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STUDY ON THE EARTHQUAKE RESISTANCE BEHAVIOR OF STRUCTURE IN MOUNTAINOUS REGION AFFECTED BY SOIL-STRUCTURE INTERACTION

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ABSTRACT

The major difference between structure built in mountainous region and structure on the flatland is the difference at the bottom of the structure. Due to the difference, the structures in mountainous region will be serious irregularity and obvious effect of soil-structure dynamic interaction. Under the influence of the soil and the slope, the effect of soil-structure interaction will be more significant, thereby it affects the seismic behavior of structure built in mountainous region. The framework of uneven-height columns in the first story, built in mountainous region, was as the research object, the analysis model of soil-structure interaction was set up, the internal force and displacement of the building under earthquake action affected by soil characteristics and slope parameters were analyzed, the earthquake resistance behavior of structure affected by soil - structure interaction were studied. The result is useful for the seismic design of structure in mountains regions.

KEYWORDS: Soil-structure interaction, Structure in mountainous region, Seismic design of building

Introduction

The foundation of structure is usually assumed to be rigid in the seismic response analysis model. In fact, the foundation is not a rigid body. It can be deformed under seismic action. The deformation of foundation can cause interaction between upper-structure and the foundation. It is called soil-structure interaction. Existing studies have shown that period of structure can be extended and response of the structure can be decreased when the soil-structure interaction is considered [1]. Therefore elastic soil-structure interaction is usually beneficial to the structural seismic

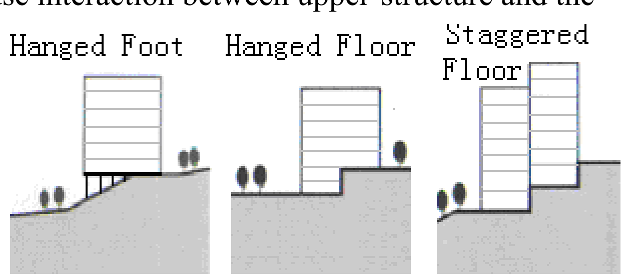

Figure.1. unique mountain architecture

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behavior, and the method which reduced internal force of structure is often used to consider the influence of soil-structure interaction on the structure [2].

In order to take full advantage of terrain environment, mountain buildings are usually built conforming to the shape of the mountain. So unique mountain architecture such as hanged foot, hanged floor, staggered floor, and others may emerge [3](Fig.1). The foundations of such buildings are not flat, varying with topography. They are Ramp-like or step-like. Structures built on the slope-like or step-like foundations are more vulnerable to the influence of soil-structure interaction. These effects are embodied in two aspects: first, the influence of local topography on strong ground motion, it may be different about the strong ground motion of different locations on the slope; second, the interaction may be more obvious between the foundation and structure.

In this paper, typical mountain building structures are researched to analyze the influence of soil-structure interaction on seismic behavior of mountain building structures.

2. Research Method

This paper has studied the differences of deformation and internal force under earthquake action between the assumptive rigid foundation mountain building model and soil-structure interaction model. Used the comparison analysis method, the influence of soil-structure interaction is investigated. Comparative analysis model is showed in Fig.2, where Fig. 2a is the rigid assumptive foundation model, Fig. 2b is the soil-structure interaction model. The main effect factor of soil-structure interaction is the ratio of structural stiffness to foundation soil stiffness. Angle of slope of the foundation is an important factor to mountainous architecture. The comparative analysis models are designed by different slope angle, different structure and foundation stiffness ratio. Numerical analysis method is used to study the influence of soil-structure interaction on structures.

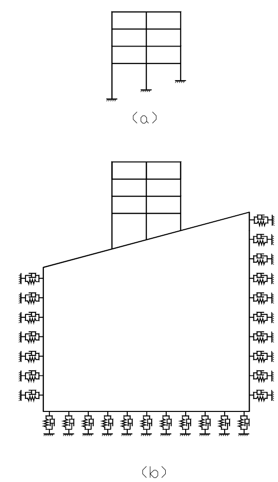


Figure 2 Analysis model

3. Analysis model

Planar elastic finite element analysis model is used as shown in Fig.2. In this model, beam element is used to simulate the upper frame and plane strain element to the foundation soil. The superstructure is a 4 floor 2 span reinforced concrete frame structure with 6 meter column meshes spacing and 3 meter storey height, the height of bottom columns changes with the slope angle and the minimum height is 3 meter. In this model, the beam section size is 250mm×600mm and column section size is 500mm×500mm, the strength grade of concrete is C30, the value of elastic modulus Ec is 3.0 x10^4 N/ mm^2, shear modulus Gc is 0.4 times of the elastic modulus, Poisson ratio Vc is 0.2, bulk density is 25KN/m^3, damping ratio coefficient is 0.05.

