Statistical analysis of geo-electric imaging and geotechnical test results – a case study

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For conjunctive use of geoelectric imaging and geotechnical site investigations in geotechnical characterization of major civil engineering construction sites, an objective assessment of influencing factors is important. Here, we present multiple regression analyses of both geoelectric (Electrical Resistivity Tomography, ERT; Induced Polarization Imaging, IPI) and geotechnical site investigations (Standard Penetration Test, SPT) for two profiles at a construction site for CGEWHO Complex in Greater Noida region, Delhi to assess the role of influencing formation factors like sand, fines and water content. Achieved results show that SPT 'N' and IPI are well predicted by a linear multiple regression. On an average, the nonlinear regression has improved predicted SPT 'N', resistivity and chargeability by 28.55%, 22.45% and 9.58%, respectively. The influence of sand and fines content is more than that of water content in the prediction of chargeability and SPT 'N'. RMS error is less in prediction of IPI chargeability (average error of 1.96%) in comparison to SPT 'N' value (average error of 11.35%). As factors affecting chargeability (IPI) and SPT 'N' are similar, non-invasive IPI can be used along with few geotechnical site investigations for detailed geotechnical site investigations.

Keywords. SPT; ERT/IPI; multiple regression analysis; geoelectric imaging; geotechnical tests; linear and nonlinear multiple regression analysis.

1. Introduction

Geotechnical tests (Standard Penetration Test, SPT; Cone Penetration Test, CPT; Static Cone Penetration Test, SCPT; Dynamic Cone Penetration Test, DCPT and others) are performed to assess the mechanical properties of shallow soils either offshore or onshore before undertaking major civil engineering constructions. However, these point observations are both time-consuming and expensive. So, they are curtailed to a limited number, which itself is subjective and this decision very much depends on the experience and

technical expertise of a geotechnical engineer. On the other hand cost-effective geoelectric imaging methods provide 2-D/3-D resistivity and chargeability sections of subsurface on detailed scales and their recent conjunctive use in geotechnical site characterization has received wide attention (Sastry *et al.* 2012).

Index properties of soils (e.g., shape and size of grains, grain size distribution, water content, lithology, density index, and consistency), shear strength governed by Coulomb equation, formation and structure of soils and soil-phase relationships rule the results of geotechnical tests (Craig

Figure 1. Site location map of proposed construction site of CGEWHO Complex in Greater Noida, India.

1978; Terzaghi 1943; Terzaghi and Peck 1996). SPT is affected by sand, grain size, clay, water content and porosity (Murthy 2008). SPT 'N' is directly proportional to grain size and clay content and inversely proportional to porosity and water content (Murthy 2008; Bowles 2001). CRP has been used by Yoon *et al.* (2009) for assessing the local behaviour in soft offshore soil. Apart from undrained shear strength there are other soil parameters (plasticity index, pore pressure coefficient, and over-consolidation ratio) that have an

impact on SCPT measurements (Remai 2013). The quality of groundwater influences resistivity while it has no role on SPT 'N'. Pidlisecky *et al.* (2006) have developed 3-D distribution of electrical conductivity by the cone-based electrical resistivity tomography.

Detailed studies on electrical conductivity property of sedimentary rocks are undertaken by several workers (Li and Oldenburg 1991; Revil and Glover 1997, 1998; Revil *et al.* 1998; Revil and Leroy 2004). Laboratory studies have revealed that

Figure 2. (a) True chargeability section for profile A-B (ref. figure 1). (b) True resistivity section for profile A-B (ref. figure 1).

