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# The empirical relationship between soil resistivity and soil strength parameters as an alternative to soil investigation

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## ABSTRACT

The present study involves the correlation of field electrical resistivity with strength properties of soil along Sunwal to Lamahi section of New Butwal 400kv transmission line alignment. Geologically the area is located in Quaternary deposit of Terai plain and Siwalik. The objective of this study is to find out correlation and empirical relationships between field electrical resistivity with strength properties of soil such as Cohesion (c), Internal Angle of Friction (ø), Moisture Content (w), Bulk Density (d) and Fine Content (fc). To obtain the results, undisturbed samples from thirty six number of test pits up to 3.0m depth and five number of boreholes up to 10.0m depth were extracted by using split-spoon sampler. These samples were tested in the laboratory of Geological Investigation Department and soil strength parameters were calculated. The field resistivity values were computed by using Wenner Alpha arrangement. The resistivity values up to 10.0 m depth for boreholes and up to 3.0m depth of test pits were taken for the analysis. The results obtained were compared and correlated with soil strength properties obtained from boreholes and test pits. Results from both the laboratory tests and field electrical resistivity tests indicate that there is consistent in the correlation between the resistivity and soil strength properties. The regression plots of the electrical resistivity (ρ) values against each of the determined strength parameters shows an empirical relationship ø = 2.2167ln (ρ) + 19.671, c = 25.143e-0.005ρ, w = 131.52 ρ -0.499, d = 0.0009ρ + 1.1697 and fc = 83.256e-0.004ρ with Angle of Internal Friction, Cohesion, Moisture Content, Bulk Density and Fine Content respectively.

**Keywords**: Correlation; Strength properties; Geotechnical; Electrical resistivity

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## INTRODUCTION

For several decades, geophysical prospecting method coupled with geotechnical analysis has become increasingly useful in evaluating the subsurface for both pre and post engineering investigations. Shallow geophysical tool is indirect method to evaluate subsurface soil for engineering study to obtain comparative information such as subsurface lithology and their thicknesses, competence and depths to its upper interface, and competence of the material that make up the overburden, especially the shallow section which serves as host for foundations of engineering structures (Aina et al., 1996; Adewumi and Olorunfemi, 2005; and Idornigie et al., 2006). Moreover, direct geotechnical investigation helps to calculate exact value of geotechnical parameter. This information assist the engineers to locate and design the foundation of engineering structure accurately. Lack of knowledge of the properties of subsurface may leads to the failure of most engineering structures. Therefore, it is of great importance to carry out a pre-construction investigation of a proposed site before design in order to ascertain the fitness of the material. The pre-construction investigation may involve direct mechanical boring, pitting and trenching for subsoil sequence delineation, groundwater table mapping, soil sampling, and geotechnical laboratory analysis. It may also involve non-invasive geophysical investigation (Olorunfemi et al., 2010). Where site investigation involves both geotechnical and geophysical methods, it is often to reduce the investigation cost (by reducing the number of test pits) and improve on the subsoil imaging through 1-D and 2-D geophysical data gathering and modeling (Olorunfemi and Mesida, 1987; Barker, 1997; and Olorunfemi, 2008). Geophysical investigations are mostly non-invasive whereas geo technical investigations are mostly invasive. Compact subsoil is characterized by reduced porosity and moisture content with consequent increase in electrical resistivity. It is therefore possible to use electrical resistivity measurements as indices of subsoil competence and other engineering properties.

This research is aimed for establishing a relationship between electrical resistivity and several geotechnical parameters in the form of an empirical equation. To fulfill the objective of this research, the study area is selected along Sunwal to Lamahi section of New Butwal 400kv transmission line alignment. In total forty two tower locations were chosen for the analysis and among these twenty one locations are situated at residual and colluvial soil deposits of Siwalik and twenty one points are in Quaternary deposits of Terai Plain. In total of fifty eight soil samples were collected and tested in laboratory for angle of internal friction, cohesion, moisture content, fine content and bulk density.

## GEOLOGICAL SETTING

The study area is located long Sunwal to Lamahi section of New Butwal 400kv transmission line alignment as shown in Fig. 1. In total forty two tower locations were chosen for the analysis and among these twenty two locations are situated at residual and colluvial soil deposits of Siwalik and twenty two points are in Quaternary deposits of Terai Plain as tabulated in Table 1.

**Table 1: Location of transmission towers with lithology of study area**

| S.N | Lithostratigraphy | Transmission tower/Angle point |
|---|---|---|
| 1 | Quaternary Deposit of Terai | AP1, AP3N, AP4N, AP5N, T26, AP8, AP9, T58, , AP30, AP32, AP34, AP38,T192A, AP41, T235, AP49, T356 AP74, T369, T382, T387 |
| 2 | Lower Siwalik | AP7B AP7C, T77, T78 AP12A, AP12D, , AP12GN, T88, T114 T118, AP 22N, AP23N, T133, AP28, AP49, T348, T402 T407, AP87, T432 |
| 4 | Upper Siwalik | AP60 |

Main objectives and scopes of present study are as follows:

To carry out field investigation works to acquire geotechnical parameters (direct method) and resistivity (indirect method) of the sub-surface strata for the establishment of empirical relationship along the study area. Exploratory core drilling (five locations) and test pits excavation (thirty seven locations) with standard penetration tests and laboratory tests of soil samples retrieved from SPT for the calculation of geotechnical parameters. Soil resistivity test of forty two locations to determine soil resistivity of respected locations.

