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Site characterization with surface waves in Kazakhstan

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ABSTRACT

The South and Southeast Kazakhstan regions exhibit notable seismicity due to intricate tectonic interactions, albeit experiencing infrequent catastrophic earthquakes. Proximate to the convergence of the Eurasian and Indian plates, this region witnesses frequent seismic activity, particularly in cities like Almaty near mountainous terrain. Given the significant seismic activity, comprehensive site characterization is imperative. Traditionally, evaluating dynamic soil properties relies on conventional borehole logging techniques. However, the emergence of the multi-channel analysis of surface waves (MASW) offers advantages in cost, time efficiency, and non-invasiveness. Despite its benefits, MASW remains underutilized in Kazakhstan and is absent from local building codes, unlike neighboring CIS countries. This study aims to demonstrate the applicability of the MASW method for site characterization in Kazakhstan's seismic regions. Through extensive work, shear wave velocity (Vs) values were estimated and compared with reference data obtained from seismic refraction and dilatometer testing. The results showed significant agreement, highlighting the suitability and effectiveness of the MASW method in Kazakhstan.

Keywords: multi-channel analysis of surface waves (MASW), shear-wave velocity, surface waves, non-invasive seismic methods

1. Introduction

Borehole logging is a prevalent method for evaluating subsurface strata characteristics and composition (Hobiger et al. 2013; Moon et al. 2016). However, traditional borehole logging encounters limitations, particularly in Kazakhstan, where its conventional approach may incur significant temporal and financial costs, especially when shallow bedrock is not encountered. Additionally, the invasive nature of boreholes poses ecological risks and provides limited insights (Hobiger et al. 2013; Moon et al. 2019). Moreover, the reliability of borehole data diminishes for sites characterized by lateral variations in soil composition as the distance between the site of interest and the borehole log location increases.

The borehole logging process involves various stages, from site drilling to retrieving soil samples, which undergo extensive laboratory analysis to delineate their properties. However, caution is necessary when analyzing soil samples obtained through this method, particularly in assessing low-strain dynamic soil properties below 10^{-6}, given the intrusive nature of the sampling process, which can disturb the samples. The correlation between small-strain stiffness of soil and dynamic soil parameters, notably shear wave velocity (V_S), is crucial for assessing the impact of dynamic loading events such as earthquakes, site amplifications, and liquefaction (Moon et al. 2017). Consequently, the strain range below 10^{-6} assumes particular significance.

In-situ geophysical seismic surveys, encompassing techniques such as seismic reflection, refraction, and down- and cross-hole testing, offer alternative means to assess dynamic soil properties in the construction sector. However, these methods have been underutilized in Kazakhstan. Furthermore, utilizing one or more boreholes per test for down-hole and cross-hole surveys requires prior borehole logging, increasing the overall cost of site investigative efforts. Non-invasive geophysical techniques serve as excellent replacements for borehole logging, overcoming the limitations of traditional methods. These non-invasive technologies include various surface wave and seismic techniques, including seismic refraction, reflection, or multi-channel analysis of surface waves (MASW). Despite their potential advantages, these alternative methodologies are not widely adopted in Kazakhstan's construction industry, except for a limited number of projects (Silacheva et al. 2020).

Surface wave methods have gained prominence in geotechnical engineering as a viable avenue of development. These techniques primarily aim to calculate V_S at specific sites and enable the characterization of geotechnical properties through surface wave dispersive behavior analysis (Moon et al. 2016; Moon et al. 2017; Abdialim et al. 2021; Abdialim et al. 2023). This study aims to assess the application of the MASW method to site characterization in seismically active regions of Kazakhstan by comparing with the results obtained by geophysical measurements like seismic refraction or seismic dilatometer test (SDMT).

2. Multi-channel Analysis of Surface Waves

Among various geophysical measurement techniques today, one noteworthy method is the MASW. Since its introduction by Park et al. (1999), MASW has gained popularity for evaluating the geotechnical properties of shallow-depth sites, offering valuable insights into subsurface conditions. It presents several advantages over standard borehole logging techniques (Socco et al. 2010; Xia 2014; Garofalo et al. 2016).

