A study on the response of country rock of grottoes reinforced by prestressed anchors during seismic loadings

Rendong Qiu[1,2], Yucheng Shi[1,2], Junjie Sun[1,2], Xiumei Zhong[1,2], Changhua Fu[1,2], Lijun He[1,2], and Mingqing Hu[1,2]

[1] *Lanzhou Base of Institute of Earthquake Prediction CEA, Lanzhou 730000, China*
[2] *Lanzhou Institute of Seismology CEA, Lanzhou 730000, China*
Email:qiurend@163.com

ABSTRACT :

In this paper, the authors research the response of grottoes' country rock with prestressed anchors during seismic loadings by a numerical analysis method. Its primary objective is to advance our understanding on the stability of country rock of grottoes while an earthquake occurs. It is well know that prestress anchors can enhance the strength of grottoes' country rock. During a seismic loading, e.g. an earthquake event, however, the reinforcing capability of prestressed anchors is still a question. Here we choose three models in two-dimension to analyze the stability of country rock reinforced by prestressed anchors, which all are in the north region of Mogao Grottoes, Dunhuang of Gansu province, China. As a result of numerical analysis of displacement and stress field during seismic loadings with different peak ground acceleration (PGA), spectra and durations, we understand the characteristics of dynamic response and vibration regularity of rock mass reinforced by prestressed anchors better than before. Furthermore, some other results reveal that displacement and stress of rock mass increase, range of stress concentration expands, and the damages probability of country rock goes up with the increase of PGA, characteristic period and duration of seismic loads. The authors believe that this paper could provide a theoretical basis and a practical reference for the preservation of grotto relics and seismic retrofit and seismic hazard mitigation for rock mass.

KEYWORDS: seismic loadings, prestressed anchor cable, country rock, dynamic behaviour

1. INTRODUCTION

The essence of prestressed anchor cable is to take full advantage of greater rigidity and mechanical properties of the material to strengthen or reinforce rock mass and soil body, and play rock&soil mass of self-stability to ultimately achieve the stability of the structure(Jiebing Zhu et al., 2002).With the development and expansion the area of application in the field of geotechnical anchoring technology, there are many new problems to be further studied and resolved. Earthquake is common form of seismic loads, in the engineering and rock dynamics research, it is an urgent problem and one of the main contents that rock response, stability analysis methods and control means with seismic loads(Haibo Li et al., 2003; Qianrong Lei et al., 1992; SHARMAS et al., 1991; Weizhong Chen et al., 1998; Yonglai Zheng et al., 1999).At the present, the study on the dynamic response of rock mass reinforced by prestressed anchors during seismic loadings attract little attention. The paper base on the World Heritage of Mogao Grottoes at Dunhuang North reinforcement works as an example, adopt dynamic finite element analysis, focus on impact on the dynamic breaking characters of dangerous rock reinforced by prestressed anchors under seismic loads, offer reference for grottoes' geotechnical engineering disaster mitigation and heritage conservation work .

2. THE MODEL ESTABLISHMENT

2.1. Geotechnical Conditions and Seismic Loads characteristic

Lower Pleistocene Yumen group(Q_1) ,middle Pleistocene Qiuquan group(Q_2) and upper Pleistocene Gebi group(Q_3) are in the North of Mogao Grottoes and its underlying stratum. The rock attitude is all nearly

horizontal. There are four engineering geology groups in the North of Mogao Grottoes, from top to bottom ,named A,B,C and D separately. Each group's mechanics parameters are showed in Table 1.
Peak ground acceleration (PGA), characteristic period (Tg) and duration time (t) which have different engineering meaning are considered in seismic input. Because of lacking strong earthquake record, the author take synthesis of simulated earthquake waves(①Tg =0.25s,PGA=0.1g,t=20s; ②Tg =0.55s,PGA=0.1g,t=20s) from fitting target spectrum, according to the result of seismic risk analysis, based on seismic response spectrum about seismic environment and site condition. Seismic input(Tg = 0.25s, PGA=0.1g) reflects the value of seismic loads under local basic seismic intensity of Mogao Grottoes in the future.