## MATERIALS AND METHODS

The primary data for the analysis of this study was carried out by two investigative methods: either through a destructive (direct) method or a non-destructive (indirect) method. Direct method included borehole drilling, test pitting and laboratory test of soil samples however resistivity test of soil was applied as an indirect technique. The boreholes were drilled in five locations up to the depth of 15m but the samples were collected only up to the depth of 10m because the resistivity data were also taken up to the same depth. In thirty seven locations, test pits were excavated with maximum dimensions 3m*3m*3m. Altogether forty two respective locations were selected for the data collection to the correlate the soil strength parameters and soil resistivity of soil.

To obtain the soil strength parameters fifty eight disturbed soil samples of different locations and depths were collected and carried to the laboratory. Angle of internal friction, cohesion, moisture content, fine content and bulk density were calculated of these soil samples.

Wenner's 4 pole methods was used in determining the soil resistivity of the study locations. In this method, 4 electrodes were used (4 electrodes embedded to the ground in straight line along North-South and East-West directions) out of which 2 electrodes were responsible for current flow through the ground and the remaining 2 electrodes were used for measurement of voltage. Basically, the Werner 4 pole arrangement is used as in Fig. 2. From Fig. 2, it can be seen that 'a' is the distance


**Fig. 1: Geological map of the study area (After DMG 1983).**

between two electrodes (Electrode spacing). The depth of the electrodes should not exceed 1/20th or less of electrode spacing 'a'. Using the above arrangement, the resistance can be measured using the following equation:

$$\rho = 2.\pi.a.R$$

Where, ρ = resistivity in Ω m, R= resistance in Ω and

a= spacing between electrodes in meter

If the depth of electrode 'b' is not less than 1/20th of spacing 'a', then the general formula is

$$\rho = \frac{4\pi aR}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}}$$

Where, ρ = resistivity in Ω m,

R= resistance in Ω,

a= spacing between electrodes in meter and b=depth of electrode in meter

The AEMC earth resistance tester instrument (Model 6472) was used to measure the resistivity of soil which is shown in Fig. 3. The received data from this instrument was transferred via DataView® software for data storage, real-time display, analysis, report generation and system configuration.

The results obtained from soil resistivity tests from field and laboratory tests for soil strength properties (angle of internal friction, cohesion, moisture content, fine content and bulk density) were correlated. The correlations between soil resistivity and strength properties of the soil samples were evaluated using least-squares regression linear, logarithmic, polynomial, exponential, and power curve fitting approximations methods. The approximation equations with correlation coefficient were obtained. The correlation and regression was processed by using Microsoft Excel.

## DISCUSSION AND INTERPRETATION

Relationship between soil strength parameters and resistivity value of soil are demonstrated shown in Fig. 4, FIg. 5, Fig. 6, Fig. 7, and Fig. 8). The regressions show moderate correlations between these variables with coefficient of determination ranges from R2 = 0.5031 to 0.6508. From the regression lines of angle of internal friction, cohesion, moisture content, fine content and bulk density with resistivity values of respected depth, the empirical formula is developed for the soil samples of study area.

### Relationship between angle of internal friction and resistivity of soil

The correlation between angle of internal friction and soil resistivity values is depicted in Fig. 4 and field data of resistivity values and angle of internal friction of different locations with respective depth is tabulated in Table 2. The produced regression trend shows a non-linear (Logarithmic) relationship with the coefficient of determination, $R^2$ was equal to 0.5175 with Angle of internal friction and Resistivity. The potential reason that attributes to the high friction angle is due to the low moisture content. The factor for the increment angle of friction is due to high percentage of sand composition and hence, it triggers the resistivity to be increased. Moreover, soil porosity could also the reason for this increasing trend. Generally, porosity will affect the pore size and air voids volume which in turn the saturation degree to be lower or higher. Saturated pores can create bridges between particles and develops particle contact (Nimmo, 2004, Santamarina and Cho, 2015)). Thus, lower and higher resistivity in function with friction angle of soil material is the results of the mentioned statement. The equation to calculate friction angle from resistivity is given as follow;

$$\varphi = 2.2167\ln(\rho) + 19.671$$

Where, **ρ** is the resistivity of soil (Ω.m) and ø is friction angle.