MASW presents various applications and has proven to be a valuable tool; however, it also comes with several limitations and constraints. The method's effectiveness is confined by its survey depth, associated with the maximum recorded wavelength and array size. Nonetheless, this limitation is often mitigated by employing both active and passive MASW techniques simultaneously. Another potential limitation lies in the method's evaluation of averaged recordings from two or more sources, assuming a homogeneous horizontal layered soil model across the survey area. Furthermore, field conditions may hinder the generation of high-resolution VS profiles (Park et al. 2007). Despite these limitations, MASW can still offer benefits, particularly in Kazakhstani cities where portability and mobility are paramount. Given that the uppermost layer of soil in these areas predominantly consists of loam soils (Zhussupbekov et al. 2023), utilizing geophysical methods presents a rational and cost-effective means of understanding the dynamic characteristics of the near-surface layer.

The MASW technique can be categorized into active (Fig. 1a) and passive (Fig. 1c) methods based on differences in acquisition parameters such as seismic energy type, geophone array type, and recorded frequency range. Each method specializes in a particular frequency range (Fig. 1e) and corresponding maximum and minimum depth (Park et al. 2007).

Due to the dispersion of high-frequency surface wave energy with depth, active source surface waves exhibit greater sensitivity to shallow, near-surface depths but less to deeper layers. Conversely, surface waves generated by ambient noise predominantly contain low-frequency components, rendering the results more relevant at greater depths but lacking sufficient data for shallow layers. Depending on the depth of interest, these techniques can be employed separately or combined to develop a practical approach for comprehensive study. In areas like the Almaty basin with significant bedrock depths (Poggi et al. 2023), a combined approach maximizes the depth of interest, enhancing the relevance of results across all depths (Moon et al. 2017). This strategy offers an efficient and popular means of characterizing geotechnical sites while providing valuable insights into subsurface features.

2.1. Data Acquisition

During the data acquisition procedure for active MASW, a sledgehammer strike positioned at a specific offset induces the generation of surface waves. The traversal of these waves is recorded using a linear array comprising 12 to 24 geophones. The spacing between geophones remains constant and is correlated with the minimum thickness for the first soil layer (Ólafsdóttir 2016). As a result of the strike, surface waves of varying frequencies are produced, with lower-frequency components penetrating to greater depths. The spatial distribution of the strike is captured by the geophones (Fig 1b) and will be utilized to estimate the phase velocity dispersion curve.

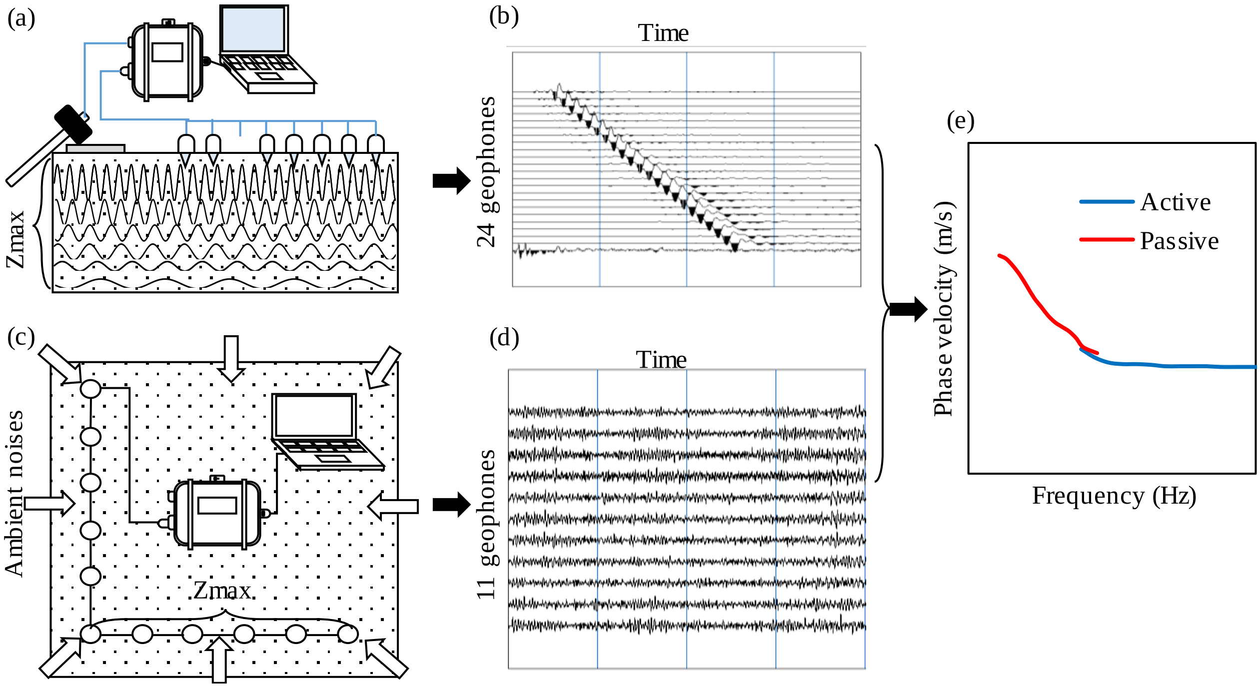

Figure 1. Schematic of Active and Passive MASW data acquisition (a,c), recorded data (b,d) respectivelty; and (e) combined phase velocity dispersion curve

