Topographic effects on seismic response of long-span rigid-frame bridge under SV seismic wave^{*}

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Abstract

Seismic ground motions of two neighboring mountains and the free surface between them are calculated under the SV seismic waves with three different incident angles. The results are then taken as the inputs of multi-point seismic excitations for the foundation of a long-span bridge built over the valley in the analysis considering the integrated influence of traveling wave and topography. On the basis of a dynamic analytical method, a finite element model is created for the seismic responses of a four-span rigid-frame bridge of 440 m. The pier-top displacement and the pier-bottom internal force of the bridge are calculated. Then the results are compared with those considering traveling-wave effect only. The conclusions can serve as a seismic design reference for the structures located on the complex mountain topography.

Key words: traveling-wave effect; topographic effect; multi-point excitation; rigid-frame bridge; seismic response

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Introduction

Irregular topography has a great influence on wave propagation, which has been manifested in many earthquake damages and has attracted extensive attentions from scholars in China and abroad. However, due to complex boundary conditions, local topography is usually simplified as circular ridge, single-faced slope or step-like terrace in investigating the influence of topographic amplification on the seismic ground motion (Louse *et al*, 1988; Dominic *et al*, 2005; Stewart and Sholtis, 2005). The studies have shown that the ground motion is obviously amplified along the ridge or slope crest, but it is slightly amplified or even de-amplified at the toe of slope or base. Therefore, the differential ground motions between adjacent points should not be neglected. Besides, such factors as incident wave type (P, SV or SH) and angle, *etc*, should also be taken into account. Up to now, certain achievements have already been obtained from the analysis of systematic parameters (Ashford and Sitar, 1997; Anastasios *et al*, 2004; Bouckovalas and Papadimitriou, 2005; FANG, 2005). However, the above literatures mainly focus on the influences of to-

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pographic effect, scattering phenomenon near the slope crest and soft-soil cover in the slope area on the seismic ground motion, while only few of them involve seismic response of structures built on those areas.

In recent years, many large-span continuous rigid-frame bridges have been built in China, and the seismic responses of such bridges under multiple-point excitations have attracted much attention. At present, traveling wave effect is often performed in the non-uniform excitation analysis (Rassem *et al.*, 1996; LI and SHI, 2003; ZHANG *et al.*, 2005), that is, seismic waves are assumed to travel along the ground in a certain velocity, waveform dose not change, but arrival time lags and amplitude decays. For a bridge built on a smooth and homogenous rock foundation, the traveling-wave assumption is simple and accordant with the actual situation. However, this method considers only the differences of phase and amplitude among the points, so further modification is needed for stimulating the multi-point earthquake ground motions of complex topographic sites.

As large bridges may be built to span the valley where topography is more complex, two neighboring asymmetric mountains are selected as an analytic model, which is more close to the actual situation. On the basis of the previous studies of P waves (WANG *et al.*, 2006), the authors have selected the SV waves with three different incident angles, which is especially critical to a large-span bridge. The ground motion responses of ridges and base reflect a combined influence of scattering ridge and traveling wave. The results are then used as multi-point inputs for a continuous 440m-long and four-span rigid-frame bridge. The topographic effect on earthquake ground motion under the incident SV waves is investigated and the seismic responses of bridge are calculated. The research results can be used as a reference in designing earthquake-resistance engineering structures.

1 Local irregular topography and ground-motion time history

1.1 Finite-element discrete model for irregular local topography

Two neighboring asymmetric mountains are used to simulate the irregular topography and the dimension of each part is illustrated in Figure 1. A 10 m×10 m square mesh is used in the finite-element analysis. The horizontal distance of the bottom of each mountain is defined as the width of the mountain and the vertical distance from the peak to the bottom is defined as the height of the mountain. The height-width ratio of the left mountain is 0.25.

