

# Lateral Non-Homogeneities Characterization Using Seismic Surface Wave

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## Abstract

Seismic surface waves are well-suited for the study of the elastic profile of soils. Therefore this technique was adopted to evaluate the properties of stone columns used for ground improvement. A scaled-down model of typical stone columns in soft clay was constructed. Measurements were made on stone columns, under controlled conditions so that the properties of the materials used in the model under test were within limited ranges. The dispersive curve produced in this study demonstrated an increased phase velocity with increasing wavelength for the measurements on the clay (between columns), and decreased phase velocity with increasing wavelength for the measurements on the column. The results showed that were useful in characterization of the lateral non-homogeneities works such as vibro-stone column. These results pointed to the results can be influenced by the positioning of sensors with respect to the survey target. Benefit of this technique can be applied as a tool in quality control.

Keywords: Stone column, seismic surface wave testing, quality control.

## 1. Introduction

One of the main parameters to make predictions of ground movement is the ground stiffness profile (Matthews *et al.* 1996). Stiffness can be defined as the resistance of the body to deformation under applied force (Clayton, 2011). Traditionally, the measurement of the stiffness profile is carried out by using laboratory and in-situ, invasive, field tests. Geophysical methods, such as seismic surface wave techniques, offer a non-intrusive and non-destructive approach to measure the very small strain stiffness profiles. Moreover, seismic surface wave approaches provide a cost-effective way to assess site conditions. Uncertainty in the design stage of a stone column is associated with the design assumption used in estimating the amount of settlement.

The parameters that determine the quality of the ground treatment can be measured using laboratory tests. However, the process of sample retrieval required for laboratory testing often introduces additional difficulties associated with sample disturbance and the reliability of the sample in representing the entire site. As a result, sample retrieval from site for laboratory testing may not be sufficient to replace field-testing. Penetration testing, dynamic probing, field vane

shear tests and plate loading tests are examples of conventional field-test techniques used for quality control testing. In-situ zone tests using large-scale loading are one of the best indicators to characterize the foundations on improved ground but may only demonstrate the stiffness of the upper layers of the ground (Charles and Watts 2002). A comparison between geophysical seismic-based techniques and conventional geotechnical load-testing methods for the measurement of the ground stiffness profile was presented by Matthews *et al.* (1995), drawing the conclusion that geophysical testing can deliver results of significant quality, whilst avoiding any of the disadvantages associated with either laboratory or physical field tests.

The aim of this paper was to evaluate the seismic surface wave test in characterizing the lateral non-homogeneities via testing on model of stone columns. Measurements were made on scaled-down from typical stone column and under controlled conditions so that the properties of the materials used in the model under test were within limited ranges.

## **2. Previous Work**

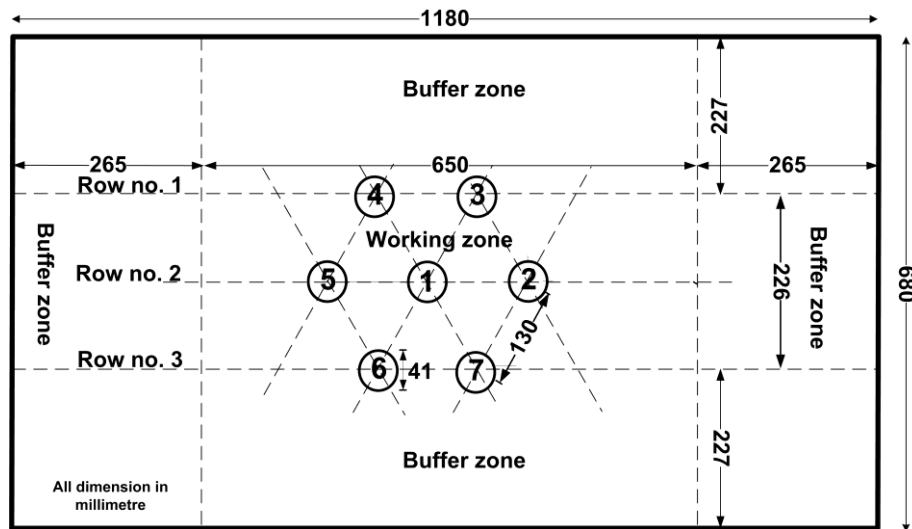
As reviewed by Nasseri-Moghaddam (2006), lateral heterogeneities are not usually the main consideration in applying the theories associated with surface wave analysis. The majority of surface wave applications for civil engineering have been used to characterize materials that are assumed to consist of laterally homogenous layers (Forbriger 2003). These are based upon spectral analysis of surface waves (SASW), continuous surface wave analysis (CSW) and, more recently, on multi-channel analysis of surface waves (MASW). Jefferson *et al.* (2008) applied SASW to qualitatively assess changes to ground properties laterally after vibro-replacement stone columns (VSC) treatment had taken place. Moxhay *et al.* (2001) and Redgers *et al.* (2008) applied the CSW technique to measure the stiffness-depth profile of dynamically stiffened ground and VSC. Their results produced a profile of average of shear wave velocity versus depth between the stiffening columns and the surrounding soil. The analysis used in such approaches assumes that the soil behaves as a layered half-space that is laterally homogeneous and isotropic. Thus, the results represent the mean velocity of the whole horizontal layer corresponding to the respective wavelength.

