GEOTECHNICAL INVESTIGATIONS IN GRAVEL-BOULDER DEPOSITS

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Summary

Geotechnical investigation through gravel-boulder formations poses difficulties due to the problems of drilling in such deposits. Various drilling methods such as percussion, rotary and DTH have been used on projects with different degree of success; a combination of two methods is usually effective. In addition to drilling, geophysical tests and load tests help in better assessing the stratigraphy and selecting suitable values of safe bearing capacities.

Two case studies are presented here to demonstrate the geotechnical investigation methodologies. The first one is for a bridge on the Jammu-Pathankot highway where percussion drilling combined with odex (DTH) drilling was used to drill the boreholes. This was supplemented by electrical resistivity tests and footing load tests. The second case study is for a bridge on the Kohalpur-Mahakali highway in the Terai region. Here, percussion drilling and resistivity tests were performed.

Keywords: gravel-boulder deposits; boreholes; percussion drilling; odex drilling; resistivity tests; footing load tests.

1. Introduction

Gravel / boulder formations are a driller’s nightmare – advancing boreholes through these deposits is a slow and difficult process. Particularly where gravel size exceeds 50-100 mm and the percentage of boulders/gravel in the formation exceeds 30-50 percent, drilling 100-150 mm diameter boreholes by standard methods such as shell and auger (percussion) or rotary techniques using diamond bits as specified in IS: 1892-1979 is extremely slow and often fails.

Therefore, geotechnical investigations in boulder deposits pose a veritable challenge. Engineers have tried different methods with varying degrees of success. Boreholes by appropriate methods combined with geophysical methods and load tests, a reasonable assessment can be made to evaluate the stratigraphy and the safe bearing capacity for foundation design.

Used in conjunction with boreholes, geophysical tests such as electrical resistivity tests and seismic refraction tests can confirm continuity of various strata and the depth of layers. In strata containing boulders and rock in which drilling is time consuming and expensive, substantial savings in cost and time can be achieved by judicious inclusion of geophysical tests in the geotechnical investigation program.

2. Behaviour of Gravel-Boulder Deposits under Load

IS: 10042-1981 [1] states that “the performance of bouldary deposits under load is a matter of intelligent guess. The behaviour of boulder deposits under high loads depends upon the size and quantity of gravel-boulder and also the nature and amount of the filler”.

Where the boulder/gravel is the predominant material and filler material (sand) exists only in the interstices of the boulder, its behaviour will depend upon the state of packing of the boulders, nature and the size of the boulder and the gradation. If the quantum of filler material is less, the load carrying capacity is high and the compressibility is low.

If there is substantial filler material in the interstices of the boulders/gravel, there is an initial compression stage followed by low compression stage when the load carrying capacity is high. The boulder-soil matrix, unlike ordinary soil, shows certain peculiar characteristics when the boulder proportion is large (>30 percent); the deposit shows an initial rapid compression followed by a stage where the compression decreases considerably as the boulders take over the load-carrying function.

3. Geotechnical Investigation Methods

3.1 Boreholes

3.1.1 Percussion Drilling

Advancing borehole by percussion method (mechanized shell and auger) is the most commonly employed method to drill boreholes for geotechnical investigation in gravel / boulder strata. Chiselling may be done using heavy sinker bars pulverize the boulders, push the gravel into the surrounding strata, thus helping the borehole to advance. But, due to the large size of the boulders, driving / pushing casing may damage its shoe. The bore tends to collapse while withdrawing drilling/sampling tools.

3.1.2 Rotary Drilling

Another method is to use rotary drilling. Usually, holes of NX or HX diameter are used. But in many cases, the gravel tends to slip under the drill bit and blocks the progress of the hole. Grouting the boulders using cement slurry is a reasonably effective solution to keep the hole open; however the scheme is slow since after each run of 1-1.5 m, time has to be given for the grout to set.

3.1.3 Large Diameter Boreholes

Large diameter holes (400-500 mm diameter) using piling rigs have been tried at some project sites, but with limited success. Bailer boring or using DMC methods have been successful in some cases. Cleaning the hole and conducting SPT on the natural strata can be difficult. Also, quality of the samples collected may be questionable. However, the cost of the borehole may be quite high.