Table 1 Mechanical parameters of different rock layers

Petrofabric	Modulus (MPa)	Poisson ratio	Density (g/cm^3)	Compressive strength (MPa)	Tensile strength (MPa)	Cohesion (MPa)	Internal friction angle
Q_3	100	0.30	2.30	-	0.20	0.10	50
A	200	0.28	2.30	9.50	0.36	0.20	65
B	87	0.30	2.20	12.6	0.54	0.10	50
C	300	0.27	2.35	8.60	0.47	0.25	67
D	500	0.26	2.40	15.8	0.67	0.30	70

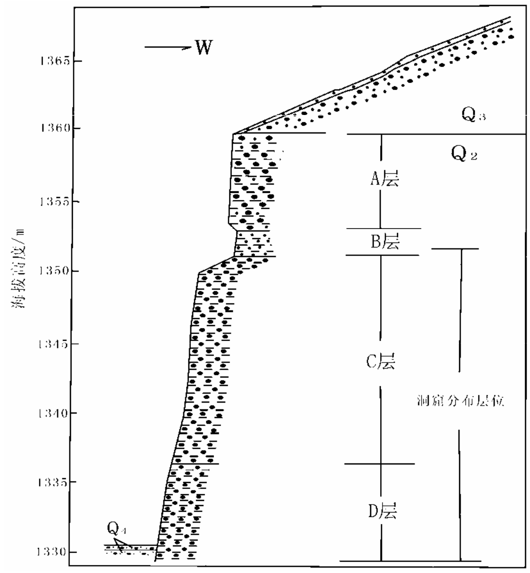


Fig.1 Strata sector of Mogao grotto

2.2. Analysis Model

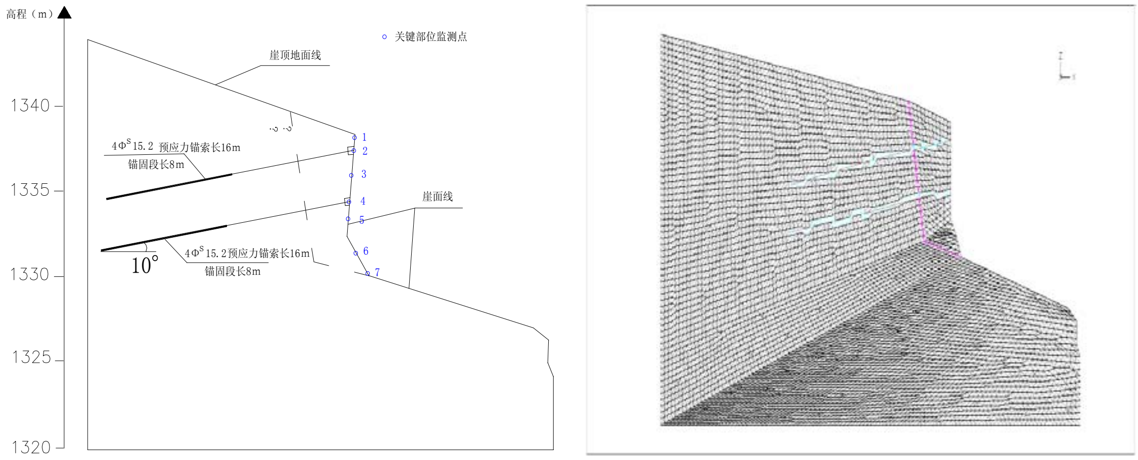
The author takes three reiforced slope section as the analysis object, dangerous rock mass in model Ⅰ are reinforced by two-layer prestressed anchor cables, four-layer prestressed anchor cables in model Ⅱ, combined reinforcement with three-layer prestressed anchor cables and anchors in model Ⅲ. Detailed design informations are in Fig.2.

