Geoelectric *versus* MASW for geotechnical studies

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We explore the role of non-invasive multi-electrode electrical resistivity imaging (ERT) and induced polarisation imaging (IPI) as an alternative to multichannel analysis of surface waves (MASW) for geotechnical site characterisation in view of their higher near-surface spatial resolution. By using regression equations, we assess the relative performance of ERT, IPI and MASW in predicting geotechnical test results (standard penetration test (SPT), dynamic cone penetration test (DCPT) and static cone penetration test (SCPT)) in a site investigation on our IIT Roorkee Campus, India. The results indicate that the average root mean square (RMS) errors in predicting SPT based on ERT, IPI and MASW are 16.95%, 21.9% and 28.03%, respectively. Likewise, the average RMS errors in predicting DCPT based on ERT, IPI and MASW are 15.4%, 15.3% and 56.99%, respectively, and the average RMS errors in predicting SCPT based on ERT, IPI and MASW are 20.15%, 18.65% and 36.49%, respectively. In view of higher resolution for near-surface investigations, ERT/IPI seems to score over MASW in geotechnical site investigation studies. So, a leading role for non-invasive and cost-effective ERT/IPI in geotechnical site investigations is envisaged.

Keywords. SPT; DCPT; SCPT; ERT; MASW; regression equation.

1. Introduction

The present practice of soil investigations (Appendix A and table A1) in geotechnical engineering provides point information depthwise and involves digging and drilling, which are costly. It gives a considerable detailed information needed for a foundation engineer and designer. However, as near-surface soil conditions and earth materials are highly heterogeneous, simple point-wise soil investigations are not sufficient to meet the real scientific needs, e.g., collapsible soils, expansive soils, the presence of organic clays, etc. Until now, the multichannel analysis of surface waves (MASW) method is being used to assess the shear velocity distribution in the subsurface in a non-invasive

manner and its results can be transformed to standard penetration test (SPT) ‘N’ using regression equations (Anbazhagan *et al.* 2013a,b). In view of higher subsurface spatial resolution, we propose to use more effective non-invasive geoelectrical imaging technology (Ward 1990; Loke and Barker 1995, 1996a,b) based methodology for geotechnical characterisation of a site.

Engineering geophysical methods, including geoelectrical methods, were tried by several workers (Giao 2001; Giao *et al.* 2002, 2003; Sastry and Viladkar 2004; Drahov *et al.* 2006; Pujari and Nanoti 2006; Gautam *et al.* 2007; Mondal *et al.* 2007, 2008; Pujari *et al.* 2007). Geotechnical characterisation and liquefaction potential of sites using surface waves have been undertaken by several

workers (Joh 1996; Matthews *et al.* 1996; Foti 2000; Matthews *et al.* 2000; Xia *et al.* 2000, 2002; Hadidi and Gucunski 2003; Oh *et al.* 2003; Xu and Butt 2006; Sitharam *et al.* 2008; Vipin *et al.* 2008; Anbazhagan *et al.* 2013a). Linking the soil properties with resistivity (Rucker and Noonan 2013; Siddiqui and Osman 2013; Sumedha and Sastry 2016) and shear wave velocity (Anbazhagan *et al.* 2017) was attempted by several workers. Prediction of two-dimensional (2D) geotechnical parameters for near surface was attempted by Rumpf and Tronicke (2014).

A more fundamental soil development aspects of Indo-Gangetic Alluvium were dealt by Srivastava *et al.* (2015).

