Applicability of HVSR in site effect of loess slope covered on mud rock

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Abstract: Taking the loess slope covered on mud rock as a research site, this study is based on theoretical foundation of the Horizontal-to-Vertical Spectral Ration (HVSR) and Sediment-to-Bedrock Spectral Ration (SBSR), site earthquake response of the loess landslide covered on mud rock calculated by use of the software FLAC3D, dynamic response of earthquakes was revealed, the simulation between HVSR and SBSR has been discussed, applicability of HVSR has been analyzed. The results show that: The maximum horizontal displacement is found in the cliff part of the slope, the peak acceleration is the largest at the back edge of the slope and the vertical interface, as the elevation increases, the dominant frequency moves toward the lower frequency, and the higher frequency components are absorbed, the dominant frequencies obtained by HVSR spectrum ratio and SBSR spectrum ratio, and they are basically consistent with the fourier spectrum, the amplitude of HVSR and SBSR spectrum ratio are similar to the change rule of peak acceleration. Therefore, HVSR method can be applied to study the site effect of loess slope covered on mud rock.

1. Introduction
With the wide covering area, the loess area in China is divided into discontinuous regions due to its geomorphic types, such as plateau, beam as well as hill, thus making the gully vertical and horizontal. Therefore, the stability analysis of slope area has a significant engineering role in both building industry and traffic industry. Moreover, located in the area with frequency earthquake, the area with loess landslide triggered by earthquake is large, causing great damage to people and economy. Within those, contact-face slope is severely affected by earthquake [1]. Apart from those, site effect not only is one of the key factors triggering slippage of loess slope, but also becomes an important issue that the field of earthquake engineering is concerned with.

SBSR method is the most classical method in the methods of site effect. However, due to the limitation of the selection of factory sites, currently, the HVSR method is adapted to study the site effect. Yu et al. [2] obtained spectrum ratio function of amplitude via comparing, analyzing and referring to spectral ratio method and HVSR method, verified the amplification effect of seismic ground motion and determined the multiple relationship in peak between two methods. Dai et al. [3] used the HVSR method to analyze slope topography and magnification effect of ground motion by valley terraces and proved the feasibility of HVSE method to analyze the magnification effect of...
ground motion. Tang et al. [4-5] adapted HVSR method to analyze ground motion amplification effect of ridge topography recorded by strong earthquakes of main shock and explore the reliability of the results via numerical simulation. They found that the results of numerical simulation agreed well with the observation record analysis results and verified that HVSR method was suitable for the ridge topography. Chen et al. [6-9] and their teams adapted HVSR method for the inversion of site cover thickness, assess the site effect and verify the influence of site conditions on ground motion. Yutaka Nakamura expressed that HVSR method has certain similarity in micro-vibration and seismic motion. Herak et al. [11-12] simply promoted and applied the HVSR method for the inversion of shallow velocity structure in site. Based on the former researches, Parolai et al. [13] analyzed the similarity of HVSR method and SBSR method and confirmed the difference between these two method. Rong et al. [14] made the primary research on the applicability of HVSR method to the site effect of loess under the effect of strong earthquake record and earthquake aftershock record in the original site. Li [16] made the primary research on the influence factors of HVSR method in the application of strong motion.

Most of those researches bases on the records of strong earthquake or aftershock. And there are few researches concerning the HVSR method that is applied in the site effect of mudstone overlying loess slope. Therefore, this paper employs FLAC3D, the finite difference software, to establish mudstone overlying loess slope. After inputting the time history of different components of the main shock recorded by the Tangyu Strong Earthquake Station at the Wenchuan earthquake on May 12, 2008, the characteristics of dynamic responses under the influence of earthquake are obtained and the HVSR method applied in this site effect is analyzed.

2. Theoretical foundation

SBSR method is the earliest and classical method applied in studying site effect, which was introduced by Brocherdt. According to the definition of SBSR method, the transfer function of the site in the domain of earthquake engineering generally refers to the change of the dynamic response characteristics of the output of the seismic wave in the process of transmission of various sites relative to the input. Moreover, dynamic response of surface dynamic response to dynamic response at the bedrock is used to describe the amplification effect of the places. Therefore, the amplification effect of the site could be expressed as formula (1):

$$SBSR = \frac{H_s(f)}{H_B(f)}$$

where $H_s(f)$ and $H_B(f)$ represents the Fourier spectrum of the horizontal component of ground motion and Fourier spectrum of horizontal component of ground motion at bedrock respectively, both of which is under the influence of horizontal seismic loading.