Figure 3. (a) True chargeability section for profile C-D (ref. figure 1). (b) True resistivity section for profile C-D (ref. figure 1).

the sensitivity of measured geophysical properties to solid–fluid, fluid–fluid and solid–solid interfaces in granular and fractured materials (Knight *et al.* 2010). Shevin *et al.* (2007) have estimated clay content in soil through resistivity measurements both in field and laboratory. Clay content, fluid conductivity and microstructure affect electrical properties in a complex fashion (Slater and Glaser 2003). Resistivity of earth materials is inversely proportional to porosity, clay content and water content, while it is directly proportional

to grain size of rock matrix and air content in vadose zone. Niwas *et al.* (2006, 2007) have proposed a computational scheme for simplifying the nonlinear electrical response of shaly sand reservoir. IP method can be used to characterize clay and shaly sands (Sumner 1976; Marshall and Madden 1959; Patella 1973) in the subsurface. The IP logging can be operated in the frequency and time domains to estimate the hydraulic properties of shaly sands (Vinegar and Waxman 1984; Worthington and Collar 1984; Börner *et al.* 1996;

Table 1. *Subsoil borelog at borehole location B13.*

Depth (m)	Water table (m)	I.S. classification	Grain size analysis			Liquid limit (%)	Plastic limit (%)	Natural water content (%)
			Gravels (%)	Sand (%)	Fines (%)			
1.5		CL	0.0	4.8	95.2	32.3	19.9	18.1
3.0		ML (NP)	0.0	30.2	69.8	NP	NP	17.4
4.5		SM (NP)	4.0	78.0	18.0	NP	NP	27.4
6.0	6.50 ▼	SP-SM	1.0	89.0	10.0	NP	NP	27.8
7.5		SP-SM	7.3	84.4	8.3	NP	NP	26.2
9.0		SP-SM	0.5	92.2	7.3	NP	NP	26.2
10.5		SP-SM	1.0	90.2	8.8	NP	NP	26.3
12.0		SM (NP)	1.0	84.0	15.0	NP	NP	25.6
13.5		SP-SM	1.3	93.0	5.7	NP	NP	26.0
15.0		SP	0.0	95.7	4.3	NP	NP	26.1
18.0		SP-SM	0.0	92.5	7.5	NP	NP	23.1
21.0		CI	2.5	15.0	82.5	39.0	20.5	23.5
24.0		CI	3.3	7.7	89.0	38.4	22.7	21.5
27.0		CI	0.0	14.5	85.5	39.0	22.3	21.2
30.0		SM (NP)	0.0	87.5	12.5	NP	NP	26.5

Lesmes and Morgan 2001; Slater and Lesmes 2002; Titov *et al.* 2002, 2004). The role of water content and cation exchange capacity (CEC) of clay minerals/shale was investigated by Kiberu (2002).

Sastry *et al.* (2013) used geoelectric imaging for geotechnical site characterization when conventional geotechnical field tests failed. Gautam *et al.* (2007) have explored the possibility of predicting site geotechnical test results (SPT, DCPT and SCPT) through a conjunctive use of geoelectrical (ERT and IPI) and few geotechnical data. Even though their prediction is based on regression analysis, they have not carried out any quantitative multiple regression analysis to fix the key parameters affecting both types of measurements.

Till date, to our knowledge, proper in-depth analysis and performance of geo-mechanics related geotechnical tests (SPT, DCPT, SCPT and other similar tests) and geoelectrical characteristics (resistivity, chargeability) governing geoelectric imaging results (ERT and IPI) of near-surface soil have not been thoroughly explored. Sumedha and Sastry (2016) have reported initial multiple regression results concerning geoelectric and geotechnical site investigation results.

So, the present study is devoted to a combined multivariate analysis of both data sets (ERT/IP and SPT) acquired at a study region (construction site for CGEWHO Complex) in Greater Noida, Uttar Pradesh, India with a prime objective of identifying the key factors controlling mechanical and electrical properties of near surface soils. In

this article, section 2 is devoted to methodology and multi-regression analysis, section 3 to discussion and section 4 to conclusions.

2. Methodology

In an experiment, for establishing either a linear or non-linear relationship between independent and dependent variables, one opts for a multiple regression analysis (MRA), which provides additional statistical information about the regression results.