3.1.4 DTH Odex Drilling

Down-the-hole vibratory hammer with air flushing and simultaneous lowering of casing (DTH odex drilling) is an effective way of drilling through strata with large sized boulders / pebbles. The vibratory hammer pulverizes the boulders and the air flushing removes the cuttings. The method is normally not used for geotechnical investigation but may be used in conjunction with percussion or rotary drilling. Sampling should be done carefully to obtain the representative samples of the natural strata.

3.2 Geophysical Tests

The commonly used geophysical tests used for assessing the stratigraphy are electrical resistivity tests and seismic refraction tests. In this paper, use of resistivity tests is illustrated as a geotechnical investigation tool.

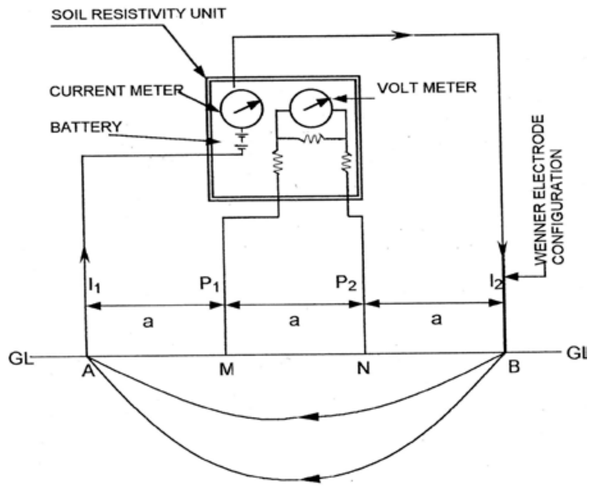

Fig.1: Schematic of Electrical Resistivity Test

Resistivity is governed by Ohm's Law, which states that the change in potential across a resistor is proportional to both the current and the resistance. It is a fundamental property of the material and is independent of geometry.

Electrical resistivity tests can be effectively used to assess the continuity of the strata and to identify layering. For geotechnical engineering purposes, resistivity testing can provide information regarding lithology that can be correlated with borehole information [2].

The test may be performed using Wenner's four-electrode configuration. In this method, four electrodes are spaced at equal distance along a line as illustrated on Fig. 1. The test procedure is in accordance with IS: 3043:1987 [3].

The following equation is used to compute the apparent resistivity for the Wenner configuration:

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

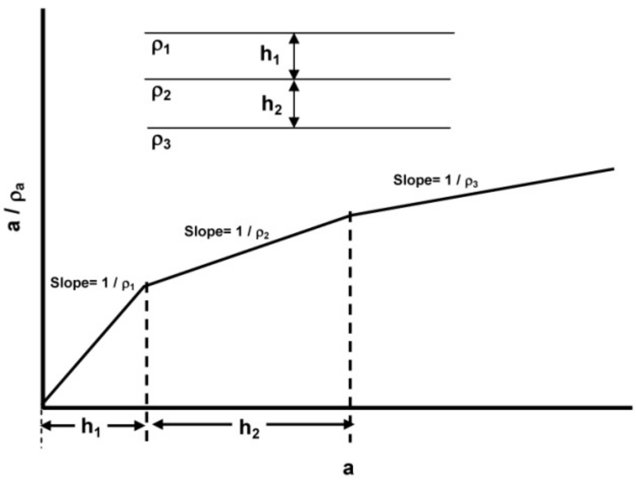

Fig.2: Inverse slope method

where:

ρ = apparent resistivity

a = electrode spacing

R = resistance

ρ represents the true resistivity of the material if the formation is homogeneous and isotropic in nature. However, it represents only the apparent resistivity ρ_a if the formation consists of two or more layers of different resistivities. The apparent resistivity, depending on the geology, may be a crude weighted average of the true resistivity of the different layers. The effective depth of current penetration, and hence that of the investigation, increases with increase in electrode spacing.

Based on an analysis of layered formations and empirical studies, Sanker Narayan & Ramanujachary [4] proposed a graphical procedure for computing the true resistivity of various layers. The analysis is called the Inverse Slope Method as illustrated in Fig. 2.

Since the resistivity values vary with moisture content, salinity, level of groundwater, degree of compactness, mineralogy and other factors, caution should be exercised in selecting the appropriate resistivity ranges corresponding to the different soil ranges.

