A Preliminary Study on Distribution Law of Lateral Earthquake Load Along Slope's Height

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ABSTRACT :

Total 18 simulated acceleration time histories for intensity 6, 7, 8 and 9 were adopted as inputs, two different height slops which were located in some power station area were selected as the analyzed models which were simplified linear elastic models in computation, the seismic responses of the slopes and the horizontal variation of the maximum response accelerations at different height levels were analyzed by means of a wave propagation finite element method. The numerical results show that the acceleration changes along the height direction nonlinearly with a little bit complicated pattern, and the changing patterns, in general, are similar. The acceleration does not increase immediately after the slopes' height is getting taller from the bottom of the slopes, and it starts to increase rapidly with the height level at a height of half to two thirds of the total slopes' height. It gets a maximum amplification value of 1.0 to 1.91 at the top of the slopes. In general, the maximum amplification factor increases gradually with the total height of the slopes, and just a few get values greater than 1.5 (about 0.5%). From these understanding, two coefficients of lateral seismic load with relative height (ratio of height to the total height of the slope) for these two slopes are proposed in this paper, and one is in a bilinear form, the other is in a fourth order exponential curve, both with the same maximum value of 1.5.

KEYWORDS: slope, earthquake load, distribution law of lateral earthquake load along height, wave propagation finite element

1. INTRODUCTION

China is very mountainous country with earthquake. There are many naturally developed slopes and artificial slops by large numbers of engineering constructions, such as hydropower stations, roads, railways and mines. Therefore, landslide disasters by earthquakes occurred frequently (LI S. D., 2001; Liu H. S., 2006; SHI D., 2006), which has caused enormous economic losses. Thus, It is an important issue to study the seismic stability of slope and search effectively protecting methods and remedial engineering measures in geotechnical engineering field and earthquake engineering field, which have significant economic and social meanings on reducing earthquake-induced disasters, ensuring the major infrastructure construction, protecting people's lives and property safety, and promoting the harmonious developments of our country. In this paper, the horizontal variation of the maximum response accelerations at different height levels are analyzed by a wave propagation finite element method based on the practical examples to provide the reference for the study on the seismic stability of slope.

2. INTRODUCTION TO WAVE PROPAGATION FINITE ELEMENT METHOD

2.1. Choosing model

Currently, linear visco-elastic model, nonlinear viscoelastic model and elastic-plastic model are used to calculate dynamic response of soil. In all of these models, the linear viscoelastic model is a relatively simple soil constitutive model and it can be considered as linear elastic model when the viscocity action of model is much smaller than the elastic action up to the viscocity being assumed to degenerate to zero. The stress-strain curves of linear elastic model are two lines coincided completely, the area with two lines is zero. In other words, there is not loss of energy. The rate of straight line is equal to elastic modulus of soil and there isn't phase deference between stress and strain. The soil is a highly nonlinear material. So strictly speaking, the linear-elastic model isn't suitable to the relationship of stress-strain of soil. But regarding the small deformation, the displayed nonlinear and energy dissipation in soil are not prominent so that the linear elastic model can be used. Moreover, when soil nonlinear constitutive model and complex elastic-plastic model are not enough perfect and the numerical methods which are used in these model are not enough steady-going, the analysis on linear-elastic dynamic response of soil still has something referential value. Even if under large deformation, it can show some significant rules. So, the linear-elastic model is used to analyze slope in this paper, namely soil is regarded as homogeneous continuous and isotropic linear-elastic medium, thus, it's constitutive relation can be analyzed by Hooke's law. The basic equation of the linear elastic deformation of plane problems include balance equation, geometric equation, physics equation, deformation equation and boundary conditions equation, the detailed expression of derivation and the relation between common elastic constants can be seen in the related references (Zhang K. X., 1989; Huo J. R., 1991; Yu X. F., 1995). By means of these equations, the dynamic analysis of the unit length of the slope can be solved as plane strain problem.