In our case, the chosen independent factors affecting both geotechnical (SPT 'N') and geoelectrical (resistivity and chargeability) parameters are sand (x_1), fines (x_2) and water content (x_3) of near-surface soil. Thus, field test results like SPT 'N', inverted ERT (true resistivity) and IPI (chargeability) logs/sections constitute the dependent parameters.

2.1 Site and geological description

Our study region (figure 1) belongs to Pleistocene–Holocene period (Gupta and Subramanian 1994) and it is located at CGEWHO Complex, Greater Noida (Okhla Industrial Development Authority, NOIDA), a satellite town (28.57°N, 77.32°E) of Delhi. It is bound on the west and south-west by the Yamuna River and by the Hindon River on the north, east and south-east (Kikon and Singh 2014). The soils at the site belong to the 'Indo-Gangetic Alluvium' and are river deposits of the Yamuna and its tributaries (Parkash *et al.*

Table 2. Subsoil borelog at borehole location B35.

Depth (m)	Water table (m)	I.S. classification	Grain size analysis			Liquid limit (%)	Plastic limit (%)	Natural water content (%)
			Gravels (%)	Sand (%)	Fines (%)			
1.5		CL	0.0	13.7	86.3	32.9	19.5	28.5
3.0		SM (NP)	0.0	86.7	13.3	NP	NP	14.4
4.5		SP-SM	0.0	89.2	10.8	NP	NP	27.1
6.0	6.50 ▼	SP-SM	0.0	92.0	8.0	NP	NP	26.6
7.5		SP-SM	0.0	94.2	5.8	NP	NP	24.4
9.0		SP-SM	0.0	93.7	6.3	NP	NP	26.3
10.5		SP	0.0	95.3	4.7	NP	NP	28.2
12.0		SP	0.0	95.5	4.5	NP	NP	25.9
13.5		SP	0.5	95.2	4.3	NP	NP	27.4
15.0		SP	5.3	90.0	4.7	NP	NP	46.9
18.0		SP	1.8	94.7	3.5	NP	NP	30.4
21.0		SP-SM	2.5	91.7	5.8	NP	NP	22.3
24.0		SP/SP-SM	0.5	94.5	5.0	NP	NP	22.9
27.0		CL-ML	0.0	27.0	73.0	25.9	19.1	25.4
30.0		SP/SP-SM	0.0	95.0	5.0	NP	NP	24.1

2001). The Pleistocene and Recent deposits of the Indo-Gangetic Basin (Krishnan 1986) are composed of gravels, sands, silts and clays. The soils at the site classify primarily as sandy silt/clayey silt to about 2–3 m depth, underlain by fine sand to about 15 m depth (Gupta *et al.* 2010).

2.2 Data acquisition, processing and interpretation

Figure 1 depicts the position location of different geoelectrical field profiles and boreholes for SPT studies in the study region. The ERT and IPI data (figure 1) were acquired using SYSCAL Jr. 48 electrode system with a 6-m electrode separation along a profile (A–B) and 8 m along profile (C–D) under Wenner–Schlumberger configuration (Pazdirek and Blaha 1996). Three-fold objectives that govern the choice of electrode separations are outlined in section 3. Data was processed using software PROSYS II and interpreted through software RES2D INV (Loke and Barker 1995). For illustration sake, we consider inverted ERT/IPI sections along Profiles AB and CD with projected nearby SPT boreholes (figure 1), leading to coincident depth-wise SPT ‘N’, true resistivity and chargeability logs for a multiple regression analysis in later sections.

