Geophysics-assisted control and evaluation of ground improvement

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ABSTRACT

There is an increasing demand in geotechnical construction business for process monitoring and construction control. The non-destructive nature and subsurface imaging capability of geophysical methods are what is needed for such applications. Jet grouting in particular is an important underground construction technique that channels cement grout suspension with a high pressure jet nozzle into surrounding soils to cut through the soils and form a soilcrete column. This paper uses jet grouting as an example to demonstrate the importance of fully taking engineering considerations into account for the planning and interpretation of geophysical surveys. The in-hole ERT (electrical resistivity tomography) is proposed to assess diameter profile of soilcrete column, which is critical in pilot construction and when jet grouting is used to create a barrier. For evaluating the overall area replacement ratio (degree of reinforcement) when jet grouting is used to reinforce soft soils, seismic surface wave is suggested. For both purposes, quantitative interpretation with engineering precision is proposed.

Keywords: surface wave, electrical resistivity tomography (ERT), ground improvement, jet grouting

1 INTRODUCTION

Geophysics has played an important part in geotechnical and geo-environmental investigations or site characterizations in the phase of engineering planning and design (Greenhouse et al. 2004). While this application continues to evolve, there is an increasing demand in geotechnical construction business for process monitoring and construction control. For example, quality control of compacted soils, evaluation of pavements, assessment of various ground improvements, process monitoring of geo-system under construction or subjected to environmental change, etc. The non-destructive nature and subsurface imaging capability of geophysical methods motivate new developments in these types of applications. This paper uses jet grouting as an example to demonstrate the importance of fully taking engineering considerations into account for the planning and interpretation of geophysical surveys.

Ground improvement is the primary application of many geotechnical construction techniques, making construction on incompetent soils possible by enhancing their characteristics. It is often carried out to modify the ground to increase shear strength and reduce compressibility and permeability of soils in situ. A range of ground improvement solutions are available, including dynamic compaction, pre-compression, and improvement by stiffening columns. Among these, improvement by column-type techniques, such as jet grouting, stone columns, and deep soil mixing, are frequently used. These techniques are special in that the ground becomes highly heterogeneous after installing the improvement columns. In this paper, we focus on a commonly-used technique, the jet grouting, which channels cement grout suspension with a high pressure jet nozzle into surrounding soils to cut through the soils and form a soilcrete column.

Before a geophysical method can be properly devised for process control or performance evaluation of an underground construction, it is important to identify the key engineering parameter to be measured and what can be achieved by the geophysical method. It would have been ideal if the improved columns can be spatially delineated in 2D or 3D in terms of seismic or electrical properties. However, this is not yet possible by current geophysical technology due to geological complexity and resolution limitation of geophysical methods. Instead, critical engineering parameters that can be obtained by geophysical method are identified and quantitative interpretation from geophysical measurements are proposed here.

There are different types of purpose for ground improvement. It may be used as a reinforcement of soft ground to achieve overall competence against shear failure or excessive settlement. Sometimes it is used as a local improvement to create some sort of barriers against undesirable seepage or piping failure. Figure 1 illustrates a jet grouting site. During a pilot construction, the assessment of achievable column diameter is the most important. Column diameter is also the key parameter of quality assurance when ground improvement is to create some sort of barrier. To delineate the constructed column diameter underground, in-hole ERT is proposed. On the other hand, when jet grouting is used to construct soil reinforcement, spacing of columns is controlled to achieve the designed area replacement ratio (ratio of total column cross-sectional area to the total treatment area). While it is possible to use surface wave method to directly measure the effective shear modulus after ground improvement as a parameter for engineering analysis. Figure 1 depicts the difference in loading direction and wave propagation direction. As a result, the measured effective shear modulus may be quite different from the effective modulus in the loading direction. In this regard, it is proposed to use surface wave method to evaluate the overall area replacement ratio, from which proper engineering analysis can be formulated.

