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SEISMIC LANDSLIDE SUSCEPTIBILITY ASSESSMENT BASING ON NEWMARK MODEL CONSIDERING SITE AMPLIFICATION

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Abstract

Earthquake is a great threat to people's lives and property. Earthquakes of high magnitude happen every year around the world. With the increase of population and rapid development of economy, land suitable for engineering construction is becoming less. Sometimes engineering activities have to be carried out in regions with frequent earthquakes. Therefore, risk assessment of regional seismic disaster is of great significance for guiding engineering activities. Newmark permanent displacement method, as a simple and clear physical and mechanical model, has been extensively applied in quantitative risk assessment of regional seismic landslides. However, in most previous regional assessment studies, the effect of amplification on permanent displacement was ignored, leading to a deviation of result to the measured displacement. Microtremor measurement, as a simple field test method, can reflect the amplification effect of slope on dynamic characteristics. In this paper, microtremor observation is used to evaluate the amplification effect of slope. Through FFT of velocity waveform from microtremor observation, the predominant frequency of observation point can be analyzed. And the spectrum amplitude corresponding to predominant frequency indicates the vibration mode of slope. Therefore, ratio of spectrum amplitude is determined as amplification factor of slope. An improved Newmark model is proposed considering the amplification effect using amplification factor.

Dayong expressway from Huaping to Lijiang section is one of the national roads under construction in Yunnan province with a total length of 126 km. A 50 km section of Dayong expressway is located in the affected region of Chenghai fault zone, only 2 km nearby Chenghai fault zone. An area containing ancient landslide was selected as the study area. The risk of regional seismic landslide is assessed basing on Newmark model, and site amplification effect is paid special attention to through microtremor measurement. In the affected region of Chenghai fault zone, 13 measuring points of different position are selected to observe microtremor of the slope. The relationship between spectrum amplitude and slope height, degree is established by multiple linear regression. The site amplification effect of study area is evaluated basing on DEM and fitting equation above. The maximum value of amplification factor reached 3.595. In addition to microtremor observation, other field tests including UAV photography and high-density surface wave test were also conducted to investigated the site conditions. And an acceleration wave recorded at Chenghai observation station under 2019 Yongsheng earthquake was utilized as the input wave of Newmark model. Finally, the permanent displacement of study area was calculated using Newmark model considering amplification effect. The result considering amplification and one without considering amplification were compared. Without amplification effect, the maximum value of permanent displacement in study area is 5.1cm. Area with permanent displacement greater than 5cm increases after considering amplification effect. Neglecting amplification effect is strong factor which leads to deviation of permanent displacement using traditional Newmark model.

Keywords: susceptibility assessment; seismic landslide; microtremor; amplification effect; permanent displacement.

1. Introduction

As common sudden natural disaster, earthquake has a serious impact on safety of human lives and properties. Generally, earthquakes will cause secondary geological disasters like landslides, rock collapse, sand liquefaction and so on. For example, the Ms 8.0 Wenchuan earthquake in China was induced by the geological activity of Longmenshan fault [1]. This earthquake killed 68000 people and injured hundreds of thousands of people and landslides and collapses triggered by earthquake had a profound impact on local people. The 2013 Ms 6.6 Lushan earthquake was also caused by Longmenshan fault, resulting in about 3000 landslides [2]. As one of the main disasters caused by earthquake, seismic landslides have attracted more and more attention from researchers. Assessment of seismic landslide susceptibility can evaluate high risk region and provide guidance for engineering activities and seismic prevention, which has been developed with the improvement of GIS (Geographic Information System).

There are two kinds of evaluation method for seismic landslide susceptibility [3]: deterministic method and non-deterministic method. The deterministic method is mainly based on mechanism analysis of seismic landslide to assess slope safety. The non-deterministic method mainly uses statistical method to establish quantitative evaluation model between various influencing factors and historical seismic landslides, and applies this model to predict the susceptibility of regional slopes in study area. Among them, Newmark permanent displacement model is the most commonly used deterministic method for evaluation of seismic landslide because of its clear physical meaning and simple calculation. More and more scholars are deeply studying Newmark model. Jibson [4,5] established 4 simplified Newmark models basing on Arias intensity, critical acceleration and critical acceleration ratio with 2270 seismic records. Yuqiao Qin et al. [6] presented an improved Newmark model considering slope aspect and vertical ground motion. Siyuan Ma et al. [7] combined Newmark model with machine learning method to propose a more effective comprehensive evaluation method for regional seismic landslides susceptibility. Although Newmark model has been extensively used, it does not take amplification effect of slope into account, which leads to a deviation between calculation result and actual displacement. The amplification effect has been often observed in field investigation, shaking table test, numerical simulation and other situations [8,9,10]. And microtremor observation is a convenient method to study the dynamic amplification characteristic of slope. Javier Lermo et al. [11] use strong motion data and microtremor data to analyze the site effect and predominant period of Mexico City. Horizontal-to-vertical (H/V) spectral ratio technique was adopted by W. Wang et al. [12] to study the site effect and geological information of Beijing.