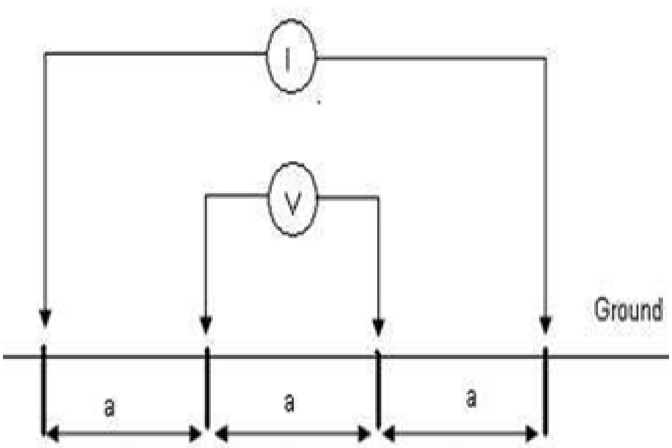


**Fig. 2: Wenner's four pole arrangement.**

**Fig. 3: AEMC earth resistance tester model 6472.**

**Table 2: Location wise data of angle of internal friction and resistivity of soil.**

| Locations | Depth (m) | Angle of internal friction(ϕ) degree | Resistivity value (ρ) Ωm | Remarks | Locations | Depth (m) | Angle of internal friction(ϕ) degree | Resistivity value (ρ) Ωm | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| **AP1** | 1.5 | 30.9 | 108.76 | Soil Samples extracted by rotary drilling | T78 | 3 | 30.3 | 79.11 | Soil Samples extracted by test pitting |
| | 3 | 32.3 | 111.13 | | AP12A | 3 | 31.2 | 42.73 | |
| | 5 | 31.3 | 89.45 | | AP12D | 1.5 | 29.55 | 232.6 | |
| | 10 | 27.9 | 77.42 | | AP12G | 1.5 | 31.4 | 95.81 | |
| **T58** | 3 | 30.3 | 160.29 | | AP12GN | 3 | 30.4 | 156.1 | |
| | 5 | 25 | 56.29 | | AP13N | 1.5 | 32.6 | 147.34 | |
| | 7.5 | 27.3 | 43.23 | | T114 | 1.5 | 29.8 | 49.7 | |
| | 10 | 27.54 | 57.62 | | AP19 | 3 | 30.7 | 89.15 | |
| **T166/Ap30** | 1.5 | 34.6 | 511.1 | | AP22N | 3 | 27 | 11.78 | |
| **T427** | 1.5 | 27.3 | 51.05 | | AP23N | 3 | 32.5 | 115.4 | |
| | 3 | 27 | 50.7 | | T133 | 3 | 31.8 | 202.5 | |
| | 5 | 27.3 | 37.07 | | AP28 | 1.5 | 28.65 | 146.4 | |
| | 7.5 | 27.95 | 38.11 | | AP32 | 3 | 25.65 | 82.54 | |
| | 10 | 26.3 | 41.05 | | AP 34 | 1.5 | 31.26 | 138.25 | |
| **T432** | 1.5 | 26 | 17.31 | | | 3 | 32.12 | 176.94 | |
| | 3 | 28.7 | 20.25 | | AP38 | 3 | 24.9 | 80.8 | |
| | 5 | 30.96 | 26.78 | | T192A | 3 | 34.7 | 257.12 | |
| | 10 | 30.2 | 26.68 | | AP41 | 3 | 28.5 | 63.35 | |
| **AP3N** | 3 | 29.6 | 153.6 | Soil Samples extracted by test pitting | T235 | 3 | 26.17 | 19.7 | |
| **AP4N** | 3 | 31.9 | 159.29 | | AP49 | 3 | 26.8 | 32.3 | |
| **AP5N** | 3 | 34.97 | 517.59 | | AP60 | 3 | 28.97 | 61.91 | |
| **AP7B** | 3 | 29.4 | 321.66 | | T348 | 1.5 | 25.8 | 51.4 | |
| **AP7C** | 3 | 33.9 | 414.03 | | T356 | 3 | 26.7 | 17.605 | |
| **T26** | 3 | 33.29 | 425.19 | | AP74 | 3 | 24.9 | 21.5 | |
| **AP8** | 1.5 | 35.5 | 277.75 | | T369 | 3 | 31.3 | 161.68 | |
| **AP9** | 3 | 28.1 | 119.86 | | T382 | 1.5 | 24.7 | 36.81 | |
| **T77** | 3 | 26.9 | 57.74 | | AP79 | 1.5 | 30.8 | 48.01 | |