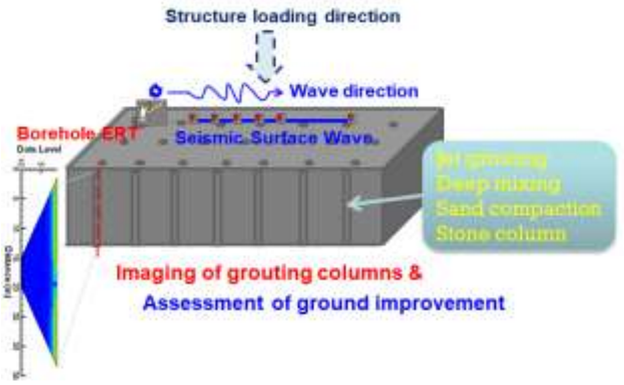

Fig. 1. Illustration showing a jet grouting site and how in-hole ERT and seismic surface wave can be used to image grouting column and assess overall level of reinforcement.

2 LEVEL OF JET GROUTING REINFORCEMENT ASSESSED BY MASW

It is quite appealing to engineers to be able to image the subsurface by non-intrusive geophysical methods. However, there is a gap between the expected scale of variation and geophysical resolution. Current technology cannot image geometry of jet grouting columns non-destructively. In fact, there is even no significant difference between result of MASW survey line through grouting columns and that in between columns. In a complex ground after ground improvement by jet grouting as shown in Fig. 1, Lin et al. (2012) showed that the overall shear wave velocity of the improved ground is effectively measured by the multi-sation analysis of surface wave (MASW) method. Instead of imaging the grouting geometry, the work of ground improvement was reflected in the apparent velocity increase measured by MASW, making it a possible candidate for evaluating the overall area replacement ratio (degree of reinforcement). The field case in Lin et al. (2012) showed that the percentage increase of shear wave velocity was very close to the design replacement ratio of ground improvement. In order to come up with a quantitative interpretation, the homogenization of shear wave velocity measured by the surface wave method is investigated in the heterogeneous ground with improved columns by 3-D numerical simulations. Figure 2 shows one such model. 20-m-long improved columns were installed 5 m below the surface. The cross section of the improved columns was set to be 1m x 1m. The spacing between two adjacent columns (S, center to center), Vs of soil, and Vs of grout were varied to study the effect of area replacement ratio (Ra) and velocity contrast on velocity improvement.

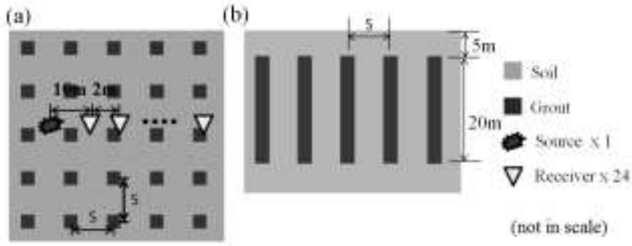

Fig. 2.Column-installed earth models and surveying configuration (a) plan view (b) side view.

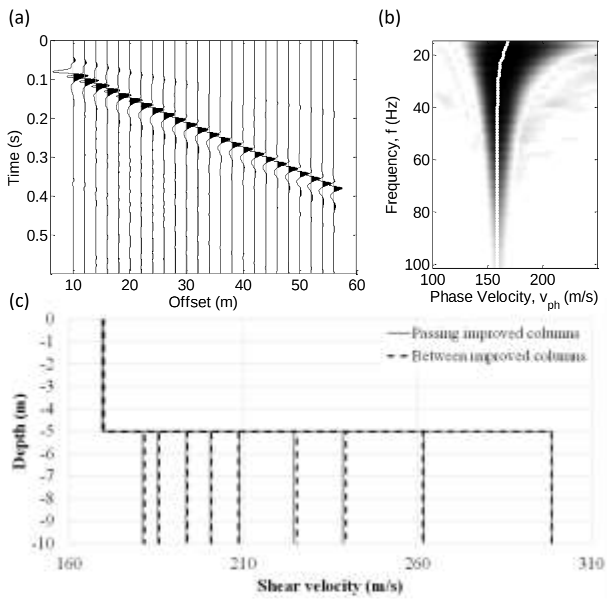

Fig. 3. (a) Example synthetic seismogram of surface wave testing in column-installed soils; (b) the corresponding dispersion image of (a); (c) inverted 2-layer Vs profiles for various of area replacement ratio.