In this paper, basing on traditional permanent displacement Newmark model, an improved model to assess regional seismic landslides susceptibility is presented considering amplification effect. To study the amplification effect of study area, the spectrum amplitude corresponding to predominant frequency is analyzed through microtremor observation. A parametric evaluation was conducted to generate regression equation using slope degree and slope height, and amplitude ratio of spectrum is determined as the amplification factor of slope. Finally, the improved Newmark model considering amplification effect was applied to study area to calculated the permanent displacement under the impact of seismic fortification design.

2. Newmark model considering amplification effect

2.1 Newmark permanent displacement model

Newmark permanent displacement model was first proposed by Newmark in 1965 for dam stability analysis under seismic motion [13]. In this model, it is considered that the failure of dam depends on the cumulative deformation under dynamic action which differs from previous mechanical analysis. Latterly, this method was gradually introduced into the risk assessment of slopes. Now Newmark model has become one of the most commonly used deterministic methods to evaluate susceptibility of regional slopes under earthquakes.

In Newmark model, sliding body of slope is assumed as rigid body and sliding surface is assumed as a plane parallel to slope. And permanent displacement is caused by earthquake action that makes sliding body to move. There are two parts to apply Newmark model: one is to calculate the acceleration that makes the sliding body in critical state basing on limit equilibrium analysis (Fig.1), the other part is to integrate two times the seismic acceleration time-history waveform which exceeds critical acceleration-from acceleration to displacement (Fig.2).

The critical acceleration a_c is calculated by the safety factor F_s of slope. The formula for safety factor F_s is:

$$F_s = \frac{c}{\gamma t_0 \sin\alpha} + \frac{\tan\varphi}{\tan\alpha} - \frac{m\gamma_w \tan\varphi}{\gamma \tan\alpha} \tag{1}$$

Where c is the cohesion; γ represents the unit weight of sliding soil; t_0 is the slope-normal thickness of sliding soil; α is the slope angle; φ is the friction angle; m is the ratio of t_0 which is saturated. Then critical acceleration a_c can be calculated basing on pseudo static method:

$$a_c = (F_S - 1) g \sin\alpha \tag{2}$$

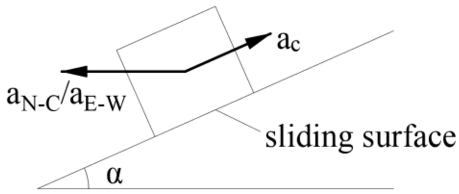


Fig. 1 Illustration of sliding body

In Fig.2, the top red line represents critical acceleration, the seismic wave beyond a_c makes sliding body move. And permanent displacement of slope is accumulated until the relative velocity between sliding body and sliding surface comes to 0. It can be expressed as Eq. (3):

$$D_N = \int\int_t (a(t) - a_c) \mathrm{d}t\mathrm{d}t \tag{3}$$

where D_N is the permanent displacement of Newmark model; $a(t)$ is the time history waveform of seismic acceleration.

In the seismic risk assessment of regional slopes, Newmark model has been extensively used because it quantitatively evaluates the effect of earthquake on slope from the aspect of deformation. However, Newmark model did not consider the amplification effect of slope. The morphology of slope and geological conditions have obvious amplification effect on seismic wave which can be observed in post-earthquake disaster investigation. It was also found that the results of Newmark model were smaller than actual displacement. Therefore, considering amplification in Newmark model is of great significance for accurately evaluating the displacement of seismic slopes.

