RESPONSE OF CAVERNS IN JOINTED ROCK TO HIGH FREQUENCY EARTHQUAKE MOTIONS

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SUMMARY

A numerical study was made of the response of an unlined cavern at two depths in a heavily jointed medium when excited by horizontally polarized shear waves. A hybrid rigid block and finite element model with a Columb representation for the shear behavior along joints between rigid blocks was used. Damage was postulated to be related primarily to large displacements along critical joints between the rigid blocks. It was found that these displacements are largest for wave lengths about twice the cavern height and decrease with depth of burial.

INTRODUCTION

Underground siting of storage and production facilities is becoming increasingly attractive. When such facilities are located in areas of high sesmic risk, they must be designed to safely resist expected levels of dynamic excitation. While it is advantageous to place such facilities in sites with minimal jointing, it is unavoidable that such sites are, at least in part, heavily jointed. Therefore, an understanding and predictive capability for cavern behavior in jointed rock during seismic excitation is quite important. In this paper, the computation of shaking response is based upon a recently developed numerical procedure [2, 3, and 4] that models the jointed rock mass near caverns as though it were composed of rigid blocks that deform only along the joints between rock blocks. Specifically, the response of an unlined cavern at two depths is studied for excitation with horizontally polarized shear waves of varying frequency.

EXPECTED MOTIONS

Expected motions are a function of cavern depth as well as epicentral distance. At large epicentral distances where 0.5 to 5 Hz surface waves dominate, it can be argued that peak motion decrease with depth. Therefore, shallower caverns would be subjected to the largest

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peak motions. Conversely, at very small epicentral distances where body waves dominate, a depth dependence of motions is unlikely: the closest caverns would be subjected to the largest peak motions.

Until recently, little was known about design motions for deep underground structures at small epicentral distances. McGarr's [5] measurement of near field motions for local Richter Magnitude (M) 1.4 earthquakes induced by deep longwall mining in South Africa can be employed to estimate such motions. His measurements show that these motions are dominated by 20 to 400 Hz shear waves. His correlations of M and the product of focal distance and peak particle velocity show that an M/4, 400 m from a cavern, would produce peak particle velocities of 30 cm/sec. Accordingly, input for the models of deep caverns (600 m or at depths relatively unaffected by surface waves) was chosen to be horizontally polarized, sinusoidal, shear waves with frequencies of 10, 30 and 50 Hz. Conventional correlations were employed to determine the frequency range of motions for shallow caverns when perturbed by large but distant earthquakes. On the surface, peak particle velocities of 30 cm are typical of M 6.5 earthquakes 50 km from the fault rupture [1]. Correlations also show these peak motions to occur at frequencies of 2 to 4 Hz [6]. Therefore, the response of shallow caverns was investigated with 5 to 30 Hz horizontally polarized harmonic shear waves. While particle trajectories of surface waves differ from those of shear waves, these test motions will allow initial conclusions as to the order of magnitude importance of the dominant frequency.

CAVERN MODEL GEOMETRY

The 25 m span cavern shown in Figure 1 was shaken under shallow and deep confining conditions. Shallow was modeled as 60 m from the ground surface to the cavern roof and deep as 600 m. The horizontal to vertical field stress ratio was selected as 1.0.

The model rock mass was divided into two regions: a near cavern region of rigid blocks and a surrounding continuum region shown in Figure 1. The rigid blocks were geometrically defined by joints whose constitutive properties closely approximate the behavior of real rock joints. The rigid blocks allowed the rock mass near the cavern to deform locally along joints as would be the case in a real rock mass.

The joint geometry was constructed to be asymmetrical and defines single and multiple blocks with three and four edges that can move into the opening. As described in detail in [4] the joint stiffnesses fall within the range reported in the literature and shearing resistance was selected as 48^0 so that all blocks were statically stable. The joint stiffness of the rigid block portion in combination with the joint density yield a shear wave propagation velocity of 6,640 m/sec that is maintained in the continuum element region (to prevent artificial reflections).