Conventional geotechnical SPT borehole measurements followed by laboratory analysis of soil samples for index properties of soils and subsequent analysis were undertaken. The soil classification is predominantly grain size based. The grain size distribution is carried out by the mechanical

sieve analysis for coarse-grained soils and hydrometer analysis for fine-grained soils (Ranjan and Rao 2000). Further classification is also done on the basis of the plasticity characteristics obtained via the Atterberg limits (for fine-grained soils like, clay and silt) method. A set of standard sieves is used to perform mechanical sieve analysis. Fine-grained soils having more than 50% material passing the No. 200 (0.075 mm sieve) are classified as silt (M) and clay (C), based on their liquid limit and plasticity index (Ranjan and Rao 2000). Soils can have dual symbols. These are used when the percentage of fine-grained fraction lies in the range of 5–12%. Possible dual symbols are GM-ML, GM-MI, GM-MH, GC-CL, GC-CI, GC-CH, SM-ML, SM-MI, SM-MH, SC-CL, SC-CI, SC-CH as per Indian Standard (IS: 1498-1970). Water content is the ratio of the weight of water to the weight of soil solids (%). The moisture content (%) is obtained on basis of laboratory oven drying method. The geotechnical laboratory measurements of each borehole yield depth-wise distribution of sand (%), fines content (%) and water content (%).

For proper correlation of geoelectric data with geotechnical data (SPT ‘N’), we project numerous nearby boreholes on to geoelectric profile sections (ERT/IPI profiles) and consider respective SPT ‘N’, resistivity and chargeability logs for a multi-regression analysis. As units of input data (ERT/IPI, SPT and geotechnical laboratory data) are different, we normalize the individual data (ERT/IPI, SPT and geotechnical laboratory

(A)

(B)

Figure 4. Stack of normalized plots of dependent (SPT 'N', resistivity, chargeability) and independent (sand, fines and water saturation) variables for some boreholes on A-B and C-D profiles (figure 1) (A) Stack plots of normalized (dependent and independent) variables at borehole B13 for profile A-B. N.F., $\bar{x}$, 1σ and 2σ are respectively normalizing factor, mean, standard deviation and two times standard deviations for depth-wise logs of normalized resistivity (NR), chargeability (NC), SPT 'N' (NSPTN), sand (NS), fines (NF) and water content (NW) are respectively shown in panels (a)–(f). (B) Stack plots of normalized (dependent and independent) variables at borehole B-33 for Profile A-B. N.F., $\bar{x}$, 1σ and 2σ are respectively normalizing factor, mean, standard deviation and two times standard deviations for depth-wise logs of normalized resistivity (NR), chargeability (NC), SPT 'N' (NSPTN), sand (NS), fines (NF) and water content (NW) are respectively shown in panels (a)–(f). (C) Stack plots of normalized (dependent and independent) variables at borehole B-35 for profile C-D. N.F., $\bar{x}$, 1σ and 2σ are respectively normalizing factor, mean, standard deviation and two times standard deviations for depth-wise logs of normalized resistivity (NR), chargeability (NC), SPT 'N' (NSPTN), sand (NS), fines (NF) and water content (NW) are respectively shown in panels (a)–(f). (D) Stack plots of normalized resistivity (NR), chargeability (NC), SPT 'N' (NSPTN), sand (NS), fines (NF) and water content (NW) are respectively shown in panels (a)–(f). (E) Stack plots of normalized (dependent and independent) variables at borehole B-36 for profile C-D. N.F., $\bar{x}$, 1σ and 2σ are respectively normalizing factor, mean, standard deviation and two times standard deviations for depth-wise logs of normalized resistivity (NR), chargeability (NC), SPT 'N' (NSPTN), sand (NS), fines (NF) and water content (NW) are respectively shown in panels (a)–(f).

(c)

(D)

Figure 4. (Continued.)

data) sets by their respective maximum values. In order to match the depth-wise sampling of true resistivity and chargeability logs to that of SPT 'N', we adopted cubic splines for mathematical interpolation.

2.3 Multiple-regression analysis results

True resistivity and chargeability sections for two profiles, A–B and C–D with projected geotechnical borehole (SPT) locations are shown in figures 2 and 3, respectively. Details of sub-soil borelogs at borehole location B13 and B35 are provided in tables 1 and 2, respectively.

