Seismic Analyses for the Deposition Tunnel in Fractured Rock by 3DEC

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Abstract

In order to consider the operation safety of spent nuclear fuel final disposal (SNFD), the way of final disposal is to emplace waste canister in deep underground opening, so the tunnel stability which is the important issue for operational period must be faced. Taiwan is located in the Circum-Pacific seismic zone; therefore, the impact of earthquake on the safety of the tunnel should be highly paid attention, and SNFD program in Taiwan has planned the research path including seismic hazard and tunnel structural capacity perspectives. At this moment, for the purpose of operation safety confirmation of the SNFD repository design in the offshore island crystalline rock mass of Taiwan, the seismic stability analysis of deposition tunnel was carried out. Since the fractures in deep granite rock mass might be the key to the instability of the tunnel during the earthquake, the 3DEC was used to analyze the stability of tunnel during normal and earthquake period, and analysis cases also compared intact rock and fractured rock to realize the difference on seismic performance. The results show that the safety factor of tunnel during normal period is directly affected by the fractures, while the safety factor is relatively high in the intact rock, but the impact of the earthquake on the safety factor is relatively small. From the study experience, the tunnel time history analysis by 3DEC has been understood, so the future research plan can be made. And the more fracture related parameters has been planned to input to evaluate the impact on tunnel stability in the future.

1. Introduction

In design of the tunnel section, it not only needs to meet the basic requirement of space, also consider the rock mechanics parameters, stress conditions and other factors to confirm compliance with safety standards. Earthquake should be the natural disasters that may cause the tunnel to be unstable during operation. In order to confirm the stability of the deposition tunnel during operation, such as the study of H12 [1] in Japan, the stability of the tunnel during the earthquake should be evaluated. And Mohr - Coulomb failure criteria usually is used to calculate the safety factor of the tunnel section to represent the margin of stability. Traditionally the numerical analysis method for the stability of tunnel used continuum mechanics software. However, the fractures in rock mass probably play important role on the stability of tunnel section, so the modeling of fracture in stability analysis is necessary. In this study, three-dimensional distant element method software 3DEC was used to consider the intact rock and fracture rock cases, in order to evaluate whether the existence of fracture has a significant effect on the stability of tunnel section.

2. Analysis methods and considerations

In this study, the discrete fracture network (DFN) data of the offshore island crystalline rock mass (ITRI, 2015) shown in Table 1 were used, and the stability analyses during normal operation and earthquake period were performed to explore the influence of the fractures. The deposition tunnel size is referred to the Table 1 in SNFD2017 reference case disposal design and engineering technology and parameter description (2016) [3]. The cross section is shown in Fig 1, and tunnels are located at 500 m depth. In order to avoid the boundary effect of the numerical model, the Rock model size is generally required to be at least 5 times the tunnel size. Because the tunnel section width is 4.2 m and the height is 4.8 m, the model size is 21 m x 24 m.

DFN parameters include the randomness of fracture sets, so the stability analysis should be performed for large number of case to find the worst one. Due to limited time and research target, the analysis cases did not consider the randomness of fractures. For the modeling of fractured rock mass, multiple sets of DFN will be established to cut the whole rock model, the element size of the model should be small enough to avoid the generation of longer elements. However, it will take large amount of computational resources and time for seismic analysis, so the element size would take 0.5 m after assessment. Although, totally five sets of DFN data are obtained from the geological survey results of the offshore island crystalline rock mass. Since the seismic analysis will take over 3 months if considering 5 sets of DFN in one case at the same time, in order to speed up the research progress, this study only used two sets of DFN which have higher P_{32} ratios to discuss the influence before and after the earthquake.

On the other hand, for comparing the difference between the stability of the intact rock mass and the fractured rock mass in the normal period, five sets of DFN were used because the computational time can be controlled in research schedule. The tunnel model in fractured rock built by 3DEC is shown in Figure 2.

The analysis cases include (1) the stability during normal period in no fractured rock mass; (2) the stability during earthquake in no fractured rock mass; (3) the stability during normal period for 5 sets of DFN in rock mass; (4) the stability during earthquake for 2 sets of DFN in rock mass.

The calculation of the safety factor is based on the Mohr-Coulomb failure criterion, which takes into account the stress state to confirm whether the rock mass has entered the plasticity. The comparisons of the stress conditions among normal period, earthquake period, fractured rock mass and intact rock mass will be made, and they can provide the information of the impact level to become a basis for subsequent verification and test plan.

3. Material parameter and boundary condition

From geological investigation data, rock mass can be partitioned into weathered rock layer R0, which is 70 m thickness from the ground surface, and granite gneiss body R1. In order to simplify the input parameters of the model, the parameters are summarized as Table 2. The fracture related mechanical parameters have not been investigated, so the 3DEC built-in parameters as shown in Table 3 are used.