A very good coverage of Spectral-Analysis-of-Surface-Wave (SASW) and Multichannel-Analysis-of-Surface-Wave (MASW) methods is available in the literature (Seshunarayana and Sundararajan 2004; Park *et al.* 2005; Seshunarayana 2006) and these methods are routinely used in site testing. However, a similar progress has not been made in the application of geoelectrical imaging to geotechnical site characterisation. As evident from the literature, very meagre attention has been paid to this important aspect (Roth *et al.* 2002; Roth and Nyquist 2003). The recent literature (Cosenza *et al.* 2006; Gautam *et al.* 2007; Gautam 2009) shows that scientific efforts are limited to site-specific qualitative correlations between geoelectrical and geotechnical data (SPT). Even though the qualitative correlations are available for shear wave/elastic moduli and SPT (Iyisan 1996; Morgan *et al.* 2005; Ulugergerli and Uyanik 2007), no worthwhile predictive effort has been made to complement the geotechnical tests at a site. The development of theoretical dispersion curves based on SPT data has been attempted by Sudhish Kumar *et al.* (2006). An initial predictive effort using the geoelectric imaging has been made by Gautam *et al.* (2007) to complement the geotechnical tests. But, the relative assessment of electrical resistivity imaging (ERT), induced polarisation imaging (IPI) and MASW in predicting the geotechnical test results in the field study is an urgent need for near-surface investigations.

Here, by using regression equations, we attempt an inter-comparison of relative performance of ERT, IPI and MASW in predicting the geotechnical test results (SPT, dynamic cone penetration test (DCPT), static cone penetration test (SCPT)) in a field study on our campus. Our analysis indicates that ERT/IPI-based prediction of

SPT/DCPT/SCPT results is significantly superior to MASW-based estimates, thereby emphasising the urgent need for adopting ERT/IPI-based methodology for geotechnical site characterisation. Recently, Sastry and Sumedha (2014) have reported the supremacy of geoelectric imaging over MASW in geotechnical site characterisation of a site.

2. Methodology

- (1) We normalise the geoelectric (ERT and IPI), MASW (shear wave velocity (V_s)) and geotechnical test (SPT, DCPT and SCPT) results by their respective maxima to render their non-dimensional entities.
- (2) We develop regression equations that relate the observed non-dimensional geoelectrical (resistivity (ERT), induced polarisation (IP)) and shear wave velocity (V_s) logs from the respective 2D image data with geotechnical data, which are referred to a pair of boreholes at/in close proximity of geoelectrical profile. An average regression equation is developed for the pair of boreholes. The geotechnical data includes normalised SPT/DCPT/SCPT values. Shear wave logs are obtained from the MASW data analysis.
- (3) We predict the geotechnical test results (SPT/DCPT/SCPT logs) on the basis of relevant average regression equations arrived at step 2. Analogously, the shear wave velocity logs derived from the MASW data need to be converted to SPT/DCPT/SCPT logs.
- (4) We perform the error analysis (root mean square (RMS) error) for both ERT/IPI and MASW derived SPT/cone penetration test (CPT) profiles/sections to understand the relative performance of ERT/IPI and MASW methods in predicting geotechnical test results (SPT/DCPT/SCPT).

3. Site investigations

3.1 Site location map

Figure 1 refers to the position location of the study region, wherein different geoelectrical (ERT and IPI along profile A–B), MASW (profile E–F) and geotechnical test site (SPT, DCPT and SCPT) locations are included.

Figure 1. Location map of the proposed library site, IIT Roorkee, India.

3.2 Geology of the study region

The study region (figure 1) namely the site for construction of New IIT Roorkee Library is located on a river terrace of the Solani River and it belongs to Indo-Gangetic Alluvial Plains and falls in Uttarakhand State, India. The Ganga–Solani Plain is a small unit with sandy to loamy sand soils (Parkash *et al.* 2001).

The vast Indo-Gangetic Alluvial plains are located at the south of the Sub-Himalaya and extend up to the Aravalli in the west, Satpura and Vindhyan ranges in the south. This basin was considered to be a foredeep. The development and

evolution of the foredeep into the Indo-Gangetic basin has taken place in three stages related to different phases of Himalayan orogenic movements (Kumar 2005). Major parts of Indo-Gangetic plains are marked by relatively a subhumid to a humid climate and high rate of sedimentation (Parkash *et al.* 2001). The bulk of the exposed sediments range in age from Middle to Late Pleistocene and are generally referred to as the Older Alluvium. The plains associated with the rivers Ganga, Yamuna and its tributaries are overlain by poorly to moderately developed soils and their clear association with some rivers can be identified from satellite images (Parkash *et al.* 2001).