As an example, synthetic seismogram and dispersion image for one simulation case (S=2.75 m, Ra = 13.3%, Vs of soil=170 m/s, and Vs of grout = 800 m/s) were shown in Fig. 3a and b. Similar to field experience, the shot record seems "normal" even though the earth model was highly heterogeneous with grouted columns. Figure 3b show the inverted 2-layer (top ungrouted and bottom grouted layer) velocity profile for area replacement ratio ranging from 6.3% to 44.4%. The inverted Vs profiles were almost identical for survey lines passing through columns and that in the middle between columns. This phenomenon agrees with the field observation.

The percentage increase of Vs (abbreviated as VPI) due to ground improvement was further analyzed for each case and plotted against the area replacement ratio as shown in Fig. 4. As expected, VPI increases with area replacement ratio. Two conditions of velocity contrast (VC = Grout Vs/Soil Vs) were simulated. Their velocity increase trends with area replacement ratio are similar. The VPI forVC=10 is only slightly greater than VC=4.7. VPI increases with increasing VC, but it will reach an asymptotic limit. For VC greater than about 5, VPI is governed by area replacement ratio and not sensitive to VC. For jet grouting, this is usually the case. Based on the results of 3-D numerical simulations, an quantitative relation between VPI and Ra can be obtained as indicated by the curve in Fig. 4.

The homogenization behavior of Rayleigh wave is quite complex since it involves elliptical particle motion including both longitudinal and transverse movements. The relation between VPI and Ra shown in Fig. 4 is based on 3-D numerical simulations. It is believed that the regularly arranged columns can be treated as an equivalent transversely isotropic medium based on long-wave assumption. The apparent shear modulus exhibited in the results of numerical simulations should be some sort of combination of the equivalent shear modulus in the propagating direction and depth direction. A theoretical relation between VPI and Ra may be further discussed and derived. Before that, we believe that the relation derived from the numerical simulations can be practically applied to assess the replacement ratio of jet grouting.

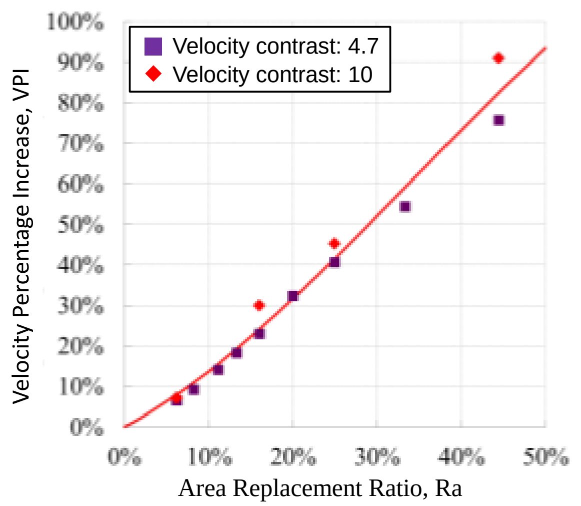

Fig. 4. The quantitative relation between velocity percentage increase and area replacement ratio.

JET GROUTING DIAMETER ASSESSED BY IN-HOLE ERT

Quality assurance of jet grouting is conventionally conducted by visually inspection at shallow depth and soilcrete core sampling at deep depth. They are time consuming and not cost effective. Only a small proportion of the site is tested to evaluate the construction quality. Some indirect measurement emerged such as hydrophone or painted bar approach, which utilizes erosion or vibration phenomenon at the vicinity of designed soilcrete column radius to determine whether the grouts have reached the designed diameter. However, these tagged detection methods can only reveal that the get grouts have reached the marked location but the actual formation of cement grout are not known.