3.3 Load Tests

Plate load tests / footing load tests may be effectively used to assess the in-situ bearing capacity of the gravel-boulder deposit. To obtain meaningful results, the size of the test plate / footing should be at least equal to 10 times the size of the largest particle. Thus, for gravel, pebbles, boulders, etc., the minimum required plate size shall be rather high, ranging from 100 to 300 cm or even more. For such large size, either a suitably stiffened plate or RCC footing shall be required. Also, the load required being large, the cost of the test is very high.

4. Case study-1: Bein Bridge on Jammu-Pathankot Highway (NH-1A)

4.1 Bridge Details

The site for the Bein Bridge in the Jammu-Pathankot section of NH-1A is located in the foothills zone of the Himalayas. The salient details of the bridge are as follows:

Structure No.	: 56/1 on NH-1A
Bridge Length	: 259 m
No. of Spans	: 10
No. of Abutments	: 2
No. of Piers	: 9
Span length	: 25.9 m
Average bed level of river	: RL 368.5 m
Maximum scour level at Piers	: RL 366.1 m
Proposed Founding level	: RL 364.69 m (approx. 3.8 m below EGL)

Bed protection was planned to limit possibility of scour.

4.2 Regional Geology

The project area is covered by alluvial deposits of the River Jhelum and its tributaries. It is in the northern rim of the Indo-Gangetic Basin where it joins the foothills zone of the mountains. It is one of considerable faulting and structural strain. The alluvium in this zone consists primarily of coarse gravel / boulders / cobbles, grits sands and clays. It conceals two or three transverse ridges and pre-Tertiary basins due to crumpling and dislocation of the basement floor during the Himalayan Orogeny.

Overall, favourable conditions prevailed for the quick accumulation of sediments in the zone of lodgment at the foot of the mountains. The alluvium is underlain by the Muree and the Siwalik deposits [5]. The deposits in the area consist primarily of large size pebbles, sub-rounded boulders and gravel. The sand infill in between the voids is less than 20-30 percent.

4.3 Generalized Stratigraphy of the Area

Fig.3: Boulders, pebbles on river bed

The alignment of NH-1A in the section between Jammu and Pathankot is in the foothills zone of the Himalayas. In this sector, boulders and pebbles / shingles are the principal material encountered at shallow depths. As per local information, boulders are likely to be met to at least 70-80 m depth. At several locations, some intermediate sand and clay layers are met within the bouldary formation.

In the project area, the pebbles, boulders and gravel range in size from 20 mm to more than 200 mm with isolated boulders of even 500 mm size being met at places. The pebbles / boulders are rounded to sub-rounded due to the river action.

Sand is present as a filler material in the interstices of the boulders and the proportion of sand in the deposit may be between 15 to 30 percent. The voids are only partially filled with sand. The packing of the boulders is generally medium to compact. The photo on Fig. 3 illustrates the nature of the gravel-boulder deposition.

4.4 Geotechnical Investigation

The investigation methodology used a combination of three methods –

1. Boreholes through gravel/boulders by odex (DTH) method using compressed air in conjunction with boring by bailer/shell in sand and clay layers.
2. Geophysical testing (electrical resistivity tests), and
3. In-situ load tests on a model footing.

4.5 Boreholes through Gravel-Boulder Formation

Fig.4: Odex & Percussion Boring

Initially, percussion boring was attempted using heavy sinker bars and chisel. However, where large pebbles / boulders were present, progressing the borehole was found to be slow and difficult. In such cases, the boreholes were advanced by DTH method. The vibratory hammer of the DTH machine pulverizes the boulders, which are brought out by using an air compressor. After drilling every 1.5 m using DTH, the percussion rig was set in place. The borehole was cleaned out using a bailer to remove all disturbed material. Standard penetration test was conducted in accordance with IS: 2131-1981 [6] after the borehole was cleaned. Fig 4 is a photo of odex drilling in progress in conjunction with the percussion boring.

It is usually difficult to even obtain representative disturbed samples of the bouldary strata since the boulders are broken during chiselling / drilling. Undisturbed samples cannot be collected in such strata. Fig. 5 illustrates the alternate use of DTH and percussion for drilling and sampling.