## **3. Experimental Setup**

The construction of the laboratory-scale stone column model was based upon a typical stone column design. The advantage of using a laboratory model is that the materials are known and controlled. The model consisted of a soft clay bed with pre-compacted gravelly sand columns. The inner dimensions of the container (a box) were 1180 mm, 680 mm, 500 mm in length, width and depth respectively. The properties of clay and gravelly sand used for construction of the physical model are shown in Table 1 and were determined in accordance with BS1377: 1990. The clay mixtures had an average moisture content of 40 %, with approximately 16 kPa undrained shear strength, thus simulating a very soft ground condition. The clay was compacted with a vibratory plate to achieve a density of at least 95 % maximum dry density compaction. The columns were installed in an arrangement of an equilateral triangular grid with a uniform separation of 130 mm (Figure 1), representing a scaled-down 2 m columns spacing on a typical site. These dimensions provided a scaling factor of approximately 10 in comparison with actual stone columns.

**Table 1:** Summary of the properties of clay and gravelly sand.

Type of soil	Clay	Gravelly sand
Plasticity test; Plastic limit Liquid limit Plasticity index	26.3 % 47.4 % 21.1%	Non plastic
Compaction test; Optimum water content, OWC Maximum dry density, MDD Bulk density	23.5 % 1550 kg/m <sup>3</sup> 1920 kg/m <sup>3</sup>	9.5 % 1865 kg/m <sup>3</sup> 2045 kg/m <sup>3</sup>
Particle size (coarse fraction); Gravel 3.18 - 2.00 mm Coarse sand 2.00 - 1.18 mm Medium sand 1.18 - 0.6 mm Fine sand < 0.6 mm	No coarse fraction	34 % 54 % 7 % 5 %
Specific gravity	2.60	2.70



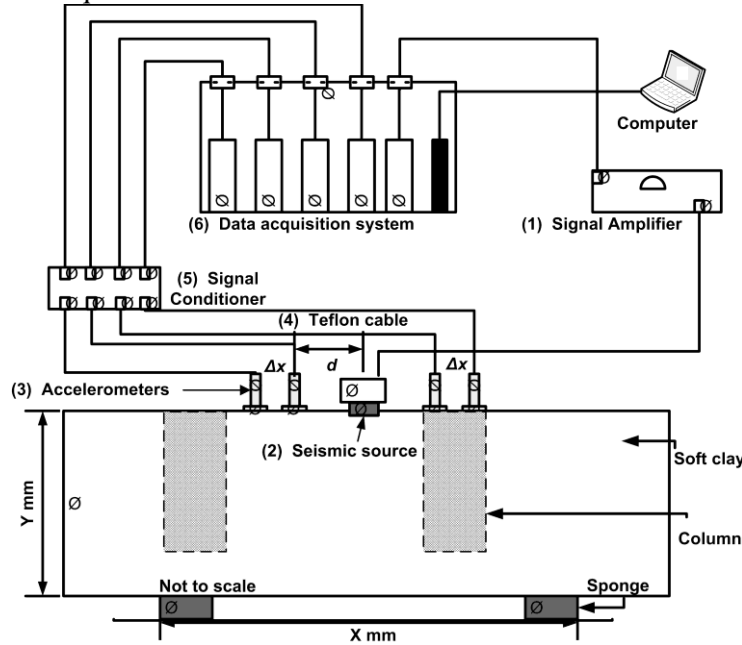
**Figure 1:** Final layout of stone columns (marks as 1 to 7)

The gravelly sand was mixed at the optimum water content of approximately 10 %. The gravelly sand was compacted at least 98 % of the maximum dry density of 1865 kg/ m<sup>3</sup> (based on compaction test). The compacted gravelly sand in the PVC pipe mould was kept in a freezer for 24 hours at -4 °C. This freezing technique was also used by Sivakumar *et al.* (2004) to obtain reliable column densities. The freezing technique was chosen as it maintained the column diameter and column length throughout the installation the columns in the test box, whilst keeping densities effectively the same for each test