2.3. The Principle of Finite Element Analysis

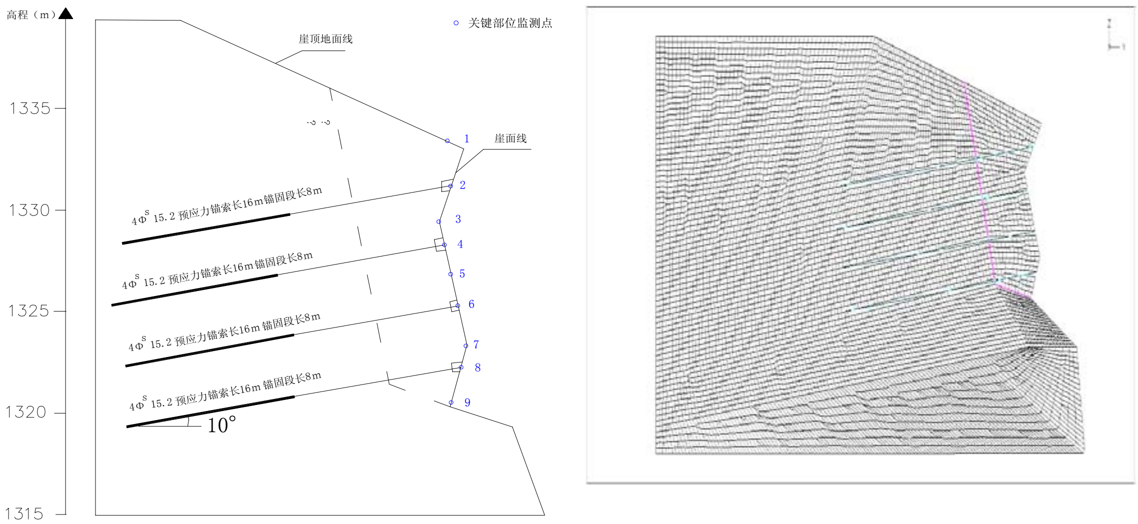
The seismic response of rock&soil mass is a transient dynamics process under the seismic loadings, the equation of motion in the moment of t+△t for the finite element system is expressed as follows:

$$\underline{M}\ddot{\underline{u}}_{t+\Delta t}+\underline{C}\dot{\underline{u}}_{t+\Delta t}+\underline{K}\underline{u}_{t+\Delta t}=\underline{M}\underline{I}(\ddot{u}_g)_{t+\Delta t} \tag{1}$$

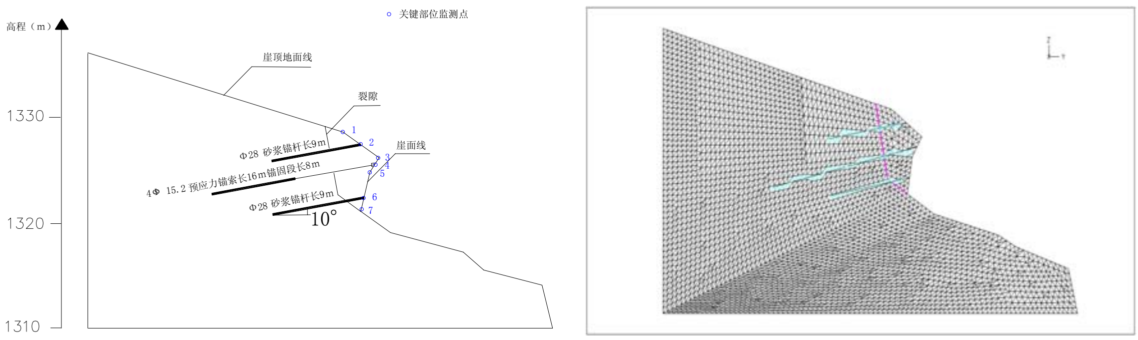
$\underline{M}$ —system total mass matrix , $\underline{C}$ —system total damping matrix, $\underline{K}$ —system total stiffness matrix, $\underline{I}$ —unit oscillating vector, $\underline{u}''_{t+\Delta t}$ —system nodes acceleration vector, $\underline{u}'_{t+\Delta t}$ —system nodes velocity vector, $\underline{u}_{t+\Delta t}$ —system nodes displacement vector, $(u_g)_{t+\Delta t}$ —rock base acceleration, Newmark implicit time integration methods is used to solve the movement balance equation.



Model Ⅰ



Model Ⅱ



Model Ⅲ

Fig.2 Design details and the finite element models

2.4. Prestressed Anchor Cables and the Initial Ground Stress

In the prestressed cable anchoring system, the steel cables only have the axial tension capacity , couldn't be compressed or bended .This paper take anchor cables as nonlinear elastomer,Fig.3 is mechanics characteristic curve(stress-strain curves shows only tensile strength but no compressive strength).