Fig.5: Borehole drilling in progress. Left:Drill bit for odex drilling. Right: Bailer being used to clean borehole prior to conducting SPT

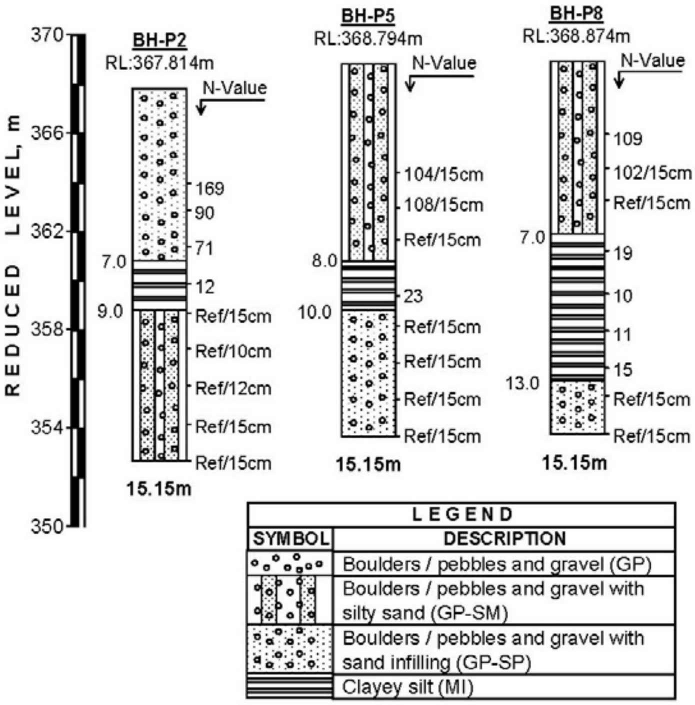

Fig.6: Typical Borehole Data – Bein Bridge

Table 1: Interpretation of Resistivity Values – Bein Bridge

True Resistivity, ohm-m	Interpreted Stratigraphy
30-75	Sand and silty sand
10-50	Stiff clay and sandy silt
> 100	Hard clay
50-100	Sand with gravel / pebbles
> 200	Pebbles and boulders intermixed with sand

4.6 Stratigraphy at Bridge Location

The deposits met at the site classify as boulders / gravel with sand infilling from the ground surface to about 5.0 m depth. Below this, clayey silt is met to about 7.0 to 8.0 m depth. This is underlain by boulders / gravel with sand to final explored depth of 15.0 m.

The boulders / cobbles size range from 100 mm to more than 300 mm. About 30-40 percent of the material is gravel size (4.75-100 mm size) and about 10-20 percent of the material may be more than 300 mm in size (boulders). In general, the packing of boulders is medium to compact. The borehole profiles are illustrated on Fig 6.

4.7 Electrical Resistivity Tests

Electrical resistivity test has been used to assess the continuity of the strata and to identify layering. For geotechnical engineering purposes, resistivity testing can provide information regarding lithology and can be correlated with borehole information (Ravi Sundaram & Sanjay Gupta, 2001[7]).

The interpretation is based on true resistivity values interpreted from the inverse slope method in conjunction with geology of the area and borehole data. After evaluation of available borehole data, geology of the area, range of measured resistivity values and comparison with published resistivity values, an assessment was made of the probable range of resistivity in each of the different layers.

The range of resistivity values and the interpreted stratigraphy as assessed by the authors after review of borehole data and comparison with published values are summarized on Table 1.

As can be seen some of the ranges overlap. Interpretation has been done by comparing the true resistivity values with the nearby borehole data to develop a profile consistent with the expected stratigraphy.

Typical result from a test conducted at P-9 is presented on Fig. No.7.

The resistivity tests indicated that the boulder formation is continuous to over 50 m depth.

