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EFFECTS OF IRREGULAR TOPOGRAPHY WITH DIFFERENT SOIL CONDITIONS ON EARTHQUAKE GROUND MOTION

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Abstract

The finite element method for analysing the effects of irregular topography on earthquake ground motion is presented in this paper.The emphases is laid on the discussion about the differences of the effects of irregular topography induced by the different soil conditions.The computer program also dealt with here.

Introduction

Based on the investigations into destructive earthquakes in China in recent years[1, 2],it has been found that the earthquake damage at the top of an isolated-protruding spur or an isolated hill is generally much more serious than that at the flat sites.And many simiral examples were also found during great earthquakes in other countries[3, 4].The present"Aseismic Design Code for Industrial and Civil Buildings(TJ 11—78)[5]"in China has pointed out: "Generally,the disadvantageous districts for the buildings to resist earthquakes belong to class III soil,long—protruding spurs, isolated hills and non—rocky(incruding bad-cemented tertiary sedimentary rock) slope sites etc."Although the harmful effect of the local isolated-protruding topography conditions on earthquake damage was recognized early in the past, but up to now, the quantitative study on this problem has been far from being desired.The aseismic design codes of various countries in the world have not comprised the quantitative evaluvation method mentioned above.It is only recommended in the Chinesecode[5]that the said unfauorable sites should be avoided as far as possible in selecting constructive tive sites.In practice, however, in somecases,such sites cannot be actually avoided (for many reasons) .Most of constructions will have to be made in the mountain regions in China.That is why the problem of the effect of topography on the motion and damage of earthquake has become a significant theme in the research concerned.

Since it has been realized that the effect of local topography on earthquake damage remains to be an important aspect in earthquake engineering, a lot of analytical work has been done in the world in recent years. Most of these theoritical studies have adopted analytical methods and it has been assumed that the topography has a simple geometric configuration.For complex irregular topography, it is very difficult to obtain an accurate result by the analytical method.At present, the study on complex irregular topography can be carried out accurately only by means of the three-dimensional finite element method.In this way, the work of computation was very heave, and it usually required a faster and bigger computer,which was very expensive.In this paper we present a finite element model ofbi-directional shear deformation, by which a three-dimensional problem is reduced to a two-dimensional one, thus the computation can be greatly simplified.

The experiences from destructive earthquakes have shown that the effects of irregular topography with different soil conditions on earthquake ground motion are very different.Generally speaking, the effect of hard bedrock topography is slighter than that of topography with soft soil conditions.

The historic earthquakes in loess region indicated that the earthquake damage in loess region is heavier than that in non—loess regions. One of important reasons perhaps is that loess is loose and soft, and the topography in loess region is more complicated.So the effect of topographical condition in loess region will be evident than that in non-loess regions.The emphases of this paper is laid on the discussiou about the differences of the effects of irregular topography induced by the different soil couditions.

Finite Element Model of Bi-Directional Shear Deformation

In order to analyse the effect of isolated-protrudiug irregular topography on earthquake damage, a finite elemeut model of bi-directional sheardeformation is presented. The model is shown in Fig. 1 .

Assumiug the pure shear deformation condition, for all nodal points, we have

$$W_i = V_i = O; \quad U_i = U_i(X,Y) \tag{1}$$

where U_i, V_i, W_i,are displacement components in X,Y,Z directions of

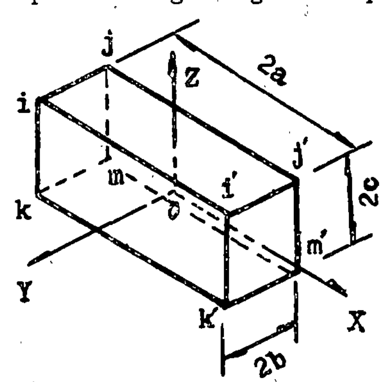

图1 双向剪切变形有限元模型

Fig. 1 Fiuite elemet model

the poinn i respectively.

