Paper No.473

"USE OF ELECTRICAL RESISTIVITY TESTS FOR GEOTECHNICAL INVESTIGATIONS FOR BRIDGES"[+]

By

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CONTENTS

1. BACKGROUND INFORMATION

The Ministry of Surface Transport (MOST) specifications for major bridges states that geotechnical investigation must be done at every pier and abutment location. The normal practice is to drill boreholes at every location to a depth of "1.5 to 2B" (where B = foundation width) below founding level. This is sometimes supplemented by static cone penetration tests.

The Paper presents the use of electrical resistivity test as an investigation tool to supplement the borehole data. The technique is time saving and is particularly useful in the current scenario of fast track projects in the highways and infrastructure sector.

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

2. PROJECT DETAILS

The Kohalpur-Mahakali Highway (also known as the East-West Highway)

[+] Written comments on this Paper are invited and will be received upto 15th December, 2001

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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. 1 presents a vicinity map showing the route investigated and the important rivers of the area.

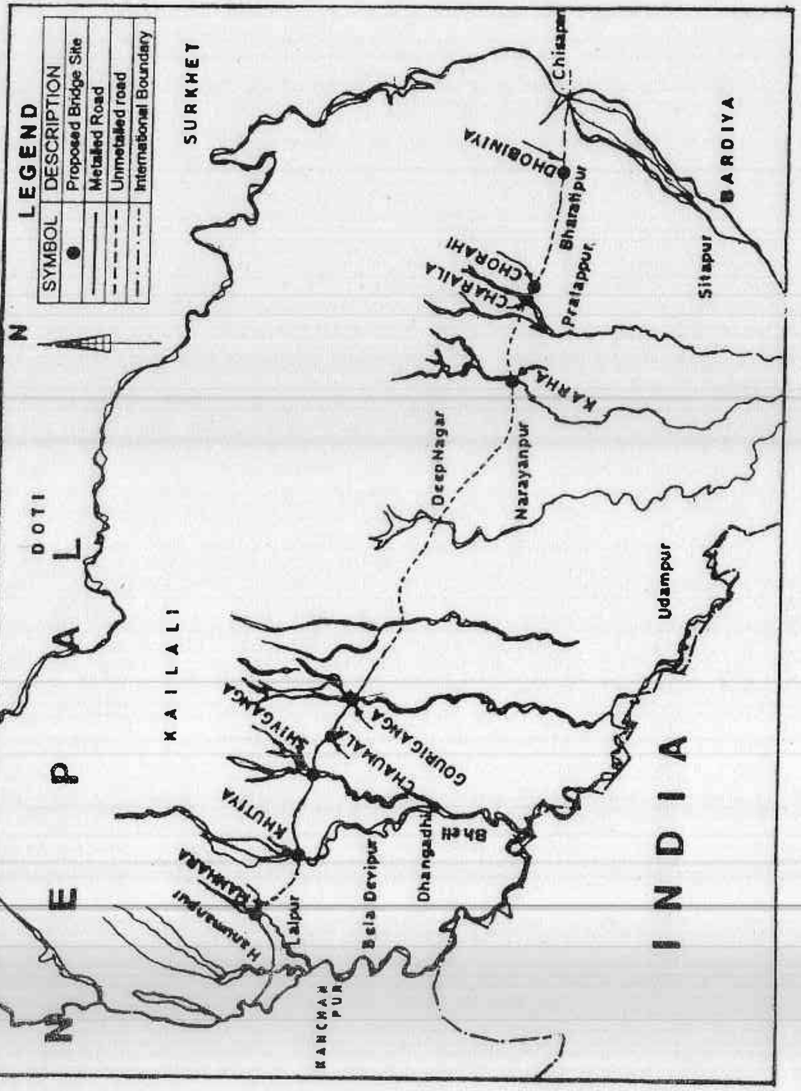


Fig. 1. Vicinity map

3. GEOTECHNICAL INVESTIGATIONS

3.1. Scope

The geotechnical investigation between km 51.5 to 117 (chainage 0.0 km at Mahendranagar) of the Kohalpur–Mahakali Highway (Nepal) included work at nine bridge locations. While advancing boreholes through strata containing large sized boulders/pebbles of 100 to 200 mm size, drilling problems were encountered at three bridge locations, namely *Charaila, Chorahi* and *Dhobiniya* in the sector between km 106 and 117.