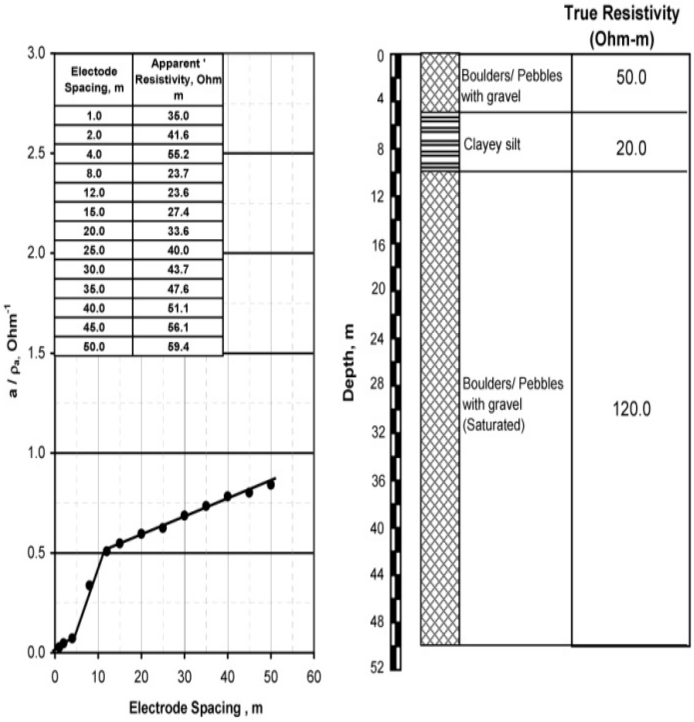

Fig.7: Litholog interpreted from Electrical Resistivity

4.8 Footing Load Tests

The footing load test is a model foundation test and can help in making a better assessment of the behaviour of boulder strata under the load. Load test data on suitable size model footing can be used effectively to assess safe bearing capacity of bouldary deposits.

Two footing load test were performed at the site of the Bein Bridge at the locations of Pier P-1 and P-6 on a RCC footing of size 2.5 m x 2.5 m at the proposed foundation level. The footing was cured for over 28 days prior to conducting the test.

The test procedure was in general accordance with IS: 1888-1982 [8]. Dead load was used through kentledge to provide the reaction. The footing was loaded by pushing up against the dead load using two hydraulic jacks of 300 T capacities each. Four dial gauges were used to measure the footing settlement with reference to a stable reference bar. After reaching the final load, the load was removed in stages to measure elastic rebound. Fig 8 shows the footing load test in progress. The bearing pressure versus settlement plot is presented on Fig, 9.

Fig.8: Footing Load test in progress

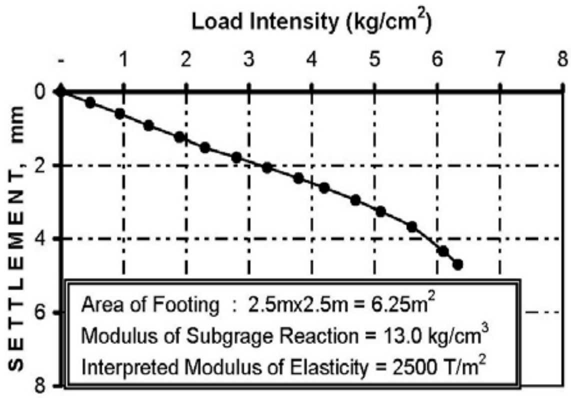

Fig.9: Footing Load test – Load-Settlement Curve

The tests results are extrapolated for 8 to 10 m wide square footing using the following equation as given in IS 1888-1982:

$$\frac{S_f}{S_p} = \left[\frac{B_f(B_p + 0.3)}{B_p(B_f + 0.3)}\right]^2 \quad \ldots \qquad (1)$$

where

S_p = Settlement of test plate/footing of size B_p

S_f = Settlement of test plate/footing of size B_f

Based on the test results on a footing of 2.5 m size at P-1, the settlement of the footing is 1.7 mm corresponding to a load of 25 T/m^2. The extrapolated settlement for 8 to 10 m wide footing shall be about 10 to 15 mm. Some of the salient points interpreted from the test are listed below:

1. The ultimate bearing capacity of the boulder strata exceeds the maximum applied pressure of 6.5 kg/cm^2. Applying a safety factor of 2.5, the safe bearing capacity exceeds 25 T/m^2.

2. The back-calculated value of ϕ exceeds 42°.
3. The settlement at each applied load is essentially immediate.
4. The modulus of subgrade reaction (k) calculated as per IS 9214:1979 [9] works out as 13 kg/cm^3.
5. Using the correlation, $$k = \frac{E}{B(1-\mu^2)} \quad (2)$$

the modulus of elasticity (E) of the boulder deposit was calculated as 8875 T/m^2.