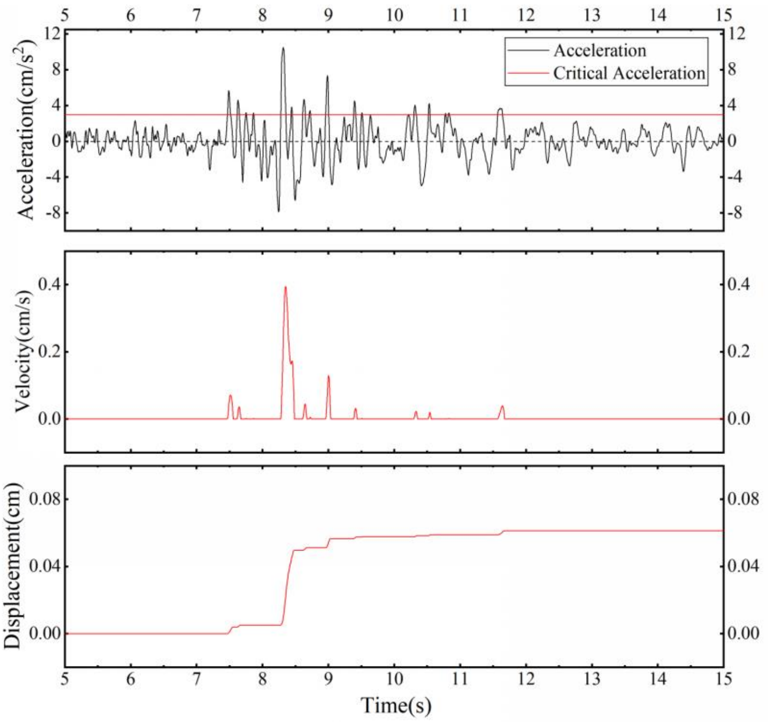


Fig. 2 Sketch of two-stage integration process in Newmark model

2.2 Amplification effect analysis basing on microtremor observation

Even if there is no earthquake, there are still tiny vibrations on the earth's surface. The amplitude of vibration is about 10^{-8} cm in the quiet mountain and approximately 10^{-4} cm in the city. This kind of tiny vibration caused by environment is called microtremor. The source of microtremor is usually considered to be caused by traffic, mechanical operation, etc. or by natural sources like meteorological changes, wave impact, etc. Fig.3 shows the typical velocity waveform of microtremor observation. The waveform has components of three directions: north-south, east-west, up and down. Normally, the vibration amplitude in horizontal direction is larger than that in vertical direction. The frequency of microtremor wave is between 0.1Hz and 20Hz. The peak value in low frequency domain below 1Hz is mainly caused by natural phenomena such as sea waves. The high frequency wave above 1Hz is mainly caused by human activity such as traffic etc. The waveform of source is complex and random. Microtremor observation has been extensively used as a convenient method to investigate the dynamic properties (frequency and mode of vibration) of ground surface. On this basis, microtremor observation is applied to study the amplification effect of slope.

The microtremor signal can be decomposed into many harmonic components. The signal can be transformed into frequency spectrum curve using FFT (fast Fourier transform). To ensure the correctness of signal, we choose five sections (A, B, C, D and E) of one waveform for Fourier transform (Fig.4). When the spectrums of five sections show consistence, these are the frequency spectrum of observation point. Three direction components of microtremor wave all can be transformed by FFT. To study the amplification effect in horizontal direction, the average of N-S and E-W components was used to evaluate the horizontal spectrum of slope using Eq. (4):

$$a_{\mathrm{h}} = \sqrt{a_{\mathrm{N\text{-}S}} \times a_{\mathrm{E\text{-}W}}} \quad (4)$$

where a_{h} is the spectrum in the horizontal direction.

In the typical spectrum of velocity wave at observation point, there can be many peaks in the curve of frequency spectrum. And every peak determines one natural frequency of slope. The peak reaches maximum at the predominant frequency. And the value of spectrum amplitude at each natural frequency corresponds to the vibration at measuring points. Che et al. [14] used microtremor to describe the vibration modes of timber structure at different natural frequency. By observing microtremor at different position of slope, the spectrum amplitude at predominant frequency of observation points can be obtained. The ratio of spectrum amplitude indicates the amplification effect of slope. Therefore, spectra ratio is determined as the amplification factor of slope to seismic wave. The mathematical formula of amplitude factor is:

$$f_a = \frac{a_{hpi}}{a_{hp}} \tag{5}$$

where f_a is amplification factor; a_{hpi} is the peak spectrum value at predominnant frequency in horizontal direction of the i-th observation point; a_{hp} is the peak spectrum value at predominnant frequency of the observation point at the foot of the slope. Newmark model considering amplification effect can be calculated as:

$$D_N = \int\int_t \left(f_a \cdot a(t) - a_c \right) \mathrm{d}t\mathrm{d}t \tag{6}$$

3. Case study

3.1 Study area

Chenghai fault zone is an ancient fault located in Yunnan Province, China. There were active geological activities in the area near Chenghai fault zone. And Dayong expressway is a national highway in the construction process in Yunnan province. About 50km section of Dayong expressway is parallel to Chenghai fault zone (Fig.3). The distance between this section of expressway and fault is 3km approximately at average. This dangerous section passes through Binchuan Country, Taoyuan town, Chenghai town and other towns. Fig.5 illustrates the epicenters of historical earthquakes near Chenghai fault from 2008 to 2019. The size and color represent the magnitude of historical earthquakes. It can be seen that the quantity of historical earthquakes is large and most of them were small earthquakes. The earthquake with higher magnitude in the area affected by Chenghai fault zone recently is the Ms 4.9 Yongsheng earthquake on July 21, 2019 (Fig.3). There was few disasters and casualties induced by Yongsheng earthquake. However, it offers proof that Chenghai fault is an active fault and the possibility of occurrence of severe earthquake affected by Chenghai fault in the future exists, which puts potential threat on the safety of Dayong expressway. Therefore, it is necessary to assess the susceptibility of regional slopes under the impact of earthquake to avoid the effect of seismic landslides on engineering activities.