Owing to the same reason as mentioned above we also have in this case, there are only 4 independent displacements, which can completely define the deformation state of the whole element.

$$U_i = U_i', \quad U_j = U_j', \quad U_m = U_m', \quad U_k = U_k',$$
$$\{U\}^e = [U_i U_j U_m U_k]^T \tag{2}$$

In order to express the displacement $\{U\}^e$, it is assumed that the element U is given in the form of polynomials with coodinate variables Y and Z;

$$U(Y,Z) = a_1 + a_2 Y + a_3 Z + a_4 YZ \tag{3}$$

According to the previous assumption on the deformation conditions, every element has only two stress components $б_{xy}$, $б_{zx}$ and strain components τ_{yz}, τ_{zx}.

By means of Eq. 3, the displacements of any point of the element can be expressed by its nodal displacement as follws;

$$U(Y,Z) = [N]\{U\}^e \tag{4}$$

where

$$[N] = \frac{1}{4bc}\left[(b+y)(c+z)(b-y)(c+z)(b+y)(c-z)(b+y)(c-z)\right]$$

Strain of the element can be also expressed by the nodal displacement as follosw;

$$\varepsilon(Y,Z) = [B]\{U\}^e \tag{5}$$

where

$$[B] = \frac{1}{4bc}\begin{pmatrix} (b+y)(b-y)(b-y)(b+y) \\ (c+z)(c+z)(c-z)(c-z) \end{pmatrix}$$

According to the above Eqs., we can obtin the stiffness matrix of the element as follows;

$$K = 2a\int_{-b}^{b}\int_{-c}^{c}[B]^T[D][B]dy\,dz \tag{6}$$

$$= \frac{ag}{3}\begin{pmatrix} 2\left(\frac{b}{c}+\frac{c}{b}\right) & \left(\frac{b}{c}+2\frac{c}{b}\right) & \left(\frac{b}{c}+\frac{c}{b}\right) & \left(2\frac{b}{c}+\frac{c}{b}\right) \\ & 2\left(\frac{b}{c}+\frac{c}{b}\right) & \left(2\frac{b}{c}+\frac{c}{b}\right) & \left(\frac{b}{c}+\frac{c}{b}\right) \\ & & 2\left(\frac{b}{c}+\frac{c}{b}\right) & \left(\frac{b}{c}+\frac{c}{b}\right) \\ \text{Symmetric} & & & 2\left(\frac{b}{c}+\frac{c}{b}\right) \end{pmatrix}$$

where

$$[D]=\frac{E}{2(1+\mu)}\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}=[G]\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}$$

and E,G,and μ are material constants i.e.E is Young's modulus, G is shear modulus,and μ is Poisson's ratio.

We can also obtain the mass matrix of the element as follows:

$$[m]^e = 2a\rho\int_{-b}^{b}\int_{-c}^{c}[N]^T[N]\,dy\,dz \tag{7}$$

$$=\frac{2abc\rho}{9}\begin{pmatrix}4 & 2 & 1 & 2\\ & 4 & 2 & 1\\ \text{sym.} & & 4 & 2\\ & & & 4\end{pmatrix}$$

where ρ is the mass density of the material.

In order to obtain the damping matrix,the Raleigh damping can be assumed,which is of the following form

$$[C]^e=\alpha[m]^e+\beta[k]^e$$

where α and β are constans to be determined by the two unequal frequncies of vibration.

Earthquake Response Analysis

Concerning the response of a mountain to earthquake ground motion, we have the dynamic equilibrium equations;

$$[M]\{\ddot{U}\}+[C]\{\dot{U}\}+[K]\{U\}=-[M]\ddot{U}_0(t) \tag{8}$$

in which [M],[C],and [K] are mass, damping, and stiffness matrices of the whole mountain.They are assembled from the matrices $[m]^e$,$[c]^e$ and $[k]^e$ of the elements respectively. $\ddot{U}_0(t)$ is the input earthquake motion of the bottom of the mountain.

In this study it is not the stresses of the mountain but the displacement,velocity,and acceleration response processes at the different parts of the mountain are of main concern.By using the step-by-step integration procedure,we integrate Eq. 8 directly.