Before undertaking a multiple regression analysis exercise, all data sets are normalized borehole-wise by respective maxima. MS excel based softwares, Analysis of variance (ANOVA) and Statistical package for social sciences (SPSS) have been used to carry out linear and nonlinear multiple regression analyses respectively.

Figure 4 shows the stacks of normalized plots of both dependent (SPT 'N', true resistivity and true chargeability) and independent variables (sand, fines and water content) of two boreholes each along profiles A–B (figure 4a, b) and C–D (figure 4c, d). These input stacks contain dimensionless variable logs along with vertical bands of their means ($\bar{x}$), $\pm 1\sigma$ ($\bar{x} \pm$ one standard deviation) and $\pm 2\sigma$ ($\bar{x} \pm$ two times standard deviation). The depth-wise variation of any of the dependent/independent variables can be qualitatively analyzed using figure 4. The quantitative results are summarized in figures 5–8. In figures 5–8, we include multi-regression based prediction results concerning a pair of boreholes on each profile (A–B and C–D).

2.3.1 Regression analysis

After performing MRA, one can get regression equation linking independent variables with that of dependent variable along with relevant statistical information in a standard format, often referred to as ANOVA (analysis of variance) table. Besides, comparative plots of original and reconstructed dependent variable versus depth are also provided so that one can judge the quality of a linear regression. If necessary, one can opt for a non-linear multiple regression analysis. The linear multiple regression analysis is dealt in three stages, viz., regression statistics, analysis of

variance (ANOVA) including regression coefficients and prediction quality.

The adjusted R^2 is normally recommended in multiple regression analysis, if more than one independent variable, x exists. Great interest is in R^2 term as it reveals the variation of dependent variable, y_i around $\bar{Y}$ (its mean) is explained by x_{1i} through x_{ni} .

2.3.2 Regression statistics

After performing linear multiple regression analysis, one can get standard outputs as depicted in tables 3 and 4 (for profile A–B) with relevant regression equations. Both these tables refer to same borehole, B13 on Profile A–B. Similar tables for other boreholes on profiles A–B and C–D are not included here, but a gist of all the boreholes appear in tables 5–7.

2.3.3 Analysis of variance (ANOVA)

Here the analysis is carried out in respect of regression, residual and total. Under regression mode (Kleinbaum *et al.* 1988), depending upon the degrees of freedom (df, number of independent variables) the sum of squares (SS), mean square (MS) and F-statistic (F) are evaluated. A low F-test significance (Kleinbaum *et al.* 1988) indicates that results accrued are not random.

3. Discussion

The geoelectric imaging sections clearly indicate that the heterogeneities exist in both lateral and vertical depth directions and nowhere have we assumed a homogeneity condition for our study.

The choice of 6 and 8 m for electrode spacings along geoelectric profiles, A–B and C–D is made on three considerations, viz., expected 1-D subsurface lithologies from geological view point as the site is away from foothills of Himalaya, to match the profile extents with the spread of boreholes in study area and to meet the deep resistivity and chargeability information matching with SPT logs. This choice conforms to our primary goal of multi-regression analysis of resistivity, chargeability and SPT in terms of influencing parameters like sand (%), fines content (%) and water content (%) at different borehole positions.

The present study is a small beginning, which is limited to three independent variables that influence both geoelectric and geotechnical data sets.

Figure 5. Observed and predicted (both linear and non-linear) SPT 'N', chargeability and resistivity curves at B13, profile A–B. (a) SPT 'N' curves. (b) Chargeability curves. (c) Resistivity curves.

Figure 6. Observed and predicted (both linear and non-linear) SPT 'N', chargeability and resistivity curves at B33, profile A–B. (a) SPT 'N' curves. (b) Chargeability curves. (c) Resistivity curves.