During the investigation on parallel section of Chenghai fault and Dayong expressway, some ancient landslides were found. Ancient landslides as deposits are easily activated by seismic motion. An area containing ancient landslide, shown in Fig.3, was selected as the study area.

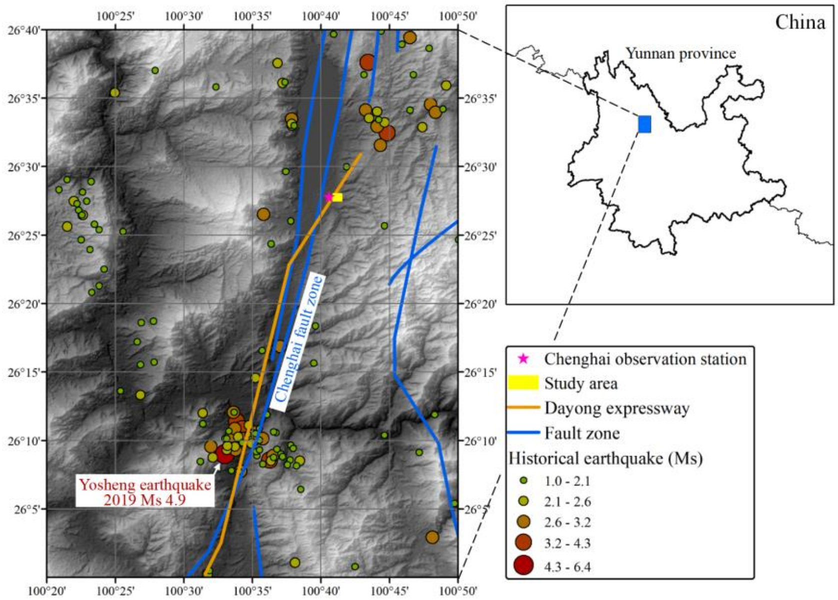


Fig. 3 Regional seismicity of Chenghai fault zone area

3.2 Field test

To apply the Newmark model and study the amplification effect of slope, some field tests were conducted. Field tests contains UAV (unmanned aerial vehicle) photography, microtremor observation and high-density surface wave test.

3.2.1 UAV photography

Using UAV to shoot the terrain and geomorphic characteristics of study area, obtain the three-dimensional data, and build the DEM (digital elevation model) of study area as shown in Fig.4. Aerial photography area is about 7km^2. The elevation of study area ranges from 1573m to 1813m. The maximum height of slope is about 200m. The blue line in Fig.4 is Dayong expressway. The east end of line is a tunnel and it extends to the west along the middle of slopes.

DEM is expressed as grid data in GIS as shown in Fig.4. With GIS, regional calculation becomes more convenient. Similarly to the calculation method of GIS, Newmark model can be applied to each grid, and then assemble the grids into regional data.

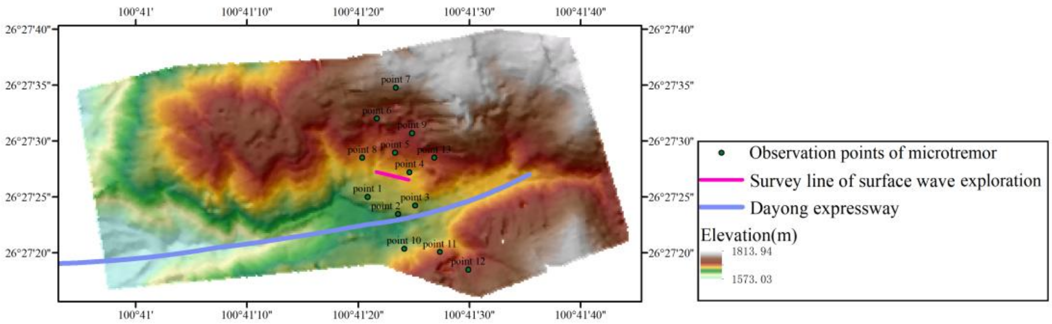


Fig. 4 Study area and location of microtremor observation points

3.2.2 Microtremor observation

Thirteen observation points were set up in the study area to observe microtremor. Observation points were evenly distributed on the slope and the positions of them were marked on DEM (Fig.4). The observation duration of each observation point is 1800s and Fig.5 shows one typical part of velocity waveform. During data processing, filter signals with 0.5-50 Hz filters to avoid noises. Five sections of 50s signal were selected for FFT at each observation point. And use Hanning window to smooth the spectrum. The FFT results of some observation points are shown in Fig.6.