METHOD OF COMPUTATION

As described in detail in previous articles [3] the hybrid rigid block procedure is an extension of earlier models to include edge-to-edge sliding along joints, wave transmission by continuum elements, and a silent boundary that allows motion to be prescribed and spurious reflections to be absorbed at the same boundary.

As shown in Figure 2, edge-to-edge interaction is enforced by transforming joint normal stresses, σ_n, to a single force, N, that acts through the centroid of the compressive contact stress distribution. The normal contact stresses are assumed to vary linearly and are proportioned to the joint closure by the joint normal stiffness. Joint shear forces are proportioned to the shear displacement by the joint shear stiffness before maximum shearing resistance and afterwards are set equal to the joint Mohr-Coulomb frictional sliding resistance.

Computations are divided into static and dynamic portions. The initial static interblock stress of the rigid block portion are found through a stiffness method [2] that eliminates all tension and excess shearing stress along joints. Dynamic interblock stresses and displacements are then found by explicit time integration of the equations of motion of the response to the dynamic excitation [3].

The silent boundary [4] was specially developed to both prescribe motions and eliminate artificial reflections at the same boundary. It operates by prescribing the boundary nodal forces as those arising from the wave minus the difference between the calculated and imposed forces determined from the plane wave relationship between stress and particle (nodal) velocity.

DEEP AND SHALLOW RESPONSE WITH VARYING FREQUENCY

The 600 m deep cavern model was exercised with the nine motions described in Table 1. As shown in Figure 3, only the 30 and 50 Hz motion at 3 m/sec, ten times the expected peak motion of 0.3 m/sec, produced significant displacement along joint 19. Joint 19, located midway up the cavern wall in Figure 1, experiences the greatest relative displacement among all joints in the model. Therefore, to simplify the presentation, only displacements along joint 19 are presented.

As shown in Figure 4, if failure were defined as sliding a percentage of the joint length, then even the 50 Hz motion would not have exceeded a 2% criteria. Joint length criteria are based upon considerations of joint roughness that provides a significant component of the sliding resistance.

The same cavern model was then exercised at the 60 m depth for the 0.3 m/sec design motion at frequencies of 5, 10 and 30 Hz. Only for the 30 Hz motions was intermittent sliding observed. The 5 and 10 Hz excitation only produced elastic motions and no sliding along critical joint 19. The relative displacement along joint 19 for the 60 and 600 m depths are compared in Figure 5. Even though intermittent sliding results at 60 m depths, the total displacement is still only 2 cm or 0.25% of the joint length.

Table 1. Cases Examined for 600 m Depth

maximum velocity \ sinusoidal frequency	10 Hz	30 Hz	50 Hz
0.3 m/sec	-	5.8 g 1.6 mm	9.6 g 0.1 mm
1.5 m/sec	-	29 g 8 m	48 g 0.5 mm
3.0 m/sec	19 g 47 mm	58 g 16 mm	96 g 1.0 mm

The intermittent sliding pattern is expected and was predicted by Newmark [5]. This intermittent pattern results from the absorption of sliding energy as well as the oscillation of normal forces across the joint as shown in the 600 m case in Figure 6.

CONCLUSIONS

Subject to the limited cavern geometry and excitation motions that were studied, the following observations were made.

1. The rigid block model displays expected intermittent deformation patterns when caverns are subjected to non catastrophic earthquake shaking.
2. For the prototypical cavern studied, shear wave lengths of about twice the cavern height (relatively very high frequency motions) produced the greatest relative displacement per cycle of excitation.
3. All other considerations being equal, shallow buried caverns may experience larger relative deformation than those more deeply buried.

