NUMERICAL ANALYSES OF REINFORCED UNDERGROUND OPENINGS SUBJECTED TO SEISMIC LOADINGS

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1. INTRODUCTION

The Yucca Mountain Site Characterization Project is investigating the feasibility of locating a high-level radioactive nuclear waste repository at Yucca Mountain, Nevada. As a part of the site characterization efforts, an Exploratory Studies Facility (ESF) is being designed and constructed to provide an underground facility for research and study of the host horizon. Three types of loads, geostatic, seismic and thermal, are considered during the design analysis of ESF underground opening stability. This paper examines the potential impact of the earthquake-induced dynamic loading on the stability of the ESF underground openings. Design and construction of the ESF consist mainly of a loop tunnel and associated test alcoves. The 7.62-meter diameter main access loop, which includes Topopah Spring North Ramp, Main Ramp, and Topopah Spring South Ramp, is being excavated by a tunnel boring machine. Test alcoves are being excavated either using drill and blast techniques or by mechanical methods.

The ESF main access loop will eventually become an access tunnel for the permanent repository if the site is determined to be suitable. It is essential to ensure long-term stability of openings by using adequate and maintainable ground support systems. The installed ground support systems need to be designed to withstand the maximum seismic events specified in design requirements. The major components of the ESF ground support systems include rock bolts, shotcrete and steel sets.

The propagation direction of seismic waves generated by earthquakes is generally random with respect to any underground structure. This feature complicates the analysis of underground openings in the rock mass behaving distinctively in compression, tensile and shear. This is especially true when certain discontinuity features such as

joints, beddings and faults exist. Therefore, predicting the behavior of the underground structures that are subjected to potential seismic loadings is a very challenging engineering task. Recent advances in numerical modeling techniques enhanced by powerful, yet less expensive computers provide new avenues to deal with the challenge. For ESF design, it is essential to make sound engineering analysis of potential damage to the underground openings and associated ground support systems. As a product of the ESF design effort performed in geotechnical design analysis work, this paper only presents some of typical numerical results obtained.

2. WORK DESCRIPTION

To study the stability of the underground openings subjected to seismic loading, both two- and three-dimensional computer models have been constructed along the tunnel alignment. Finite difference codes FLAC¹ and FLAC3D² as well as distinct element codes UDEC³ and 3DEC⁴ are used to perform the numerical analyses. These codes are developed by ITASCA Consulting Group and have been benchmarked by the design team to meet the project requirements.

ESF openings pass through four major rock formation units: the Tiva Canyon (TCw), the upper Paintbrush Tuff (PTn), uppermost Topopah Spring (TSw1), and middle Topopah Spring (TSw2). Table 1 shows the elastic and strength properties for each unit. The best estimated ratio of in-situ horizontal to vertical stress falls within 0.25 and 0.50. The PTn rock formation is the weakest unit. The major portion of the tunnel will be excavated in the relatively competent Tsw1 and Tsw2 units. Seismic loadings are simulated after the tunnel and alcoves have been excavated under the in situ stress loading condition.

Seismic loading is applied to each computer model after the rock mass and ground support systems surrounding the

tunnel have reached a new equilibrium stage. Viscous boundary conditions are used to prevent the outward-propagating waves from reflecting back into the model at boundaries. The sinusoidal shear velocity wave is applied at the bottom boundary and propagates upward. This shear wave causes horizontal ground vibration (shaking) and is a leading cause of structural damage. The compressional wave in the vertical direction is treated in a similar way.

Table 1. Rock Mass Properties

Rock Formation Unit	Young's Modulus (GPa)	Poisson's Ratio	Cohesion (MPa)	Friction Angle (deg.)
TCw	6.70 - 27.71	0.2	1.2 - 3.0	53 - 55
PTn	2.50	0.2	0.3 - 0.5	40 - 44
TSw1	5.66 - 18.90	0.3	0.7 - 1.9	41 - 43
TSw2	6.37 - 23.51	0.21	1.3 - 3.8	49 - 50

Figure 1 shows a typical mesh refinement surrounding the opening. The rock bolts are represented by one-dimensional truss elements while shotcrete and steel sets are represented by two-dimensional beam elements with three degrees of freedom at each end of a beam segment.

3. RESULTS

The numerical analyses provide valuable information about the stability of the opening and the resultant loads on the structures. A sample of these results documented in the report⁵ is presented in this paper. Figure 2 illustrates an input shear velocity wave underneath the model and the monitored ground vibration at the top of the model after the wave has propagated through the model. Energy dissipation due to ground damping distorts the wave shape and reduces the amplitude. Figure 3 shows comparisons in tunnel closures and load changes in ground supports after static and seismic loadings. Vertical and horizontal closures of the tunnel respond noticeably to the seismic loadings but quickly mobilize to static closures once the wave passes. There is an increase in the maximum loads in the tunnel liner due to seismic loading. Numerical results have indicated that the load changes are not significant enough to cause damage to the installed ground support systems. Numerical analyses have also revealed that seismic loading can sometimes cause the shotcrete liner to be partially in compression and partially in tension momentarily. In this regard, adequate liner fiber reinforcing is prudent, though the stress has not gone beyond either compressive or tensile strength of the liner. Different rock formations respond differently in dynamic movement to applied seismic loads.

Figure 1. Close-ups of Numerical Models for Analyses.

Figure 2. Simulated Seismic Velocity Waves.

(a) Tunnel Closures

(b) Axial Force Distribution in Tunnel Lining

(c) Bending Moment Distribution in Tunnel Lining

Figure 3. Comparisons in Tunnel Closures and Load Changes in Ground Supports after Static and Seismic Loadings.

The tunnel experiences a maximum dynamic closure of 2 mm in TCW, 7 mm in TSw1 and 12 mm in TSw2. The tunnel still remains stable, as incated by all three models.

4. CONCLUSIONS AND DISCUSSIONS

While there are no well-established analytical or empirical formulae capable of predicting the potential damage characteristics from an earthquake to underground openings, numerical modeling methods have served as a very useful engineering tool for examining the excavation stability and guiding the selection of ground support systems, bolting patterns and excavation sequence. Numerical results have also indicated that for the underground openings, the seismic wave frequency does not have a significant effect on rock displacement or loads in support elements. Such numerical responses are realistic in considering that the deep underground tunnels are confined by the surrounding rock and are, therefore, less sensitive to frequency value. Rapid and inexpensive parameter studies through numerical modeling have allowed for gaining insight into the design concerns caused by unavoidable uncertainties in geological data and material behaviors. Numerical analyses provide a foundation for design validation, which occurs through further back analysis of field instrumentation data and observations to be collected during construction.

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