Based on the definition of HVSR put forwards by Nakamura [13], the features of the site under strong earthquake were obtained. Compared with SBSR method, HVSR method focuses on the changes of variation of the horizontal and vertical Fourier spectral ratios of the loess site. In addition, HVSR method is described via the ratio between Fourier spectrum $H_s(f)$ of the horizontal component and Fourier spectrum $V_s(f)$ of the vertical component of the surface ground motion, which could be expressed via formula (2):

$$HVSR = \frac{H_s(f)}{V_s(f)}$$

In conclusion, under earthquake loading, it is assumed that the Fourier spectrum $H_B(f)$ of the horizontal component of the ground motion at the site bedrock approximates the Fourier spectrum $V_B(f)$ of the vertical component of the ground motion, that is, $H_B(f) \approx V_B(f)$ and overlying soil layer has no obvious amplification effect on vertical component of seismic wave. Therefore, the ratio between Fourier spectrum $V_s(f)$ of the vertical component of the ground motion and the Fourier spectrum $V_B(f)$ of the vertical component of the ground motion approximately equals to 1. Then formula (2) could be converted to formula (3):

$$HVSR = \frac{H_s(f)}{V_s(f)}$$
However, the Fourier spectrum $H_B(f)$ of the horizontal component of the ground motion at the site bedrock approximates the Fourier spectrum $V_B(f)$ of the vertical component of the ground motion, that is, $H_B(f) \approx V_B(f)$ but overlying soil layer has an obvious amplification effect on vertical component of seismic wave. The ratio $SR_V(f)$ between Fourier spectrum $V_s(f)$ of the vertical component of the ground motion and the Fourier spectrum $V_B(f)$ of the vertical component of the ground motion could be expressed by formula (4). Then the formula (2) could be converted to formula (5):

$$HVS_0 = \frac{H_B(f)}{V_s(f)} \cdot \frac{H_B(f)}{V_B(f)} \approx \frac{H_B(f)}{V_s(f)} \cdot \frac{V_B(f)}{V_s(f)} = SBSR$$

Combined formula (3) and (5), it is found that under the appropriate energy of different component seismic wave, the HVSR method in theory could replace the SBSR method to study the site effect of loess if the loess has no obvious amplification effect on vertical component of seismic wave. If the loess site produces a certain ground motion response to the vertical component of the seismic wave, in theory, the HVSR method and SBSR method exists a certain multiple relationship. However, essentially, SBSR method could be replaced by the HVSR method to study the site effect of loess.

3. Numerical model of slope and calculation parameters

3.1. Establishing numerical model

Based on the on-site investigation of slopes and borehole data [1], this paper establishes a model with 259616 units by FLAC3D command. The mesh of mudstone is the same as that of overlying loess. The height of the model is 200 meters and it bottom is 480 meters. The height of slope is 140 meter, the head is 100 meter, and the slope degree is 25. The calculation model of the loess slope on the mudstone and the layout of the monitoring points are shown in Figure 1. The position of the monitoring point selects four sections, including the trailing edge of the landslide (A6x), the top of the slope (shoulder) (A5x), the waist of the slope (A3x), and the toe of the slope (A1x). x=1, 2 , 3 represents loess layer, interface and mudstone.

The calculation includes static calculation and dynamic calculation. And the static calculation adapts elastic-plastic model, which obeys Culon-morper rule. Without any external force, the model is balanced under the condition of gravity acceleration. Dynamic calculation uses dynamic multi-step method, thus effectively reducing the time of calculation. Via the large deformation calculation mode, the deformation under dynamic load is analyzed.
3.2. Calculating parameters
Different materials in FLAC3D calculation need to define different physical and mechanics parameters. The cohesion, internal friction angle and density could be obtained by indoor soil test. The bulk modulus as well as shear modulus could be calculated by formula (6) and (7) respectively.