Figure 1 Finite-element model for seismic analysis of neighboring asymmetric mountains (unit: m)

1.2 Ground-motion time history under SV incident wave

The SV waves are assumed to propagate from the down-left side of the site. The second-order artificial transmitting boundaries are applied to the left side, right side and the base of the discrete local topographic model (LIAO, 2002). The acceleration, velocity and displacement

time histories are calculated in the 2-D explicit concentrated-mass finite-element program, which are then input as seismic inputs into the abutments and piers of the bridge in the later analysis (WANG, 2004). As the results depend on seismic records to a large extent, three actual earthquake records with different frequency-spectrum characteristics are chosen to simulate the seismic waves propagating from the bedrock. In the following figures and tables, (1) denotes Ninghe E-W wave records (Tangshan aftershock) obtained at Tianjin Hospital (1976, peak acceleration: 104.18 cm/s^2); (2) represents El-centro N-S wave records (1940-05-18, peak acceleration: 341.695 cm/s^2); (3) indicates Northridge wave records (1994-01-17, peak acceleration: 460.1 cm/s^2). The peak acceleration is rectified to 1.96 m/s^2 and the predominant periods are 1.0 s, 0.55 s and 0.28 s, respectively.

The propagating velocity of SV waves of Ninghe earthquake record is taken as 882 m/s. To avoid the occurrence of inhomogeneous Rayleigh plane wave when SV waves reflect on the free surface of the slope, the incident angles are restricted to $\theta=0^\circ, 10^\circ, 20^\circ$. When the topographic effect is ignored and the traveling-wave effect is considered only, the topography with a level free surface is taken into calculation. a_t denotes the peak acceleration of ground motion when the topographic effect is considered, a_w denotes the peak acceleration without considering the topographic effect, and parameter $\alpha=a_t/a_w$ describes the topographic amplification influence. Figure 2 illustrates the time histories of horizontal (x direction) and vertical (y direction) accelerations for all bridge supports ($\theta=20^\circ$). The α -values of three seismic waves in the horizontal and vertical directions with the incident angles of 0° and 20° are shown in Table 1.

Table 1 α value of three seismic waves

Bridge supports	$\theta=0^\circ$ in horizontal direction			$\theta=20^\circ$ in horizontal direction			$\theta=20^\circ$ in vertical direction		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Abutment A	1.17	1.41	1.36	1.19	1.48	2.25	2.46	1.63	1.70
Pier 1	0.87	0.94	1.15	1.13	1.26	1.65	2.14	1.82	1.81
Pier 2	0.63	0.69	0.66	0.91	0.95	0.92	1.63	1.73	1.58
Pier 3	0.71	0.90	0.78	0.71	0.63	0.78	2.53	1.15	0.99
Abutment B	0.91	1.06	1.01	0.68	0.60	0.64	2.75	1.75	1.40

The calculated results indicate that the incoming SV waves have a reflection on the inclined free surface of the left mountain slope, which leads to the reflected P and SV waves impinging obliquely at the free ground surface. And their superposition on the incoming SV waves may lead to the amplification at the crest and the de-amplification in the valley. Therefore, the horizontal acceleration of the abutment A and the first bridge pier is amplified, while the peak ground motion of the other piers in the valley is close to or lower than that in the level field. The differential motion between the abutment A and the first bridge pier is much apparent, while the values of the other neighboring bridge piers are lower than that in the level site. The peak accelerations and α -values calculated from El-centro wave and Northridge wave are higher than that from Ninghe wave. It shows that the topographic amplification effect on the earthquake wave with rich high-frequency components is significant. For the case under the propagating SV seismic waves, the existing researches focus mainly on the topographic amplification effect on the horizontal ground motion. But according to the calculation results, the effect on the vertical component should also be considered. There is no vertical acceleration in the propagating SV waves in the uniform horizontal soil, however, in the mountain topography, the peak accelerations of the vertical

Figure 2 Time histories of horizontal acceleration at all bridge supports

components at the other piers are close to or even higher than that of the incoming waves except that at the first pier. When the incident angle equals to 20° , the α value at the third pier under El-centro wave and Northridge wave is relatively low (1.55 and 0.99, respectively), except that, the vertical peak acceleration is 1.4~2.75 times larger in a mountain topography than that in a uniform level field and the waveform changes greatly. In addition, the vertical differential ground motion between the adjacent points is very apparent, and the amplification effect under the Ninghe wave with a long predominant period is remarkable.