4.9 Safe Bearing Capacity for Design

Considering the potential for saturation and possibility of local variations, the maximum settlement of the foundation at P-1 under an applied bearing pressure of 25 T/m^2 may be on the order of 10 to 15 mm. Some consolidation settlement will also occur in clay layer met between 5 to 8 m depth (RL 363.5 ~ 360.5 m).

The geotechnical investigation carried out confirmed the continuity of the strata and provided a basis for selection of net bearing pressure for design. The footing load test was used as the basis for evaluating the immediate settlement of the boulder deposit.

For bearing capacity analysis, the soil parameters used were:

c = 0 ϕ = 42 degrees

Table 2 presents the soil parameters used for settlement analysis.

Depth, m		Soil Classification	γ, T/m^3	E, T/m^2	p_c, T/m^2	e_0	c_{c1}	c_{c2}
From	To							
0	5.0	Boulders / gravel with sand	1.90	5000	-	-	-	-
5.0	8.0	Clayey silt	2.00	1200	30	0.68	0.015	0.20
8.0	15.0	Boulders / gravel with sand	2.20	9000	-	-	-	-

where
γ = bulk density
E = modulus of elasticity
p_c = pre-consolidation pressure
c_{c1} = compression index for stress level ≤ p_c
c_{c2} = compression index for stress level > p_c

The E value of the top layer to 5 m depth was conservatively selected as 5000 T/m^2 to account for any local variations. The soil parameters for the clayey silt layer between 5 and 8 m are based on the SPT values and laboratory test results.

Using the above design parameters, the factor of safety against shear failure exceeds 3. The settlement of 8-10 m size foundations of the bridge foundations was calculated as 24.3 mm for a design net bearing pressure of 25 T/m^2. The testing generated the necessary confidence that the structure is safe as designed.

5. Case study-2: Charaila Bridge on Kohalpur-Mahakali Highway (Nepal)

5.1 Project Details

The Kohalpur-Mahakali Highway (also known as the East-West Highway) runs almost parallel to the Indo-Nepal border, about 15 to 30 km inside Nepalese territory. The sector investigated is in District Kailali of south-west Nepal. Several bridges are being constructed across minor and major rivers along the road alignment. Fig. 10 presents a vicinity map showing the route investigated and the important rivers of the area.

5.2 Bridge Details

The site for the Charaila Bridge is located in the Terai region of the Himalayas. The salient details of the bridge are as follows:

Bridge Length	: 259 m
No. of Spans	: 10
No. of Abutments	: 2
No. of Piers	: 9
Span	: 25.9 m
Average bed level of river	: RL368.5 m

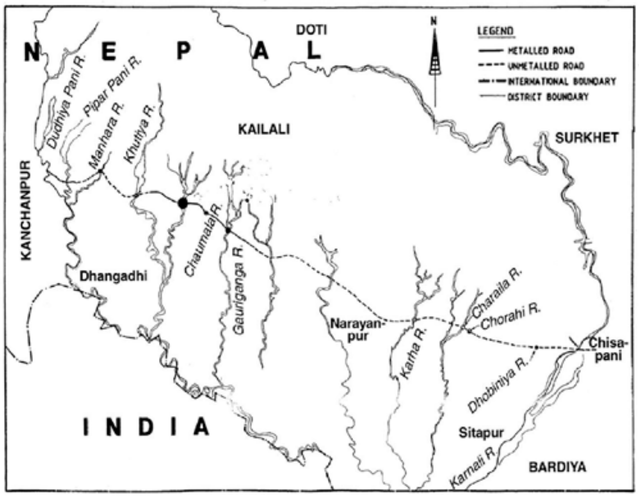

Fig.10: Vicinity Map – River Charaila

Maximum scour level at Piers : RL 366.1 m
Proposed Founding level : RL 364.69 m
(approx. 3.8 m below EGL)
Bed protection was planned to limit possibility of scour

5.3 Regional Geology

The region between the Rivers Mahakali, Seti and Karnali expose the Siwaliks and the Lesser Himalayas to the north of the Main Boundary Thrust (Bashyal, 1982 [10]). The area is bordered by Kumaon Himalayas in the north and west and Indo-Gangetic alluvial plains in the south.