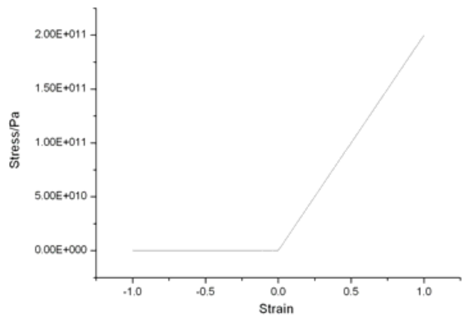


Fig.3 The graph of the stress and strain relationship of prestress anchor cable

The initial ground stress usually is the undisturbed stress in stratum. The original stress is made up of soil self-weight and tectonic stress. Without regard to tectonic stress, initial stress is equivalent to soil self-weight. According to the elastic theory, The equation calculating the initial stress of soil under self-weight is expressed as follows:

$$\{\sigma_0^0\} = \begin{Bmatrix} \sigma_x^0 \\ \sigma_y^0 \\ \sigma_{xy}^0 \end{Bmatrix} = \begin{Bmatrix} \dfrac{\mu}{1-\mu}\gamma y \\ \gamma y \\ 0 \end{Bmatrix} \tag{2}$$

y -depth from surface, γ - bulk density, μ -Poisson's ratio.

Original stress is computed firstly under self-weight, and then the response laws of grottoes' country rock with prestressed anchor cables are discussed during the seismic loadings .

2.5. Yield Function of material

Rock mass is regard as perfect elastoplastic material, its yield function is as follows(Itasca Consulting Group Inc, 1999):

$$f_s = \sigma_1 - \sigma_3 N_\varphi + 2c\sqrt{N_\varphi} \tag{3}$$

$$f_t = \sigma_3 - \sigma_t \tag{4}$$

σ_1 , σ_3—the maximum principal stress, the minimum principal stresses, σ_t—unaxial tensile strength of rock , the equation about N_φ is as follows:

$$N_\varphi = \frac{1+\sin\varphi}{1-\sin\varphi} \tag{5}$$

When $f_s < 0$, shear failure occurs in the rock mass; $f_t > 0$, tensile failure occurs in the rock mass.

3. CALCULATION RESULT AND ANALYSIS

3.1. Analysis on Results of Stress in the Key Position of the Reinforced Slope

In order to know the mechanism of seismic deformation of the rock mass reinforced by the prestress anchor cables under the seismic loadings, some key points on the finite element models are observed in the analytic process. The observed points are showed as the Fig.2. The stress states of these points are studied. The computed results of these points are also shown in Table 2.

Table 2 The calculation results of the different parts of the reinforced rock mass

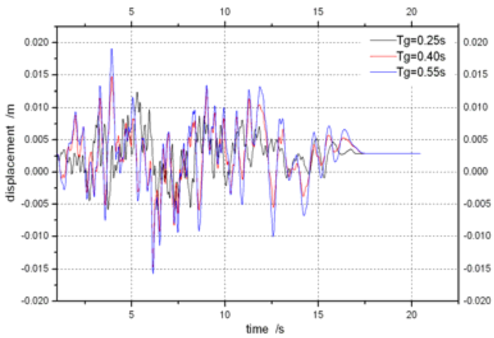
PGA=0.1g, Tg=0.25s, t=20s					PGA=0.2g, Tg=0.25s, t=20s		PGA=0.3g, Tg=0.25s, t=20s	
Monitoring points	σ_1(Pa)	σ_3 (Pa)	f_s	f_t	f_s	f_t	f_s	f_t
Model Ⅰ								
①	3574	-92783	>0	<0	>0	<0	>0	<0
②		-657606	>0	<0	>0	<0	>0	<0
③	25493	-102976	>0	<0	>0	<0	>0	<0
④	-398569	-1348070	>0	<0	>0	<0	<0	<0
⑤	264956	-4267	>0	<0	>0	<0	>0	>0
⑥	292995	-10653	>0	<0	>0	<0	>0	>0
⑦	352650	-23380	>0	<0	>0	<0	>0	>0
Model II								
①	79784	-13924	>0	<0	>0	<0	>0	<0
②	-314469	-827891	>0	<0	>0	<0	<0	<0
③	9947	-280219	>0	<0	>0	<0	>0	<0
④	-99998	-693892	>0	<0	>0	<0	>0	<0
⑤	153731	-11177	>0	<0	>0	<0	>0	>0
⑥	-32252	-520029	>0	<0	>0	<0	>0	<0
⑦	219024	-3374	>0	<0	>0	<0	>0	>0
⑧	-11380	-566105	>0	<0	>0	<0	>0	<0
⑨	209896	-250574	>0	<0	>0	<0	>0	>0
Model III								
①	59911	-14103	>0	<0	>0	<0	>0	<0
②	34791	-33023	>0	<0	>0	<0	>0	<0
③	52178	-10488	>0	<0	>0	<0	>0	<0
④	-187491	-1183800	>0	<0	>0	<0	<0	<0
⑤	-47681	-712458	>0	<0	>0	<0	>0	<0
⑥	27886	-123246	>0	<0	>0	<0	>0	<0
⑦	71177	-50147	>0	<0	>0	<0	>0	<0