2.2 Wave propagation finite-element simulation

In this paper, the method of combined similar difference and finite-element discrete by lumped mass method (Liao Z. P., 2002) was used to transform the solving of the motion equation of internal nodes into a decoupling explicit time-domain step-by-step integral format. The explicit methods are characterized by the response at some step which is a linear combination of the response of this step, the last step or more steps, which needn't decoupling of the equation and have less calculation. Based on this method, Chen X. L. (2001) simulated the seismic response of retaining wall, and Chen X. M.(2003) analyzed the horizontal variation of the maximum response acceleration at different height of retaining wall. The detailed algorithm and the relative considerations can be seen in the references (Liao Z. P., 2002; Yang B. P., 1992; Zhou Z. H., 2000; Liu J. B., 2000)

3. ANALYSIS ON DISTRIBUTION OF EARTHQUAKE LOAD ALONG SLOPE'S HEIGHT

The I-I section slope and II-II section slope from the region in which some power station would be built were selected as the analyzed objectives, see Fig. 1. The I-I section slope has three test points, they are A (0.00,345.40), B(283.01,336.50) and C(549.47,302.50) respectively; the II-II section slope has three test points too, they are D(0.00,295.20), E(314.26,336.50) and F(597.34,328.20) respectively. The unit is meter.

3.1 Inputs of seismic motion

The characteristics of seismic motion of engineering site are very complicated, which will be very different with earthquake size, distance and site-dependent character. By far, the strong earthquakes are scarce and their observation records are inadequate. Hence, in order to simulate the characteristics of seismic motion well,

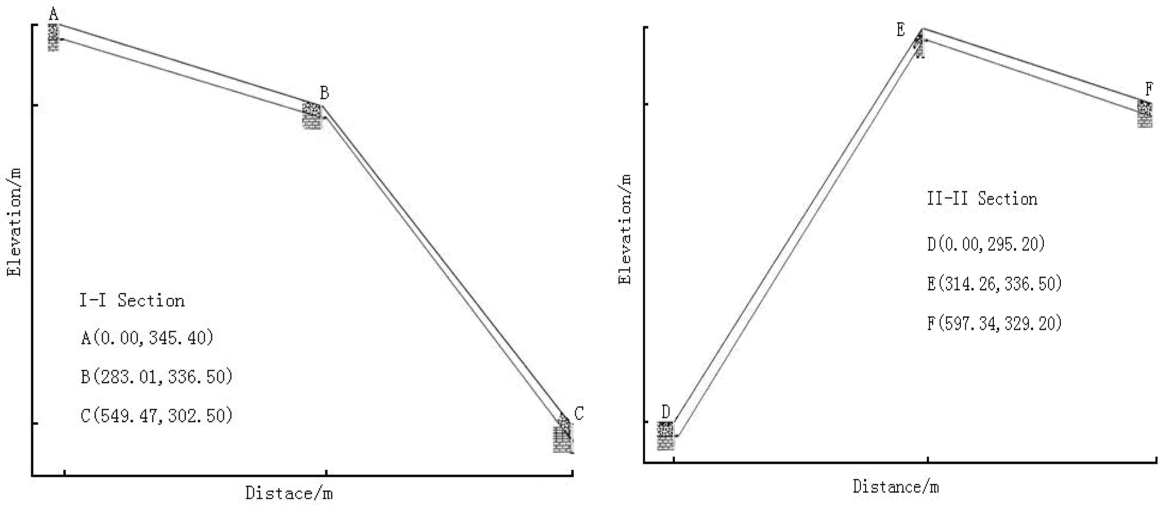


Fig.1 Two slopes of some planned power station

the time history functions of acceleration which are generated by the trigonometric function method are adopted as inputs.