3.2. Boreholes

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.

3.3. Resistivity Tests

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 at several locations along the bridge alignment as well as at upstream and downstream locations.

4. ELECTRICAL RESISTIVITY TESTS

4.1. General Principles

Resistance is the property that impedes the flow of current through a material. Electrical resistance is a function of both the material type and the electrical current flow geometry. When electricity passes through the earth, it encounters resistance to its flow from the soil/rock materials. The resistance offered to the current flow is dependent on the mineralogy, particle arrangement, water content and salinity of the underlying earth layers (Woods, 1994)[1].

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.

In soils or rocks, the flow of an electrical current occurs through:

(i) the pore water which acts as a conductor, and

(ii) the soil or rock which may act as a conductor or an insulator/resistor depending upon the nature of the mineral.

Hence, the nature of the pore water as well as the mineral will affect the resistivity. Resistivity can provide information about soil type. For example, a clay will conduct electricity through both the pore water and the clay itself, whereas a sand will transmit current primarily through its pore water.

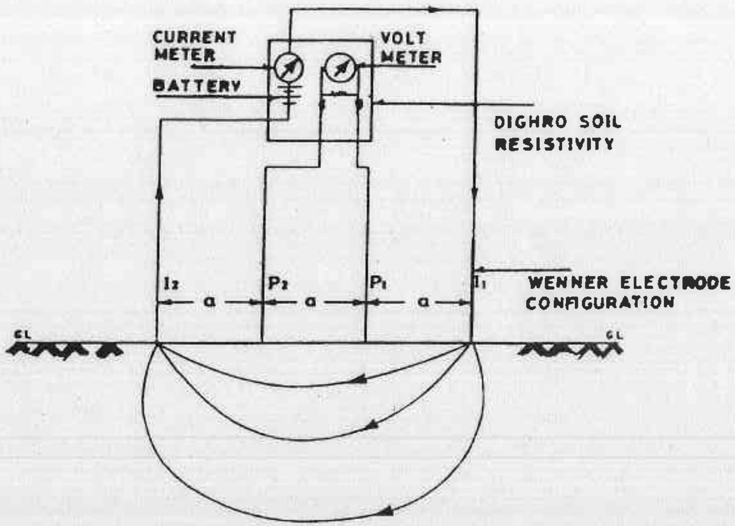
4.2. Measurement of Earth Resistivity

There are various electrode configurations which can be used to measure earth resistivity. The most commonly employed configurations are the Wenner and the Schlumberger arrays. The work presented in this Paper uses the Wenner configuration.

In the Wenner spread, the electrodes are uniformly spaced. The electrodes are expanded about a fixed centre to conduct the test at different electrode spacings. A four electrode Wenner array, as illustrated in Fig. 2, with a maximum current electrode separation of 120 meters was used to obtain the vertical profile of resistivities at different locations to about 40 m depth.

The apparent resistivity offered by these layers is calculated using the relationship between electrode spacing and the current used to generate the measured voltage difference, after nullifying the natural potential (if any) of such materials. The following equation is used to compute the apparent resistivity for the Wenner configuration :

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



NOTE

I_1 AND I_2 ARE CURRENT ELECTRODES
P_1 AND P_2 ARE POTENTIAL ELECTRODES

Fig. 2. Schematic of resistivity test

where :

ρ = 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 P_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 resistivities of the different layers. The effective depth of current penetration, and hence that of the investigation, increases with increase in electrode spacing.

4.3. Field Applications

For geotechnical engineering purposes, resistivity testing can provide information regarding lithology and can be correlated with borehole information. It is also useful for locating the groundwater table and for identifying freshwater aquifers. The Geological Society Engineering Group Working Party (1988)[2] recommends that resistivity testing is an excellent approach with well developed analysis techniques for identifying depth to rock, stratigraphy and lithology as well as for groundwater exploration.

4.4. Typical Range of Values

The common rock-forming minerals have very high resistivities. For example, the resistivity of quartz is 10^{11} ohm-m. Impervious rocks and porous but dry rocks have high resistivities. Resistivity decreases with increasing water saturation and salinity.

The common range of resistivities of some rocks is shown in Fig. 3 (Karanth 1987)[3]. It may be observed that the resistivity of a rock is not unique to it and that there is considerable overlapping of resistivity ranges of several rock types, depending on clay content, water saturation, quality of water, salinity and porosity.