The calculation results show that compressive stress concentrate on the tip of the prestressed anchor cables, the tensile stress mostly focuses on the middle of the two-layer anchors, stress concentration also appears in the prominent position and corner of the reinforced slope. The prestressed anchor cables could control fractures development effectively, but if enhancing prestress blindly, it will result in nothing but failure of rock structure, because it brings stress concentration in the rock mass around the prestressed anchor cables. Due to limitations of space (The paper haven't listed the stress field in the position of fractures), the position of fracture is at the position of catastrophe under the repeated action of the seismic loadings.

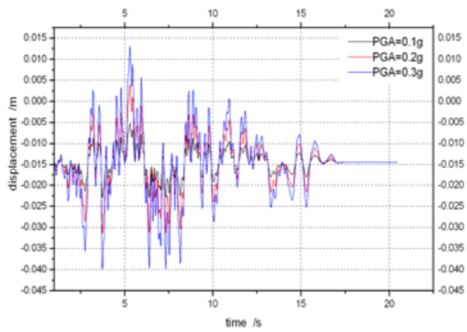
Under the seismic loadings(Tg=0.25s, PGA=0.1g, t=20s), dangerous rock mass which are strengthened by prestressed anchor cables are safe and the reinforced rock mass won't be broken down.

3.2. Analysis for the Computed Results Affected by the Characteristic of the Seismic Loadings

The results are determined by three factors of seismic loadings. One factor is the peak ground acceleration, the two others are the characteristic period and the duration of seismic loadings. Analysis results show that the value of stress is correlated with the peak ground acceleration in the same characteristic period and duration condition, the larger peak ground acceleration the larger stress value. It also shows that the value of stress is correlated with the characteristic period in the same peak ground acceleration and duration condition, the longer characteristic period the larger stress value. The results are affected by the peak ground acceleration and the characteristic period significantly.



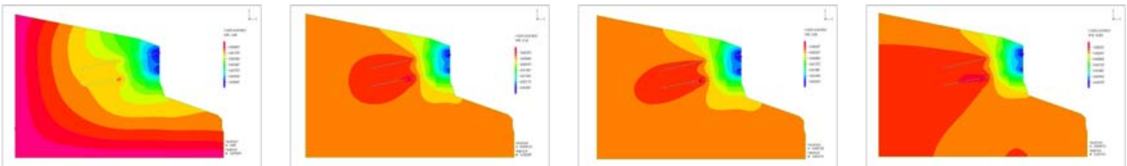
(a) t=20s, PGA=0.1g



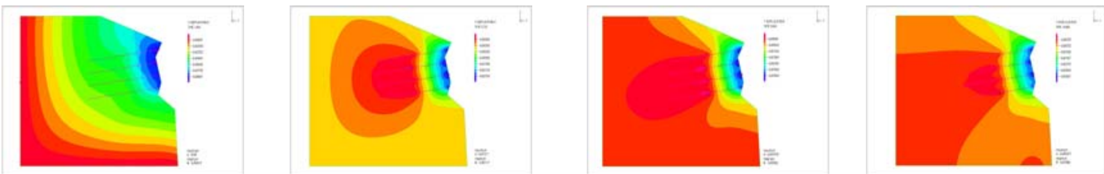
(b) t=20s,Tg=0.25s

Fig.4 Time history of the displacement of the reinforced slope under different PGA or Tg

