 6m respectively. Maximum lateral displacements observed at the right wall of cavern for the aforementioned scenario were -32.6mm, -25.1mm, and -19.8mm respectively with the increase in spacing of oblique joints. The incorporation of oblique joints along with horizontal joints substantially increased the magnitude of lateral displacements along the right wall of cavern, however, the magnitude of lateral displacements procured for the oblique joint with horizontal joints was lower as compared to lateral displacements pertaining to the model having vertical joints along with horizontal joints.

The assessment of both displacements attained along the cavern periphery as per this study depicts a crucial insight into the stability of underground cavern under both intact rock mass formation as well as in jointed medium. The agglomeration of discontinuities increases the chances of collapse of underground structures which has been highlighted in this study. The magnitudes of both vertical as well as lateral displacements as attained in this study would aid the readers to adopt various remedial measures which would aid in asserting the stability of underground caverns constructed in fractured rock masses. Presence of multiple joints having different orientations increased the magnitudes of displacements along the cavern periphery which is crucial to consider before the construction of underground cavern at such locations. It was also observed that increased frequency of joints induces substantial increment in the displacements which reduces with the increment in spacing of joints. Table 9 conveys a comparative study of the displacements procured at the crown, left wall and right wall of the cavern for two types of joint sets as per this study. The horizontal, vertical and oblique joints have been abbreviated as H, V and O joints respectively in Table 9. It was also observed that the magnitude of horizontal displacement at crown for models consisting of oblique joints was greater in comparison to the models comprising of vertical joints; however, the magnitudes of procured lateral displacements were substantially less as compared to the vertical displacements.

It can be observed that for underground caverns constructed in a medium comprising of horizontal and vertical joint sets will induce more lateral displacement at the side wall as compared to medium comprising of horizontal and oblique joint sets. However, the vertical

TABLE 9. Comparative study of displacements due to varying joint sets

Max. Displacement (mm)	H (4m) and V (2m) joints	H (4m) and O (2m) joints	H and V joints (both 4m)	H and O joints (both 4m)	H (4m) and V (6m) joints	H (4m) and O (6m) joints
At cavern crown						
Vertical	-7.81	-8.10	-6.26	-7.40	-5.59	-7.17
Horizontal	-0.68	-1.47	-0.42	-1.21	-0.37	-1.19
At left wall						
Vertical	-0.80	-1.64	-0.69	-1.19	-0.49	-0.96
Horizontal	40.3	27.1	36.2	20.2	23.8	18.6
At right wall						
Vertical	-0.78	-1.48	-0.51	-1.27	-0.39	-1.03
Horizontal	-50.0	-32.6	-41.8	-25.1	-31.0	-19.8

displacements procured at the cavern crown depicted higher magnitudes for the model comprising of oblique and horizontal joint sets in comparison to the models consisting of horizontal and vertical joint sets. It was also observed that with proliferation in spacing of vertical or oblique joints in the model resulted in lower magnitudes of displacements in both the directions. The observed displacements for models with discontinuities were higher as compared to model having only intact rock formation. The subtle comprehension of displacements obtained in this study under various types of rocky formations aids to provide a holistic insight regarding the remedial measures to be taken into account for ascertaining long term stability of underground caverns.

4. CONCLUSIONS

The stability analysis of underground cavern has been performed in this study with the aid of 3DEC software under various types of intact rock as well as jointed rock mass formations and the maximum displacements procured at the cavern periphery has been reported in this study. Preliminary part of this study comprises of assessment of cavern wall deformations under two different types of geological rock mass formations followed by assessing the cavern stability with horizontal joints at different spacings and the following conclusions have been attained.

- The percentage increase in vertical displacement at the crown was nearly 260% when analysed with moderately hard rock properties in comparison to hard rock properties. The percentage increase in horizontal displacement when analysed with moderately hard rock properties were almost 170% for both right and left walls in comparison to hard rock properties.
- The vertical and lateral deformations were much more predominant at the cavern crown and cavern walls respectively.
- Incorporation of horizontal joints in the models resulted in increased instability to the cavern walls as compared to intact rock mass. Presence of joints especially its frequency, plays a significant role on the magnitude of both vertical and horizontal displacements.
- This study indicated that as the frequency of horizontal joints reduced, the vertical displacement at the cavern crown also reduced and similar trend in the lateral displacements were also observed at the cavern walls.