The floor dead load is 4KN/m^2, the floor live load is 2KN/m^2, and the floor gravity load representative value is 5 KN/m^2; the roof dead load is 5KN/m^2, the roof live load is 2KN/m^2, and the roof gravity load representative value is 5KN/m^2. Because the width of the load acting on the frame beam is 6 meter, the line load on the frame beam caused by the gravity load representative value is 30KN/m. The gravity load representative value convert into bulk density of beam is

$225KN/M^3$.

Usually artificial boundary is adopted to simulate the foundation soil boundary under the action of earthquake. The common artificial boundary is such as viscous boundary proposed by Lysmer, consistent boundary introduced by White, superposition boundary offered by Smith, paraxial boundary proposed by Clayton, and transmitting boundary proposed by Liao, Zhenpeng In addition, viscous-spring boundary based on viscous boundary was proposed by Deeks[4]. Based on the viscous-spring boundary, Liu, Jingbo proposed the viscous-spring boundary parameter for pressure wave and shear wave:

$$K_{bp} = A_b \frac{E}{2r_b}, C_{bp} = \rho V_P A_b \quad (1)$$

$$K_{ts} = A_b \frac{G}{2r_b}, C_{bp} = \rho V_S A_b \quad (2)$$

Where Kbp, Kts are spring parameters of viscous-spring boundary for press wave and shear wave respectively; Cbp, Cts are damping parameters of of viscous-spring boundary for press wave and shear wave respectively; Vs, Vp are pressure wave velocity and shear wave velocity respectively; G is shear modulus of soil; E is elastic modulus of soil; r_b is the coordinate of artificial boundary in the polar coordinate system; ρ is mass density; A_b is soil area corresponding to parameters.

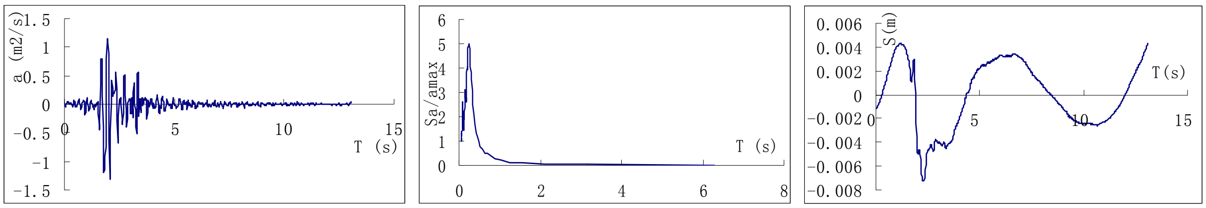
In the model, the average thickness of the foundation soil is 30 meters and the length is 36 meters. The viscous-spring boundary, as show in formula (1) (2), is set on the two sides of the foundation soil model.

When the example is designed, two parameters are taken into account, the angle of the slope and the stiffness ratio of structure to soil. The models are designed by different slope angles, 30 degrees, 15 degrees and 0 degrees, and labeled as P1, P2 and P3 corresponding to the angle. The stiffness ratio is reflected by the fundamental period ratio of the structure to the soil Rp, which is achieved by adjusting the soil basic period, as that of the structure is unchanged. The basic-period ratio maybe is less than, or close to, or greater than 1, and are denoted as S1, S2, S3 correspondingly, whose parameters are shown in Table 1. Above all, there are nine kinds of soil - structure interaction models, as well as corresponding nine assumed rigid-foundation models.