#### 4. Stone column evaluation

An illustration of the laboratory setup is shown in Figure 2. A script was written within Matlab to control a National Instruments data acquisition system, in which a 16-bit analogue output module generated the transmission waveforms. An audio power amplifier was used to

drive the electromechanical vibrator with the excitation signals. On the receiver side, sensors consisted of four piezoelectric accelerometers with a frequency range of 1 Hz to 10 kHz that were coupled to the soil surface with nails. The accelerometers were connected to an analogue signal conditioner and were then sampled by a 24-bit sigma-delta analogue-to-digital converter module with a sampling rate of 50 kHz. The data collected were stored, and processed after the completion of a data acquisition session.



**Figure 2:** Illustration of the seismic source located between the sensor-pair on column and clay.

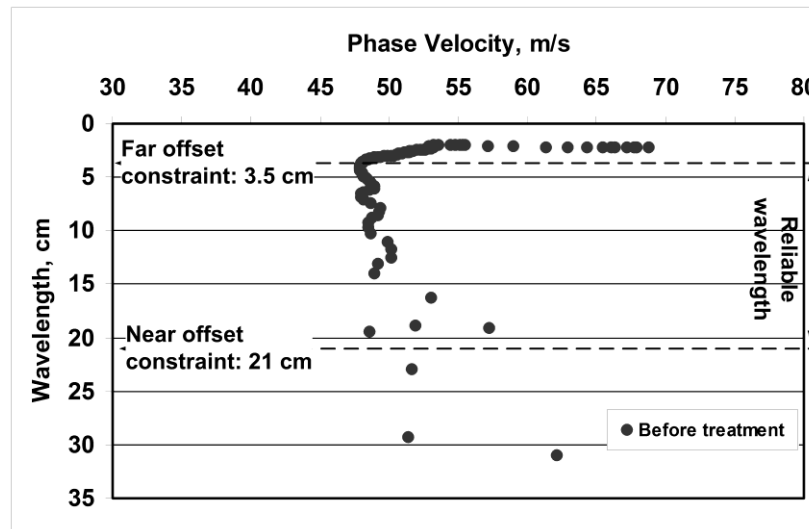
## 5. Experimental Procedure

The array of receivers consisted of up to four piezoelectric accelerometers. The seismic source was located at the middle of sensor-pairs. The distance between the source and the first receiver,  $d$ , was set at 7 cm and receiver spacing,  $\Delta x$ , was 3 cm. The stepped-frequencies applied ranged from 50 Hz to 3000 Hz. The larger range of frequency offered the advantage of being able to select the useful wavelengths that fulfil the frequency/wavelength constraint. The excitation waveform consisted of a 1 second continuous wave pulse shaded with a Tukey-window to reduce spectral side-lobes and increase the dynamic range of the narrow band of interest. Using a stepped-frequency approach, the frequency range of the sinusoidal wave was varied from 50 Hz up to 3000 Hz with a step-size of 10 Hz. For each frequency step, five repetitive measurements were obtained for averaging.

Measurements were first made on the soft clay container before the installation of columns to obtain a control dataset. The equipment was then set up on the soft clay that contained the gravelly sand columns. A series of measurements were made: sensor-pair on column and sensor-pair between columns. This is only possible in situations where the locations of the columns are known. As this is true in most ground improvement works, the knowledge of the columns' locations would be used for planning the survey to reduce ambiguities associated with measurement at the clay-column boundaries.