Multiple joint sets in the form of vertical as well as oblique joints were also included in the model along with horizontal joints. The vertical joints and oblique joints were varied at a spacing of 2m, 4m, and 6m whereas horizontal joint spacing was kept as 4m and following conclusions have been attained.

- Comparative study between models comprising of intact rock mass as well as horizontal joint at 4m with vertical joints at 2m depicted 313.2% increase in vertical displacement at cavern crown and percentage increase in horizontal displacements at left and right wall of cavern were found out to be 340% and 363% respectively. Whereas in comparison to model consisting of horizontal joint along with vertical joints at 6m spacing, the percentage increase in vertical displacement at crown was observed to be 196%. For the model comprising of horizontal joint set with vertical joints at 2m interval, the percentage increase in horizontal displacements was observed to be 160% and 187% at the left and right wall respectively in comparison to the model having horizontal joint along with vertical joints at 6m interval.
- Comparison between intact rock mass model and model comprising of lateral joints along with oblique joints at 2m spacing showed 329% rise in vertical displacement at cavern crown. The percentage increase in vertical displacement reduced to 279.3% when the spacing of oblique joints was increased to 6m.
- The models containing horizontal joints in combination with vertical and oblique joints revealed that displacements at the cavern crown is higher with oblique jointing and the cavern sidewalls depicted comparatively higher magnitudes of horizontal displacements in presence of vertical joints.

The executed numerical modelling study elucidates the response of massive buried caverns under various types of rocky formations. Such studies will lead to safe design and execution of cavern projects as well as aid in taking proper remedial measures while designing in intricate rocky formations.

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Persian Abstract

چکیده

غارها دهانه‌های زیرزمینی عظیمی هستند که برای اهدافی مانند تأسیسات دفاعی و دفع زباله‌های هسته‌ای حفاری شده‌اند که برای لایه‌های ضعیف متشکل از توده‌های سنگی شکسته چالش‌برانگیز می‌شود و ممکن است منجر به فجایع آینده شود. این مطالعه به بررسی پایداری یک غار نعل اسبی در انواع مختلف توده‌های سنگی گرانیتی و همچنین سنگ‌های شکسته اختصاص دارد. دو نوع مختلف از سازندهای گرانیتی محاسبه شده و جابجایی های به دست آمده در امتداد حاشیه غار در قسمت مقدماتی این مطالعه نشان داده شده است. یک افزایش در جابجایی عمودی در تاج ۲۶۰٪ و جابجایی جانبی تقریباً ۱۷۰٪ برای هر دو دیوار برای سنگ با هوازدگی متوسط مشاهده شد. علاوه بر این، پیامدهای ناشی از جهت گیری و فرکانس مجموعه های مفصلی بر روی جابجایی های ایجاد شده نیز بررسی شده است. این مطالعه با در نظر گرفتن ترکیبی از مجموعه های مفصلی با فواصل مختلف برای بررسی تأثیر آنها بر دیواره های غار، تازگی خود را به دست می آورد. وجود ناپیوستگی‌ها نشان می‌دهد که فاصله مفصل افقی به شدت باعث افزایش بزرگی تغییر شکل می‌شود که با کاهش فرکانس اتصال کاهش می‌یابد. متعاقباً همراه با اتصالات افقی در فاصله ٤ متری، مجموعه درزهای عمودی و مایل نیز در فرکانس های مختلف گنجانده شد. در نظر گرفتن درزهای عمودی در فاصله ۲ متری با اتصالات افقی باعث افزایش ۳۱۳/۲ درصدی جابجایی عمودی در تاج غار و همچنین افزایش ۳٤۰ درصدی و ۳٦۳ درصدی تغییر شکل جانبی در دیواره چپ و راست نسبت به سنگ سالم شد. در مورد اتصالات مورب با فاصله ۲ متر با اتصالات افقی، افزایش تغییر شکل عمودی در تاج به ۳۲۹٪ در مقایسه با سنگ دست نخورده افزایش می یابد.