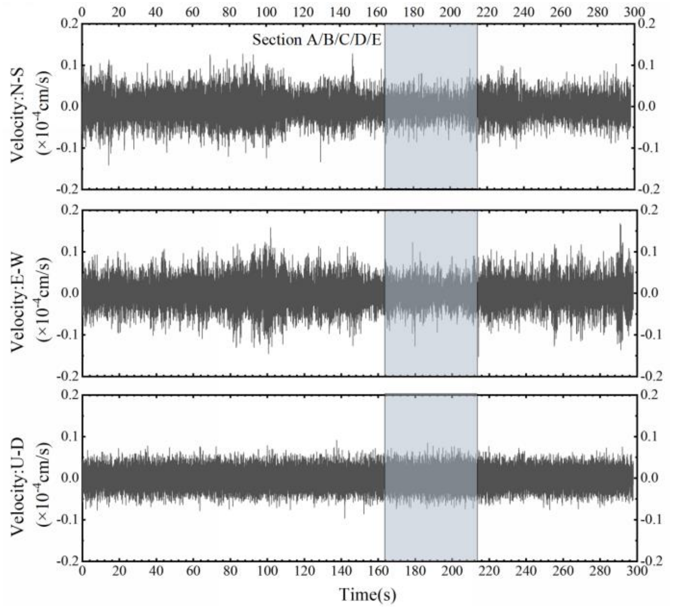
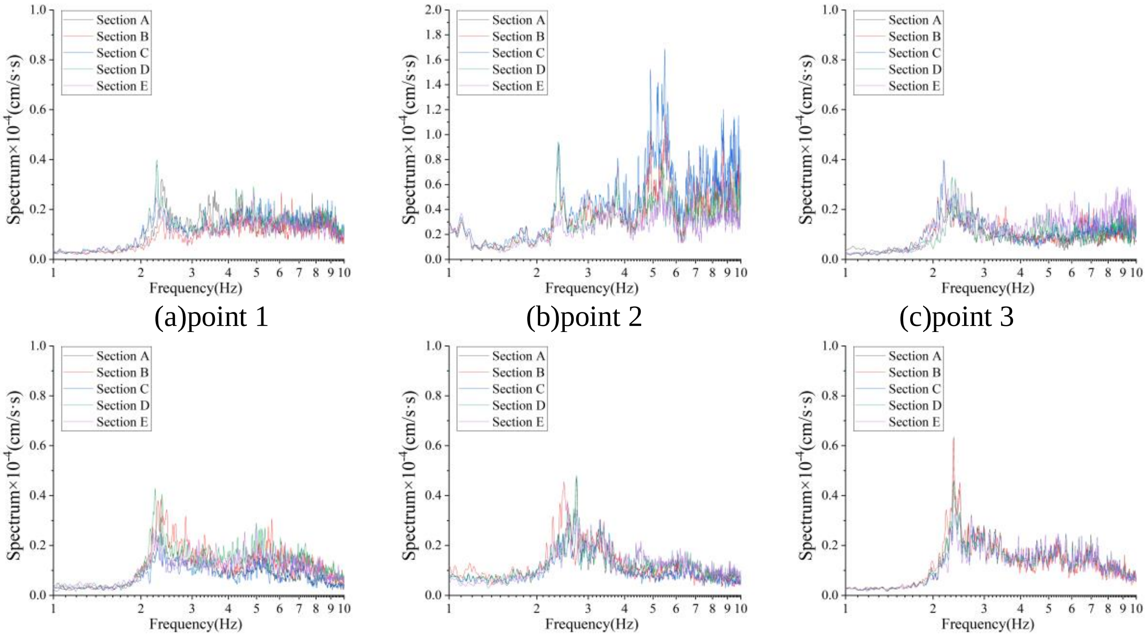


Fig. 5 Typical waveform of microtremor observation (point 1)



(a)point 1 (b)point 2 (c)point 3

(d)point 4 (e)point 5 (f)point 6

Fig. 6 FFT spectrum of observation points (point 1-6)

From Fig.6 it can be seen that all frequency spectra of observation points have a peak between 2.0 Hz and 3.0 Hz. It indicates that the predominant frequency of slope is 2.0-3.0 Hz. At some observation points there are also peaks in the range great than 3.0 Hz, which means the higher natural frequency of slope. But the spectrum amplititude of these peaks is smaller than that at predominant frequency because deformation of slope under free excitation is dominated by the first-order frequency. However, for observation point 2, the amplitude of predominant frequency is not the highest. The location of point 2 is close to the construction of expressway. During the field test, area near point 2 had been excavated for the foundation of expressway.

Therefor, the thickness of surface soil near point 2 is smaller than that of other points. And thickness and hardness of surface soil have an obvious effect on microtremor observation. The excavation reduces the thickness of surface soil and enlarges microtremor signal of high frequency components. In summary, the data of observation point 2 is not valid and it will be deleted in following analysis.