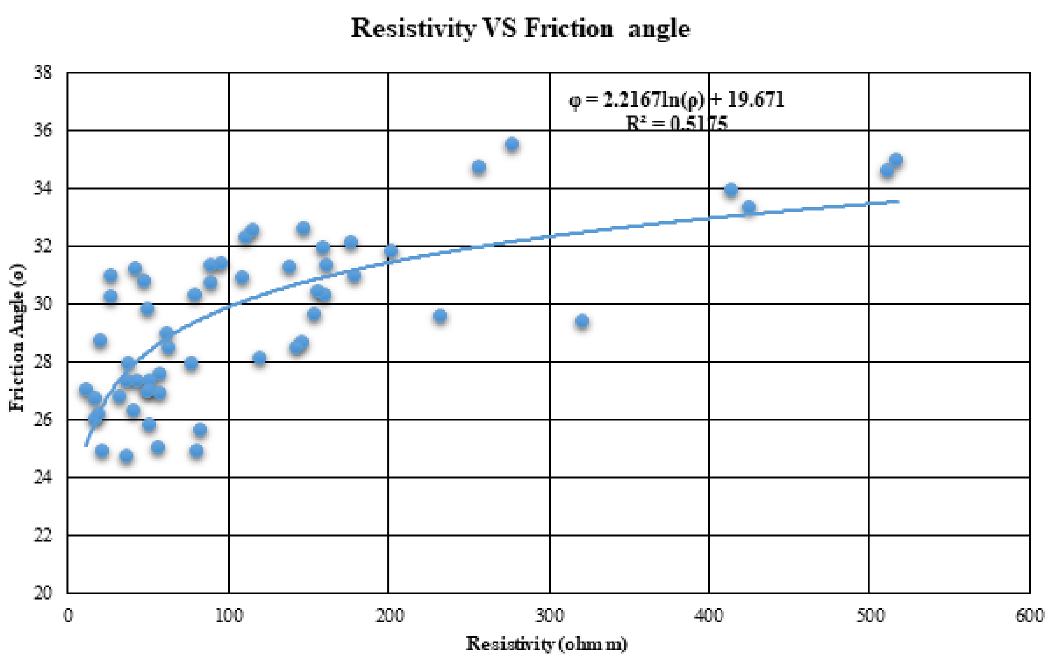


**Fig. 4: Correlation between resistivity and angle of internal friction.**

**Relationship between cohesion and resistivity of soil**

The regression trend of cohesion and soil resistivity is shown in Fig. 5 and data are tabulated in table 3. The result presents a moderate relationship between cohesion and resistivity with coefficient of determination $R^2 = 0.523$ as shown in Fig. 5. Referring to obtained relationship, it can be concluded that resistivity value increases with decrease of cohesion. The reason behind this phenomenon is due to soil becomes sandy and at this point the cohesion will be less (Fenton and Griffiths, 2003). Hence, the moisture content will also be less. This is associated with its density, compression of clay particle and bonding between the particles of very fine clay (Keper et al. 1987)

The produced empirical formula for cohesion(c) calculation from resistivity is given as follow;

$$\mathbf{c = 25.143e^{-0.005\rho}}$$

Where **c** is cohesion of soil and **ρ** is resistivity of soil.

**Table 3: Location wise cohesion and resistivity data of soil.**

| Location | Depth (m) | Cohesion (KN/m²) | Resistivity value (ρ) Ωm | Remarks |
|---|---|---|---|---|
| **AP1** | 1.5 | 13.17 | 108.76 | Soil samples extracted by rotary drilling |
| | 3 | 9.15 | 111.13 | |
| | 5 | 15.6 | 89.45 | |
| | 10 | 17.7 | 77.42 | |
| **T58** | 3 | 0.4 | 160.29 | |
| | 5 | 0 | 56.29 | |
| | 7.5 | 19.7 | 43.23 | |
| | 10 | 18.2 | 57.62 | |
| **T166/Ap30** | 1.5 | 12.47 | 511.1 | |
| **T427** | 1.5 | 19.1 | 51.05 | |
| | 3 | 20 | 50.7 | |
| | 5 | 20 | 37.07 | |
| | 7.5 | 16.7 | 38.11 | |
| | 10 | 21.5 | 41.05 | |
| **T432** | 1.5 | 23.9 | 17.31 | |
| | 3 | 17.1 | 20.25 | |
| | 5 | 10.94 | 26.78 | |
| | 10 | 9.4 | 26.68 | |
| **AP3N** | 3 | 12.5 | 153.6 | Soil Samples extracted by test pitting |
| **AP4N** | 3 | 7 | 159.29 | |
| **AP5N** | 3 | 0 | 517.59 | |
| **AP7B** | 3 | 15.5 | 321.66 | |
| **AP7C** | 3 | 10.9 | 414.03 | |
| **T26** | 3 | 11.85 | 425.19 | |
| **AP8** | 1.5 | 0 | 277.75 | |
| **AP9** | 3 | 22 | 119.86 | |
| **T77** | 2.4(3) | 18.8 | 57.74 | |

| Location | Depth (m) | Cohesion (KN/m²) | Resistivity value (ρ) Ωm | Remarks |
|---|---|---|---|---|
| T78 | 3 | 12.8 | 79.11 | Soil Samples extracted by test pitting |
| AP12A | 3 | 10.7 | 42.73 | |
| AP12D | 1.5 | 12 | 232.6 | |
| AP12G | 2 | 11.3 | 95.81 | |
| AP12GN | 3 | 14.9 | 156.1 | |
| AP13N | 1.5 | 10 | 147.34 | |
| T114 | 1.2 | 12.8 | 49.7 | |
| AP19 | 3 | 6.1 | 89.15 | |
| AP22N | 3 | 20.5 | 11.78 | |
| AP23N | 3 | 11.6 | 115.4 | |
| T133 | 3 | 14.6 | 202.5 | |
| AP28 | 1.5 | 18 | 146.4 | |
| AP32 | 3 | 0 | 82.54 | |
| AP 34 | 1.5 | 25.2 | 138.25 | |
| | 3 | 20.9 | 176.94 | |
| AP38 | 3 | 0.35 | 80.8 | |
| T192A | 3 | 0 | 257.12 | |
| AP41 | 3 | 15.9 | 63.35 | |
| T235 | 3 | 22.76 | 19.7 | |
| AP49 | 3 | 20 | 32.3 | |
| AP60 | 3 | 16.4 | 61.91 | |
| T348 | 1.5 | 4 | 51.4 | |
| T356 | 3 | 20.3 | 17.605 | |
| AP74 | 3.1 | 11.25 | 21.5 | |
| T369 | 3 | 8.8 | 161.68 | |
| T382 | 1.5 | 6.4 | 36.81 | |
| AP79 | 1.5 | 8.8 | 48.01 | |