Regression Equation:

$$y = -9.155x_1 - 8.216x_2 - 0.180x_3 + 10.28 \text{ (Linear)}$$

$$Y = -23.511x_1 - 13.253x_2 + 4.674x_3 + 4.231x_1^2 - 3.286x_2^2 - 3.956x_3^2 + 19.201 \text{ (Non- Linear)}$$

(a)

Regression Equation:

$$y = 0.149x_1 + 0.145x_2 + 0.0054x_3 + 0.750 \text{ (Linear)}$$

$$y = 1.584x_1 + 0.092x_2 - 0.012x_3 - 0.724x_1^2 + 0.565x_2^2 + 0.016x_3^2 + 0.044 \text{ (Non- Linear)}$$

(b)

Regression Equation:

$$y = 8.260x_1 + 7.555x_2 + 1.330x_3 - 8.753 \text{ (Linear)}$$

$$y = 3.645E-12 \exp(26.64x_1) - 2.006 \exp(-20.981x_2) + 0.094 \exp(2.854x_3) - 0.24 \text{ (Non- Linear)}$$

(c)

Figure 7. Observed and predicted (both linear and non-linear) SPT 'N', chargeability and resistivity curves at B35, profile C-D. (a) SPT 'N' curves. (b) Chargeability curves. (c) Resistivity curves.

(a)

(b)

(c)

Figure 8. Observed and predicted (both linear and non-linear) SPT 'N', chargeability and resistivity curves at B36, profile C–D. (a) SPT 'N' curves. (b) Chargeability curves. (c) Resistivity curves.

Table 5. Summary of multivariate regression analysis results (SPT and chargeability) for profile A–B (figure 1).

Profile A-B (field investigation methods)														
IP (true chargeability inversion error = 1.2%)														
Borehole location	Sts (P -value ≤ 0.05)				Sts (P -value ≤ 0.05)				SPT					
	Sand (x_1) weights	Fines (x_2) weights	Water content, (x_3) weights	Ad R^2 (%)	Prd, ε (%) & Std (%)	Remarks	Sand (x_1) weights	Fines (x_2) weights	W (x_3) weights	Ad R^2 (%)	Prd, ε (%) & Std (%)	Remarks		
B13	1.899	2.141	0.512	F, S, W	50.3	5.8, 8.5	1, 5	1.649	2.477	1.874	F, W	51.8	17.6, 26	1, 5
B23	1.187	1.252	0.137	F, W	76.2	1.3, 2.8	1, 5	2.680	2.176	0.613	W	55.2	7.7, 11.9	1, 5
B24	0.022	0.110	0.110	F, W	66.6	22.8, 5	1, 5	- 0.039	0.495	0.493	F, W	75.1	13.3, 25.4	1, 5
B33	- 0.093	0.012	0.274	W	46.3	4.6, 6.5	1, 5	- 1.543	- 1.177	1.297	S, F, W	74.6	11.6, 23.7	1, 5
B34	0.029	0.039	0.004	F, S, W	93.0	0.09, 0.3	1, 5	- 3.278	- 2.501	0.254	S, F, W	93.8	5.7, 23.7	1, 5

Remarks explained:

1. High adjusted R^2 value, low RMS error and linear multivariate regression analysis is reliable.
2. Low adjusted R^2 value, high RMS error and linear multivariate regression analysis is rejected, non-linear regression to be checked.
3. Low adjusted R^2 value, none of the three independent parameters is statistically significant and linear regression analysis is unreliable.
4. High adjusted R^2 value, high RMS error and linear regression analysis is rejected.
5. Result improved with non-linear multiple regression analysis.

Sts: statistically significant factors, Ad R^2 : adjusted R^2 , Prd: prediction RMS error, Sd: standard deviation, Nor: normalized, S: sand, F: fines, W: water content.

Table 6. Summary of multiple regression analysis results (SPT and chargeability) for profile C–D (figure 1).