RECOMMENDATIONS FOR FURTHER WORK

Rock joint properties need to be further defined, particularly those relating sliding resistance to deformation (the normal and shear stiffnesses) as well as dilation. Other work has shown that changes in the normal and shear stiffnesses employed in these models leads to differences in shaking induced displacements. In addition, degradation of sliding resistance with cyclic motion needs to be studied. Even though present joint models can include such degradation, little laboratory data exist to serve as a basis for such degradation functions.

ACKNOWLEDGEMENTS

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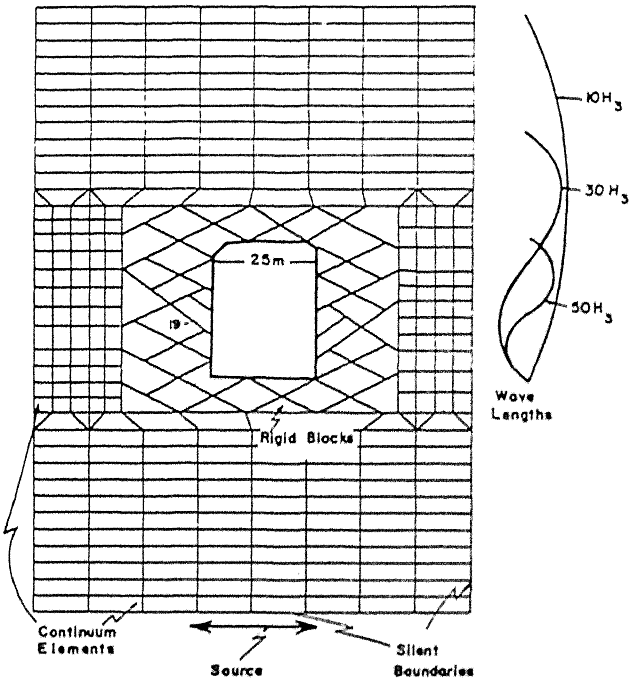
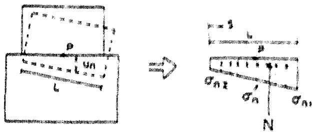
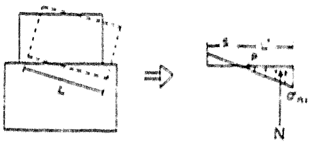


Figure 1.
Cavern and Mesh of Numerical Model



(a) Full Penetration



(b) Partial Penetration

Figure 2
Relation Between Penetration and Contact Force
for Edge-to-Edge Block Interaction