Table 1 The soil parameters of model

Models	**Rp**	**Structural period (s)**	**Soil thickness (m)**	Vs **(m/s)**	**Density** kg/m^3	**Poisson's ratio**	**Damping ratio**	**G** $\times 10^3 kN/m^2$	**E** $\times 10^3 kN/m^2$
S1	0.63	0.58	30	120	1800	0.2	0.05	25.92	62.21
S2	1.25	0.58	30	240	2000	0.2	0.05	115.20	276.48
S3	2.50	0.85	30	480	2200	0.2	0.05	506.88	1216.51

The bedrock under the foundation soil is regarded as infinite stiffness, so the bottom of the foundation soil can be considered as a fixed boundary. The seismic input of the models is supplied by the bedrock and the selected ground motion wave is USA01870. In order to make it easier for data analysis, the peak acceleration of the wave is modified to $1.0 m/s^2$. The acceleration time, acceleration responding spectra and displacement time history of the wave are shown in Fig.3 respectively. The difference of the ground motion on the slope should be considered in rigid-foundation models. So the inputs for rigid-foundation models are got as the follows: firstly, the upper-structure is deleted for soil-structure interaction model, and the foundation soil model is gained. Then displacement time history in X and Y direction, corresponding locations of the column bottoms on the slope, is calculated in the foundation model. Then the displacement time history is used as the input for rigid-foundation models.



(a) Aeceleration time history (b) Aeceleration response spectra (c) Displacement time history

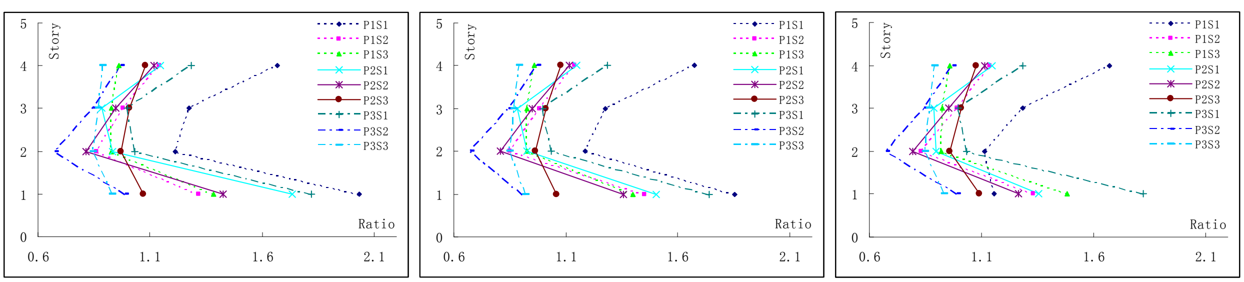
Figure 3 The ground motion USA01870

4. Analysis

The ratio of the response of soil-structure analysis model to the response of assumed rigid foundation model is defined as reduction coefficient. The Story drift and lateral displacement of 3 columns are studied, and the regularities of shear, axial force and moment reduction coefficient at the bottom of the column of every floor are studied, respectively.

4.1 Displacement response

(1) Reduction of column drift



(a) Lateral column lower side of slope (b) Interior column (c) Lateral column upside the slope

Fig.4 Reduction coefficient of column drift

Fig.4 shows the reduction factors of every column's interlayer displacement in the different analysis models.

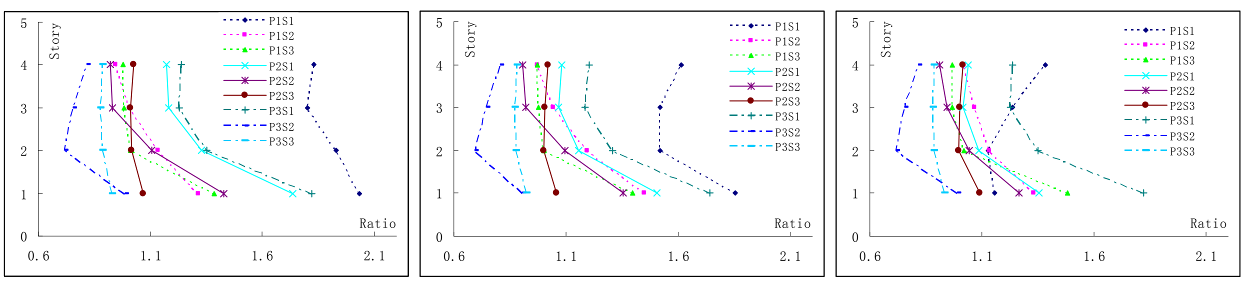
Considered the soil structure interaction, the interlayer displacement of columns seems to be magnified, in the case of mountainous structures. No matter what the soil stiffness is, it is commonly found that the interlayer displacement of columns has magnified. Moreover, with the increase of the slope angle, the magnified phenomenon becomes more significant. But In the case of the structure on the flat ground (the slope angle: α =0), the magnified phenomenon is only occurred in those models whose soil's stiffness is smaller than the upper structure's stiffness (such as model P3S1). When it comes that the soil stiffness is bigger than the upper structure's stiffness, the interlayer displacement of the columns seems to be reduced.