4. Data acquisition, processing and interpretation

The geoelectrical investigations pertain to resistivity and IPI imaging data acquisition. ERT and IPI data using the SYSCAL Jr. 72 electrode system with a 2 m electrode separation along the A–B profile (Wenner–Schlumberger configuration) was acquired. Further, the MASW data and interpreted results were provided to us by Kumar (2013). He has used MASW equipment, Mc Seis MASW of 24 detectors with a 2 m receiver spacing.

5. Results

True resistivity and chargeability sections are shown in figures 2 and 3 for profile A–B. We adopted the outlined methodology for ERT and IPI profiles along A–B (figure 1). Shear wave velocity logs at geotechnical test locations for profile A–B are shown in figure 4(a–f). A summary of achieved results is included in table 1.

Figures 5 and 6 refer to inferred SPT on the basis of ERT, figures 7 and 8 on the basis of IPI and figures 9 and 10 to that of MASW. Figures 11 and 12 refer to inferred DCPT on the basis of ERT,

figures 13 and 14 on the basis of IPI, figures 15 and 16 to that of MASW. Figures 17 and 18 refer to inferred SCPT on the basis of ERT, figures 19 and 20 on the basis of IPI and figures 21 and 22 on the basis of MASW.

6. Discussion

In Appendix A, we have included relevant details of SPT, DCPT and SCPT operations and relevant data acquisition.

In figure 4, normalising factors for each V_s logs are mentioned for respective SPT/DCPT/SCPT data. Generally, the V_s logs seem to maintain constant behaviour (somewhat featureless) beyond 4–6 m range and this probably influenced the prediction quality of geotechnical test data results (figures 9, 10, 15, 16, 21 and 22).

In general, the average RMS errors for predicting geotechnical test results (SPT, DCPT and SCPT) are less for ERT/IPI based in comparison to that of MASW (figures 5–22 and table 1). Broadly, it is due to the higher resolution of ERT/IPI over MASW for near-surface investigations. Further, the shear wave velocity (V_s) estimation from the MASW data utilises the surface wave dispersion analysis (Park

Figure 2. True resistivity section along profile A–B.

Figure 3. True chargeability section along profile A–B.

Figure 4. Shear wave velocity logs at geotechnical test locations for profile A–B.

Table 1. Predicted geotechnical test results in terms of RMS error (%) form ERT, IPI and MASW for profile A–B.

Investigation method	Predicted geotechnical test results in terms of RMS error (%)								
	SPT			DCPT			SCPT		
	Profile A–B			Profile A–B			Profile A–B		
	B1	B3	Average error	D1	D2	Average error	S1	S2	Average error
ERT	14.2	19.7	16.95	10.6	20.2	15.4	16.5	23.8	20.15
IPI	19.4	24.4	21.9	6.5	24.1	15.3	17.8	19.5	18.65
MASW	26.70	29.36	28.03	53.71	60.28	56.99	48.35	24.62	36.49

$$\text{Regression Equation: } y = -0.333x^2 + 0.547x + 0.542$$

Figure 5. Plot of observed *vs.* computed SPT based on ERT at borehole location-B1 at profile A–B.

$$\text{Regression Equation: } y = -1.668x^2 + 1.603x + 0.382$$

Figure 7. Plot of observed *vs.* computed SPT based on IPI at borehole location-B1 at profile A–B.

$$\text{Regression Equation: } y = -0.333x^2 + 0.547x + 0.542$$

Figure 6. Plot of observed *vs.* computed SPT based on ERT at borehole location-B3 at profile A–B.

$$\text{Regression Equation: } y = -1.668x^2 + 1.603x + 0.382$$

Figure 8. Plot of observed *vs.* computed SPT based on IPI at borehole location-B3 at profile A–B.

et al. 2005) while the apparent resistivity/apparent chargeability inversion based on subsurface physical property discretisation (either 2D or three dimensional) and depth of investigation concepts (Loke and Barker 1995, 1996a, b) to yield more refined ERT/IPI sections.

It may be noted that the stiffness of soil at refined scale influences DCPT and SCPT measurements (Murthy 2008) while ERT/IPI are influenced by bulk properties of the medium at relatively cruder scale (electrode separation of 2 m in our case). The probable reason for relatively

Figure 9. Plot of observed *vs.* computed SPT based on MASW at borehole location-B1 at profile A-B.