Assuming that the accelereation response varies liearly at the interval Δt, we have

$$\{\ddot{U}\}_t=\{\ddot{U}\}_{t-\Delta t}+(\{\ddot{U}\}_t-\{\ddot{U}\}_{t-\Delta t})\tau/\Delta t \quad (0\leqslant\tau\leqslant\Delta t) \tag{9}$$

integrating Eq. 9 twice,we obtain

$$\{\dot{U}\}_t=\{\dot{U}\}_{t-\Delta t}+\frac{\Delta t}{2}\{\ddot{U}\}_{t-\Delta t}+\frac{\Delta t}{2}\{\ddot{U}\}_t \tag{10}$$

$$\{U\}_t = \{U\}_{t-\Delta t} + \Delta t\{\dot{U}\}_{t-\Delta t} + \frac{\Delta t^2}{3}\{\ddot{U}\}_{t-\Delta t} + \frac{\Delta t^2}{6}\{\ddot{U}\}_t \quad (11)$$

By using Eq. 8, we heve, at time t;

$$[K]\{U\}_t + [C]\{\dot{U}\}_t + [M]\{\ddot{U}\}_t = -[M]\ddot{U}_0(t) \quad (12)$$

Substituting Eqs.10 and 11, into Eq.12, we obtain

$$[Q]\{U\}_t = -[M]\ddot{U}_0(t) - [C]\{A\}_{t-\Delta t} + [K]\{B\}_{t-\Delta t}$$

where

$$[Q] = [M] + \frac{\Delta t}{2}[C] + \frac{\Delta t^2}{6}[K]$$

$$\{A\} = \{\dot{U}\}_{t-\Delta t} + \frac{\Delta t}{2}\{\dot{U}\}_{t-\Delta t}$$

$$\{B\} = \{U\}_{t-\Delta t} + \Delta t\{\dot{U}\}_{t-\Delta t} + \frac{\Delta t^2}{3}\{\ddot{U}\}_{t-\Delta t}$$

Triangularizing the matrix $[Q]$, $[Q] = [L][L_0][L]^T$, then for each stpe using the above equations, we obtain displacements, velocities and accelerations of diffrent points at the mountain surface. The results are expressed in terms of distribution of the relative maximum displacements and velocities as well as the absolute accelerations along the surface of the mountain. Further more, the Fouriar spectra and response spectra of these acceleration response processes are calculated, and the characteristics of the earthquake ground motion at different parts of the mountain are studied.

Effect of Topography with Soft Soil and Hard Bedrock on the Earthquake Motion

We have mentioned above that the effects of topography on ground motion are different under different soil conditions. This has been identified many times by the field observations. Generally speaking, the softer the soil, the more obvious effect of topography on ground motion will become. And as for the isolated topography with hard bedrock the effect is not obvious if the elevation is less than 30m. For example, during the 1970 Tonghai Earthquake, there were many cases which showed the significant effects of isolated and protruding hills on damage. According to the statistic analysis of damaged dwellings of 67 villages located on isolated and protruding topography, the damage indexes were greater then those on the plain (0.07 to 0.25).

The effect of isolated and protruding topography on damage with various soil conditions are shown in Fig. 2. It can be seen from the average tendency that, in a statistical sense, the effect of topography is expanding the damage to structures, and the softer the soil, the more obvious the effect.

The experiences of the past earthquakes in loess region indicate that the eeffect of topography on earthquake damage there is more obvious than that in the non-loess regions.The great 1920 Haiyuan earthquake indicated that if a village about 100m above the river bed is compared with other villages at the river banks, the earthquake intensity of the former would be about one degree higher than that of the latter.