In this paper, considering 4 sorts of intensity, which were intensity 6, 7, 8 and 9, thereinto, intensity 6 and intensity 7 considered the impact of near earthquake and teleseism respectively, total 6 scenario earthquakes were adopted. Each scenario earthquake was simulated into 3 acceleration time histories. Then, total 18 simulated acceleration time histories are adopted as inputs. For example, the 3 simulated acceleration time histories for intensity 8 are showed in Fig. 2. After being tested by related coefficient with Eqn. (1), these verified time histories were irrelevant to each other. The specific simulation method of acceleration time histories has been expounded well in the related literatures (Huo J. R., 1991; Hu Y. X., 1999, 2006; GB. 50011-2001, 2001; Chen X. M., 2003).

$$\rho = \left| \frac{\frac{1}{N}\sum_j a_{1j} \cdot a_{2j}}{\sqrt{\frac{1}{N}\sum_j a_{1j}^2} \cdot \sqrt{\frac{1}{N}\sum_j a_{2j}^2}} \right| \tag{1}$$

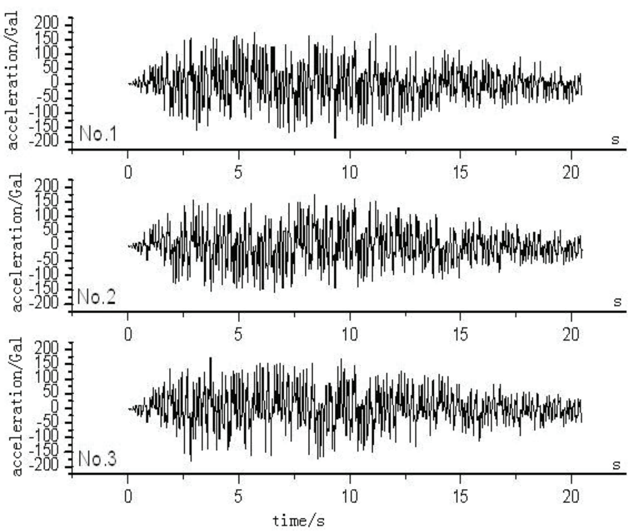
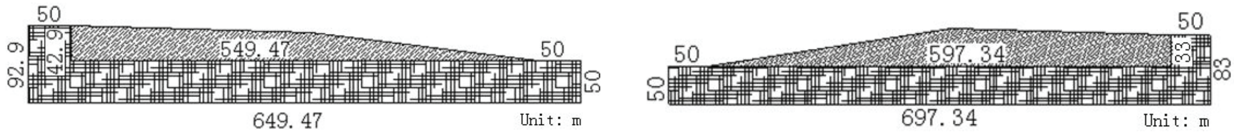


Fig.2 Acceleration time histories for Intensity 8

3.2 Finite element discretization of the soil

The size of computational region is usually taken 1.0 to 3.0 times of the size of diffuse source based on the experience on solving the near-field wave motion scattering problems. In this paper, the size of both side of slope and the depth of cover soil in front slope are taken 1.0 to 2.0 times of the size of slopes' height, and the thickness of both side and bottom of slope model are taken 50m, which are about 1.2 times of size slopes' height. The sections of selected for computation slopes are showed in Fig. 3.



（a）I-I Section slope （b）II-II Section slope

Fig. 3 Section plane of selected slopes

The size of the most finite element grid of the analyzed soil could take the regular value 2m×2m, while the size of finite element grid of the irregular surface of slopes were different to the regular grid.

In order to analyze the seismic response of the slopes, enough feather points of slopes were selected to output their seismic response values. The interval of feather points was assigned a value of 50m in horizontal direction while 2m in vertical direction, see Fig. 4.

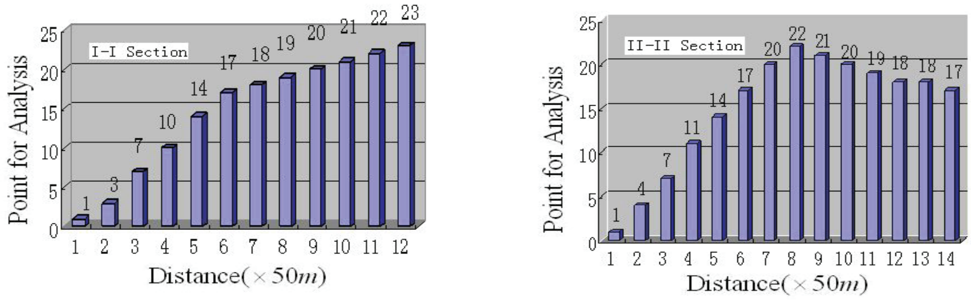


Fig. 4 The numbers of output points of slopes for seismic response

3.3 Seismic response of slopes

The section which the highest point of I-I section is in has total 23 points. Every point has different seismic