Figure 10. Plot of observed *vs.* computed SPT based on MASW at borehole location-B3 at profile A-B.

Figure 11. Plot of observed *vs.* computed DCPT based on ERT at borehole location-D1 at profile A-B.

bad performance of MASW in the prediction of DCPT/SCPT test results in comparison to SPT prediction could be due to insufficient sampling/resolution. The data acquisition, processing and inversion/interpretation errors of both ERT/IPI and MASW could also be another important factor controlling the prediction quality

Figure 12. Plot of observed *vs.* computed DCPT based on ERT at borehole location-D2 at profile A-B.

Figure 13. Plot of observed *vs.* computed DCPT based on IPI at borehole location-D1 at profile A-B.

Figure 14. Plot of observed *vs.* computed DCPT based on IPI at borehole location-D2 at profile A-B.

of geotechnical test results. Also, as the relationship between geoelectric imaging (ERT/IPI) with geotechnical test results (SPT/DCPT/SCPT) is nonlinear and guided by both electric

Figure 15. Plot of observed *vs.* computed DCPT based on MASW at borehole location-D1 at profile A-B.

Figure 16. Plot of observed *vs.* computed DCPT based on MASW at borehole location-D2 at profile A-B.

Figure 17. Plot of observed *vs.* computed SCPT based on ERT at borehole location-S1 at profile A-B.

and mechanical properties of near-surface soil, the entire system of regression equations is site specific and one has to undertake our outlined methodology to arrive at them. This aspect may not be construed as lacunae of our method but should be accepted as a natural option for linking two different physical fields governed by relevant soil properties. The complex soil development processes immensely influence the near-surface soil

Figure 18. Plot of observed *vs.* computed SCPT based on ERT at borehole location-S2 at profile A-B.

Figure 19. Plot of observed *vs.* computed SCPT based on IPI at borehole location-S1 at profile A-B.

Figure 20. Plot of observed *vs.* computed SCPT based on IPI at borehole location-S2 at profile A-B.

properties (Srivastava *et al.* 2015), which in turn render the regression equations linking geoelectric and geotechnical test results to be site specific. It may be understood that no theoretical advances can address this issue.

Figure 21. Plot of observed *vs.* computed SCPT based on MASW at borehole location-S1 at profile A–B.

Figure 22. Plot of observed *vs.* computed SCPT based on MASW at borehole location-S2 at profile A–B.

7. Conclusions

On the basis of combined ERT, IPI, MASW and geotechnical test results (SPT, DCPT and SCPT) pertaining to the study region, our prediction of geotechnical test results shows that the ERT/IPI-based estimates are better than MASW-based estimates. However, the underperformance in the prediction of DCPT/SCPT test results based on ERT/IPI could be due to bulk volume earth

medium response in contrast to the high spatial resolution of point data (DCPT and SCPT). Further, the complex soil development processes immensely influence both electrical and mechanical properties of soil, which in turn render the regression equation development to be site specific and no theoretical advance can address this issue. Thus, the non-invasive ERT/IPI with proper data acquisition parameters can be a good alternate choice for geotechnical site characterisation when compared to MASW in view of their higher resolution. This fact emphasises a greater leading role for ERT/IPI in non-invasive geotechnical site investigations in future.

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Appendix A

A1. Subsurface exploration and geotechnical tests

The *in-situ* geotechnical tests in the field have the advantage of testing the soils in their natural, undisturbed condition to obtain various parameters for the design of foundations (Ranjan and Rao 2005). The purpose of subsurface exploration is to obtain information that will aid the geotechnical engineer in:

1. determining the nature of soil at the field site and its stratification;
2. selecting the type and depth of foundation suitable for a given civil structure;