\[ K = \frac{E}{3(1-2\mu)} \]  
\[ G = \frac{E}{2(1+\mu)} \]  

where E represents elasticity modulus and \( \mu \) represents poisson ratio.

| material  | density (g/cm³) | cohesion (kPa) | internal friction angle (°) | poisson ratio | bulk modulus (MPa) | shear modulus (MPa) |
|-----------|----------------|----------------|-----------------------------|--------------|--------------------|---------------------|
| loess     | 1.32           | 21.60          | 23.00                       | 0.30         | 75.00              | 35.00               |
| mudstone  | 2.00           | 680.00         | 34.20                       | 0.25         | 415.00             | 249.00              |

The specific parameters of model are shown in Table 1.

4. Calculating results of slope

4.1. Deflection analysis of monitoring points in slope
The monitoring data of horizontal displacement in loess layer (Figure 2a) and vertical area of slope waist (Figure 2b) under the action of horizontal component load of Tangyu seismic wave (VIII degree) are shown in Figure 2.

In the first 20 seconds, the horizontal displacement increment in monitoring points in loess layer is relatively small; after 20 seconds, the horizontal displacement of the shoulder (A51) and waist of the slope (A31) increases rapidly; after 50 seconds, the horizontal displacement of slope shoulder demonstrates a stable trend, but that of slope waist still increases. Compared with shoulder and waist of slope, the horizontal displacement of slope toe (A11) and trailing edge (A61) have little increment.

The horizontal displacement of slope waist is maximal so that the mud-stone under earthquake loading (A33), mudstone overlying loess and horizontal displacement of parting area (A32) are analyzed, taking the changes of horizontal displacement of slope waist as an example. From figures, it is known that mudstone basically stays in a stable state under the effect of earthquake loading; from the 30 seconds, the horizontal displacement of parting area begins to increase sharply and after 45 seconds, it is gradually stable; after 20 second, the displacement of mudstone keeps rising.

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Figure 2. The horizontal displacement of monitoring points

In conclusion, under earthquake loading, the mudstone layer basically stays at a stable state; the horizontal displacement increment in parting area is relatively large; due to the resistance of soil, the rear edge of the slope in the loess layer is deformed lowly; the slope shoulder slips due to the effect of driving force of soil on the trailing edge of slope, seismic force and empty surface. Under the effect of
driving force of sliding soil in slope, seismic force and sliding force of soil in parting area, the horizontal displacement of slope waist is maximum with heave fragmentation. Soil mass stacks in slope toe.

4.2. Analysis of accelerated speed in monitoring points of slope

The monitoring data of acceleration changes in loess layer (Figure 3a) and vertical area of slope waist (Figure 3b) under the action of horizontal component load of Tangyu seismic wave (VIII degree) are shown in Figure 3.

![Figure 3. The acceleration time-history of monitoring points](image)

(a) loess layer  (b) vertical area of slope waist

From the comparison of acceleration time-history curves in each monitoring point in loess layer, it is found that the peak ground acceleration of trailing edge reaches its maximum in about 30 seconds, following by slope toe whose peak ground acceleration occurs in about 32 seconds; the peak ground acceleration of slope shoulder basically matches with that of slope waist. Except the acceleration time history at the slope toe, the peak ground acceleration of the slope loess surface increases as elevation rises.

Because of the changes of vertical soil layer, the changing rule along the elevation under earthquake load is slightly different from that in the loess layer. It demonstrates the changing rule that mudstone layer is the smallest, loess layer ranks the second place and parting area is the largest.

In a word, with the increasing of the height of slope trailing edge and loess area, the peak ground acceleration in this area reaches the highest value. The changing material in parting area, the increasing of the loess thickness in slope toe and the breakage of loess, make the peak ground accelerations in these two areas higher than other monitoring points. The loess thickness in slope waist is basically the same with that in slope toe and the peak ground acceleration of slope shoulder influenced by elevation is relatively higher. At the same time, seismic wave has a hysteresis effect on the transmission of the loess layer.