The setting of the in situ stress is referred to the field data by using Hydraulic Fracturing method in the depth of 430 m. The measured vertical stress is σ_v=11.4 MPa; horizontal maximum principal stress is σ_H= 14.43 MPa; and horizontal minimum principal stress is σ_h = 9.38 MPa; so the horizontal $K_{0,\ min}$ is 0.82 and $K_{0,\ max}$ is 1.27. For tunnel alignment, the tunnel main axial will be parallel to the maximum horizontal axis; so the tunnel radial stress will be lower, and K_x and K_y are set as 0.82 and 1.27 respectively.

Table 1 Discrete fracture network parameters

Set No.	**trend**	**plunge**	**κ**	**P_{32}**
1	65°	17°	20	15%
2	344°	38°	18	24%
3	281°	29°	16	30%
4	174°	22°	17	10%
5	175°	75°	19	21%

Note: κ is Fisher distribution parameter; P_{32} is fracture intensity (m^2/m^3).

Table 2 Rock material parameters

Density γ (kg/m^3)	Cohesion C (MPa)	Friction angle ϕ (°)	Young's modulus E (GPa)	Poisson ratio ν
2,750	27.46	51.05	44.18	0.17

Table 3 Rock fracture material parameters

Joint normal stiffness (N/m)	Joint shear stiffness (N/m)	Dilation angle Ψ (°)	Joint tensile strength (Pa)	Joint cohesion (Pa)
$2.0\ x10^{12}$	$2.0\ x10^{12}$	20	0	0

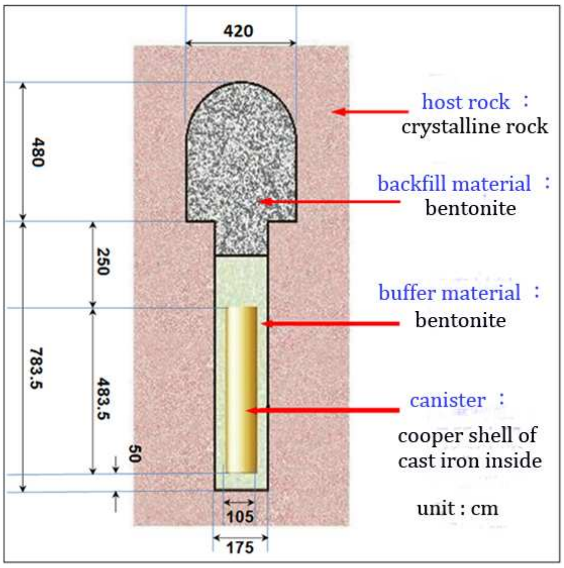

Figure 1. The cross section of disposal tunnel and disposal hole

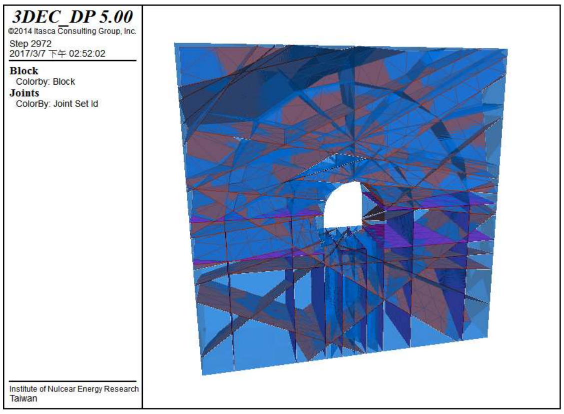

Figure 2. Tunnel model with 5 sets of DFN in rock mass

4. Input of earthquake time history

The response spectrum for tunnel design is generated by the seismic hazard analysis [4], and the PGA of spectrum compatible acceleration time history is 0.288 g. The duration is 40.96 s, and time interval is 0.01 s; so, totally there are 4,096 data points. The earthquake time history was input on the rock outcrop surface (at 70 m under the ground surface, which is the interface between the weathering layer R0 and the granite gneiss body R1). Using one dimensional site response analysis, the wave will pass down to 500 m under the ground surface, and the earthquake wave form of 500 m depth is shown in Figure 3, where the peak ground acceleration is 0.206 g. Because 3DEC dynamic analysis can only input the velocity or stress time history, it is necessary to integrate the acceleration time history to get the velocity time history as shown in Figure 4. This velocity time history was input at the bottom of the 3DEC model to perform the seismic analysis.