### Relationship between moisture content and resistivity of soil

Generally the electrical resistivity of subsoil decreases with increasing moisture content (Fahad et al. (2012)). Ozcep et al conducted research on correlation between electrical resistivity and soil water content. Relationship between moisture content and resistivity values obtained shows moderate non-linear correlations (Fig. 6 and table 4) between these two variables with coefficient of determination $R^2$ = 0.6321. From the regression line of moisture content and resistivity values, the empirical formula is developed for the soil samples of investigated area as follows:

$$\mathbf{w = 131.52\ \rho^{-0.499}}$$

Where w is moisture content and **ρ** is the resistivity of soil.

Previous studies also showed resistivity value decreases with increasing soil moisture content. At low moisture content, the movement of ions in the pore water is limited, which tends to oppose or reduce the conduction of electrical current in soil.

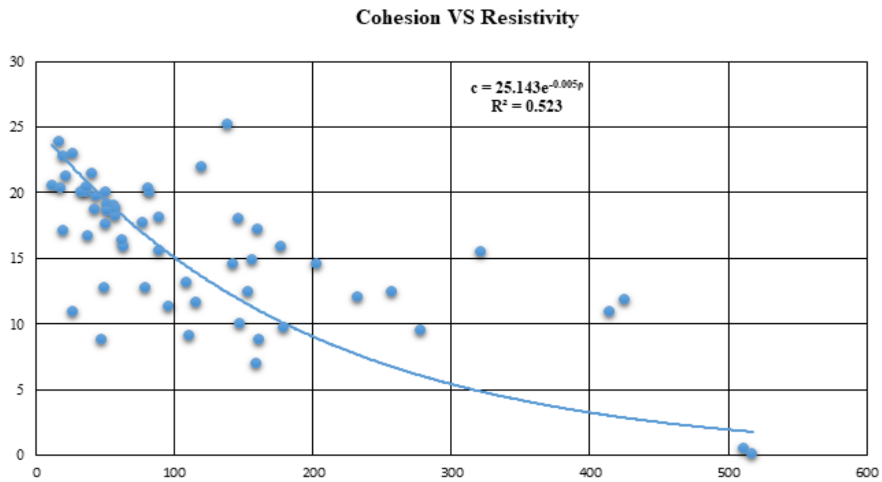


**Fig. 5: Correlation between resistivity and cohesion.**

**Table 4: Location wise moisture content and resistivity data of soil.**

| Location | Depth (m) | Moisture Content (%) | Resistivity value (ρ) Ωm | Remarks |
|---|---|---|---|---|
| AP1 | 1.5 | 20.76 | 108.76 | Soil samples extracted by rotary drilling |
| | 3 | 20.25 | 111.13 | |
| T58 | 3 | 9.52 | 160.29 | |
| T166/Ap30 | 1.5 | 4.9 | 511.1 | |
| T427 | 1.5 | 24.23 | 51.05 | |
| | 3 | 4.19 | 50.7 | |
| T432 | 1.5 | 9.89 | 17.31 | |
| | 3 | 4.36 | 20.25 | |
| AP3N | 3 | 18.55 | 153.6 | Soil Samples extracted by test pitting |
| AP4N | 3 | 9.57 | 159.29 | |
| AP5N | 3 | 5.54 | 517.59 | |
| AP7B | 3 | 12.78 | 321.66 | |
| AP7C | 3 | 20.17 | 414.03 | |
| T26 | 3 | 16.65 | 425.19 | |
| AP8 | 1.5 | 6.24 | 277.75 | |
| AP9 | 3 | 21.12 | 119.86 | |
| T77 | 3 | 19.57 | 57.74 | |
| T78 | 3 | 16.32 | 79.11 | |
| AP12A | 1.5 | 10.73 | 42.73 | |
| AP12D | 1.5 | 7.09 | 232.6 | |
| AP12G | 1.5 | 9.54 | 95.81 | |
| AP12GN | 3 | 12.61 | 156.1 | |