In contrast to the active MASW, passive MASW does not capture signals generated from known sources but relies on environmental noises generated by nature, traffic, and human activities. Triangular, circular, and L-shaped arrays are among the configurations used for passive MASW. Previous studies have shown that the right angle L-shaped array yields highly accurate dispersion curves for the passive method (Fig. 1c) (Ku et al. 2020; Hayashi et al. 2022). This configuration is known for its flexibility, allowing it to be deployed in hard-to-reach sites. The maximum depth (Z_{max}) is determined by the array length, which can reach up to 50m for the L11 configuration with a 10m spacing.

2.2. Active MASW Data Processing

The seismic data collected from active MASW can undergo the phase shift method to determine the phase velocity dispersion curve. This method relies on energy-normalized correlation as its fundamental principle. It assumes that multiple geophones record surface waves generated from a point source with specific time delays. Consequently, phase velocities of surface waves can be ascertained through frequency domain analysis of time delay estimation for a particular frequency and phase velocity pair. In the phase-shift approach, all recordings (r(x,t)) are initially transformed into the frequency domain using the Fast Fourier Transform (FFT) in Eq. (1), retaining only the phase term $P(x_j,\omega)$ after normalization to eliminate the amplitude $A(x_j,\omega)$ without preserving essential information using Eq. (2) (Dikmen et al. 2010).

$$R(x_j,\omega) = FFT(r(x_j,t)) \tag{1}$$

$$\tilde{R}_j(\omega) = \frac{R(x_j,\omega)}{\left|R(x_j,\omega)\right|} = e^{-i\mathrm{P}_j(\omega)} \tag{2}$$

The energy density (D) for each phase velocity – frequency is subsequently estimated by aggregating the normalized magnitude contribution of each geophone trace, while considering time delays, as shown in Eq. (3).

$$D = \sum_{j=1}^{J} e^{-i\mathrm{P}_j(\omega)}\, \check{R}_j(\omega) \tag{3}$$

The resulting active MASW fundamental mode phase velocity curve is then combined with passive MASW dispersion curve (Fig. 1e).

2.3. Passive MASW Data Processing

The SPAC approach was used to process the raw passive MASW data and assess the phase velocity at the central geophone of the L11 array. The real complex coherence function for 2D arrays with passive raw data fundamental mode corresponds to the Bessel function (Moon et al. 2017; Hayashi et al. 2022). Thus, by evaluating complex coherences between geophones for the fundamental mode, the optimum phase velocity for each frequency can be determined using Eq. (4):

$$\frac{1}{2\pi}\int_{\varphi=0}^{\varphi=2\pi} \mathrm{C_R}(dr,\varphi,\omega)\, d\varphi = J_0\left(\frac{\omega}{V_R(\omega)}, R\right) \tag{4}$$

Where φ represents the angle between receivers, J_0 is the zero-order Bessel function, and C_R is the complex coherence function component.

Each phase velocity-frequency result satisfying Eq.4 was subsequently selected, enabling the generation of a passive MASW dispersion curve, which was then integrated with the active MASW dispersion curve for combined inversion.

2.4. Combined Inversion

In the inversion analysis, a non-linear least square method (LSM) minimizes the disparity between the observed and calculated phase velocity, relying on an assumed model comprising a half-space and multiple soil layers (Xia et al. 1999). This method necessitates iterative performance using a forward problem-solving technique due to the intrinsic characteristics of the wave propagation theory it employs.

In the inversion process, the combined dispersion curve of the fundamental mode is initially adjusted using a one-third conversion concerning depth and Rayleigh wave velocity, serving as an initial approximation for shear wave velocity. Developing a theoretical model that effectively reduces deviations from the observed dispersion curve is imperative for the iterative execution of the inversion procedure.

3. Site investigation works

Site investigation works were conducted in Almaty, Kazakhstan, an area classified as a seismic active region (Fig. 2). Both active and passive MASW were conducted at two sites for further comparison with available data obtained through either seismic dilatometer equipment or seismic refraction technique.