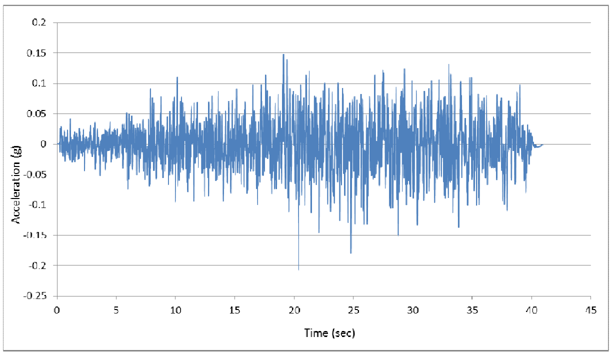

Figure 3. The input acceleration time history on the base of deposition tunnel model

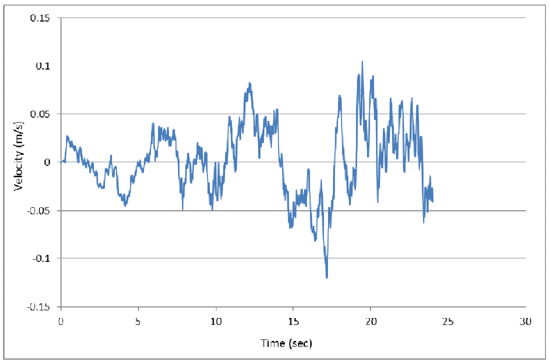

Figure 4. The input of velocity time history on the base of disposal tunnel model

5. Results and discussion

(1) Case 1: normal period, rock mass without fracture

After calculating principal stress of each element by 3DEC to generate the safety factor of each element by Mohr-Coulomb failure criterion, the minimum safety factor is 1.6658, which occurs at the bottom of the tunnel edge as shown in Figure 5.

(2) Case 2: earthquake period, rock mass without fracture

The seismic analysis is carried out and the safety factor is checked at the time point of the maximum acceleration of the earthquake. At this point, the minimum safety factor of all elements is 1.6656, which also occurs at the bottom of the tunnel edge. The safety factor is only slightly decreased than that of the normal period. This phenomenon can explain that in-situ stresses in the deep rock mass are high, and the increasing stresses due to the earthquake have less impact.

(3) Case 3: normal period, rock mass with 5 sets of DFN

The minimum safety factor is 1.2283, which also occurs at the bottom of the tunnel edge, as shown in Fig. 7, and the safety factor is significant lower when compared with case 1 (rock mass without fracture). However, in the middle of the tunnel floor safety factor is particularly high. After checking the stress and displacement, it shows there is a relative shift (displacement about 3mm), so that it leads the stress drop and have a relatively high safety factor.

(4) Case 4: earthquake period, rock mass with two sets of DFN

The safety factor of the fractured rock mass during normal period is slightly decreased, and the minimum safety factor is 1.3840, which also occurs at the bottom of the tunnel edge, as shown in Fig. 8. However, the safety factor is higher than the case 3 which with five sets of DFN. The result shows the number of DFN set is negatively correlated with safety factor, and more sets of DFN will lower the safety factor.

For earthquake period, the minimum safety factor of the tunnel is 1.4142, which occurs at the bottom of the tunnel edge as shown in Fig. 9, but it is slightly increased when compared to the safety factor for rock mass with 2 sets of DFN in normal period. This phenomenon shows that, for considering the discontinuous property of the fracture, the fractures will induce relative displacements during earthquake; they would cause the stress release of the rock mass, so the safety factor of the stress calculation is reduced. This result is different from Case 2 which the rock mass is without fracture, and it also shows the comparison between continuous and discontinuous mechanics treatment on stress analysis..

Although the safety factor changes in this case during the earthquake, but only slightly different, it can see the seismic wave impact of the deep rock mass is low.