To the magnified phenomenon, the stiffness ratio between the foundation soil and structure seems to play a great role for the magnification of interlayer displacement of columns of the mountainous structure. The softer the foundation soil is , the more magnification is(such as models P1S1, P2S1 and P3S1S). To the flat ground structure, the interlayer displacement of columns is not magnified unless the foundation soil stiffness is smaller than the upper structure's stiffness. While the foundation soil stiffness is bigger than the upper structure's stiffness, the interlayer displacement of columns will be reduced.

It is should be noted that the interlayer displacement of columns on different floors is different. Generally, the interlayer displacement of columns on bottom floor seems to be magnified; on top layers, it is less significant; but when it is on the middle floor, it seems to be reduced.

In addition, the interlayer displacement of columns whose location is different will be differently magnified. When columns are located at the lower side of slope, the interlayer displacement of columns is magnified more significantly. While located at the upside of slope, the interlayer displacement of columns is hardly magnified.

（2）Reduction of column lateral displacement



(a) Lateral column lower side of slope (b) Interior column (c) Lateral column upside the slope

Fig.5 Reduction coefficient of column lateral displacement

Fig.5 shows reduction coefficient of lateral displacement of column in different calculation examples. Reduction coefficient of the lateral displacement of column has a similar regularity to reduction factor of column story drift.

Considered soil structure interaction, lateral displacement of column shows amplification phenomenon generally. Only when the stiffness of foundation soil is less than the stiffness of superstructure, the amplification of lateral displacement possibly will appear in flat-ground structures; while amplification phenomenon of lateral displacement generally appears in mountain building structures, and the greater slope angle is, the more obvious the amplification effect is.

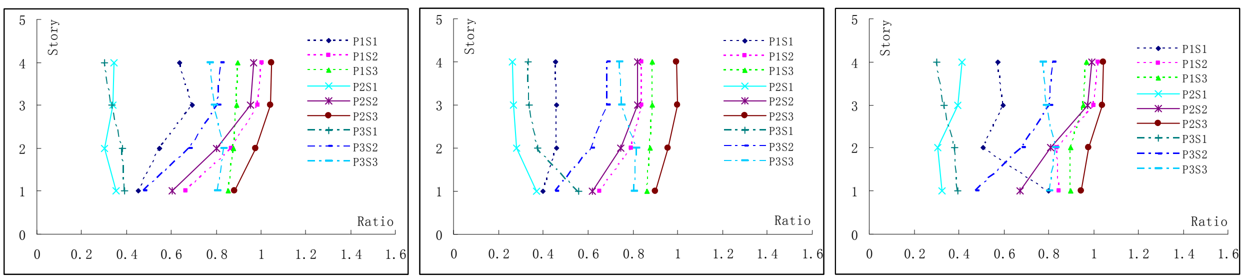
The stiffness ratio of structure to foundation soil has a significant amplification effect on the lateral displacement of column. The softer foundation soil of slope is, the more obvious the amplification effect on the lateral displacement of column is. To flat-ground structures, only when the stiffness of foundation soil is less than the stiffness of superstructure, the lateral displacement possibly of column can possibly be magnified.

The amplification effect on the lateral displacement of column is different from every floor. Generally the amplification is most on bottom floor, least on top floor.

The amplification effect on the lateral displacement of column array is different from every position of slope. The amplification is most on columns lower side of slope, least on upside columns of slope.