The parameters of the site investigation are summarized in Table 1 below. It was observed that the same configuration proved to be effective for both sites, enabling the generation of V_s profile up to a depth of 50m.

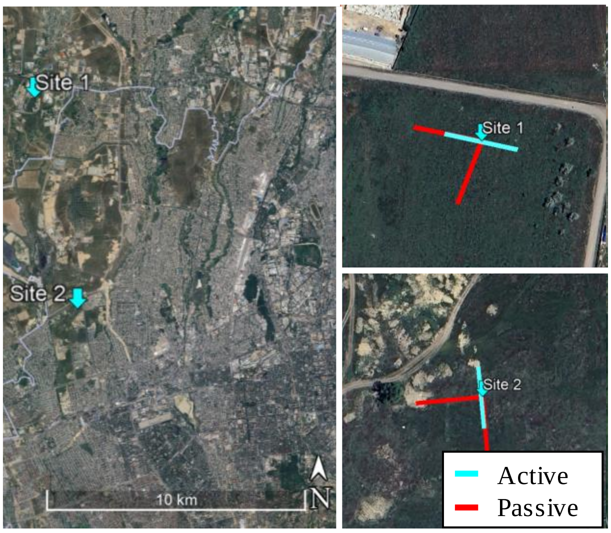

Figure 2. Site investigation locations with indication of active and passive arrays

Table 1. Data acquisition key parameters

	Active MASW	Passive MASW
Receivers	24	11
Spacing	2 m	10m
Array type	Linear	L-shape
Source	Sledgehammer	Ambient noises
Offset	7 m	-
Record length	1.0 s	32 s
Sample interval	0.5 ms	2 ms
Stacking	10	1
Recordings	2	20

4. Results and discussion

Based on the available borehole data, the top layer at site 1 was identified as collapsible soil with low stiffness, while site 2 was classified as non-plastic loam. Both sites exhibited a layer of fine sand beneath the loams, followed by plastic loams.

Active and passive dispersion curves for both sites were obtained using SeisImager software, employing the aforementioned techniques. The resulting combined dispersion curves are depicted in Fig. 3. A comparison of two dispersion curves reveals that at high frequencies (shallow depth), both sites exhibit the same phase velocity (190-200 m/s), indicating similar V_s values for both collapsible soil and non-plastic loams. Moreover, site 2 exhibited a higher phase velocity at lower frequencies, suggesting a potentially stiffer stratigraphic layer.

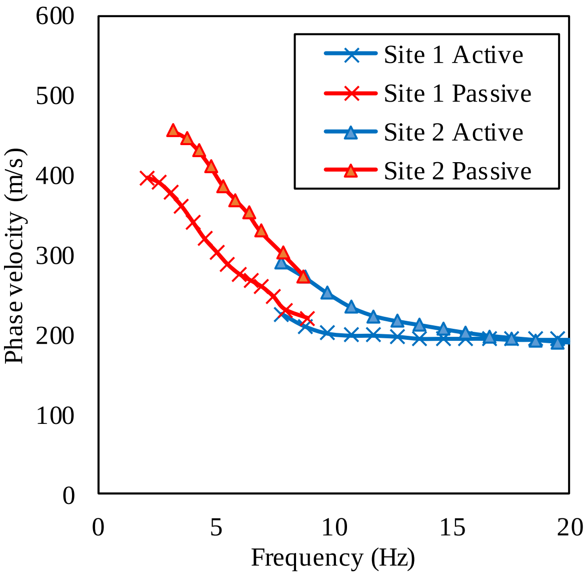

Figure 3. Combined dispersion curves for both sites

This observation aligns well with the available reference information illustrated in Fig. 4: the SDMT indicated an increase in V_s after 20m, corresponding to the presence of gravel sand.

Regarding the upper layer, MASW results revealed higher V_s values for the first 5m, corresponding to the collapsible soil layer (204 m/s for MASW and 150 m/s for refraction), but exhibited excellent agreement for site 2. Several factors may contribute to the differences observed for site 1. One potential explanation could be the spatial disparity. Unlike the borehole data, the reference geophysical information does not align with the central geophone, suggesting homogeneity in the site location and leading to discrepancies. Another potential factor could be receiver spacing, influencing the minimum depth information: due to the presence of a weak soil layer, it is very crucial to monitor shallow depths; thus, lower receiver spacing might yield lower V_s values for site 1.

