

**ASSESSMENT OF GROUND IMPROVEMENT USING THE
CONTINUOUS SURFACE WAVE METHOD**

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INTRODUCTION

During the construction process, areas of natural or man made ground often require treatment to improve stiffness and load bearing capacity of the soil. This treatment is principally required to achieve acceptable levels of settlement for future construction work.

Traditionally, monitoring of the improvement works is carried out using invasive penetration tests or expensive plate loading tests. Seismic methods may also be used to assess the degree by which the ground has been improved in terms of stiffness.

One method that shows the greatest potential in supplementing the more traditional methods of quality control is the Continuous Surface Wave (CSW) method. This surface wave seismic technique is capable of providing stiffness profiles rapidly on site and hence can be used alongside ground improvement methods. This paper discusses the use of CSW in this particular context.

CSW tests have been performed on a representative area of a commercial site immediately prior to ground improvement. The ground improvement was performed by the installation of vibro-replacement stone columns. An identical suite of tests were also performed and compared immediately after the completion of the ground treatment, on the same day as the initial test.

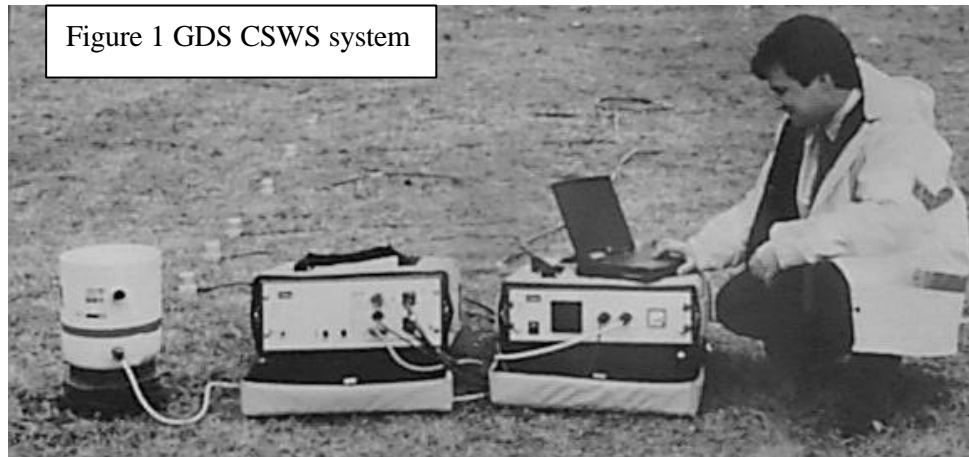
The effect of the vibro-replacement columns in improving the site is considered using the stiffness profiles obtained.

CSW TECHNIQUE

There are now two established methods for surface wave site investigation. On the one hand there is the Spectral Analysis of Surface Waves (SASW) method which uses a hammer blow as an energy source. The major limitation of this technique is a lack of frequency content, control and resolution. The Continuous Surface Wave (CSW) method, on the other hand, uses a steady-state vibrator as an energy source. Such sources have the major advantage of frequency control and hence frequency content plus good frequency resolution.

A Continuous Surface Wave System (CSWS) has been developed by GDS Instruments Ltd as shown in Fig 1. This breakthrough in site investigation technology uses low natural frequency geophones to pick up surface waves generated by a computer controlled vibrator on the ground surface. This has resulted in a ground stiffness profiling system which is fully computer controlled from start to finish. CSWS gives an on-line picture of the average shear stiffness (G_{max}) with depth profile. The value of G_{max} is known to be close to the operational stiffness around structures (Matthews, 1997). The ratio of $G_{operational}/G_{max}$ is in the range 0.5 to 0.8 for soils (Tatsuoka & Shibuya, 1992; Clayton et al., 1994; Hight & Higgins, 1994; Mukabi et al., 1994; Tatsuoka & Kohata, 1994) and near unity for sands and soft rocks (Porovic & Jardine, 1994; Matthews, 1993).

The ground surface at each location was prepared by removing the surface vegetation (0.05 m² approx) and soil to a depth of about 150 mm in order to create a flat surface on which to place the vibrator. The energy source (an electro-mechanical vibrator of peak force 498N) is placed on the prepared ground surface. A row of six 2Hz geophones were placed on a line which is co-linear with the vibrator. The vibrator was energised using the controller and drive unit at single known frequencies between 5 and 100 Hz specified to within 0.1Hz. The range of frequencies and the frequency increment are set by the operator using a laptop PC connected to the control unit. The CSWS system provides for mapping particular features in greater detail by repeating frequency ranges (and hence depths) at smaller increments of frequency. The 2.2 kVa portable generator used for powering the equipment was positioned at least 30 m away from the vibrator on a line which is perpendicular to that of the line of the geophones.



The signals received at the geophones are recorded digitally in the time domain (i.e. ground movement v. time) by the control unit and subjected to a Fast Fourier transform in order to convert the signals into the frequency domain (i.e. spectral amplitude v. frequency). The frequency domain data are used to determine the phase of the signal generated by the vibrator at each geophone location. The geophones are positioned at known distances apart, d , and so the phase information, ϕ , can be used to calculate the wavelength of the mono frequency Rayleigh wave.

$$\lambda = \frac{360.d}{\phi}$$

The phase velocity of this Rayleigh wave, V_R , is determined from this wavelength and frequency, f .

$$V_R = f.\lambda$$

It can be shown from the theory of elasticity that the relationship between the velocity of shear waves, V_s , and Rayleigh waves, V_R , in an elastic medium is given by:

$$V_R = C V_s$$

The constant C is dependent on Poisson's ratio and ranges from 0.911 to 0.955 for the range of Poisson's ratio associated with most soils and rocks if anisotropy is ignored. The maximum error in G arising from an erroneous value of C is less than 10%.