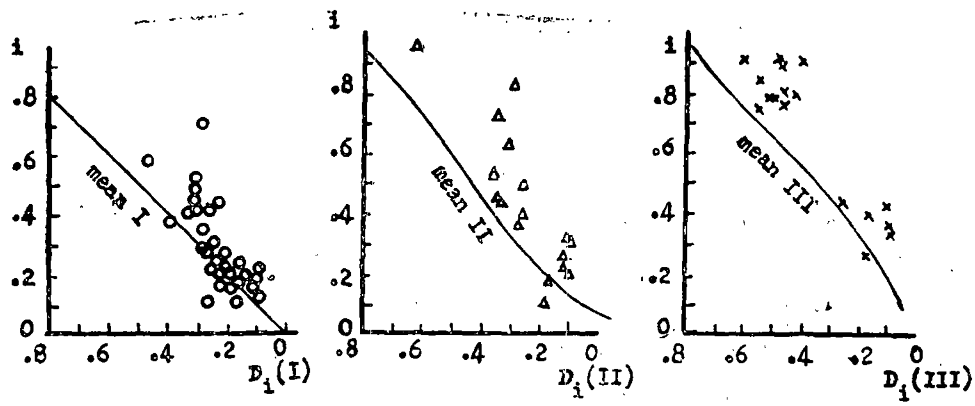

图2 1970年通海地震时局部地形的影响

Fig. 2 The effects of topography with different soil conditions

In order to compare the differences of the effect of topography with different soil conditions, some models with similar geometric configuration but different soil conditions are analysed.The physical parameters of some kind of loess and bebrock adopted in th the analyses are shown in Table 1.

Table 1 Dynamic parameters of some kind of loesses and bed bedrocks

表1 某些黄土和基岩的动力参数

Medium	Young's modulus (T/m^2)	Poisson's ratio	Unit weight (T/m^3)	Damping ratio
Hard loess	12300	0.22	1.7	0.2
Moderate loess	24070	0.25	1.6	0.2
Soft loess	31800	0.25	1.5	0.2
Bedrock	756000	0.25	2.1	0.1

The finite element computing model is shown in Fig.3.

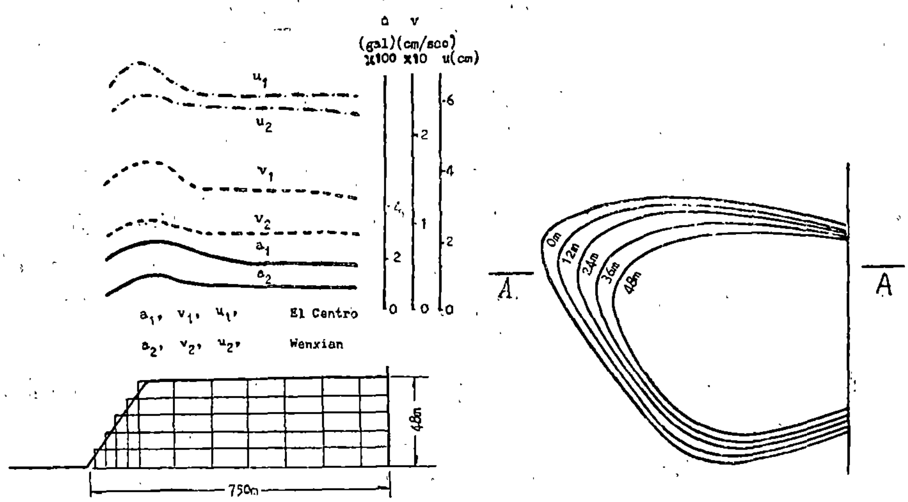

图 3　计算模型和计算结果

Fig. 3　Computing model

The calculated results for different ridge height and different soil conditions are shown in table 2.

Table 2 Calculated results for different ridge height and different soil conditions

表 2　黄土与基岩山梁的计算地面运动参数

Number of models	Height (m)	Young's modulus (t/M)	Input motion	Maximum acceleration (gar.)	Maximum velocity (m/sec)	Maximum displacement (m)	Dominant period (sec)
1	24	24070	El Centro	252	0.071	0.022	0.169
2	48	24070	El Centro	154	0.088	0.060	0.325
3	99	24070	El Centro	129	0.139	0.150	0.640
4	48	24070	Wenxian	205	0.125	0.065	0.325
5	96	24070	Wenxian	84	0.101	0.095	0.640
6	24	12000	Wenxian	186	0.081	0.035	0.325
7	48	12300	Wenxian	58	0.057	0.043	0.539
8	24	31800	Wenxian	360	0.037	0.036	0.158
9	48	31800	Wenxian	235	0.047	0.039	0.306
10	24	765000	El Centro	204	0.0328	0.0375	0.082
11	48	765000	El Centro	336	0.0195	0.0130	0.125
12	24	765000	Wenxian	213	0.0261	0.0324	0.082
13	48	765000	Wenxian	263	0.0392	0.056	0.125