4.3. Analysis of spectrum characteristics in the monitoring points of slope

Under the effect of horizontal component of seismic wave, the changes of Fourier spectrum in loess layer (Figure 4a) demonstrates an apparent changing rule. The Fourier spectrum gradually increases with the increasing of elevation and predominate frequency moves to the direction of low frequency. Compared with slope waist, the Fourier spectrum of slope shoulder is smaller, and its predominate frequency is lower, which further shows that the thickness of loess in slope waist increases due to bulk deposition caused by soil sliding during the earthquake. The changing curve of Vertical Fourier spectrum in the trailing edge of slope (Figure 4b) reflects that horizontal components of seismic waves is changed through the characteristics of different medium dynamics. From the figure, it is found that Fourier spectrum and predominate frequency of mudstone is the same as that of interface. But the amplitude of Fourier spectrum in interface is smaller and it increases with the increasing of elevation,
the predominate frequency of which moves to the low-frequency area. This further verifies the Fourier spectrum variation of seismic wave propagation in loess layer.

![Figure 4. The changes of Fourier spectrum of horizontal component of seismic wave](image)

(a) loess layer  
(b) the trailing edge of slope

![Figure 5. The changes of Fourier spectrum of vertical component of seismic wave](image)

(a) loess layer  
(b) the trailing edge of slope

Under the influence of vertical component of the seismic wave, the changes of Fourier spectrum and its horizontal component in each monitoring point of loess layer and trailing edge of the slope have larger differences in amplitude. In the loess layer (Figure 5a), with the increasing of the slope height along the slope surface, the peak value of the Fourier spectrum increases substantially in multiples and it predominate frequency is sequentially shifted to the low-frequency area. The changing curve of vertical Fourier spectrum (Figure 5b) obviously reveals the transmitting characteristic of vertical component of seismic wave in different media. From the figure, it is known that the changes of media has no obvious influence on vertical component of seismic wave and its changing rule is the same as that of loess layer with the increasing height of slope.

In conclusion, the effect of different components of seismic waves on the Fourier spectrum of the overlying soil layer of mudstone only exists in the magnitude and the transformation law of predominate frequency is basically the same. In other words, with the increasing of elevation, the predominate frequency moves to the low-frequency area, the high-frequency component is absorbed and the the change of the seismic wave transmitting media have a large influence on the horizontal component of the seismic wave.

4.4. Comparison between HVSR method and SBSR method

According to the changes of Fourier spectrum curve in each monitoring point of loess layer, the covering layer has obvious magnification effect on vertical component of seismic wave. By comparing the monitoring points of the bedrock and inputting Fourier spectra of different components of wave motion, the result that the fourier spectra of horizontal ground motion approximates that of vertical
ground motion could be obtained. Therefore, according to the theoretical analysis, the HVSR method has coefficients relationship with SBSR method.

Plotting the HVSR spectral ratio and the SBSR spectral ratio curves of the slope requires to process the the data of different components of the seismic waves at each monitoring point. Firstly, The acceleration time history curve recorded in the monitoring points is required to be corrected by baseline and baseline, thus reducing and eliminating the data error. Then, the Fourier spectrum curve, obtained by the decomposition of the acceleration time history curve, needs to be smoothed to make the dynamic characteristics of the ground motion more clear since it has more burrs. Next, two spectral ratio curves are plotted based on the theoretical analysis of HVSR method and SBSR method. If the loess layer has an obvious magnification effect on vertical component of seismic wave, the Fourier spectrum data of the surface are replaced by Fourier spectrum of the surface of the seismic wave. Finally, two spectral ratio curves that loess layer has no obvious magnification effect on vertical component of seismic wave are drawn and plotted.

![HVSR spectrum](image1.png) ![SBSR spectrum](image2.png)

Figure 6. The vertical component of seismic wave has obvious magnification effect on