Nonetheless, MASW consistently correlated highly with available data across all other instances. The V_s profile aligns well with the site's stratigraphy, indicating an increase in V_s transition zones from weaker to stiffer soil layers. This is particularly evident for site 1 at a depth of 10m, where both refraction and MASW profiles increase during the transition from fine sand to plastic loam. A similar trend is observed for site 2 at a depth of 10m, where a change in layer stiffness elevates the V_s profile.

The average V_s of the top 30 meters of soil, or known as $V_{S,30}$, serves as a commonly used criterion for classifying seismic sites and has been incorporated into various engineering design standards, including Eurocode8 and the National Earthquake Hazards Reduction Program (NEHRP) (Moon et al. 2016). $V_{S,30}$ can be computed using the Eq. (5):

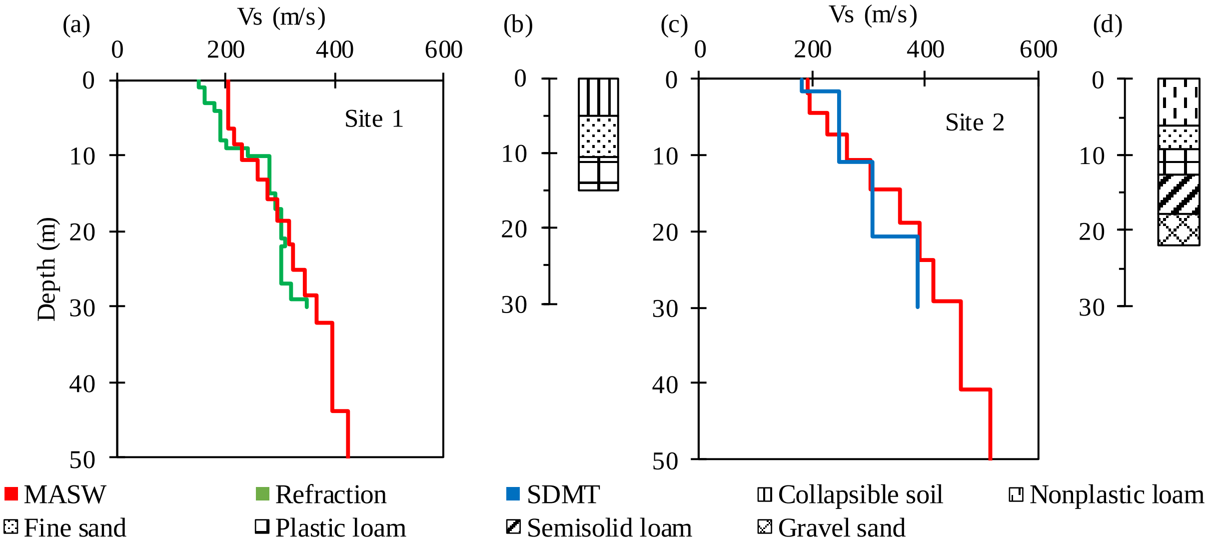

Figure 4. (a) Vs profile for site 1, (b) borehole information for site 1, (c) Vs profile for site 2, (d) borehole information for site 2

$$V_{S,30} = \frac{30}{\sum h_i / V_{S,i}} \quad (5)$$

Where h_i represents the thickness of the i^{th} layer, and $V_{S,i}$ denotes the shear wave velocity of i^{th} layer.

The $V_{S,30}$ values for the sites were determined to be 264.5 m/s and 298 m/s according to MASW results and 250 m/s and 293 m/s according to reference V_s profiles.

5. Conclusion

In Almaty, Kazakhstan, a site investigation employing the MASW technique was conducted to compare its efficiency with available geophysical and geological data. Active and passive MASW techniques were utilized to generate a V_s profile for the top 50 meters of the site and combined inversion was performed using SeisImager software.

Differences, particularly in the top layer of site 1, were noted despite generally strong correlations between MASW results and available data. Nonetheless, MASW consistently mirrored the site's stratigraphy, revealing notable increases in V_s profiles within transition zones from weaker to stiffer soil layers. This phenomenon was observed at a depth of 10 meters for both locations, where higher V_s profiles were attributed to the transition from fine sand to plastic loam.

These findings hold implications for seismic site classification, where the average V_s of the upper 30 meters of soil ($V_{S,30}$) holds critical importance. The integrated approach incorporating borehole data, dispersion curves, and MASW results offers a comprehensive understanding of subsurface conditions at sites 1 and 2. This lays the foundation for further exploration in risk assessment and seismic design within the region.

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