Conclusions

According to the abovementioned analyses, we obtain the following conclusions:

1) Generally speaking, the effect of topography condition on earthquake ground motion and earthquake damage is shown on two aspects; the

magnification of the acceleration and the alteration of spectrum characteristics of the ground motion. Both aspects are harmful for the buildings to resist earthquakes. For the topography with different soil conditions and its effect on earthquake ground motion and damage are different. The softer the soil is, the more obvious the effect will become. As for the had-bedrock, if the height of the ridge is less than 30m, the effect is not obvious. All of these are quite in agreement with the conclusions obtaine from the field investigations into destructive earthquakes in China in recent years.

2)Since the loess or loess-like soil is loose and soft, the harmful effect of the loess ridge on earthquake ground motion and earthquake damage is more obvious. As for the loess ridge, when the ridge is lower and loess harder, the acceleration on the ridge is greater than the input acceleration at its foot, but when the ridge is higher and the loess softer, the response acceleration will evidently increase with its height.

3)The characteristics of the acceleration response spectra of strong ground motion of the ridge are closely related to their geometric configuration and property of the media. For the hard bedrock ridge, the harnful effect is mainly shown on the magnifing of the peak acceleration. But as for the soft loess ridge the harmful effect is mainly shown on the alteration of the spectrum characteristics of the earthquake ground motion. For the loess ridge, we have analysed the acceleration response spectra, all if which are narrowly centered around asingle frequency. The dominant frequency of the response spectra decreases withthe height of the ridge. The characteristics of response spectra show that the loess ridge is generally disadvantageous for most of the buildings to resist eathquakes.

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不同岩土条件的不规则地形对地震地面运动的影响

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摘 要

对我国近年来几次大地震的震害考察中发现弧突山梁及弧立山包的顶部震害都比较重，国外也有不少类似的实例。虽然这种弧突地形条件对震害的不利影响，人们早已有了定性的认识，但对这个问题的定量研究，则远远不够深入。因此各国规范都还没有列入关于弧突地形条件的定量评价方法。在我国地形条件对地面运动及震害的影响问题是一个重要的有意义的课题。

世界上近年来已发表了不少关于这个问题的论著，其中大部分都是采用解析法，並假定山体为某种简单的几何形体。对于复杂的不规则地形，解析法很难得出符合实际的结果。有限元法是研究复杂地形的有效工具。但三维有限元常常要求大型快速电子计算机，工作量大，费用昂贵。本文提出双向剪切变形有限元模型，它可以把三维问题简化为二维问题，使计算工作大为简化。

震害经验表明：由不同岩土条件构成的地形，对地面运动的影响也有显著差异。一般来说，坚硬基岩地形要比软土条件的地形对震害影响要轻。黄土地区，由于黄土松软，地形条件又比较复杂、因此地形条件对震害的影响要比一般非黄土地区更为显著。本文重点是讨论不同岩土条件的不规则地形对震害影响的差异。主要结论如下：

1）地形条件对地面运动及震害的影响表现在两个方面，地震加速度的放大和地面运动频谱特征的改变。这两种影响都是对建筑物的抗震不利的。不同岩土条件的地形对地震地面运动的影响也不同。土质越软地形对震害的不利影响越明显。对坚硬基岩，当高度低于30 m，这种影响就不甚显著。

2）由于黄土特别松软、所以黄土山梁，对雾害的影响也就特别显著对黄土山梁当山梁高度较低土质较梁时，山梁上部加速度的峰值要比其基底处的输入加速度大，但当山梁较高而土质较软时，山梁加速度反应，将随山梁高度的增加而降低。在这种情况下，山梁的位移反应，总是随着山梁高度的增加而明显增大。

3）山梁地面运动加速度反应谱特征，与其介质性质和几何形态有密切关系。对于坚硬基岩的山梁，其对震害的不利影响主要表现在加速度的放大方面。对于软土山梁其不利影响主要表现在地面运动频谱的改变方面。这种加速度的放大和频谱特征的改变都是对建筑物的抗震不利的。