Table A1. *Different geotechnical site investigation methods.*

Sl. no.	Geotechnical <i>in-situ</i> tests	Description	Geotechnical parameters
1	SPT	Provides information of the penetration resistance while also collecting a disturbed soil sample for grain-size analysis and soil classification	Angle of internal friction (Φ), Young's modulus, E_s , etc.
2	DCPT	It is a quick test and helps to cover a large area. It provides the information of variability of the subsoil and unearth local soft pockets	Penetration resistance
3	SCPT	Is performed using an instrumented probe with a conical tip, pushed into the soil hydraulically at a constant rate	Tip resistance and friction resistance

3. evaluating the load-bearing capacity of the foundation;
4. estimating the probable settlement of a civil structure;
5. determining the potential foundation problems (e.g., expansive soil, collapsible soil, sanitary landfill, etc., ...);
6. determining the location of the water table exactly;
7. determining the depth and nature of bedrock, if and when encountered;
8. performing some *in-situ* field tests, such as permeability tests, van shear test and SPT;
9. predicting the lateral earth pressure for structures such as retaining walls, sheet pile and braced cuts.

The field tests that are commonly used in the sub-surface investigation (Ranjan and Rao 2005) are included in table A1.

A1.1 Standard penetration test

This is the most extensively used penetrometer test (plate A1) in almost every country. The test uses a split-spoon sampler, which consists of a driving shoe, a cylindrical split barrel which is longitudinally split into two halves. IS: 2131-1981 suggests the standard procedure for carrying out the test.

The borehole is drilled to the required depth with its bottom cleaned. The split-spoon sampler attached to the standard drill rods of the required length, which is lowered into the borehole and allowed to rest at the bottom. The SPT is carried out at every 0.75 m vertical depth intervals in a borehole and it can be 1.50 m for large depth borehole. For this the split-spoon sampler is driven into the soil for a depth of 450 mm by the blows of a drop hammer of 65 kg weight falling vertically and freely from a height of 750 mm (plate A1). The number of blows required to affect the first 150 mm of penetration, called the seating to derive, is disregarded. SPT does not perform well in a rocky formation where the boring log shows *refusal* and the test is halted. For refusal, 50 blows are required for any 150 mm and 100 blows for 300 mm penetration and 10 successive blows that produce no advance (plate A1). SPT blow 'N' values obtained in the field for sand have to be corrected as per IS: 2131-1981. After completion of the test the split-spoon sampler is withdrawn and detached from the drill rods with split barrel disconnected from cutting shoe and the coupling.

(a)

(b)

(c)

Plate A1. SPT: (a) site plan, (b) test details, (c) sampling from SPT split spoon.

The soil sample is collected carefully from the split barrel and transported to the laboratory for classification tests.

A1.2 Static cone penetration test

The SCPT is also known as CPT, which is widely used in place of SPT for soft clay silts and fine-to-medium sand deposits. The test was developed in Holland, and is therefore also called as Dutch

Plate A2. Static cone penetration test.

Plate A3. Setup and procedure of CPT.

cone test (plate A2). The penetrometer uses a cone with an apex angle of 60° with a base area of 10 cm^2 . CPT gives a continuous depth-wise record of both the cone-point-bearing resistance and the skin friction resistance, which are often used in pile foundation. A disadvantage of this device is that no samples can be obtained. This test is unsuitable for gravels, rocks and very dense sands owing to the difficulty experienced in pushing the cone. A correlation has been established between cone tip resistance q_c and recorded a number of blows N for granular soils (Ranjan and Rao 2005).

A1.3 Dynamic cone penetration test

In DCPT, a cone which has an apex angle 60° is attached to drill rods, which are driven into the soil by blows of a hammer of 65 kg, falling from a height of 750 mm (plate A3). The blows are counted for every 150 mm penetration of the cone and the cone is driven till refusal or up to the required depth. The number of blows required for 300 mm penetration is the dynamic cone penetration resistance N_{cd} . The number of blows provides an indication of uniformity or variability of the soils including the identification of any local soft pocket in the subsurface and no samples are recovered in this test. DCPTs are performed either by using 50 mm diameter cone without bentonite slurry or 65 mm diameter cone with bentonite slurry. If the tests are carried out close to a few boreholes, the data from DCPT can be compared with the SPT data and correlation can be established between them for the particular site conditions (Ranjan and Rao 2005).

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