Shear wave velocity analysis of a deep seated gravel landslide structure using the microtremor survey method

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Abstract. The depth and geometry of potential failure surface is the fundamental for evaluating the mechanisms of a landslide. Traditional techniques to acquire information on potential sliding surface are mainly drilling, pitting, and trenching, but these techniques are time consuming and expensive. In this study, microtremor signals and the dispersion curves of surface wave are extracted from the vertical component of microtremor records using the spatial autocorrelation (SPAC) method to estimate shear wave velocity structure. The results suggest that the buried depth of phyllite bedrock is approximately 47.4m, and the thickness of weathered bedrock layer is about 9.9m at about 57.3m deep, which could be interpreted as the potential sliding surface of this landslide, in accordance with borehole data. The microtremor survey method (MSM) is flexible, non-invasive, relatively quick and deployable on the landslide. It clearly demonstrat that it is an effective tool to improve the drilling success rate, and hence allow a large scale and high density investigation of structure characteristics of a deep seated landslide.
1. Introduction

The conventional ways to acquire underground structure information are mainly artificial excavation and mechanical drilling. Physical and mechanical parameters of rock and soil are measured by indoor mechanical tests with drilling cores to provide some reference for the stability analysis of landslides. These traditional techniques could obtain relatively accurate information for landslide studies. However, excavation or drilling on the unstable slopes are difficult and costly.

In the past two decades, the Microtremor Survey Method (MSM) was increasingly applied in the subsurface investigation as an effective probing tool, such as civil engineering, collapsed columns mapping, boulders and geothermal faults mapping[1,2]. The method assumes that microtremor is a stable random process, and we could estimate the shear wave velocity structure using the inversion of Rayleigh Wave dispersion curves extracted from microtremor signals [3]. MSM is featured by high resolution, no artificial sources, cheap and convenient data acquisition, without topographical restriction and particularly for density populated and vibration disturbance area.

Microtremor produced by natural phenomenon and mankind’s activity is common on the earth’s surface, and frequency is about 1Hz. It is composed mainly of body wave and surface wave (Rayleigh Wave, Love Wave, etc.), and Surface Wave accounts for about seventy percent of total signal power [4]. To provide available geological model for landslide hazards prevention and controls, this study attempted to detect the internal structure, especially potential sliding surface by combining MSM with drilling data.

2. Method

MSM has two fundamental hypotheses: firstly, it is a stationary random process in space and time, and secondly microtremor is composed of different frequency waves where the fundamental mode Rayleigh Wave energy is predominate [5]. There are two methods to exact phase velocity dispersion curves from the vertical components of microtremor: the Frequency-wavenumber (F-K) method and the Spatial Autocorrelation Method (SPAC). The former is constrained by station quantity, coverage area and recording requirement, etc. In turn, The latter can be always used to effectively estimate the shear wave velocity [3].

![Figure 1. The microtremor observation layout.](image)

- **(a) Observation array**
- **(b) Microtremor device**

The survey point $S_1$ in figure 1(a) is the center of observation array, and the other six points are observation points ($S_2$–$S_7$) equally spaced on the circumference of two circles with radius $r_1$ and $r_2$. 


respectively. The seven microtremor survey instruments were used to acquire digital signal simultaneously, and the synchronization was controlled by inner GPS clocks in collector. Each microtremor device is composed of DC power supply, GPS, digital recorder and seismometer sensor in figure 1(b).

The probing depth of microtremor array is 3 to 5 times than observation radius [3,6]. Overburden thickness of this landslide is about 50m according to preliminary engineering geological survey. So we selected inner radius \( r_1 \) of 5m and outer radius \( r_2 \) of 10m to meet the depth requirement in this investigation.

3. A case study

3.1. Study site

The survey site was on the Xishan village landslide seated in Tonghua Town, Li County, Aba Zang & Qiang Autonomic State, Sichuan province, China. According to engineering geolocial data in figure 2, the stratum structure of landslide from top to bottom was Quaternary diluvium, gravel soil, strong weathered phyllite, weathered phyllite and phyllite bedrock, respectively. The black arrow indicates the direction of this landslide, and the black bold dashed line reports the potential sliding surface speculated from boreholes in figure 2.

![Figure 2. Engineering geological cross-section of Xishan village landslide.](image)

(1) Diluvium layer. (2)Gravel soil layer. (3)Flood alluvial boulder. (4)Weathered phyllite. (5)Phyllite bedrock. (6)Borehole. (7)Crack. (8)Boundary of underlie bedrock.

To verify the surveying effect of MSM for a deep seated gravel landslide, this study selected borehole Zk1 as the research object. On the basis of the previous investigation, we conducted the microtremor array observation on the position of Zk1 using the layout and devices in figure 1. The test
is available if the probing results estimated from MSM investigation is in accordance with the borehole data on the same position Zk1.

3.2. Data acquisition
The position relative to the survey point S₁ was measured on the site based on the above selected observation radius. To collect high quality records, we needed to weed out the soil to install broadband digital seismometer sensors CMG-3ESPC and data acquisition device REFTEK72-08A from Chinese Seismic Probe Array Center (CSPAC). Then, the sensors were tested and a sample frequency of 100Hz was selected.