3.2.3 High-density surface wave test

In the process of applying Newmark model, the thickness of sliding body has to be identified. High-density surface wave test was conducted to investigate the geological structure of study area. The location of survey line is shown in Fig.4 and the length of survey line is 100m. Fig.7 illustrates the result of surface wave test-shear velocity profile of survey line. The soil in study area is layered and the shear velocity of soil ranges from 160m/s to 380m/s. According to borehole information, it can be noted that soil mass is roughly divided into three layers: silty clay, gravel and mudstone. The surface soft soil is easy to slide under the action of earthquake. By comparing the thickness of soil layer from borehole with shear vocity profile, soil with velocity less than 250m/s is determined as sliding body. The thickness of sliding body is about 5-8m.

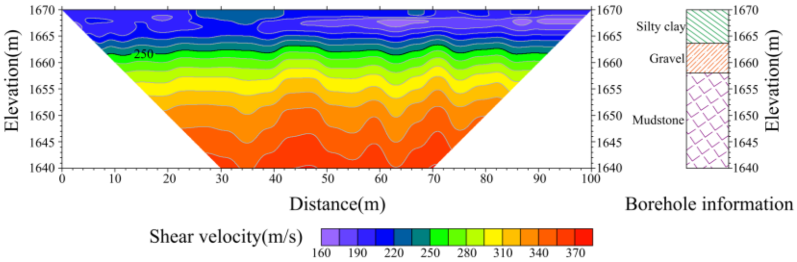
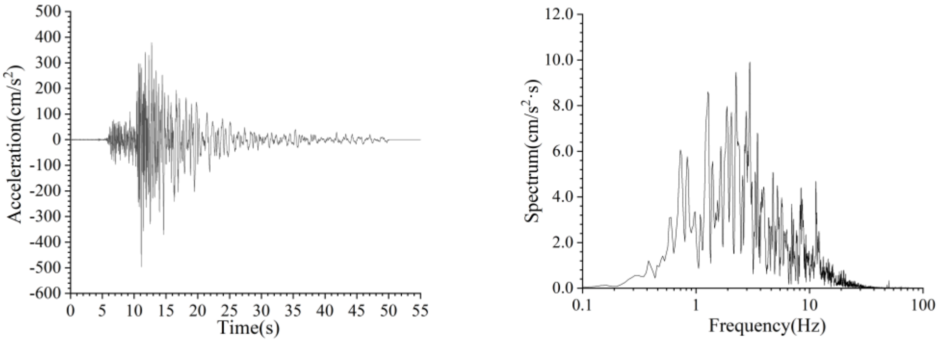


Fig. 7 Shear velocity profile of surface wave test and borehole information

4. Regional seismic landslides susceptibility assessment

4.1 Seismic acceleration waveform

Select the wave record of Chenghai observation station in 2019 Yongsheng Ms 4.9 earthquake as input of Newmark model. The position of Chenghai observation station is located in Fig.5, which is only 1.5km away from the study area. The magnitude of Yongsheng earthquake is low, so the amplitude of earthquake acceleration wave is too small to induce permanent displacement. The local seismic fortification intensity of study area is 8 degree and the design value of peak ground acceleration is 0.3g. Therefore, we amplify the seismic acceleration wave to the maximum of 378 cm/s^2. The amplified wave is as shown in Fig.8.



(a)acceleration waveform (b)acceleration spectrum

Fig. 8 Acceleration wave and spectrum (recorded at Chenghai observation station under 2019 Yongsheng earthquake)

4.2 Site amplification effect

To study the amplification effect of slope, statistical analysis of spectrum amplitude of observation points was carried on. The peak value of the average of five sections' (A, B, C, D and E) spectrum amplitude was calculated as the amplitude corresponding to predominant period. Amplification effect of slope is mainly related to topography and geological condition [15]. The geological condition of each position in study area are similar. So, the influence of topography on amplification is mainly considered. Extract slope degree and height of each observation point from DEM and analyze their correlation with amplitude at predominant frequency. Table 1 shows the value of slope degree, height and spectrum amplitude of 13 observation points.

Table 1 Spectrum amplitude of observation points

Observation point	Spectrum amplitude at predominant frequency ($\times 10^{-4}$cm/s·s)	Slope degree (°)	Slope height (m)
Point 1	0.27	6.48	120.45
Point 2	0.94	12.65	115.00
Point 3	0.29	16.75	125.11
Point 4	0.37	20.64	135.43
Point 5	0.41	22.73	152.77
Point 6	0.52	21.49	173.11
Point 7	0.68	32.64	204.96
Point 8	0.44	28.49	144.67
Point 9	0.51	24.64	166.30
Point 10	0.32	19.54	128.87
Point 11	0.47	24.45	152.97
Point 12	0.61	26.98	172.29
Point 13	0.40	15.87	157.42

Fig. 9 shows the relation between slope degree, height and spectrum amplitude of 12 observation points (without point 2) in 3-D coordinate system. It can be noted that slope degree and height have a linear positive correlation with spectrum amplitude. The higher the slope degree and height are, the stronger the spectrum amplitude corresponding to predominant frequency is. Through multiple linear regression, the relationship between spectrum amplitude and degree and height is obtained as Eq. (7):

$$a_{hp}=0.00471\cdot d+0.00397\cdot h-0.26899 \qquad R^2=0.93747 \tag{7}$$

In Eq. (7), a_{hp} is the spectrum amplitude at predominant frequency; d is slope degree; h is slope height.