An in-hole ERT technique named Cyljet (Frappin 2011), a special application of the electric cylinder method (Frappin and Morey 2001), appears to be an effective technique. The testing procedure involves pushing a slotted PVC pipe into the center of the fresh grout or re-drilling the column center after 1-2 days of curing for the in-hole DC resistivity measurements. In addition, a calibration hole can be drilled and equipped with the same slotted PVC pipe in the untreated ground to measure its natural background resistivity. The Cyljet method can generate a complete depth profile of soilcrete column diameter efficiently and cost-effectively. However, the lack of detailed survey provision and inversion methodology of this proprietary technique has limited its use in general engineering practice.

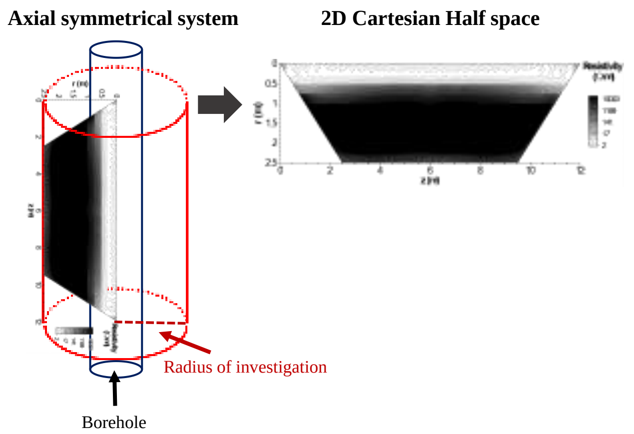

Fig. 5. Schematic of equivalent mapping from axially symmetric in-hole ERT to 2D half space surface ERT.

The in-hole resistivity survey in the center of jet grouting can be treated as an axially symmetric problem. Considering the similarity of electrical potential distribution in depth-radius section of an axial symmetric system and distance-depth section in a 2D Cartesian half space, we propose utilizing a widely available 2D Cartesian coordinate inversion system to perform ERT inversion of in-hole data for column diameter estimation, as illustrated in Fig. 5. 3D numerical simulations were performed to validate the proposed method.

The concept of using 2D Cartesian half space model to perform in-hole ERT inversion of axially symmetric data were first numerically simulated in cases of soilcrete columns with different radiuses. Figure 6a illustrates the electrode configuration in the soilcrete column with the dotted line indicating the 12 m long ERT survey line with 0.4 m electrode spacing and Wenner-Schlumberger array. The resistivity of soilcrete column and ground layer were assumed as 5 Ohm-m and 50 Ohm-m, respectively. The simulated in-hole ERT results for soilcrete columns of radius 0.4 m, 0.8 m, 1.0 m, and 1.2 m are shown in Fig. 6b-e, respectively. The results show that two distinct resistivity layers (i.e., the column and soil layers) are well resolved although looking closely reveals significant overestimation of soil resistivity. This overestimation is attributed to the transformation form axially symmetric condition to 2D half space. While it is possible to derive the mapping function between the true resistivity in axially symmetric condition and the inverted resistivity in 2D half space, the jet grouting inspection mainly concerns the column diameter. The actual resistivity values in the inverted profile is not important. Therefore, quantitative interpretation of column diameter based on such inversion scheme is next examined.