The increase of α -values in the vertical and horizontal directions seems to be proportional to the increase of incident angle. The effect of incident angle on the acceleration in the mountainous topography is more significant than that in the level field, and the α value in the horizontal directions increases more obviously than the vertical one.

2 Seismic responses of 440 m-long continuous rigid-frame bridge

2.1 Creation of structural model for rigid-frame bridge

To further study the effect on the dynamic responses of bridge induced by alternatively amplified or de-amplified ground motions in the mountain topography, a structural model of bridge

located on the neighboring mountains is proposed. The bridge consists of four spans of continuous box girders and the total length is 440 m. Figure 3 shows the overview of the bridge and the calculation sketch.

The box girder has variable sections of 5 m high and 60 cm thick at the support and 2.5 m high and 40 cm thick in the middle span, and the concrete grade is C50. The variation locus is a parabola curve. The piers are thin-walled variable rectangular cross-section piers. The sections of piers 1 and 3 are both 7.5 m×6 m and that of pier 2 is 8 m×6 m. The cross-section of pier changes the longitudinal size by 1:80 along its body and the transverse size remains in 6 m. The concrete grade is C30 (Figure 4).

Figure 3 Structural model and calculation sketch of a continuous rigid-frame bridge
(a) Layout of bridge; (b) Calculation sketch

Figure 4 Cross-section of girder and pier (unit: m)
(a) Cross section of box girder; (b) Cross section of pier

2.2 Response of bridge under Ninghe wave input

Firstly, the finite element model is used for assessing the response of the bridge, involving the simplification of the rigid-frame bridge in 3-D beam elements. And then, the accelerations shown in Figure 2 are taken as the inputs to calculate the seismic response of the bridge. The interaction of soil and structure is not considered in this paper. The dynamic equation can be seen in the literatures (HU, 1988).

The internal force of the bridge is composed of two parts: dynamic responses and pseudo-dynamic responses induced by differential ground displacements. The pier with the maximum total internal force is chosen as the contrastive object. The displacement of pier top, the internal force of pier top and pier bottom, the bending moment of girder in the middle span and the shear force of girder end are calculated. In this paper, only the internal-force time histories of pier bottom are presented for the limited space.

The calculated result shows that when the incident angle equals to zero, the maximum internal forces of girders, bending moments and shear forces of pier bottom are almost the same, whether or not the topographic effect is taken into consideration. However, the axial force varies greatly, which is about 4.0 times larger in the mountain topography than that in the level field. When the incident angle increases to 20°, the axial force is 2.0~2.7 times larger with topographic

effect than that with traveling wave effect only, while the other internal forces are less to a degree of about 0.7 times. It also indicates that the incident angle has a great influence on the internal forces of the structure. In the uniform level soil field, the bending moment, shear force and axial force of the pier bottom at the angle of 20° , compared to 0° , may result in an increase of 60%, 57% and 200%, respectively; and the bending moment M_z and shear force Q_y of the girder may increase by 60%. In the mountainous topographic field, the increases of these three kinds of internal forces in the girders and piers are more than 30%. The tendency of internal forces is the same as that of the ground motion. The internal-force time histories of pier bottom are shown in Figure 5.