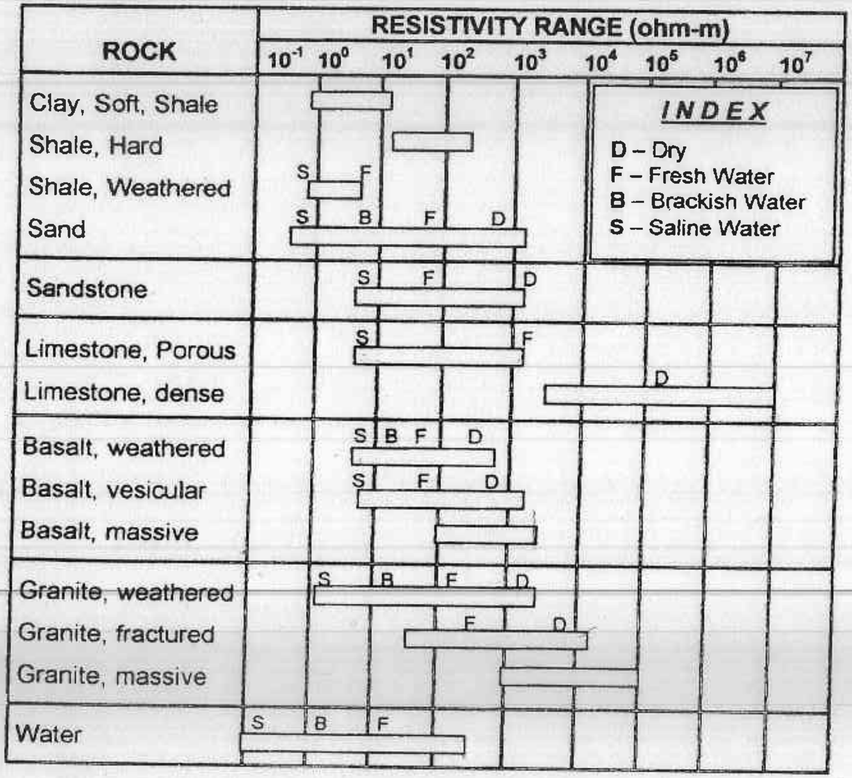


Fig. 3. General range of electrical resistivities of common rocks and water (After Karanth, 1987)

4.5. Data Analysis Technique

The stratigraphy has been interpreted based on the evaluation of the electrical resistivity tests results as well as visual observations. The principles for the analysis are as outlined herein.

Based on an analysis of layered formations and empirical studies, Sanker Narayan & Ramanujachary (1967)[4] have proposed a graphical procedure for computing the true resistivity of various layers. The analysis is called the "Inverse Slope Method". This procedure is as follows :

(1) Plot electrode spacing 'a' versus 'a/P_a' (ratio of electrode spacing to apparent resistivity).

(2) On drawing the best fitting straight line segments through the points, the intersections are read off for depths.

(3) The reciprocals of the corresponding slopes of the segments give the absolute resistivities of the layers directly.

A sketch showing the procedure is presented in Fig. 4.

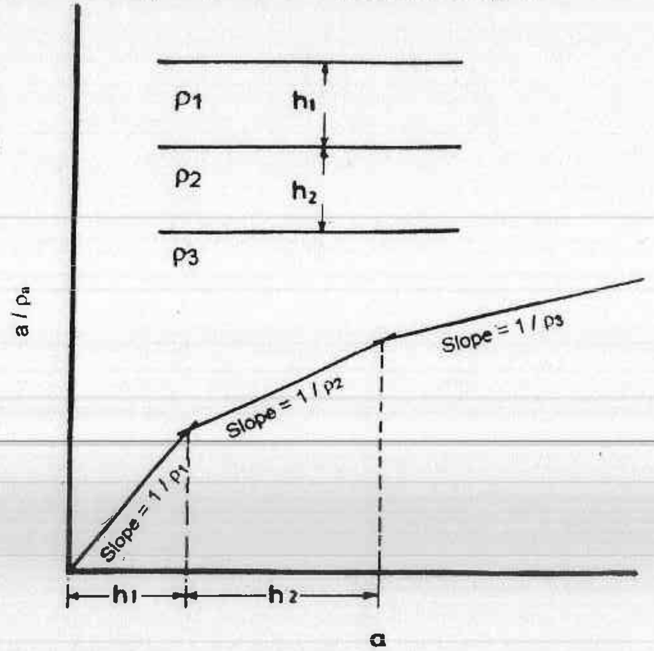


Fig. 4. Identification of geo-electric layers by Inverse Slope Method

5. BRIDGE DATA AND GEOTECHNICAL INVESTIGATION DATA

5.1. Bridge Data

The following table presents salient features of the three bridges where problems were encountered in advancing boreholes through strata containing pebbles and boulders:

Bridge over River ▶	Charaila	Chorahi	Dhobiniya
Chainage, km	106.0	108.0	117.0
Bridge Length, m	96.638	40.0	62.25
No. of Spans	3	1	3
No. of Abutments	2	2	2
No. of Piers	2	0	2
Span, m	32.2	40.0	20.75

5.2. Available Borehole Data

The boreholes along the approaches were planned to be 15 to 20 m deep. The abutment boreholes were required to be advanced to 40 m depth. The boreholes at the pier locations had to be advanced to 30 m depth. Drilling problems were encountered at some boreholes due to the presence of large size boulders/pebbles. Therefore, some of the boreholes could not be taken to the required depths. The details of the geotechnical investigation including the depths to which the boreholes could be advanced are as follows:

Bridge over River ▶	Charaila	Chorahi	Dhobiniya
Depth to which borehole data is available			
APP – 1 (approach on right bank)	15.0 m	20.0 m	15.0 m
A – 1 (right bank abutment)	40.1 m	40.0 m	25.0 m
P – 1 (Pier No. 1)	16.0 m		7.0 m
P – 2 (Pier No. 2)	13.0 m		12.0 m
A – 2 (left bank abutment)	40.0 m	22.0 m	18.0 m
APP – 2 (approach on left bank)	20.0 m	15.0 m	15.0 m

6. RESISTIVITY TESTS : DATA, ANALYSIS AND RESULTS

6.1. Resistivity Testing Programme

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.

The following table presents the details of electrical resistivity tests conducted:

Bridge over River ▶	Charaila	Chorahi	Dhobiniya
No. of Resistivity Tests Conducted			
Upstream of Bridge Alignment	3	6	7
Along Centre Line	1	2	9
Downstream of Bridge Alignment	7	2	5
Total no. of resistivity tests conducted	**11**	**10**	**21**

The resistivity data was analyzed in conjunction with the borehole data to 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.

6.2. Problems Encountered during Testing

Ideally, it would have been sufficient to conduct the electrical resistivity test at the pier/abutment locations where the stratigraphy is required to be determined. But due to certain site constraints, this could not be done. Some of the problems encountered are presented below :

(1) At some locations, the point where the stratigraphy was required is submerged (i.e., in the water body of the river).

(2) Since a spread of 120 m is required to conduct the test for 40 m electrode spacing (to investigate to 40 m depth), this entire stretch should be dry so as to conduct the test properly.

(3) At some locations, there were substantial level variations. Suitable spreads had to be selected to ensure that the electrode spread is fairly level.

In all such cases, suitable points upstream and downstream of the required point were selected to perform the test. The stratigraphy at the required point was obtained by interpolating the data from test points surrounding the pier/abutment location where the stratigraphy is required to be determined.

6.3. Interpretation of Stratigraphy from Resistivity Values

The true resistivity values have been interpreted to assess the nature of the strata. After careful evaluation of the stratigraphy, range of measured values and comparison with published values, an assessment was made of the probable range of resistivity values in each of the different mediums (soil layers) at the project sites. The following table presents the ranges used by the Authors for interpretation at these three bridge sites:

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

As can be seen, some of these ranges overlap. Interpretation was done by comparing the adjacent borehole data with the resistivity test results so as to develop a profile consistent with the anticipated stratigraphy at the location.

It is cautioned here that these ranges could vary even for similar nature of soils depending upon moisture content, salinity, level of groundwater, degree of compactness, mineralogy and other factors. The ranges will, therefore, have to be developed on site after careful review of data and comparison with borehole information.

6.4. Analysis of Data and Interpretation

The resistivity data was plotted as a graph of "a" versus "a/P_a" and analyzed as per the inverse slope method to identify the versus layers. Typical results from one test at river Charaila are presented in Fig. 5.