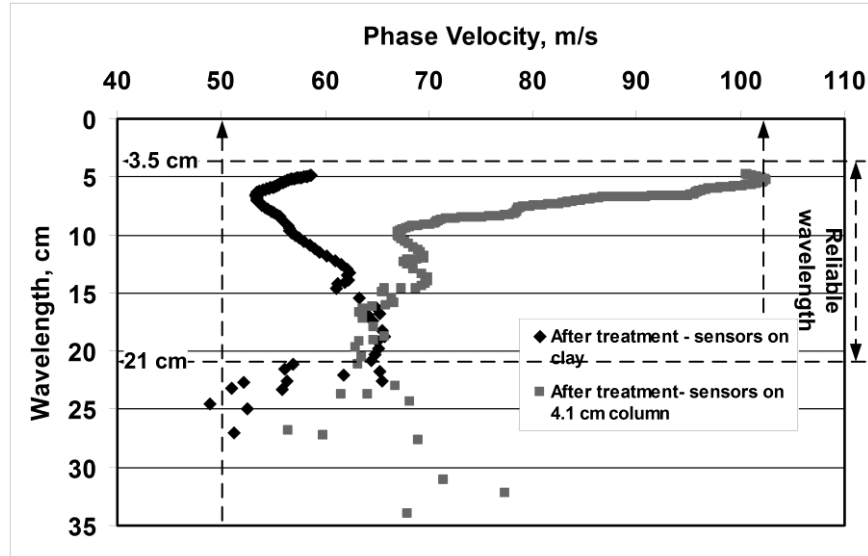
## 6. Seismic surface wave test results

Figure 3 shows the measured results of phase velocity dispersion curves before column installation as a control data set, where phase velocity dispersion refers to the variation of phase velocity with the wavelength of the excitation signal. The phase velocity for each wavelength should be similar due to the soil being relatively homogeneous. The measured phase velocities were relatively consistent between wavelengths of 3.5 cm and 21 cm and were only slightly dispersed for the wavelengths outside of this range. This phenomenon occurred due to the near- and far-offset constraints. It is worth noting that the distance from source to the first receiver ( $d$ ) was set as 7 cm. Based upon the constraints, the reliable phase velocities were for wavelengths between 3.5 cm and 21 cm. The consistent phase velocities versus wavelength measured on the clay bed indicated a relatively homogeneous material, with an average phase velocity of 50 m/s. From the literature, the phase velocity for a shear strength of 14 kPa measured using the CSW test in the field was reported to be 54 m/s (Omar et al., 2010). The measured phase velocity in the laboratory demonstrates good agreement with result in the literature.



**Figure 3:** The dispersion curves before column installation as a controlled data set.

Figure 4 shows the dispersion curves measured using sensors located on the clay region between columns and with sensors located on the 4.1 cm column. The phase velocities for sensors on clay increased with larger wavelengths. Meanwhile, the phase velocities measured on the column decreased with increasing wavelengths. Phase velocities measured with the sensors mounted on clay were slightly higher than those measured from the control test-bed (before column installation). As for measurement on the column, the highest phase velocity was 102 m/s and decreased to 63 m/s at a 21 cm wavelength. Both dispersive curves demonstrate the influence of the lateral inhomogeneities introduced by the column within the soft clay.