| Location | Depth (m) | Moisture Content (%) | Resistivity value (ρ) Ωm | Remarks |
|---|---|---|---|---|
| AP13N | 1.5 | 6.84 | 147.34 | Soil Samples extracted by test pitting |
| T114 | 1.5 | 6.93 | 49.7 | |
| AP19 | 3 | 7.92 | 89.15 | |
| AP22N | 3 | 24.54 | 11.78 | |
| AP23N | 3 | 10.9 | 115.4 | |
| T133 | 3 | 10.92 | 202.5 | |
| AP28 | 1.5 | 4.69 | 146.4 | |
| AP32 | 1.5 | 24.4 | 82.54 | |
| AP38 | 3 | 18.5 | 80.8 | |
| T192A | 1.5 | 12.32 | 257.12 | |
| AP41 | 3 | 24.43 | 63.35 | |
| T235 | 3 | 23.91 | 19.7 | |
| AP49 | 3 | 14.16 | 32.3 | |
| AP60 | 3 | 4.94 | 61.91 | |
| T348 | 1.5 | 23.77 | 51.4 | |
| T356 | 3 | 23.19 | 17.605 | |
| AP74 | 3 | 23.66 | 21.5 | |
| T369 | 3 | 7.39 | 161.68 | |
| T382 | 1.5 | 22.87 | 36.81 | |
| AP79 | 1.5 | 23.6 | 48.01 | |
| T402 | 3 | 21.84 | 50.59 | |
| T407 | 1 | 7.69 | 178.69 | |

**Relationship between fine content and resistivity of soil**

The regression trend of fine content and soil resistivity is shown in Fig. 7 and the field data of resistivity and laboratory data of fine content is tabulated in Table 5. The result presents a moderate non-linear relationship between fine content and resistivity with coefficient of determination $R^2$ = 0.6508. Referring to obtained relationship, it can be concluded that resistivity value increases with decrease of fine content. The reason behind this capacity to hold water by fine soil is higher than sandy soil hence, the moisture content may be less in non-cohesive soil.

The produced empirical formula for fine content (fc) calculation from resistivity is given as follow;

$$\mathbf{fc = 83.256e^{-0.004\,\rho}}$$

Where **fc** is fine content and **ρ** is resistivity of soil.

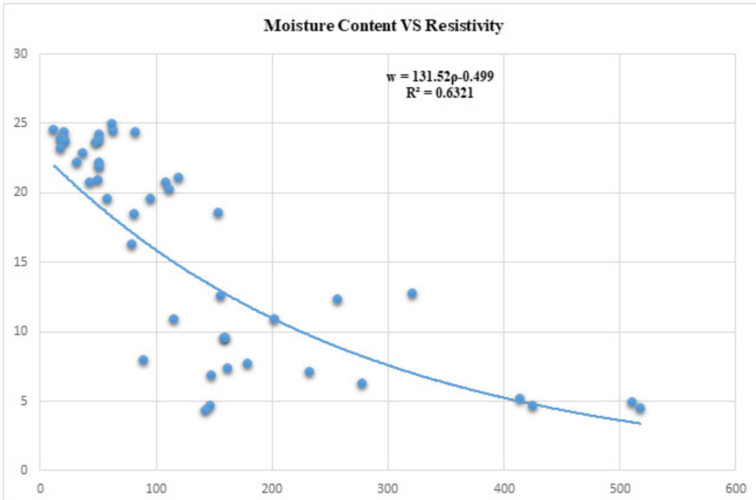


**Fig. 6: Correlation between resistivity and moisture content.**

**Table 5: Location wise fine content and resistivity data of soil.**

| Location | Depth (m) | Fine content (%) | Resistivity value (ρ) Ωm | Remarks |
|---|---|---|---|---|
| AP1 | 1.5 | 69.44 | 108.76 | Soil samples extracted by rotary drilling |
| | 3 | 43.9 | 111.13 | |
| T58 | 3 | 42.45 | 160.29 | |
| T166/Ap30 | 1.5 | 3.12 | 511.1 | |
| T427 | 1.5 | 74 | 51.05 | |
| | 3 | 87.12 | 50.7 | |
| T432 | 1.5 | 81.07 | 17.31 | |
| | 3 | 63.7 | 20.25 | |
| AP3N | 3 | 52.87 | 153.6 | Soil Samples extracted by test pitting |
| AP4N | 3 | 33.37 | 159.29 | |
| AP5N | 3 | 9.75 | 517.59 | |
| AP7B | 3 | 56.24 | 321.66 | |
| AP7C | 3 | 15.56 | 414.03 | |
| T26 | 3 | 16.35 | 425.19 | |
| AP8 | 1.5 | 57.05 | 277.75 | |
| AP9 | 3 | 97.53 | 119.86 | |
| T77 | 3 | 72.62 | 57.74 | |
| AP12A | 1.5 | 43.08 | 42.73 | |
| AP12D | 1.5 | 53.22 | 232.6 | |
| AP12G | 2 | 40.45 | 95.81 | |
| AP12GN | 3 | 58.37 | 156.1 | |
| AP13N | 1.5 | 36.16 | 147.34 | |