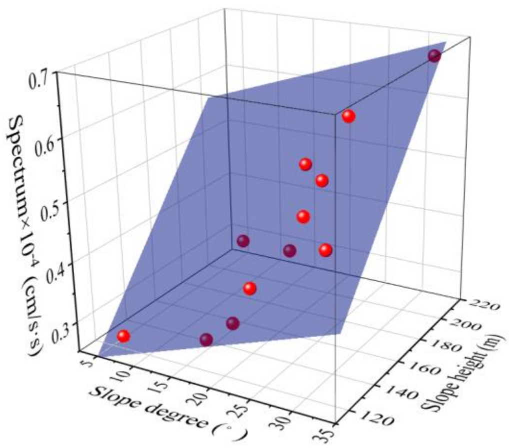


Fig. 9 Relation between slope degree, height and spectrum amplitude

Basing on Eq. (7) and DEM of study area, the spectrum amplitude of all study area can be calculated. The amplitude at the foot of slope should have the minimum value. The ratio of amplitude of study area to that at foot of slope is the amplification factor to seismic wave. Fig. 10 shows the distribution of amplification factor in study area. It can be seen that factor increases along the slope to the top and also increases where slope surface is uneven. The maximum value of amplification factor is 3.595.

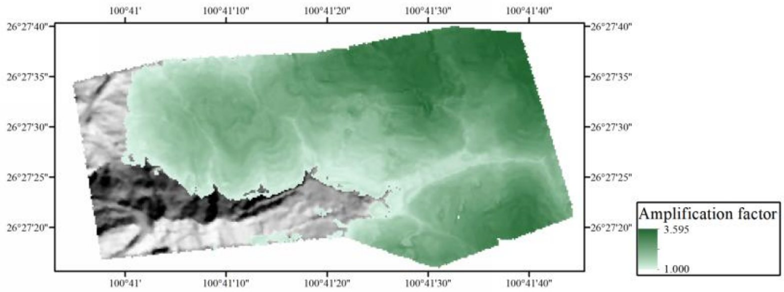


Fig. 10 Distribution of amplification factor in study area

4.3 Critical acceleration

Basing on Eq. (1) and DEM, the safety factor F_s of Newmark model was calculated. The parameters involved are shown in Table 2. The values of c, φ and γ are the results of laboratory geotechnical test. And slope degree α is derived from DEM in GIS. Then critical acceleration can be obtained according to Eq. (2). Fig. 11 shows the distribution of critical acceleration in study area. Areas with slope degree less than 10° were not calculated. The range of critical acceleration is from 0.172g to 0.605g. Where slope degree is small, critical acceleration has large value.

Table 2 Values of surface soil parameters

Soil name	**Thickness of sliding soil t_0 (m)**	**Unit weight γ (kN/m^3)**	**Cohesion c (kPa)**	**Friction angle φ (°)**	**Slope degree α (°)**	**Shear velocity V_s (m/s)**
Silty clay	8	18.8	24	32	Derived from DEM	160-250

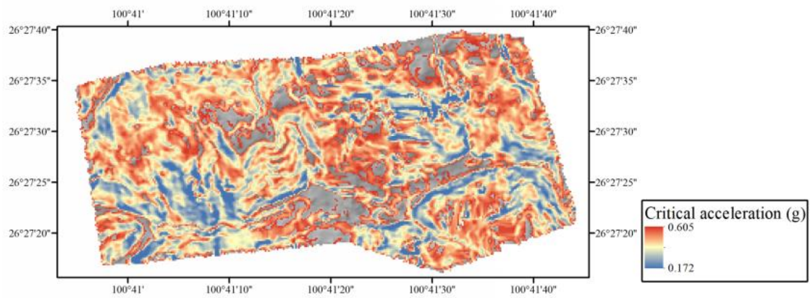
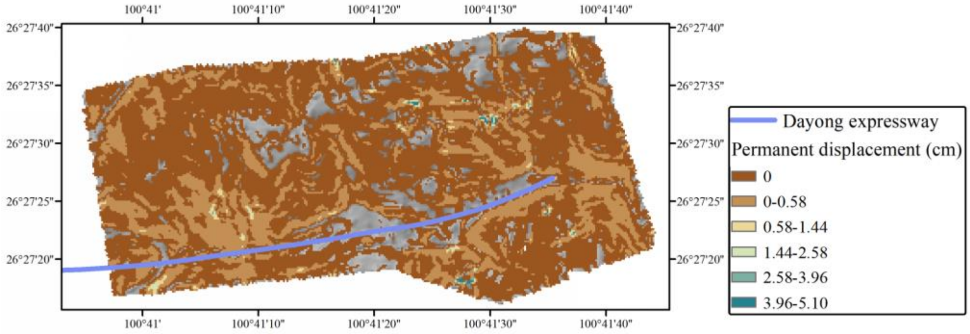