4.2 Internal force response

(1) Reduction of shear force in the bottom of columns



(a) Lateral column lower side of slope (b) Interior column (c) Lateral column upside the slope

Fig.6 Reduction coefficient of shear force in the bottom of columns

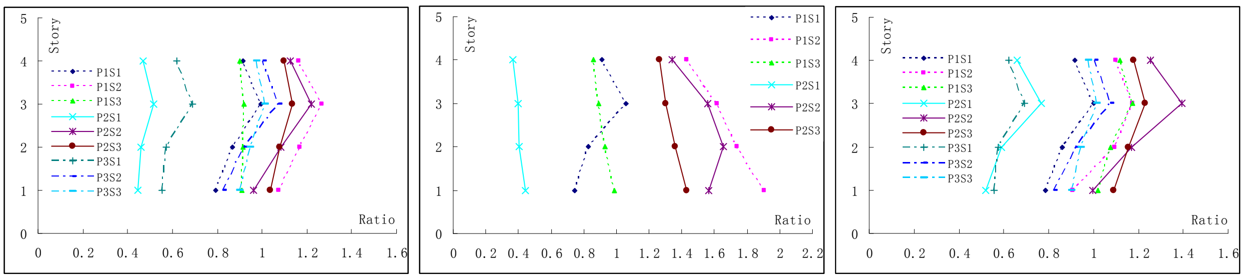
Fig.6 shows the reduction factors of the different examples about shear force at the bottom of column. Considered soil-structure interaction, the shear force of the examples at the bottom of all columns has been reduced.

Reduced effect of shear force at the bottom of column caused by the foundation soil stiffness is significant. While the stiffness of foundation soil is less than the stiffness of the upper structure, the reduction of shear force at the bottom of column is the most obvious; while the stiffness of foundation soil nears the upper structure, the reduction of shear force at the bottom of column is smaller; while foundation soil stiffness is greater than the upper structure, in a certain range, shear force at the bottom of column has a certain degree of reduction, while the foundation soil stiffness is very large (P2S3), then reduction of shear force at the bottom of column is little.

As foundation soil stiffness is different, the regularity of the reduction of shear force at the bottom of column in different slope angle model is different. As the foundation stiffness is less than the upper structure stiffness, the reduction of shear force at the bottom of column in 15 degrees slope angle model is maximum, that in flat-ground structure model is center and that in 30 degrees slope angle model is minimum. As the stiffness of foundation soil near the upper structure, the reduction of shear force at the bottom of column in flat-ground structure model is maximum, that in 30 degrees slope angle model is minimum. As the foundation soil stiffness is greater than the upper structure, the reduction of shear force at the bottom of column in flat-ground structure model is maximum, that in 15 degrees slope angle model is minimum. Thus it can be inferred that the interaction is exist between foundation soil stiffness and slope angle. In a given soil stiffness, there may be a particular slope value. As the slope angle is smaller than this value, the soil structure interaction effect of mountainous structure is more than that of flat-ground structure; As the slope angle is larger than this value, the soil structure interaction effect of mountainous structure is less than that of flat-ground structure.

In general, the reduced effect of shear force in the bottom of middle columns caused by the soil-structure interaction is higher than that of other columns. The reduced effect of shear force in the bottom of the lower floor columns is higher than that of other floor columns.

(2) Reduction of column axial force



(a) Lateral column lower side of slope (b) Interior column (c) Lateral column upside the slope

Fig.7 Reduction coefficient of axial force in the bottom of columns

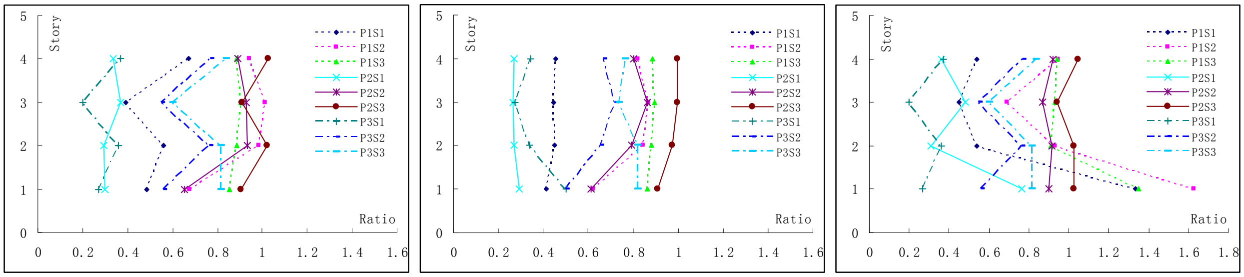
Considered soil-structure interaction, the axial force reduction factors are different in the bottom of column in different examples, as shown in Fig.7.