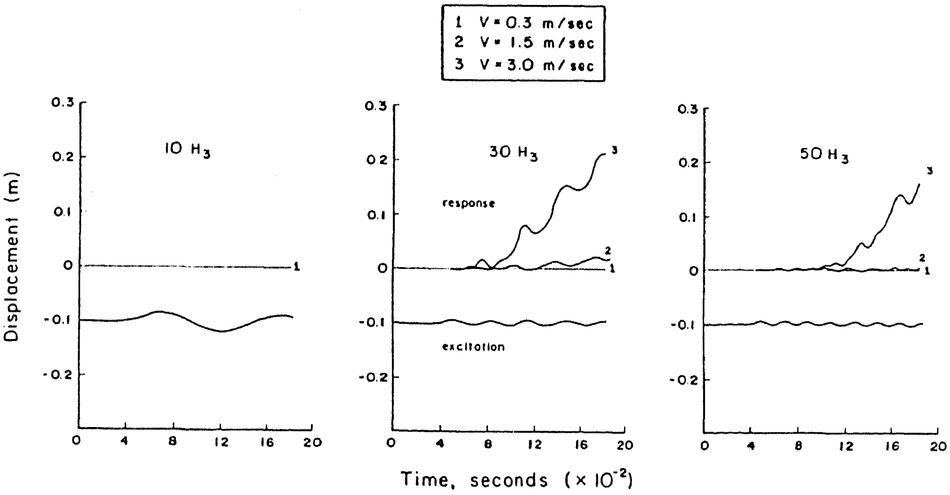


Figure 3.
Comparison of Excitation and Response of Joint 19

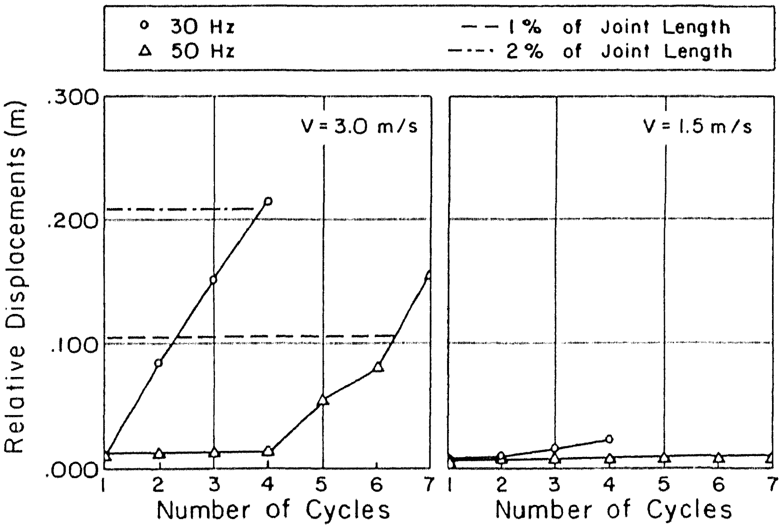


Figure 4
Response of Joint 19 versus Cycles of Excitation

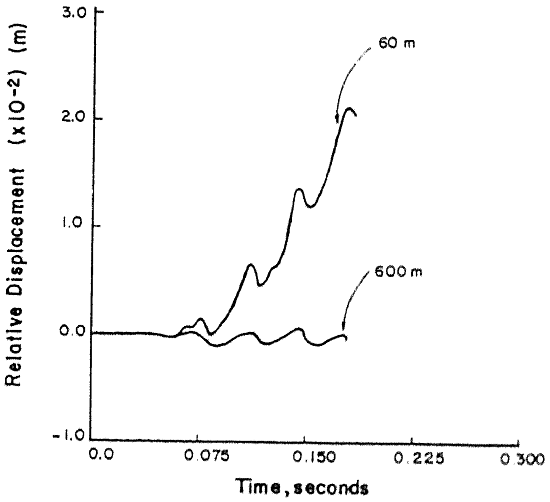
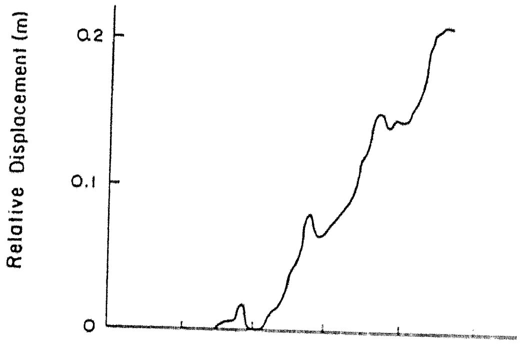
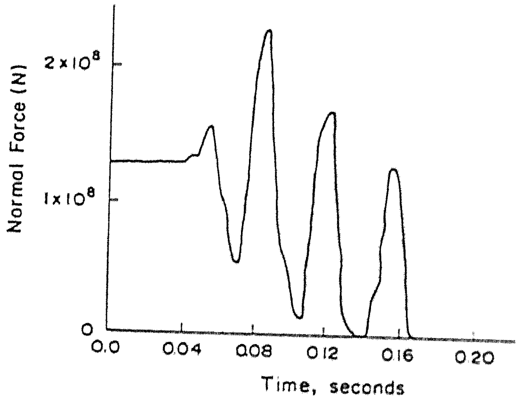


Figure 5
Comparison of Joint 19 Response for Shallow and Deep Caverns
(30 Hz, V = 0.3 m/sec)



a) Relative Displacement



b) Normal Force

Figure 6
Relationship Between Intermittent Sliding and Normal Force