The Siwalik foothills occupy a wide belt and reach a width of 52 km in southwestern Nepal. The Nepalese sub-Himalayas belt has been classified into the Lower, Middle and Upper Siwaliks (Gansser, 1964 [11]). Most of the visible sediments belong to the Middle Siwaliks and are of Middle to Late Miocene & Pliocene to Pleistocene Age.

5.4 Generalized Stratigraphy of the Area

The Recent deposit of alluvial fan comprises pebbles and boulders set in a sandy/silty matrix. The foothills along the Indo-Nepal border are called the Terai region and are very fertile and well drained. Terrace alluvium is restricted to the paleo-banks of the rivers. It is made up of coarse clusters (pebbles and boulders with sand) in the upstream reaches and grades into finer sediments downstream.

5.5 Geotechnical Investigation

The investigation methodology used a combination of two methods –

- Boreholes using mechanized bailer/shell with chiselling through the boulder / pebbles strata, and
- Geophysical testing (electrical resistivity tests).

The boreholes were progressed by mechanized heavy-duty percussion type rigs using shell. Heavy sinker bars and chisel were used to achieve penetration through the bouldary strata and hard clays. Flush threaded casing pipes of 150 mm ID (172 mm OD) were lowered by rotation and hammering. The casing pipe was kept above the boring level so as to avoid disturbance during sample collection and conducting standard penetration tests.

However, where large sized pebbles/boulders (100-200 mm size) were encountered, the casing could not be penetrated through these boulders. Due to borehole collapse and difficulties in advancing casing through this strata, the progress was very slow.

Rotary drilling was attempted at some selected locations using heavy-duty rotary drill machine. A 32 carat diamond impregnated bit was used. However, the pebbles were slipping under the bit and also causing collapse of the hole, thus making the progress of the hole very slow. Some holes were cement grouted in an attempt to advance the hole. By repeated grouting, the hole could be advanced; but the process was slow and time consuming since one has to allow the cement to set for at least 24 hours before attempting to re-drill.

Table 3: Available Borehole Data

Borehole	Depth of borehole
APP – 1 (approach on right bank)	15.0 m
A – 1 (right bank abutment)	40.1 m
P – 1 (Pier No. 1)	16.0 m
P – 2 (Pier No. 2)	13.0 m
A – 2 (left bank abutment)	40.0 m
APP – 2 (approach on left bank)	20.0 m

To evaluate the stratigraphy to the required depth of 30 m at pier locations and 40 m at abutment locations (as per the project specifications), it was decided to conduct electrical resistivity tests. The tests were conducted in accordance with IS 3043-1987 [3] at several locations along the bridge alignment as well as at upstream and downstream locations. Table 3 presents the depth to which borehole data was available.

To assess the stratigraphy to 30 to 40 m depth at the pier and abutment locations, resistivity tests were performed along the centre line of the bridge alignment as well as at upstream and downstream locations. The locations were suitably selected so as to get a clear stretch of 80 to 120 m on level dry ground.

Sufficient tests were done so as to calibrate the borehole data against the resistivity values. The tests were conducted using the Wenner Array at different electrode spacings ranging from 1 to 40 m. Table 4 presents the details of the resistivity tests conducted.

Table 4 : Resistivity Tests conducted

Location	No. of Resistivity Tests Conducted
Up-stream of Bridge Alignment.	3
Along Centre Line	1
Downstream of Bridge Alignment	7
Total no. of resistivity tests conducted	11

The resistivity data was analyzed in conjunction with the borehole data assess the probable stratigraphy at the required pier / abutment location. Using the resistivity data from the various locations at which the tests were conducted, a three dimensional picture of the stratigraphy was visualized so as to interpolate the soil profile at the required locations. Based on this analysis, a geo-electric litholog that matches with the anticipated stratigraphy is generated.

5.6 Interpretation of Stratigraphy from Resistivity Values

Table 5 presents the ranges used by the authors for interpreting the soil layers. These ranges are site-specific and have been developed after careful review of data and comparison with borehole information. Fig.10 presents one typical geo-electric litholog based on the resistivity tests conducted.