Via the calculating results, it is found that under the condition that loess layer has an obvious magnification effect on vertical component of seismic wave, the changing rule of HVSR spectrum in the loess layer (Figure 6a) is basically the same as that of Fourier spectrum in the loess layer under the effect of horizontal component of seismic wave. However, the amplitude of HVSR spectrum is relatively small and predominate frequency in loess layer overlying mudstone is about 0.8 Hz. It is shows that they has different trend of the obtained superior frequency from the SBSR spectral ratio curve (figure 6b) and the HVSR spectral ratio in the mudstone overlying loess layer. With the increase of the height, the predominate frequency moves towards the high frequency, but the predominate frequency in loess layer overlying mudstone is constant. Comparing the HVSR spectrum curve and SBSR spectrum curve could further verifies their theoretical analysis. When covering layer has an obvious magnification effect on vertical component of seismic wave, the predominate frequency of the site reflected by HVSR method basically matches that of SBSR method, but they have certain difference in amplitude. Therefore, HVSR method could replace the SBSR method to study the effect of the loess slope on the mudstone.
Figure 7. The vertical component of seismic wave has no obvious magnification effect on contrast with Figure 6, the Fourier spectra of horizontal ground motion approximates that of vertical ground motion. Provide that covering soil layer has no obvious amplification effect on the vertical component of seismic wave, curve of spectrum ratio of HVSR (Figure 7a) should approximately equal to that of spectrum ratio of SBSR (Figure 7b) according to the theoretical analysis. Via calculating two curves of spectrum ratio, it is known that the predominate frequency and amplitude of loess overlying mudstone are approximately equivalent. With the increasing of elevation of soil layer, the changing rule of predominate frequency coincides with the rule obtained by Figure 6.

Whatever loess overlying mudstone has a magnification effect on vertical component of seismic wave, the predominate frequency of the site obtained by HVSR method basically matches that of SBSR method. These two method only exists certain difference in amplitude. The predominate frequency and changing rules of elevation obtained by HVSR method are closer to the variation characteristics of Fourier spectrum in the slope.

In this paper, horizontal displacement, peak ground acceleration and spectrum characteristics could be used to reflect the characteristic variety of dynamic response under seismic action. Table 2 calculates the horizontal displacement of trailing edge, shoulder and waist, the peak ground acceleration, the spectrum characteristics as well as the maximum amplitudes of HVSR spectrum ratio and SBSR spectrum ratio under two different assumptions. After analyzing, it is known that when the peak ground acceleration of trailing edge of slope reaches the maximum, the Fourier spectrum, HVSR spectrum ratio and SBSR spectrum ratio in corresponding monitoring points are max. Comparing the waist and shoulder of slope, when the peak ground acceleration of waist is max, the increment of horizontal displacement, Fourier spectrum, HVSR spectrum ratio and SBSR spectrum ratio reach the max value. Therefore, to some degree, HVSR method could be adapted to qualitatively study the site effect of loess slope overlying mudstone.

Table 2 Comparison of maximum amplitude of parameter in monitoring points

| monitor point position | Max increment for horizontal displacement (m) | peak ground acceleration (m/s²) | peak value of Fourier spectrum | peak value of HVSR spectrum | peak value of SBSR spectrum |
|------------------------|--------------------------------------------|--------------------------------|--------------------------------|----------------------------|---------------------------|
| trailing edge           | 0.27                                       | 6.72                          | 13.74                         | 1.70                       | 3.80                      |
| slope (A61)             |                                            |                               |                               |                            |                           |
| slope shoulder          | 3.27                                       | 3.75                          | 4.62                          | 1.00                       | 3.10                      |
| (A51)                   |                                            |                               |                               |                            |                           |
5. Conclusions

(1) The shoulder and waist of the slope are relatively steep due to the seismic action, thus leading to large thrust load caused slide and deformation. The trailing edge and toe of slope have a small sliding because of soil barrier and gentle angle and the peak ground acceleration increases as elevation and degree of crushing increase.

(2) The effect of different components of seismic wave on Fourier spectrum of soil layer overlying mudstone only exists on the amplitude. With the increasing of elevation, predominate frequency moves to low frequency domain. The larger thickness of loess layer and degree of crushing, the higher predominate frequency. Moreover, the changes of transmitting medium of seismic wave has a strong influence on the horizontal component Fourier spectrum of seismic wave.

(3) To some degree, under spectrum characteristics and two different hypotheses, the change rules of spectrum ratio of HVSR and that of SBSR are similar as peak ground acceleration increases. Both of them increase with the increasing of accelerated velocity.

(4) The predominate frequencies of site reflected by HVSR method and SBSR method are basically consistent. Whether overlying loess layer has a magnified effect on the vertical component of the seismic wave just exists some influence on the amplitude of the two spectral ratios.

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