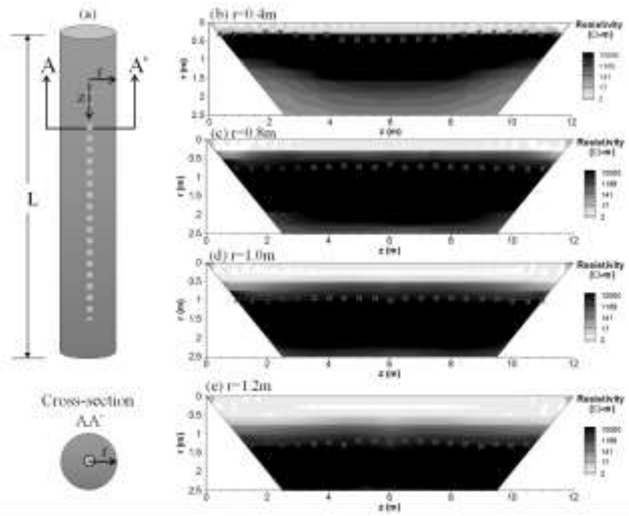

Fig. 6 (a) Illustration of uniform column and electrode layout; (b)-(e) inverted resistivity sections and estimated radius versus depth (marked as “x”).

Interface interpretation from an inverted tomogram could be subjective due to the smoothing regularization in tomography inversion. Although the resistivity of the second (soil) layer is seriously overestimated by the proposed analysis, the “exaggerated” resistivity profile actually facilitates the identification of resistivity interface for column diameter determination. The dual tangent line method was found suitable for quantitative interpretation of column radius (half of diameter). The results are marked as “x” in Fig. 6b-e. The column radius is preserved in the layer thickness when the in-hole data is inverted by 2D half space model. The maximum error of column diameter estimation is within 10%.

Soilcrete column diameter may deviate from the designed target due to geological variation or non-ideal construction control. To demonstrate the the ability of the proposed approach in detecting change in column diameter, A column with three uniform sections was used to simulate a necking soilcrete column. As illustrated in Fig. 7a, a column 1.0 m in radius has a defected necking section 0.5 m in radius and 0.2m to 1.2m in length. The inverted resistivity sections and interpreted column radius are shown in Fig. 7b-e, in which the necking phenomena are clearly shown. The electrode spacing is 0.4 m, so it is difficult to detect small necking section that is shorter than the electrode spacing (as the case shown in Fig. 7b) due to insufficient spatial resolution. In order to detect possible anomalies and provide a more reliable measurement profile, the electrode spacing should be predetermined for the targeted dimension, or the detection limitation from the used electrode spacing should be clearly stated to prevent over interpreting the result.

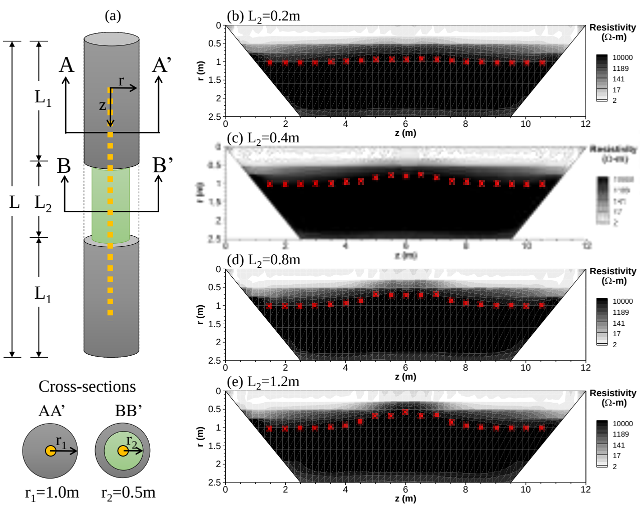

Fig. 7 (a) Schematic of the necking column case; (b)-(e) inverted resistivity sections and estimated radius versus depth (marked as “x”).

4 CONCLUSION

Geophysical methods provide profiles or images in terms of physical parameters which are usually not directly linked to the engineering properties required by engineers. This paper uses jet grouting as an example to demonstrate the importance of fully taking engineering considerations into account for the planning and interpretation of geophysical surveys. Precise quantitative approach for determining column diameter based on in-hole ERT using widely-available tools is proposed. A physics-based quantitative approach is proposed to estimate the area replacement ratio and overall quality of improvement columns from surface wave testing results. More field case studies will be conducted to further validate our recommendations.

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