Table 5: Soil Strata correlated to Resistivity values

True Resistivity, ohm-m	Interpreted Stratigraphy
30 – 75	Sand and silty sand
10 – 50	Stiff clay and sandy silt
> 100	Hard clay
50 – 100	Sand with gravel / pebbles
> 200	Pebbles and boulders intermixed with sand

A generalized surface profile along the centre line of the bridge is presented on Fig. 11. The stratigraphy beyond the depth investigated by the boreholes is obtained by interpolating and projecting the geo-electric profiles along the centre line of the bridge alignment.

Based on this evaluation, the stratigraphy at the required pier/abutment location is generated. The geotechnical parameters required for the analysis is interpreted by comparison with the borehole data and the engineer’s assessment of the trend of values.

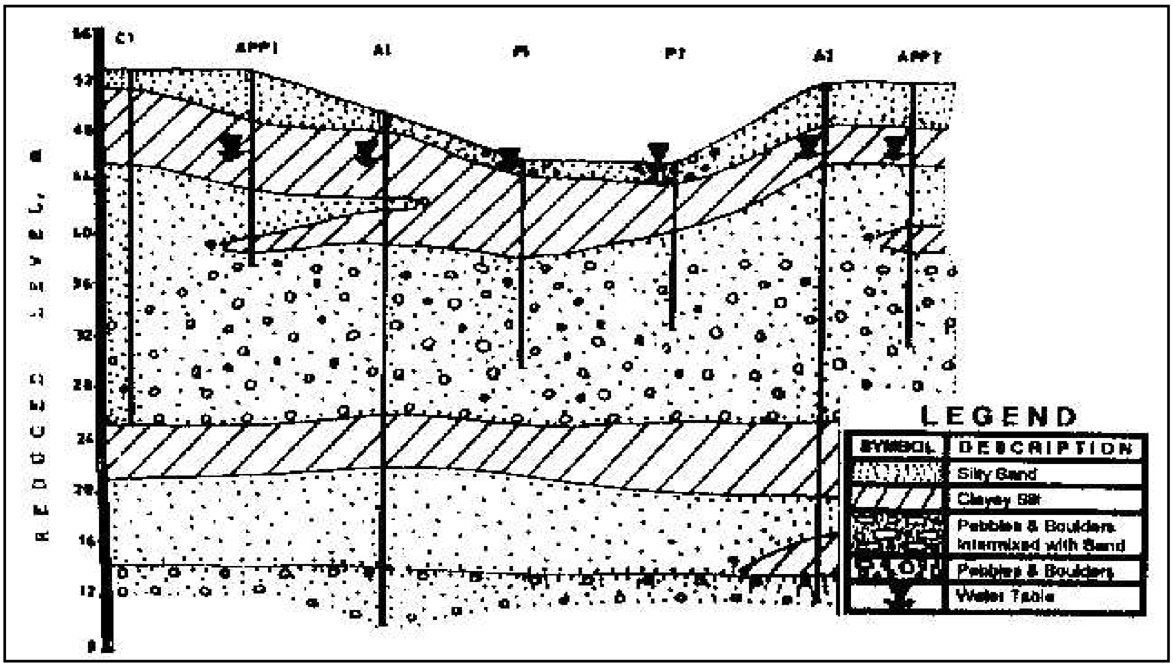

Fig.11: Interpreted subsurface profile along the centre line of the bridge

6. Concluding Remarks

In strata containing boulders / gravel, drilling is expensive and time consuming. Judicious inclusion of resistivity tests and load tests in the geotechnical investigation programme can save substantially on both time and money and also ensure the quality and reliability of the data for foundation design.

It cuts down the time required for a geotechnical investigation programme substantially. In the current scenario of fast track projects in the highways and infrastructure sector, it can be used to reduce the number of boreholes required to be drilled.

However, the inherent limitations of geophysical tests and model tests on prototype footings should be recognized. The tests should not be considered as an alternative to borehole drilling. It should be used in conjunction with sufficient borehole data for realistic interpretations of stratigraphy and anticipated load-settlement behaviour that match well with actual ground condition.

Thorough knowledge of local conditions is essential so as to correlate the results with strata conditions. Prior to conducting geophysical tests, information on geology, geomorphology and anticipated stratigraphy of the project area should be collected. The interpretations should be done by experienced personnel with a thorough understanding of geophysics.

Extrapolation of load test data should include consolidation of any cohesive strata in between the boulders / granular strata for a realistic assessment of foundation behaviour.

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