![Figure 3. Examples of microtremor records. Each trace report the vertical component of micro vibration on each sensor’s position.](image)

The instrumental stabilization time was not lower than 3 hours during data acquisition and available signals were collected at least 2 hours after instrument stabilization. We tried to avoid walking near the stations as far as possible when sensors were recording. A low pass filter with a high cut-off frequency of 10Hz was adopted. The preprocessing of microtremor mainly includes instrument response correction, tilt component removing, remean, resample and band-pass filter, etc.

3.3. Spatial Autocorrelation Coefficient
The spatial autocorrelation coefficients can be calculated using narrowband filter to separate harmonics in time domain[7]. But this method is time-consuming and poorly accurate. Okada (1994)[8] improved the computed speed and accuracy using Fourier transforms (FT) to extract spatial autocorrelation coefficients in frequency domain. The following equation is given by Asten et al. (2006) [9] to calculate spatial autocorrelation coefficients.

$$\rho(\omega, r) = \frac{1}{2\pi} \int_0^{2\pi} \text{Re} \left\{ \frac{S_A(r, \omega)S_A^*(\omega)}{\sqrt{S_A(r, \omega)S_A(r, \omega)S_A(\omega)S_A(\omega)}} \right\} d\theta$$

(1)

Where $S_A(\omega)$ and $S_A(r, \omega)$ are Fourier transform of center point O and point A on the circle, $S_A^*(\omega)$ and $S_A^*(r, \omega)$ are corresponding complex conjugate, respectively.
The distance between any two stations was different due to the both observation radius. Five type combinations are listed as follows: \( r_1, \sqrt{3} r_1, 2r_1, 3r_1 \) and \( 2\sqrt{3} r_1 \) shown in figure 4. The spatial autocorrelation coefficients of these combination patterns were calculated one by one with equation (1). More reliable results could be obtained by the azimuthal average of these coefficients.

3.4. Phase velocity of Rayleigh Wave

Based on the above calculation, we fitted spatial autocorrelation coefficients with the Bessel function of first kind and order zero to obtain phase velocity of Rayleigh Wave for different frequency when \( f \) was fixed and \( r \) was random. The circles in figure 5(a) represent the spatial autocorrelation coefficients corresponding to the distance of 5m, 8.66m, 10m, 15m, 17.32m.

Phase velocity in the range of 10Hz was calculated with the fitting using Bessel function of first kind and order zero as circles shown in figure 5(b). Phase velocity of Rayleigh Wave \( v_r \) decreased with increasing frequency corresponding to the shallower probing depth.

3.5. Shear wave velocity structure
Shear wave velocity estimated by MSM on the position of Zk1. $v_r$ is phase velocity of surface wave, $v_x$ is apparent shear wave velocity, and $v_s$ is shear wave velocity.

Shear wave velocity structure was obtained with the inversion of phase velocity of Rayleigh Wave, and the most popular method is Forking Genetic Algorithm (FGA). This method could search optimum solution of shear wave velocity mainly due to its advantage of fast calculation and strong global searching ability[10]. But it mainly depends on the initial model, and requires the layer number, each layer thickness and the velocity of the initial model.

For landslide investigation, variation of shear wave velocity along depth is interpreted as the basis of stratum structure, so it was not necessary to calculate the absolute value of shear wave velocity, but the apparent shear wave velocity is appropriate [11].

$$v_{x,i} = \left( \frac{t_i v_{r,i}^4 - t_{i-1} v_{r,i-1}^4}{t_i - t_{i-1}} \right)^{1/4}$$

Where $v_r$ is phase velocity of Rayleigh Wave, $t_i$ is cycle, $v_r$-H is converted into $v_x$-H using above equation. Finally, we transversely interpolated and fitted $v_x$ to acquire the shear wave velocity structure on the position of borehole Zk1.

4. Discussion and Conclusion
Shear wave velocity structure was evaluated with phase velocity dispersion curves exacted from the vertical component of microtremor. In figure 6(a), $v_s$, $v_r$ and $v_x$ represent the shear wave velocity,
phase velocity and apparent shear wave velocity, respectively. MSM has poor resolution for shallow landslide structure (10~20m), but it is more effective for the deeper buried interfaces.

Overburden thickness on the bedrock of Xishan village landslide was about 52m according to borehole data in figure 6(b). Here two obvious interfaces were shown at 47.4m and 57.3m depth on the Vs curve in figure 6(a), and they could be interpreted overburden thickness(180~410m/s) and bedrock interface(>515m/s), respectively. Shear wave velocity of weathered bedrock is about 457.6m/s in the range of 47.4 to 57.5m at depth. However, our survey results could not obtain more information about weathering degree of underlying bedrock due to low coverage density investigation.

Compared with borehole Zk1 in figure 2, the shallow stratum of landslide from top to bottom is Quaternary diluvium(3.6m), gravel soil(3.6~52m), strong weathered phyllite(52~59m), weathered phyllite(59~60.5m)and phyllite bedrock(>60.5m). Potential sliding surface is considered as strong weathered phyllite layer about 52m at depth. If we averaged the thickness in the range of 47.4~57.5m, potential sliding surface estimated from MSM is 52.35m at depth. This indicates that this method has high resolution for detecting deep seated landslide structure, especially for accumulative landslide on the bedrock.

Based on the above analysis and discussion, the results of this study are: (1) MSM is available for deep seated underlie bedrock landslide with high resolution without topographical restriction. (2) MSM is more effective than drilling in terms of probing depth, survey scale and cost. Hence, MSM seems to be more suitable for large scale and high density survey on a gravel landslide.

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