| Location | Depth (m) | Fine content (%) | Resistivity value (ρ) Ωm | Remarks |
|---|---|---|---|---|
| T114 | 1.5 | 52.67 | 49.7 | Soil Samples extracted by test pitting |
| AP19 | 3 | 30.03 | 89.15 | |
| AP22N | 3 | 75.51 | 11.78 | |
| AP23N | 3 | 30.49 | 115.4 | |
| T133 | 3 | 44.27 | 202.5 | |
| AP28 | 1.5 | 75.39 | 146.4 | |
| AP32 | 1.5 | 8.22 | 82.54 | |
| AP38 | 3 | 15.16 | 80.8 | |
| T192A | 1.5 | 3.08 | 257.12 | |
| AP41 | 3 | 66.13 | 63.35 | |
| T235 | 3 | 88.13 | 19.7 | |
| AP49 | 3 | 81.41 | 32.3 | |
| AP60 | 3 | 55.85 | 61.91 | |
| T348 | 1.5 | 28.34 | 51.4 | |
| T356 | 3 | 91.62 | 17.605 | |
| AP74 | 3 | 49.36 | 21.5 | |
| T369 | 3 | 42.07 | 161.68 | |
| T382 | 1.5 | 28.08 | 36.81 | |
| AP79 | 1.5 | 47.76 | 48.01 | |
| T402 | 3 | 75.56 | 50.59 | |
| T407 | 1.5 | 46.09 | 178.69 | |
| | 3 | 60.44 | 142.825 | |

### Relationship between bulk density and resistivity of soil

The regression trend of bulk density and soil resistivity obtained from the tabulated data of table 6 is shown in Fig. 8. The result presents a moderate linear relationship between bulk density and resistivity with coefficient of determination $R^2 = 0.5031$. On the basis of obtained relationship, it can be concluded that resistivity value increases with increases bulk density. The produced empirical formula for bulk density (d) calculation from resistivity is given as follow;

$$\mathbf{d = 0.0009\ \rho + 1.1697}$$

Where **d** is bulk density and **ρ** is resistivity of soil.

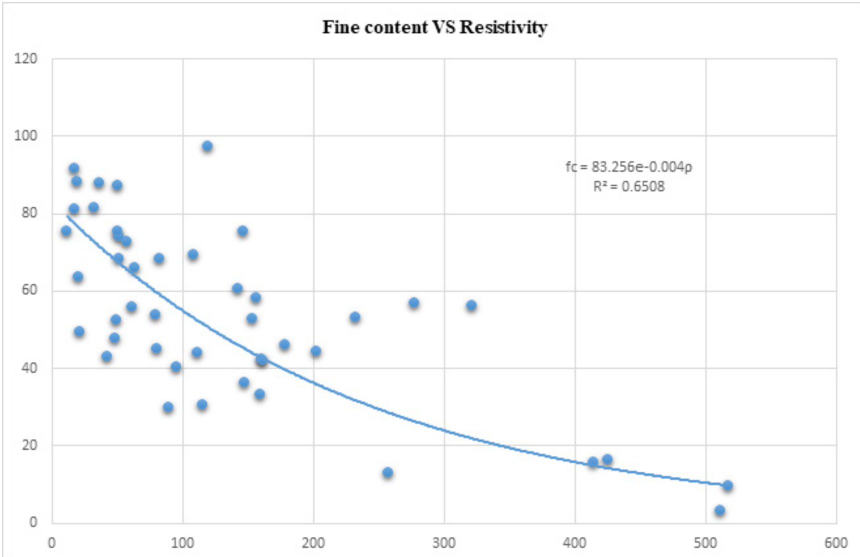


**Fig. 7: Correlation between resistivity and fine content.**

**Table 6: Location wise bulk density and resistivity data of soil.**

| Location | Depth (m) | Bulk density (gm/cm$^3$) | Resistivity value (ρ) Ωm | Remarks |
|---|---|---|---|---|
| AP1 | 1.5 | 1.52 | 108.76 | Soil samples extracted by rotary drilling |
| | 3 | 1.23 | 111.13 | |
| | 5 | 1.18 | 89.45 | |
| | 10 | 1.17 | 77.42 | |
| T58 | 3 | 1.58 | 160.29 | |
| | 5 | 1.13 | 56.29 | |
| | 7.5 | 1.48 | 43.23 | |
| | 10 | 1.26 | 57.62 | |
| T166/Ap30 | 1.5 | 1.59 | 511.1 | |
| T427 | 1.5 | 1.12 | 51.05 | |
| | 3 | 1.33 | 50.7 | |
| | 5 | 1.11 | 37.07 | |
| | 7.5 | 1.11 | 38.11 | |
| | 10 | 1.21 | 41.05 | |
| | 5 | 1 | 26.78 | |
| | 10 | 1.32 | 26.68 | |
| AP3N | 3 | 1.34 | 153.6 | Soil Samples extracted by test pitting |
| AP4N | 3 | 1.41 | 159.29 | |
| AP5N | 3 | 1.72 | 517.59 | |
| AP7B | 3 | 1.31 | 321.66 | |
| AP7C | 3 | 1.37 | 414.03 | |
| T26 | 3 | 1.42 | 425.19 | |
| AP8 | 1.5 | 1.63 | 277.75 | |
| AP9 | 3 | 1.28 | 119.86 | |
| T77 | 3 | 1.13 | 57.74 | |
| T78 | 3 | 1.18 | 79.11 | |