The axial force of interior column is zero in flat-ground structure, but that in mountain structure is much considerable. Generally, the axial force of columns in flat-ground structure will be reduced as soil-structure interaction is take into account. And the less the soil stiffness is, the more reduced effect is. But the axial force of columns in mountainous structure may be reduced or amplified.

As the foundation soil stiffness is less than the upper structural stiffness, the axial forces of columns in mountainous structure mainly appear reduction. As the slope angle is less than a particular value, the effect of soil-structure interaction to the column axial force appears more significant in mountainous structure than that in flat-ground structure. As the angle is more than the particular one, the effect of soil-structure interaction is less significant than that in the flat-ground structure. As the soil stiffness is close to or greater than the upper-structural stiffness, the axial force in columns may be amplified, especially as they are close. Moreover, the lager the slope angle is, the more significant the amplified phenomenon will be.

In general, the effect to column axial forces caused by soil-structure interaction is much more in the middle columns than that in other columns, and that in the columns of the lower floors than that in the higher floors.

(3) Reduction of column moment



(a) Lateral column lower side of slope (b) Interior column (c) Lateral column upside the slope

Fig.8 Reduction coefficient of moment in the bottom of columns

Considered soil-structure interaction, the reduction coefficient of moment in the bottom of columns in different cases is shown in Fig.8. There are similar regularity between reduction coefficient of moment and that of shear force. Generally, as soil-structure interaction is taken into account, most columns moment is reduced.

The foundation soil stiffness plays a great role on the column moment reduction. As the soil stiffness is less than upper-structure stiffness, the moment reduction is most significant. While soil stiffness and structure stiffness are close, the reduction is less.

The column moment reduction is influenced by soil stiffness and slope angle. In a given soil stiffness, there may be a particular slope value. As the slope angle is smaller than this value, the soil structure interaction effect of mountainous structure is more than that of flat-ground structure; As the slope angle is larger than this value, the soil structure interaction effect of mountainous structure is less than that of flat-ground structure.

In general, the effect to column moment caused by soil-structure interaction is much more in the middle columns than that in other columns, and that in the columns of the lower floors than that in the higher floors.

Conclusions

(1) It is obvious that the influence of soil-structure interaction on the deformation and internal force of mountainous structure. Compared with flat-ground structure, the reduction regularity of mountainous structure is extremely complex.

(2) To flat-ground structure, when soil-structure interaction is considered, the story drift and lateral displacement will be reduced generally. Only as the foundation soil stiffness is weaker than the upper-structure stiffness, the story drift and lateral displacement will be amplified. To mountainous structure, when soil-structure interaction is considered, the story drift and lateral displacement will generally be amplified. And the larger the slope angle is, the more obvious the effect is. The weaker the foundation soil is, the more obvious the effect is.

(3) Considered soil-structure interaction, the shear and the moment of column will be reduced, regardless it is flat-ground structure or mountainous structure; when the stiffness of the foundation soil is weaker than that of the structure, the reduced effect of shear force and the moment in columns is most obvious. The reduction of the column force shear and moment caused by slope angle depends on the foundation soil stiffness. If the foundation soil stiffness is given, there may be a particular slope value. As the slope angle is smaller than this value, the soil structure interaction effect of mountainous structure is more than that of flat-ground structure;

As the slope angle is larger than this value, the soil structure interaction effect of mountainous structure is less than that of flat-ground structure.

(4) Considered soil-structure interaction, the column axial force in flat-ground structure will be reduced; most of that of mountain building structure also will be reduced. However, when the stiffness of the foundation soil is close to or stronger than the structure, some of the axial force of the column will be amplified, especially the stiffness of the foundation soil close to the structure; and the bigger the slope angle is, the more obvious the amplification phenomenon is.

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