It may please be noted that the interpreted stratigraphy is a geo-electric litholog and is an average over the width investigated. The maximum spacing between the current electrodes was 120 m in this case; thus the interpreted profile is probably an average stratigraphy over the 120 m stretch.

Scatter of the data points on the "a *versus* a/P_a *plot*" has to be carefully interpreted. If at least three points lie on a straight line, one can be fairly confident that the interpretation is correct. It is cautioned here that layers could, therefore, be missed out in such an interpretation unless the data points are closely spaced.

Since the resistivity ranges for the different soil types overlap, careful judgement is required to assess the likely soil stratum encountered. This was done by comparing the results with the available borehole data as well as resistivity test results at nearby locations.

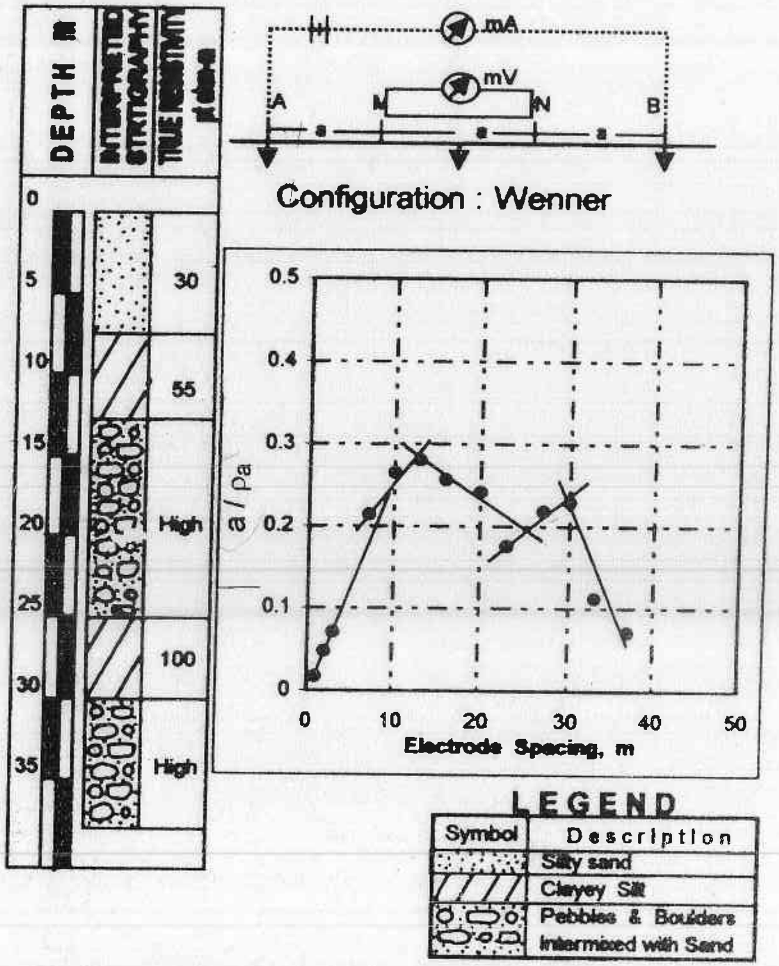


Fig. 5. Typical analysis by Inverse Slope Method river Charaila

In multi-layered deposits, it is not sufficient to identify the layers based on one individual test; comparison with data from surrounding locations as well as borehole data is very important. It is highlighted here that the interpretation is essentially a data matching technique and, therefore, profile obtained is indicative/tentative only. However, it should be confirmed with physical profile as obtained from borehole or from nearby results.

6.5. Presentation of Results

Generalized surface profiles along the centre line of the three proposed bridges are presented in Figs. 6 to 8. The stratigraphy shown on these illustrations 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.