| Location | Depth (m) | Bulk density (gm/cm3) | Resistivity value (ρ) Ωm | Remarks |
|---|---|---|---|---|
| AP12A | 1.5 | 1.19 | 42.73 | Soil Samples extracted by test pitting |
| AP12D | 1.5 | 1.31 | 232.6 | |
| AP12G | 1.5 | 1.21 | 95.81 | |
| AP12GN | 3 | 1.24 | 156.1 | |
| AP13N | 1.5 | 1.27 | 147.34 | |
| T114 | 1.5 | 1.19 | 49.7 | |
| AP19 | 3 | 1.35 | 89.15 | |
| AP22N | 3 | 1.15 | 11.78 | |
| AP23N | 3 | 1.19 | 115.4 | |
| T133 | 3 | 1.43 | 202.5 | |
| AP28 | 1.5 | 1.32 | 146.4 | |
| AP32 | 1.5 | 1.43 | 82.54 | |
| AP38 | 3 | 1.39 | 80.8 | |
| T192A | 1.5 | 1.61 | 257.12 | |
| AP41 | 3 | 1.25 | 63.35 | |
| T235 | 3 | 1.17 | 19.7 | |
| AP49 | 3 | 1.15 | 32.3 | |
| AP60 | 3 | 1.29 | 61.91 | |
| T348 | 1.5 | 1.35 | 51.4 | |
| T356 | 3 | 1.09 | 17.605 | |
| AP74 | 3 | 1.22 | 21.5 | |
| T369 | 3 | 1.22 | 161.68 | |
| T382 | 1.5 | 1.21 | 36.81 | |
| AP79 | 1.5 | 1.23 | 48.01 | |
| T402 | 3 | 1.29 | 50.59 | |
| T407 | 1.5 | 1.22 | 178.69 | |
| | 3 | 1.1 | 142.825 | |

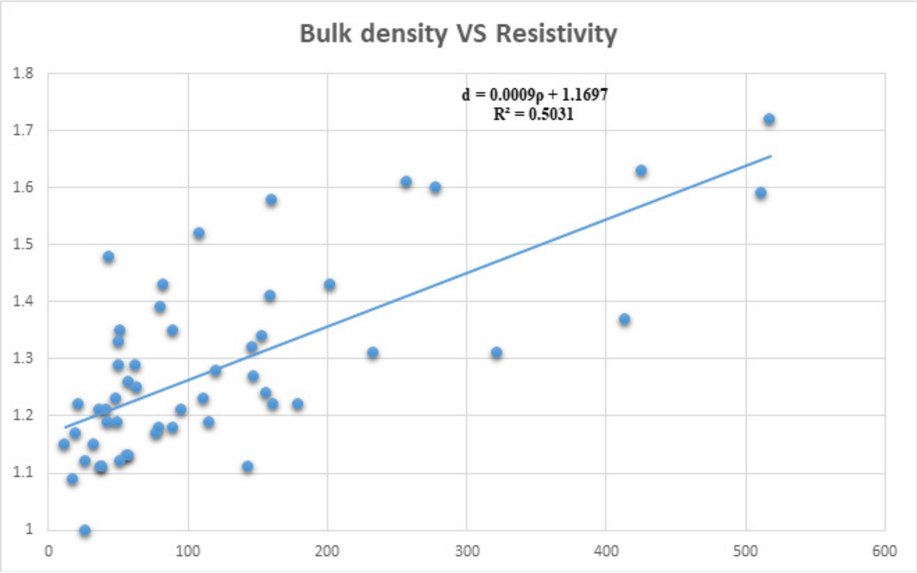


**Fig. 8: Correlation between resistivity and bulk density.**

## CONCLUSIONS

Total 41 tower locations were selected for this research. Among these locations 21 points are situated at residual and colluvial deposits of Siwalik and 21 points are situated at Quaternary deposit of Terai. Test pitting and drilling methodology were adopted for geotechnical investigation (direct) method to compute strength parameter of soil. In case of drilling and soil samples were extracted by standard penetration test. Total 58 soil samples were tested in laboratory for angle of internal friction, cohesion, moisture content, fine content and bulk density. Wenners Four pole arrangement was applied for resistivity test of soil. The resistivity value was obtained by averaging the data along N-S and E-W direction. Five empirical relationships are established in this research for the study area. Empirical relationship between angle of internal friction and resistivity of soil shows $ø = 2.2167\ln(\rho) + 19.671$ with $R^2$ value 0.5176. Empirical relationship between cohesion and resistivity of soil $c = 25.143e^{-0.005\rho}$ with $R^2$ value 0.523. Empirical relationship between moisture content and resistivity is $w = 131.52\ \rho^{-0.499}$ with $R^2$ value 0.6321. Empirical relationship between fine content and resistivity is $fc = 83.256e^{-0.004\rho}$ with value of $R^2$ 0.6508. Empirical relationship between bulk density and resistivity shows $d = 0.0009\rho + 1.1697$ value 0.5031.


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