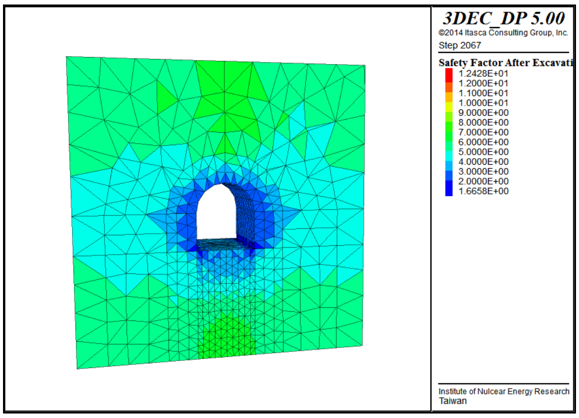

Figure 5. Safety factor for rock mass without fracture when normal period

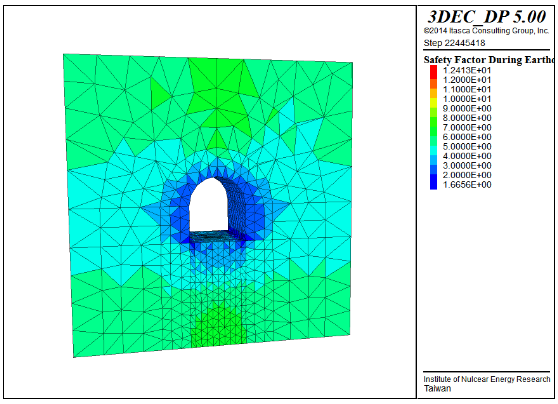

Figure 6. Safety factor for rock mass without fracture when earthquake period

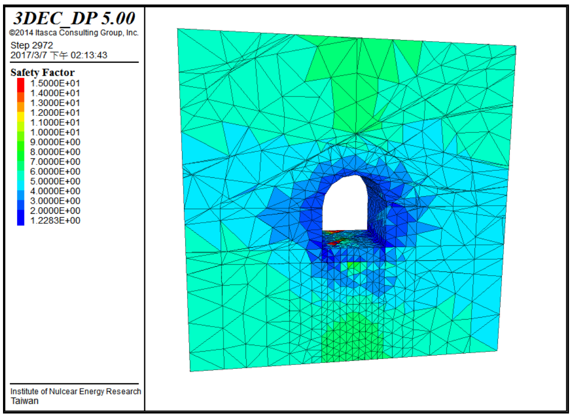

Figure 7. Safety factor for rock mass with 5 sets of DFN when normal period

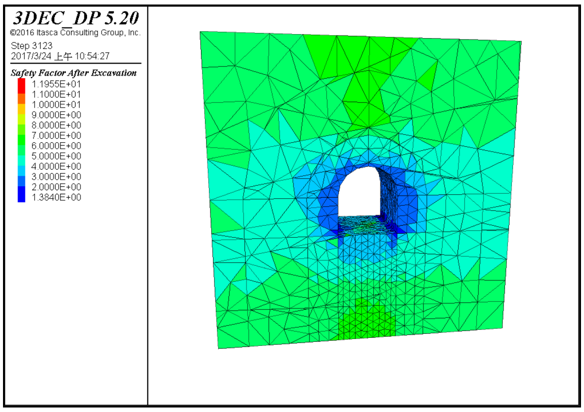

Figure 8. Safety factor for rock mass with 2 sets of of DFN when normal period

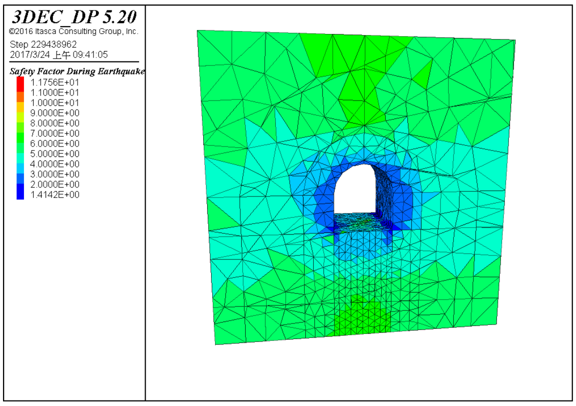

Figure 9. Safety factor for rock mass with 2 sets of DFN when earthquake period

6. Conclusion

Conclusions of the analyses are as follows :

(1) The analysis results show that the safety of tunnel during normal period in deep rock mass is highly correlated with the number of fractures. However, even five sets of fractures are considered, the minimum safety factor is still 1.2283. So if the

fractured cannot create the weak plane to form instable wedge or rock spalling, the influence would be minor.

(2) For current test site of offshore island crystalline rock mass in Taiwan SNFD program, whether in intact rock or fractured rock, the earthquake influence is slightly low, and the tunnel is still in a safe state, because the stress induced by 0.2g PGA earthquake seems low compared to that of in-situ stress.

And there are some suggestions as follows:

(1) From analysis results, the displacement caused by fracture movement will release the stress and increase safety factor; however, large displacement may result in instability. Therefore, the analysis should not only focus on the safety factor calculated from stress results, but also should check displacement results.

(2) Because seismic analysis requires a lot of computing resources and computing time, it is difficult to meet the randomness of DFN. Therefore, it is suggested that the deterministic fracture information or critical fracture should be assessed by investigation group. On the other hand, the process by using static nonlinear analysis, equivalent-static load, or frequency domain method from structural engineering experience could be introduced and developed to help determine safety factor quickly.

7. Reference

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