**Figure 4:** The dispersion curves for sensors on clay and sensors on top of the 4.1 cm column.

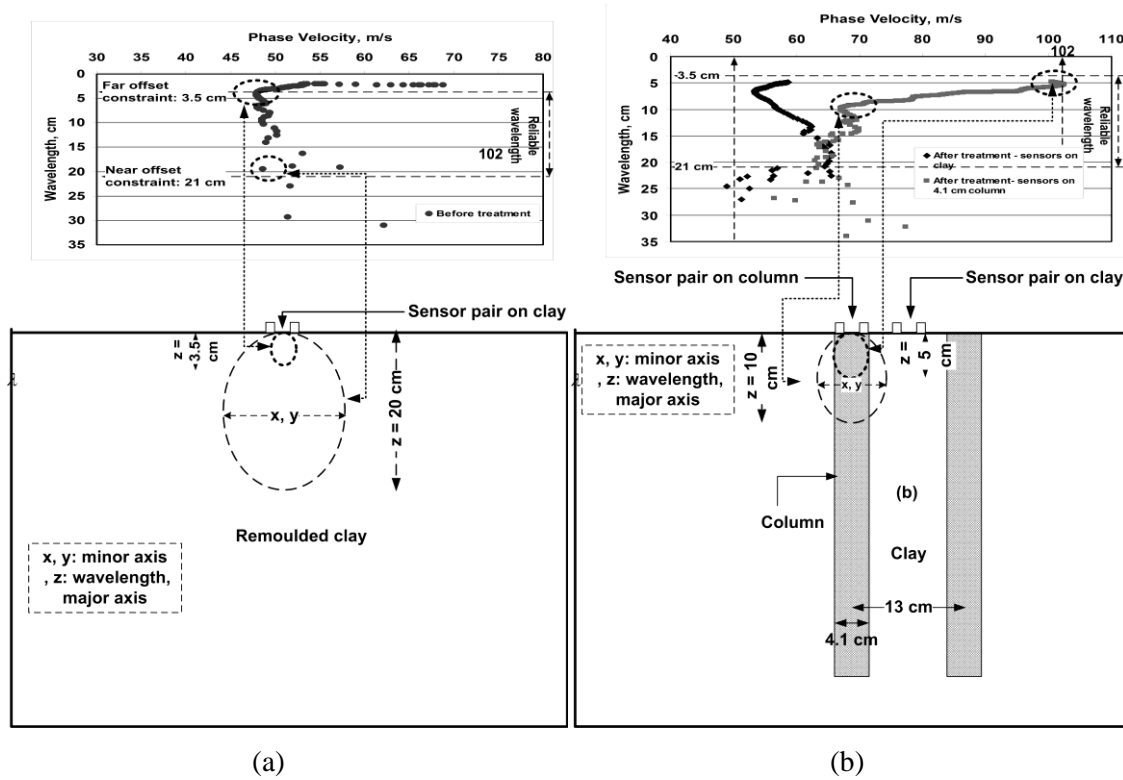
## 7. Discussion

The results demonstrated that there was an apparent relationship between wavelength and the lateral, or horizontal, span of the effective measurement region. The shape and size of the effective region of measurement in the medium in the lateral and vertical dimensions could be used to identify the sampling volume of the wavelength. To date, this observation has received little attention in the literature on the analysis of surface waves. The measured phase velocities were influenced by the volume traversed by the propagating Rayleigh wave with an elliptical particle movement, which in turn is a function of its wavelength. As a result, the measured phase velocities are directly influenced by the energy propagated by the elliptical particle motion. This is important as it suggests that the wavelength not only relates to an effective depth, but may also have a lateral span and, therefore, is associated with an effective volume.

As discussed by Abbiss (1981), Rayleigh wave energy extends to approximately one wavelength in depth, as 95% of the energy density is propagated within the one wavelength, with the rest within one-to-two wavelengths. Therefore, the amplitude of the measurable energy decreases exponentially beyond one wavelength.

A simplified shape and size of the effective region of measurement of elliptical particle motion is used to approximate the effective volume of measurement. By observing the characteristics of the dispersive curves measured with sensors located on top of the 4.1 cm diameter column, it is possible to relate the starting point of the downward trend in phase velocities along with its corresponding wavelengths to the clay-column boundary by fitting ellipses with the dimension of 5 cm in the semi-major axis, and 4.1 cm in the semi-minor axis. As shown in Figure 5, almost 100 % of the elliptical effective regions sit within the column. The starting points of the downward trend in phase velocities for both the columns were at wavelengths that individually correspond to the semi-minor axes of the fitted ellipse. Following this hypothesis, this effective region will grow as its axes grow with larger wavelengths. The growth of this effective region will present the largest change in averaged phase velocity at the stage where the ellipse begins to encroach into the surrounding clay but, as it grows further, the change in ratio of column-to-clay included within the effective region stabilises. Thus, this can explain the downward trend in phase velocities just beyond wavelengths of 5 cm (sensors on the 4.1 cm diameter column) and then stabilising with further increase in wavelength.

For the measurement on clay between columns in Figure 5, a growing effective region will begin to include nearby columns, leading to an increase in phase velocity as the wavelength increases. The volume of the effective region in relation to the volume of column inclusion was then calculated.



**Figure 5:** (a) The phase velocities consistent across reliable wavelengths between 3.5 cm and 21 cm due to unchanged soil properties, and (b) The phase velocities sharply decreased between wavelengths 3.5 cm and 10 cm due to the ellipse begins to encroach into the surrounding clay.

The relationship between the phase velocity and the volume of column in the effective region for each wavelength was important for analysing and interpreting the measured result when carrying out a quality assessment of stone columns. The phase velocity could be estimated by knowing the volume of column in the effective region, if the velocity of each individual material is known. The volume of column in the effective region can be estimated by fitting the elliptical volume as a function of wavelengths to the column (Figures 5). In reality, the defective stone columns are not known a priori. To identify any defective columns within the construction site, a comparison between the dispersive curve obtained from a known, good quality column, and the unknown quality column will facilitate the detection of defective columns.

## 8. Conclusion

The feasibility of using surface wave testing for the assessment of stone columns has been demonstrated. A laboratory experiment scaled from a typical stone column site was carried out using soft, remoulded clay and gravelly sand columns, both of which are materials with known physical properties and therefore allows detailed evaluation and comparison. The Rayleigh wave velocities measured for the soft, remoulded clay before column installation was 50 m/s and is in agreement with the literature. The measured phase velocities for clay had an average value of 50 m/s, and for the gravelly sand column, the average phase velocity measured was 138 m/s.

Another important finding in this study is that the Rayleigh wave phase velocity is not only dependent on the depth but also the horizontal spans of the soil properties. Thus, the depth and horizontal spans could be used to identify the effective sampling volume. As a result, the dispersive curve could be estimated via the relationship between the soil properties encapsulated by the sampling volume for each wavelength, and comparing this with the actual measured result to evaluate the quality of the stone columns under investigation.

## 9. Acknowledgements

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