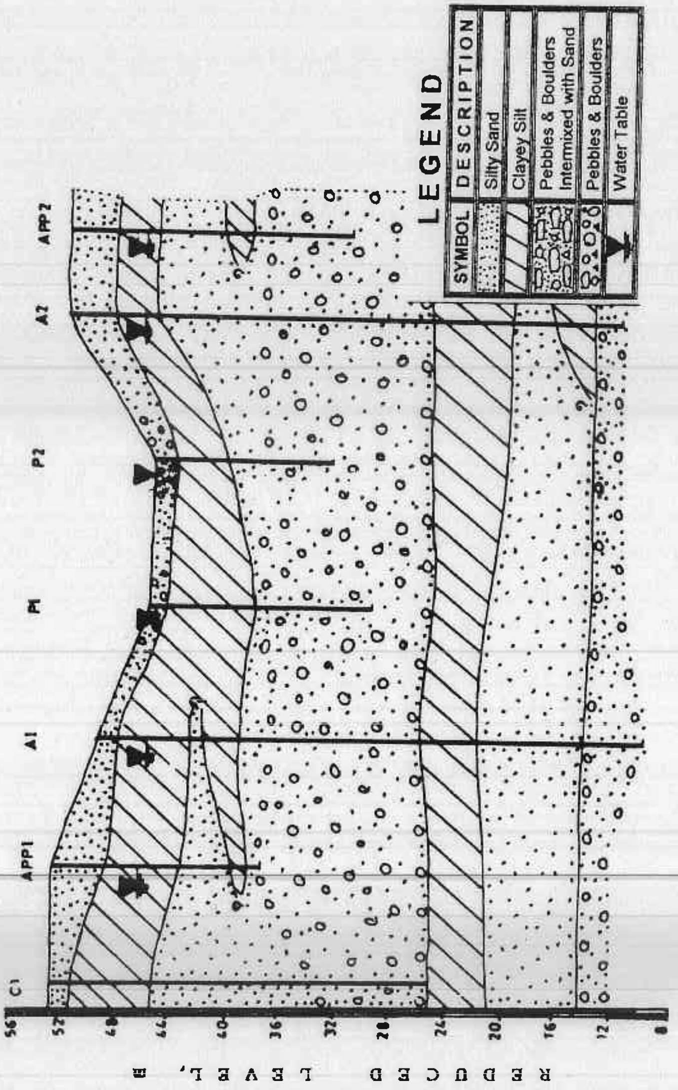


Fig. 6. Generalized subsurface profile along centre line of river Charaila

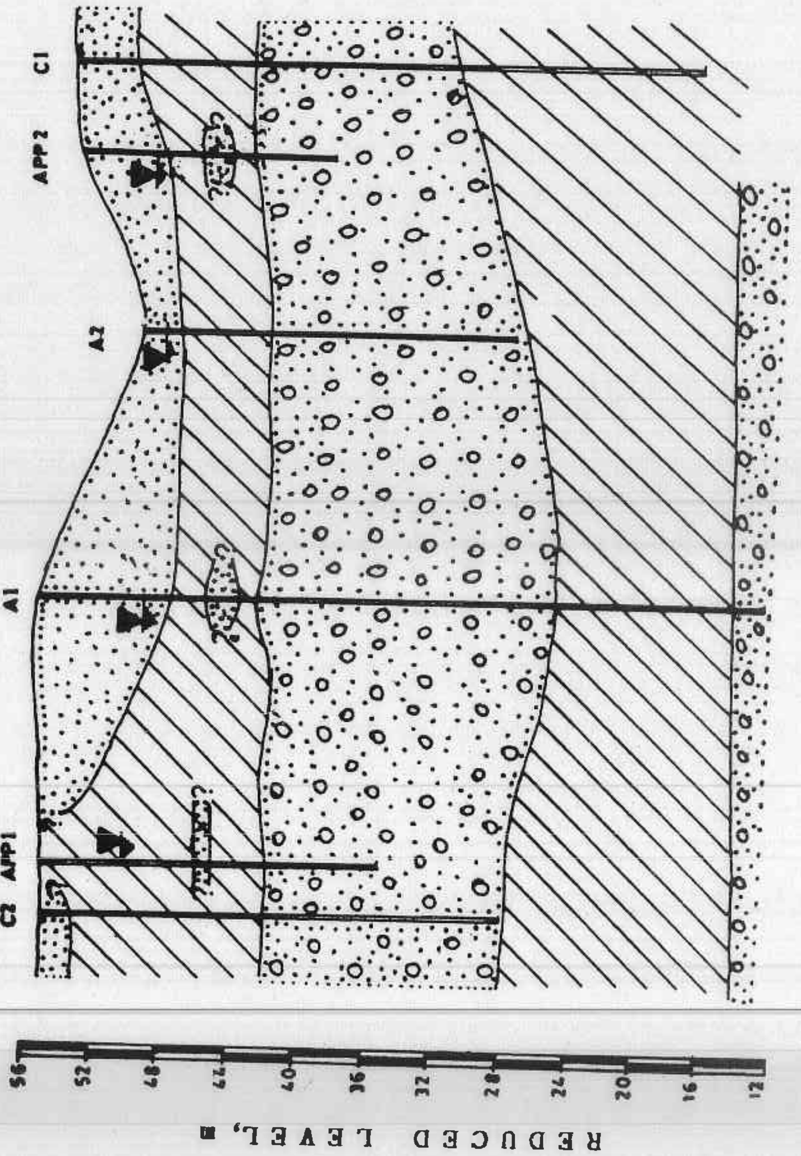


Fig. 7. Generalized subsurface profile along centre line of river Chorahi

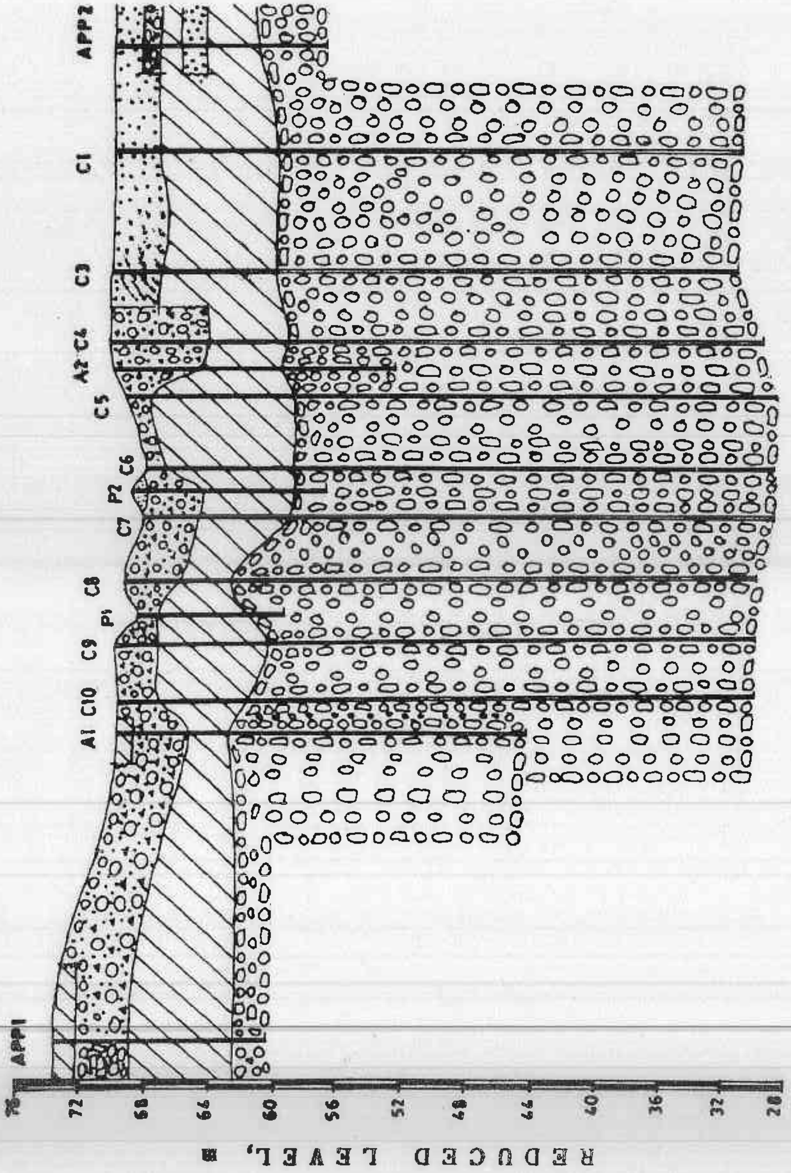


Fig. 8. Generalized subsurface profile along centre line of river Dhobiniya

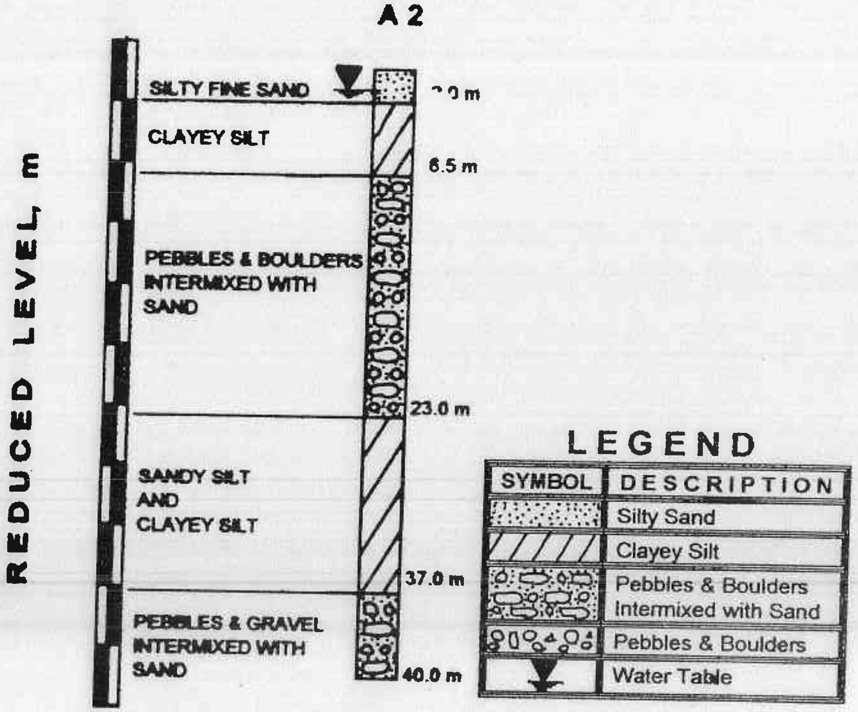


Fig. 9. Interpreted soil stratigraphy at abutment A-2 of river Chorahi

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. A typical profile for river Chorahi is illustrated in Fig. 9.

7. CONCLUDING REMARKS

7.1. Advantages of the Technique

Used in conjunction with borehole data, the resistivity test can provide a basis for geotechnical design. It can be used to identify the various layers and confirm the continuity of the various strata. The depth of each layer can also be assessed. The depth of water table and the salinity of the groundwater (a pre-cursor to assessment of corrosivity of groundwater) can also be obtained.

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.

In strata containing boulders and/or hard rock, drilling is expensive and time consuming. Judicious inclusion of resistivity tests in the geotechnical investigation programme can save substantially on both time and money.