Profile C-D (field investigation methods)														
IP (true chargeability inversion error is 1.2%)														
Borehole location	Sts (P -value ≤ 0.05)							Sts (P -value ≤ 0.05)						
	Sand (x_1) weights	Fines (x_2) weights	Water content, (x_3) weights	Ad R^2 (%)	Prd, ε (%) & Std (%)	Remarks	Sand (x_1) weights	Fines (x_2) weights	W (x_3) weights	Ad R^2 (%)	Prd, ε (%) & Std (%)	Remarks		
B1	0.236	0.207	- 0.008	S, F	50.3	1.3, 2	1, 5	0.816	1.286	0.150	32.5	16.7, 20.9	4, 5	
B12	0.015	0.023	0.003		7.5	0.5, 0.5	3, 5	- 2.393	- 2.391	0.638	S, F, W	66.5	7.8, 14.2	1, 5
B35	0.149	0.145	0.005	S, F	59	0.26, 0.4	1, 5	- 9.155	- 8.216	- 0.180	S, F	37	14, 18.2	1, 5
B36	- 0.059	0.006	0.048	W	43.7	2, 2.7	1, 5	- 8.268	- 7.473	0.261	S, F, W	73.7	9, 17.9	1, 5
B37	0.360	0.401	- 0.060	F, S, W	66.2	0.9, 0.15	1, 5	2.595	2.709	- 0.868	F, S, W	45.6	11.1, 15.5	4, 5

Remarks explained:

1. High adjusted R^2 value, low RMS error and linear multivariate regression analysis is reliable.
2. Low adjusted R^2 value, high RMS error and linear multivariate regression analysis is rejected, non-linear regression to be checked.
3. Low adjusted R^2 value, none of the three independent parameters is statistically significant and linear regression analysis is unreliable.
4. High adjusted R^2 value, high RMS error and linear regression analysis is rejected.
5. Result improved with non-linear multiple regression analysis.

Sts: statistically significant factors, Ad R^2 : adjusted R^2 , Prd: prediction RMS error, Sd: standard deviation, Nor: normalized, S: sand, F: fines, W: water content.

Table 7. Summary of multiple regression analysis results for ERT (resistivity) profiles A–B and C–D (figure 1).

Profile A–B (field investigation methods)									
Resistivity (true resistivity inversion error = 1.1%)									
Profile C–D (field investigation methods)									
Resistivity (true resistivity inversion error = 1.16%)									
Borehole location	Sts (P- value ≤ 0.05)			Sts (P- value ≤ 0.05)			Sts (P- value ≤ 0.05)		
	Fines (x ₁) weights	Sand (x ₂) weights	Water content, (x ₃) weights	Fines (x ₁) weights	Sand (x ₂) weights	W (x ₃) weights	Fines (x ₁) weights	Sand (x ₂) weights	W (x ₃) weights
B13	–3.276	–4.151	–0.721	F, S	–0.721	W	–0.203	1.159	W
B23	0.756	0.726	1.778	W	–6.618	0.043	–6.872	0.043	F, S
B24	–1.031	–1.199	–0.492	F, S, W	13.934	11.862	11.862	2.180	S, F, W
B33	–0.202	–0.821	0.906	W	–1.065	–1.629	–1.629	0.327	F, S, W
B34	1.460	0.735	0.479	W	–10.246	–10.904	–10.904	0.830	F, S, W

Remarks explained:

1. High adjusted R^2 value, low RMS error and linear multivariate regression analysis is reliable.
2. Low adjusted R^2 value, high RMS error and linear multivariate regression analysis is rejected, non-linear regression to be checked.
3. Low adjusted R^2 value, none of the three independent parameters is statistically significant and linear regression analysis is unreliable.
4. High adjusted R^2 value, high RMS error and linear regression analysis is rejected.
5. Result improved with non-linear multiple regression analysis.

Sts: statistically significant factors, Ad R^2 : adjusted R^2 , Prd: prediction RMS error, Sd: standard deviation, S: sand, F: fines, W: water content.

be extended to other index properties of soils and influencing parameters. In all such cases, one should have access to quantifiable independent parameters at large number of boreholes, which can be correlated with geoelectric logs at their respective positions on relevant profiles (ref. figure 1).