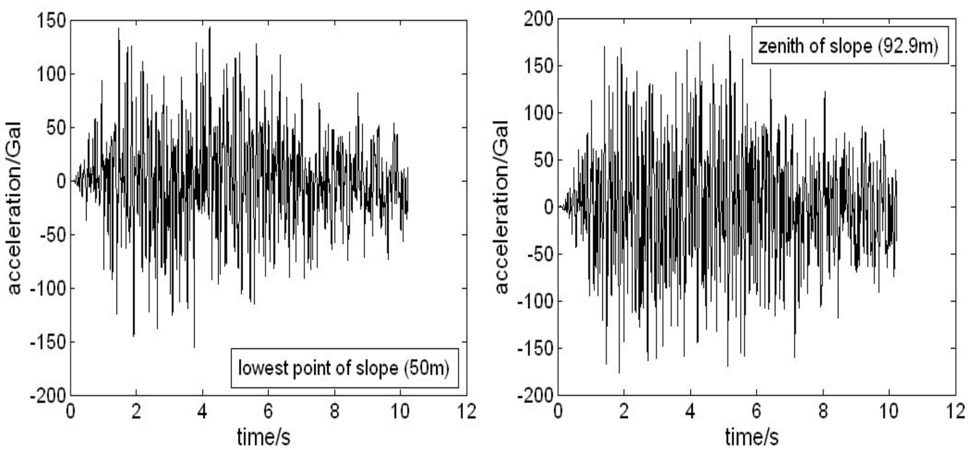


Fig. 5 Seismic response time series in Point-L and Point-Z of slop

response with an arbitrary input, for example, the acceleration time histories of intensity 8. The seismic response time histories of the lowest point (elevation is 50m) and the zenith point (elevation is 92.9m) of I-I section slope are showed in Fig. 5.

The seismic response of the zenith point of slope, as seen in Fig. 5, is larger than the lowest point. All the time histories of seismic response of 23 points are showed in Fig. 6. As can be seen from the Fig. 6, the seismic response in I-I section changes with the increase in height along the slope.

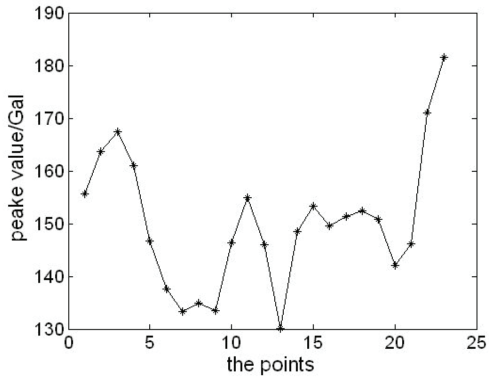


Fig. 6 Peaks of seismic response at the highest section

The variations of seismic response in others sections with other intensity are similar to the above results.

In order to compare the peaks of seismic response at different high section of the slope with the peaks of seismic response of the slope bottom for analysis the variation of seismic response along the height of slope, the related elevation of slopes is taken to summarize the results, see Fig. 7(a). From the Fig. 7(a), it can be seen that:

(1) The magnified ratio of the maximum acceleration response at the slope top does not show systematic changes in trends with steady increase in seismic intensity. So, this is both between the concern is not big. The influence of the intensity was not taken into account when the distribution coefficient of horizontal variation of the maximum response acceleration at different height levels was calculated.

(2) The magnification of the seismic response of maximum acceleration of the slopes is complicated. In general, the seismic response of maximum acceleration does not immediately increase with the increase of height. Until at some slopes' height it starts to increase rapidly with height and to reach the top of the maximum. The starting magnification and increasing rapidly slope height which is about in the 1/2-2/3 times high to slopes' height has the gradually increased trend with the increased height of slopes.