Preliminary stiffness depth profiles can be viewed on site. The maximum shear moduli, G , will be determined from the measured Rayleigh wave velocities using elastic theory as outlined in Matthews et al. (1996).

$$G = \rho V_s^2$$

A Poisson's ratio of 0.25 was assumed and an average bulk density, ρ , based on values obtained from the nearest boreholes. The depth assigned to each stiffness measurement was derived using the factored wavelength method of inverting the dispersion curve (Rayleigh wave velocity v_r wavelength) described in Matthews et al. (1996). A factor of 3 is used to determine the depth (i.e. $z = \text{wavelength}/3$) unless there is evidence suggesting that the increase of stiffness with depth is very small in which case a factor of 2 would be used.

It has been shown that simple inversion techniques such as the wavelength/depth method cannot correctly recover the stiffness depth profile when there are rapid changes of stiffness with depth (Clayton et al., 1995). In such cases interpretation of the dispersion curve using iterative forward modelling based on dynamic finite element predictions of surface motion is necessary to obtain an accurate stiffness profile.

The data obtained for this paper is displayed using the factored wavelength method only as the exact depth to each stiffness measurement is not critical. The change in stiffness due to the ground improvement is the main aim. The factor used is 3. This is primarily to enable evaluation of the ground improvement from the very simplest and quickest data obtainable from the CSWS method.

FIELD CASE

After demolition of the previous structures on the site a thick layer of sand containing some building rubble existed. The improvement works were carried out with a view to densifying the top 4-6m of sand to provide a raft type footing for the proposed works.

Vibro-replacement stone fill columns were installed at 750mm centres to densify the existing loose sand to an acceptable degree to allow future development of the site.

CSW tests were carried out before and after the stone columns were placed in order to gauge the improvement in the stiffness of the site. The CSW tests in both cases were performed directly on the existing sand, and in the case of post-testing, between the newly installed stone columns. Each of the below CSW surveys were carried out in under one hour.

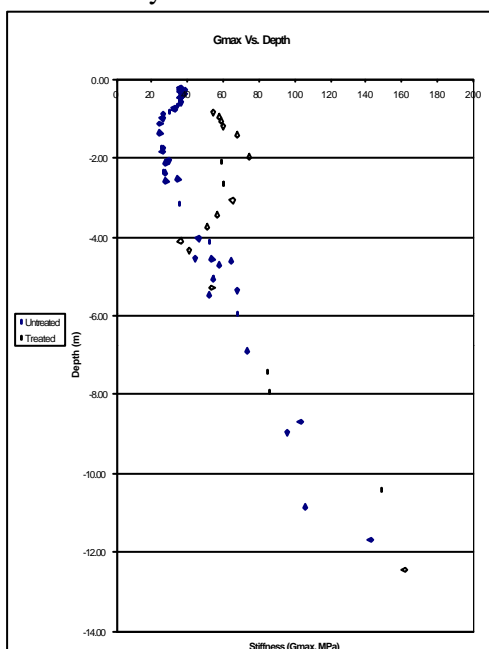


Figure 2 Pre- and Post-treatment CSW

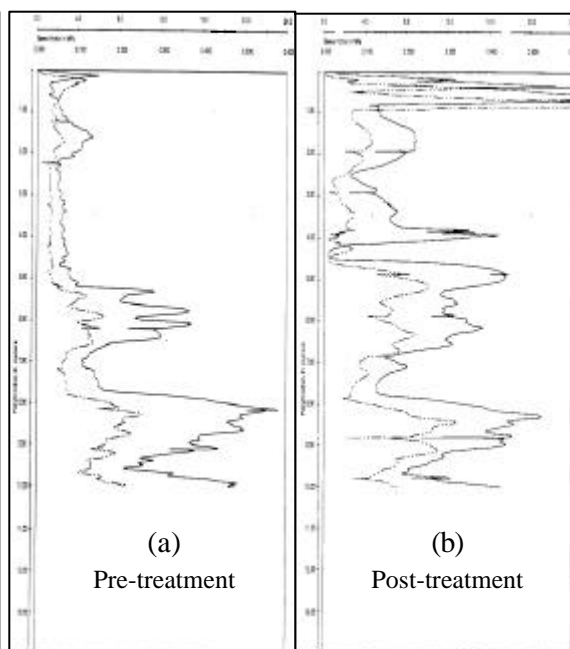


Figure 3 CPT Results

The pre- and post-treatment CSW results are shown in figure 2. From the CSW data alone the improvement in the top four metres of the sand is immediately obvious. This is best

demonstrated at 2m apparent depth where the stiffness is seen to have improved by over 100%.

The depth of improvement is to around 4m. This is also borne out in the conventional CPT testing which has been carried out on the same site. The CPT results are shown in figures 3(a) and 3(b).

The CPT results show a clear improvement in the strength of the densified sand down to 4m depth.

DISCUSSION AND CONCLUSIONS

The Continuous surface wave method is a fast, reliable, non-intrusive and non-destructive method of obtaining a profile of the engineering parameter of stiffness (G_{max}) against depth. Due to the nature of the CSW method the testing is quick (typically less than one hour per test) and cheap due to the low mobilisation costs and no need to install expensive lined boreholes.

The data from the field case demonstrates the usefulness of Continuous Surface Wave testing in the field of ground improvements.

The CSW data sets for both pre and post ground improvement correlate very well to the corresponding CPT data sets.

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