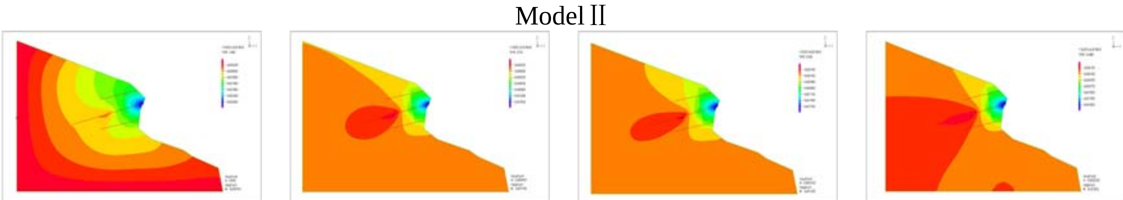
3.3. Analysis for the Horizontal Displacement Reinforced by the Prestressed Anchor Cables under the Seismic Loadings


1.84s 3.72s 5.00s 19.98s

Model Ⅰ


1.84s 3.72s 5.00s 19.98s

Model Ⅱ


1.84s 3.72s 5.00s 19.98s

Model Ⅲ

Fig.5 Displacement isograms in different moment for model Ⅰ,model Ⅱ and model Ⅲ (PGA=0.1g, Tg=0.25s, t=20s)

When the rock mass reinforced by the prestress anchor cables subject to the horizontal seismic loadings, the displacement field of dangerous rock mass reinforced is regularity in space-time. From results of the displacement field, it shows that the distribution of displacement field is closely related to the position of the anchor cables. The position of the anchorage devices and the anchorage length are the stress concentration field. The pressure state is at the part of the anchorage devices and the tensile state is at the part of the anchorage length under the forces of the prestressed cables. The largest displacement is at the end of the anchorage devices. It is up to 8 ~ 15 mm when subjected seismic loadings(PGA=0.1g，Tg=0.25s，t=20s). The instability tendency of the rock mass is controlled effectively by the prestressed cables. The safety factor of the rock mass is enhanced by the initial prestress.

4. CONCLUSIONS

The following was concluded from this study
(1) The stability of the county rock slope is affected by the spectrum characteristic of seismic loadings significantly. The results show that the displacement and stress increase with the increase of the peak ground acceleration to the rock mass. The results also show that the displacement and stress increase with the increase of the characteristic period of the seismic loadings. The damages probability of the reinforced rock mass increases with the increase of peak ground acceleration (PGA) and the characteristic period.
(2) The dynamic response and variation regularity of rock mass reinforced by the prestressed cables under seismic loadings are revealed through the numerical simulation. The displacement field distribution is closely related to the distribution of the prestressed cables. The displacement direction is determined by the prestressed cables. The position of the anchorage devices and the anchorage length are the stress concentration field. The pressure state is at the part of the anchorage devices and the tensile state is at the part of the anchorage length under the forces of the prestressed cables. The abnormal displacement appears at the position of the anchorage devices and the rock mass surface’s corner.
(3) Stress field of the rock mass is changed by the prestressed cables. The prestressed cable is an effective technique to reinforce the country rock mass. The instability tendency of the rock mass is controlled effectively by the prestressed cables. The safety factor of the rock mass is enhanced by the initial prestress.

REFERENCES

Haibo Li, Huijun Jiang, Jian Zhao, et al.(2003). Earthquake damage of underground structure and aseismatic method. *Earthquake Resistant Engineering*. **22:11**,1887-1891.
Itasca Consulting Group Inc. Universal distinct element code (version 3.1) user’s manual[R]. Minneapolis, USA: Itasca Consulting Group Inc.1999.
Jiebing Zhu, Jun Han, Liangkui Cheng, et al.(2002).Research on rockmass properties near anchor with prestressing for TGP’S permanent shiplock. *Chinese Journal of Rock Mechanics and Engineering*, **21:6,** 853-857.
Qianrong Lei, Jixin Ding. (1992). Seismology induced failure of underground tunnel. *Underground Space*. **12:4**,335-344.
SHARMAS, JUDD W R. (1991). Underground opening damage from earthquake. *Engineering of Geology*. **30:**263-276.
Weizhong Chen, Weishen Zhu, Baolin Wang, et al. (1998). Numerical simulation and testing study of large deformation for cavern’s surrounding jointed rockmass. *Chinese Journal of Rock Mechanics and Engineering*, **17:3**, 223-229.
Yonglai Zheng, Linde Yang. (1999). Earthquake damage of underground structure and aseismatic method. *Earthquake Resistant Engineering*. **4:**23-28.