Figure 5 Internal-force time history of piers under Ninghe wave inputs

Because of the scattering effect of the left mountain, there is obvious acceleration amplification at the abutment *A* and a great differential ground motion between the abutment *A* and the first pier. However, the calculation shows that the dominant differential motion does not affect the bridge response. The reasons are as follows. Firstly, for the movable bearing supported by the abutments *A* and *E*, as shown in Figure 3, the displacements along the longitudinal axis *x-x* are free, therefore, the ground motion of point *A* cannot be imposed on the bridge; Secondly, because the bridge with high piers is much flexible, the differential ground motion among the piers has less influence on it. Considering the actual situation that the longitudinal (*x-x*) displacement may be restricted, a fixed hinge in this direction is imposed on the abutment *A*, and then the internal forces of the bridge under three incident angles are calculated again.

In this supporting condition, the maximum internal-force responses of girders occur when the incident angle equals to 20° . The internal forces of girders in the mountain topography field are larger than that in the level free field, and the amplification is approximately 30%. On the other hand, the bending moment and shear force of pier bottom are also obviously larger in mountain topography than that in a level field, and the amplification is about 30%~50%, only few extreme cases are observed where the modification of peak shear force is small when the incident angle equals to 0° or 20° . The amplification of axis force of piers is still the most significant. When the

incident angle equals to 0° , the peak value that considers the topographic effect is 8 times larger than that only considers the traveling-wave effect; when the incident angle changes to 10° or 20° , the magnitude of amplification is 2.4 times or 1.8 times, respectively. The reason is that the horizontal seismic ground motion at the abutment *A* is imposed on the bridge, and the bridge rigidity in the longitudinal direction increases, then the influences of differential ground motion on the internal forces of the bridge will emerge.

2.3 Response of bridge under input of El-centro and Northridge waves

The topographic effect may be different if the spectrum characteristics of the incoming earthquake waves are different, and so are the seismic responses of the bridge. Therefore, the El-centro and Northridge earthquake records are selected as the incoming waves to calculate the ground motions and the internal forces of the bridge. The ground motion acceleration caused by these two kinds of earthquake waves with a short predominant period is obviously larger than the value of the incoming waves. However, the high-pier rigid-frame bridge in this paper is very flexible and the natural vibration period of the bridge is longer and close to the predominant period of Ninghe (Tianjin) wave, therefore, the maximal internal force is caused by Ninghe wave, El-centro wave takes the second place, and Northridge wave with the shortest predominant period causes the minimal internal force. If a comparison is made between the calculated result considering the topographic effect and that considering the traveling-wave effect only, the amplification tendency of internal force is the same as that of Ninghe (Tianjin) wave inputs. Figure 6 shows the bending moment and axial-force time history of the pier bottom with a moveable bearing at the end of the abutment *A* when the incident angle is $\theta=20^\circ$.

Figure 6 Internal-force time history of piers under El-centro and Northridge wave inputs

3 Conclusions

1) Differential ground motion among the bearing points and incident angle of the incoming waves seem to play an important role in the overall dynamic response of the long-span continuous rigid-frame bridge built in the mountain topographic field. These factors cannot be neglected in the design of bridge. Moreover, with the increasing incident angle of the incoming SV wave, the topographic amplification effect is more evident.

2) High-frequency earthquake incoming wave may be more dangerous when assessing the topographic amplification effect on the earthquake ground motion. However, the high-pier rigid-frame bridge in this paper is flexible. The response caused by the earthquake waves with a

long predominant period close to the natural vibration period of the bridge is more significant.

3) If the bridge is restricted to be simplified as a movable bearing at the ends of the bridge, the horizontal ground motion at this point cannot be imposed on the structure. Therefore, the topographic amplification at the crest will not evidently affect the bending moment and shearing force of the structure, since the bridge is flexible in the longitudinal direction. However, for those structures whose longitudinal displacement is constrained, large differential ground motion will have a noticeable influence on the response, the bending moment and shear force of the bridge at this moment is obviously larger than the case in the level free field.

4) Even a vertically propagating SV wave can result in considerable vertical ground motion in the mountain topography. The peak axial force of the bridge considering the topographic effect is much larger than that considering the traveling-wave effect only. Therefore, neglecting the topographic effect may underestimate the response for the structure built in the complex mountain field, especially for those sensitive to vertical excitations.

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