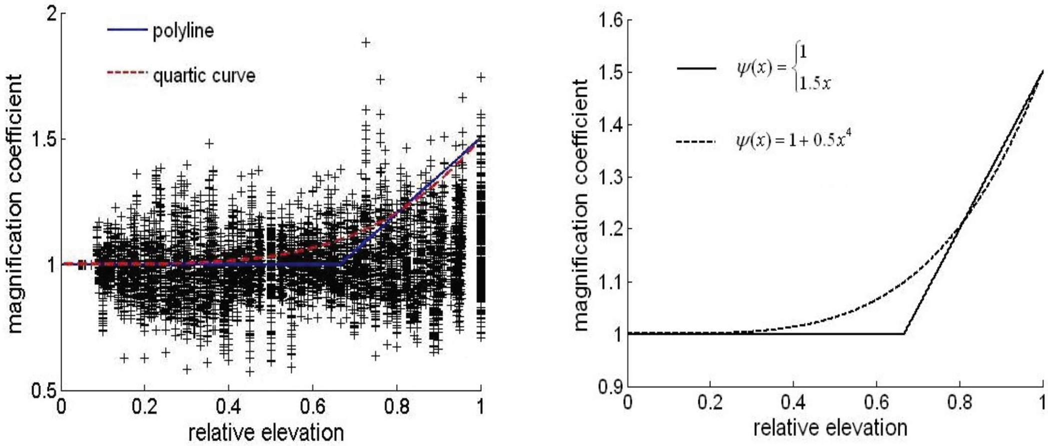
(3) The earthquake inertia force of the portion of slopes' height which has no magnified acceleration, which the earthquake inertia force of the bottom is assigned a value to, is conservative and has a certain safety redundancy as regards security.

(4) The magnification of the seismic acceleration response of the slopes maximizes and gets a value of 1.0 to 1.91. In general, the maximum amplification factor increases gradually with the total height of the slopes, and just a few get values greater than 1.5(about 0.5%). Taking into account the potential errors of the model and process of calculating, the value of the factor is proposed as 1.5 with the safest without too conservative.

From these understanding, two distribution coefficients of lateral seismic load with relative height for these slopes are suggested in this paper, and one is in a bilinear form, see Eqn. (2), the other is in a fourth order exponential curve, see Eqn. (3), both with the same maximum value of 1.5, see Fig. 7(b). If the two models of distribution coefficient are put into the summarized results (see Fig. 7(a)), the relationship between the fitting formula and the analyzed results will be revealed very well.

$$\psi(x)=\begin{cases}1 & 0\le x<2/3\\ 1.5x & 2/3\le x\le 1\end{cases} \tag{2}$$

$$\psi(x)=1+0.5x^4 \qquad 0\le x\le 1 \tag{3}$$



(a) Gather the coefficient (b) Fitting models
Fig. 7 Distribution coefficient of earthquake load along slope's height

4. CONCLUSION

The seismic stability of slope becomes an important issue in geotechnical engineering world. The study on the distribution of earthquake load along the slope's height is beneficial to the research on the seismic stability of the slope.

In this paper, the total 18 simulated acceleration time histories for intensity 6, 7, 8 and 9 were adopted as inputs, 2 slopes, which were simplified as linear elastic models, were analyzed by means of a wave propagation finite element method. From what has been discussed above, some conclusions are as follows:

(1) The numerical results show that the acceleration changes along the height direction nonlinearly with a little bit complicated pattern, and generally the changing patterns are similar.

(2) The acceleration does not increase immediately after the slope's height is becoming taller from the bottom of the slope, and it starts to increase rapidly with the height level at a height of 1/2 to 2/3 of the total height of slope. It gets a maximum amplification value of 1.0 to 1.91 at the top of the slope.

(3) The maximum amplification factor increases gradually with the total height of the wall, and just a few values (about 0.5%) are greater than 1.5.

Based on above understanding, two distribution coefficients of lateral earthquake load with relative height of the slope are proposed, one is in a bilinear form, the other is in a fourth order exponential curve,

In this paper, the simple linear-elastic model was selected to simulate the slope without taking account of the nonlinear of soil, which should be the future work of further study.

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