The multiple regression analysis shows that the factors influencing the measurements are site-specific and subsurface lithology dependent. As an example, multiple regression results for SPT and IPI for borehole location B13 (profile A–B, figure 1) are shown in tables 3 and 4. Similar analysis was made for all boreholes on both profiles, A–B and C–D (figure 1). Accrued linear multiple regression results are included in tables 5 and 6 and that of ERT separately in table 7. We tried nonlinear multiple regression and the results got improved. A comparative linear versus nonlinear multiple regression results are included in table 8.

In linear multiple regression cases of bad performance, implementation of nonlinear regression (tables 5–7) has led to a better prediction of dependent parameters (SPT, chargeability and resistivity). High prediction error for SPT (figures 5a, 6a, 7a and 8a) can be attributed to the data scatter shown for profiles A–B and C–D in figure 4(a–d). In the same vein, the better performance of IPI (figures 5b, 6b, 7b and 8b) can also be similarly explained. However, ERT fared badly in the study region mainly due to predominance of subsurface clay and non-inclusion of salinity factor as an independent variable. Further, resistivity is related to chosen independent parameters broadly in a non-linear fashion. A quantitative salinity estimate of soil water content in independent set of parameters in multiple regression study could have led to a better prediction of resistivity. However, the earlier arguments go in favour of its non-inclusion.

In the present study, ad $R^2 \leq 30\%$ is treated as low (tables 5–7) for predicted SPT-N, ERT (resistivity) and IPI (chargeability). Accordingly, tables 5–7 carry abbreviated remarks, which were explained in the respective footnotes.

4. Conclusions

In order to use geoelectric imaging in geotechnical site investigations, a multiple regression analysis of both geoelectric imaging and geotechnical site investigation results is a must. Results achieved in the present study indicate that sand, fines and

Table 8. RMS error details in predicting SPT 'N', chargeability and resistivity through multi-variate regression analysis (linear and non-linear) for borehole locations falling on profiles A–B and C–D (figure 1).

Borehole no.	RMS error (%)					
	SPT 'N'		Chargeability		Resistivity	
	Linear	Nonlinear	Linear	Nonlinear	Linear	Nonlinear
B1	16.7	11.3	1.3	1	15.3	13.2
B12	7.8	6.2	0.5	0.4	30.1	26.7
B13	17.6	7	5.8	4	17.3	14.6
B23	7.7	6.5	1.3	0.5	15.7	13.2
B24	12.3	10.4	2.8	2.5	18.8	16
B33	11.6	10.7	4.6	4	22	20.7
B34	5.7	4.5	0.09	0.05	28	26.7
B35	14	10.3	0.26	0.24	21.9	18.5
B36	9	5	2	1.7	28.1	26.6
B37	11.1	9.2	0.9	0.8	24.2	24
Average error	11.35	8.11	1.96	1.52	22.14	20.02
Decrease in error (%) from linear to nonlinear		28.55		22.45		9.58

water content influence both geoelectric imaging (ERT/IPI) and geotechnical site investigation test (SPT) results. The contribution of different formation parameters is similar in majority of cases for geoelectrical (IP) and geotechnical (SPT) parameters. Also, SPT test results are predicted with high error in comparison to IP test results. It may indicate inclusion of additional independent parameters (plasticity index, pore pressure coefficient, over-consolidation ratio) for improving the regression performance of SPT. But any such choice is constrained by their influence on other dependent variables. Our results indicate that both geoelectric and geotechnical test results are affected predominantly non-linearly by sand, fines and water content of subsurface and the extent of their exact influence is guided by local near-surface lithological variations. Thus, this study will provide a basic logic in the conjunctive use of non-invasive and cost-effective geoelectric imaging and minimum invasive geotechnical test results in geotechnical characterization of a project site.

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