7.2. Limitations

The resistivity test is an indirect method of investigation and has its inherent limitations. Some of these are :

(1) Advance knowledge of likely stratigraphy and groundwater conditions is essential for proper interpretations.

(2) Where the strata dips steeply or where the stratigraphy is variable, the interpretations from the test could be erratic.

(3) If the ground is steeply sloping or is undulating, serious errors may be introduced.

(4) The test cannot be done in a water-logged area or in flowing/standing water.

(5) Soil parameters required for geotechnical analysis, such as, shear characteristics (c-ϕ), density, specific gravity, etc. cannot be obtained from the test. It will have to be assessed from borehole data at nearby locations.

(6) In contaminated areas and in areas where localized inclusions, dykes or other features are present, the interpretation has to take into account these factors and requires a more detailed study.

7.3. Points of Caution

(1) The resistivity test should not be considered as an alternative to borehole drilling. It should be used in conjunction with sufficient borehole data for realistic interpretations that match well with actual ground condition.

(2) Thorough knowledge of local conditions is essential so as to correlate the results with strata conditions. Prior to conducting the test, information on geology, geomorphology and anticipated stratigraphy of the project area should be collected.

(3) The interpretations should be done by experienced personnel with a thorough understanding of geophysics.

(4) The designer should be aware that the interpreted geo-electric litholog, is at best an average profile over the area. The depth of the various strata and the nature of strata as interpreted from the test could vary.

(5) Use of the right kind of resistivity equipment that generates the necessary voltage required to ensure that the current flows to the depth to which the investigation is required. A resistivity meter with a 90 volt (minimum) battery pack is suggested for most applications to investigate to 100-150 m depth. A megger type equipment is not recommended. The equipment that is suitable should be decided based on the formation characteristics and the depth of investigation required.

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