Fig. 11 Distribution of critical acceleration in study area

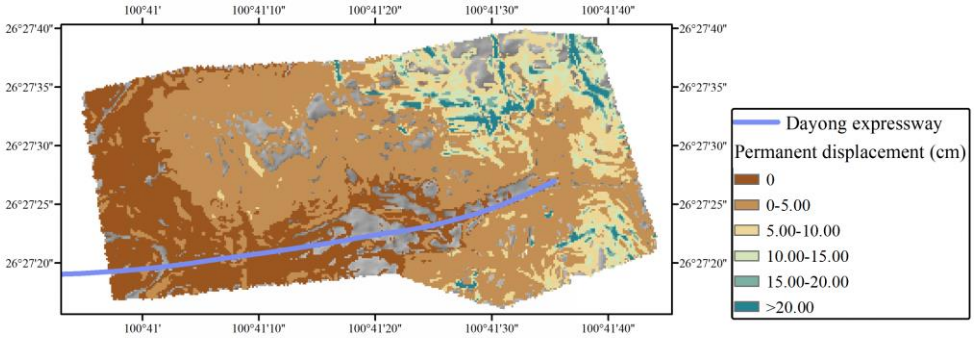
4.4 Permanent displacement

Basing on the characteristics of grid data, the permanent displacement of each grid in study area is calculated using MATLAB. Input data includes critical acceleration, amplification factor and seismic acceleration wave. For each grid, critical acceleration and amplification vary with location. In process of calculation, firstly, amplification factor and seismic acceleration are multiplied as the seismic wave considering amplification effect. Then, permanent displacement can be obtained by integrating the seismic wave minus critical acceleration.

Fig. 12 presents the distribution of permanent displacement under the impact of seismic fortification design in study area. Fig.12(a) is the result of permanent displacement without considering amplification effect and Fig.12(b) is the result considering amplification effect. It can be seen in Fig.12(a) that area with permanent displacement greater than 0 exists in study area without considering amplification effect, but this area is relatively small. Permanent displacement is concentrated in the area with large slope degree. And the maximum value of permanent displacement is 5.10cm. In previous research, permanent displacement of 5cm is often used as the threshold to distinguish landslide from non-landslide. It means that permanent displacement appears under the impact of seismic fortification design without considering amplification effect but there would be few landslides. In Fig.12(b), it can be noted that area with permanent displacement greater than 0 becomes larger after considering amplification effect. The maximum value of permanent displacement reaches 70cm. And area with permanent displacement greater than 5cm is mainly distributed around the top of slope. Considering amplification effect, landslide would occur in study area under the impact of seismic fortification design. However, the region of landslide is not large and distance between landslide and expressway is long according to the distribution of displacement in Fig.12(b), so there is little threat to engineering activities. Whether amplification effect is considered has a great influence on the evaluation results of regional seismic landslide susceptibility.



(a)without considering amplification effect



(b) considering amplification effect

Fig. 12 Distribution of permanent displacement in study area

5. Conclusions

An improved Newmark model was proposed considering the effect of site amplification. Microtremor observation is used as the test method of amplification effect. We used the spectrum amplitude ratio at predominant frequency as the amplification factor of slope. A two-stage integration process was imported to calculated the permanent displacement with input data including critical acceleration, amplification factor and seismic acceleration wave. A regional seismic landslide susceptibility assessment was conducted in an affected area of Chenghai fault zone. The main conclusions are as follows:

(1) The microtremor data of 13 observation points were collected. And the velocity spectra of 13 observation points were obtained by FFT. The predominant frequency of slope in study area is 2.0-3.0 Hz.

(2) The dynamic amplification characteristic of slope was evaluated. The spectrum amplitude at predominant frequency increases with slope degree and height. The relation between spectrum amplitude, slope degree and height can be obtained through multiple linear regression:

$$a_{hp}=0.00471\cdot d+0.00397\cdot h\text{-}0.26899$$

The distribution of spectrum amplitude in study area can be calculated basing on the above formula. The ratio of amplitude and amplitude at slope foot is used as amplification factor of slope. The maximum value of amplification factor is 3.595. This method is also appliable to analysis and calculation of a larger region.

(3) The seismic landslide susceptibility of study area was assessed basing on Newmark model considering amplification effect. Without amplification effect, the maximum value of permanent displacement in study area is 5.1cm. Area with permanent displacement greater than 5cm increases after considering amplification effect. It reveals that neglecting amplification effect is strong factor which leads to deviation of permanent displacement using traditional Newmark model.

6. Acknowledgements

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