

Delineation of contaminant zone through electrical imaging technique

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Electrical imaging technique has been found to be a powerful tool to delineate sub-surface contaminated zone, when there is sufficient resistivity contrast. Electrical tomography (imaging) involves measuring a series of constant separation traverses with the electrode spacing being increased with each successive traverse. Since increasing separation leads to information from greater depths, the measured apparent resistivities have been used to construct a pseudo-section displaying the variation of resistivities, both laterally and vertically over the section. Normally, the pseudo-section contains geometrical effects, geological noise and the distorting effects of near-surface lateral changes in resistivities, which occur close to the electrodes (electrode effects). In order to remove geometrical effects as well as to produce an image of true depths and true formation resistivities, the inversion technique is used. This technique was successfully demonstrated near Dindigul town, where groundwater was contaminated due to untreated tannery effluents.

ELECTRICAL imaging technique has been widely used in developed countries to study the sub-surface system. New inversion algorithms produce electrical images, which can represent a realistic 2D or 3D sub-surface system. As field data have become more reliable with deployment of refined techniques, electrical imaging has become very effective in delineating fracture and contaminated zones.

Electrical tomography (imaging) involves measuring a series of constant separation traverses with the electrode spacing being increased with each successive traverse. Since increasing separation leads to information from greater depths, the measured apparent resistivity values may be used to construct a vertical contoured section displaying the variation of resistivity, both laterally and vertically over the section.

Modern field systems, such as the Campus Imager System, use a multicore cable to which 50 or more electrodes are connected at takeouts moulded at predetermined equal intervals. Such a cable is very much like a seismic cable and is used in a similar way. The cable is connected to a switching module, to an earth resistance meter and to a computer through an RS232 port (Figure 1). With these systems, any electrode may be switched to act as either

current A, B or potential M, N electrodes and so within the constraints of the electrodes emplaced, any electrode arrangement can be employed.

In practice, either the two-electrode (pole–pole), Wenner, pole–dipole or dipole–dipole arrays is employed. For a line of equally-spaced electrodes, the arrays have the following advantages and disadvantages¹: (i) The two-electrode system has the greatest depth range, lowest resolution and least sensitivity to geological noise; (ii) The Wenner electrode system covers an intermediate depth range, has intermediate resolution and shows moderate sensitivity to geological noise; (iii) Pole–dipole has a good resolution, but is more sensitive to noise; (iv) Dipole–dipole electrode configuration has the smallest depth range, highest resolution and greatest sensitivity to noise.

In addition, there are practical problems which have to be overcome while using the two-electrode array and pole–dipole array, as these require the use of electrodes placed at considerable distances from the imaging line. Also, an important advantage of the Wenner array is that the number of measurements required to construct a pseudo-section is much smaller than with the other arrays.

The first stage is the construction of a pseudo-section by plotting each apparent resistivity on a vertical section at a point below the centre of the four measuring electrodes and at a depth, which is equivalent to the median depth of investigation of the array employed^{2,3}. The data are contoured to form a pseudo depth-section, which qualitatively reflects the spatial variation of resistivity in cross-section (Figure 2).

The contoured pseudo-section contains three types of information. It clearly will contain considerable sub-surface geological information, which is reflected in the general form of the pseudo-section. However, the pseudo-section also contains geometrical information, so that the anomaly across a simple structure will appear quite different for the different electrode arrays. What appears as a simple structure on a two-electrode pseudo-section may be quite complex on a dipole–dipole pseudo-section. In addition, the pseudo-section will contain a certain amount of geological noise, the distorting effects of near-surface lateral changes in resistivity, which occur close to the electrodes (often referred to as ‘electrode effects’). Although shallower than the depth range of the image,

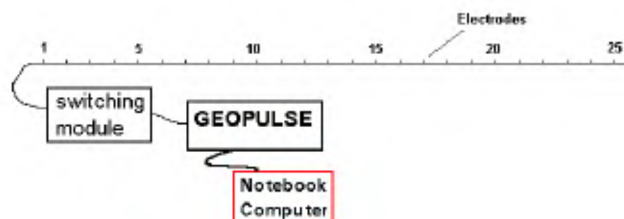


Figure 1. The basic instrument system employed in computer-controlled electrical imaging.

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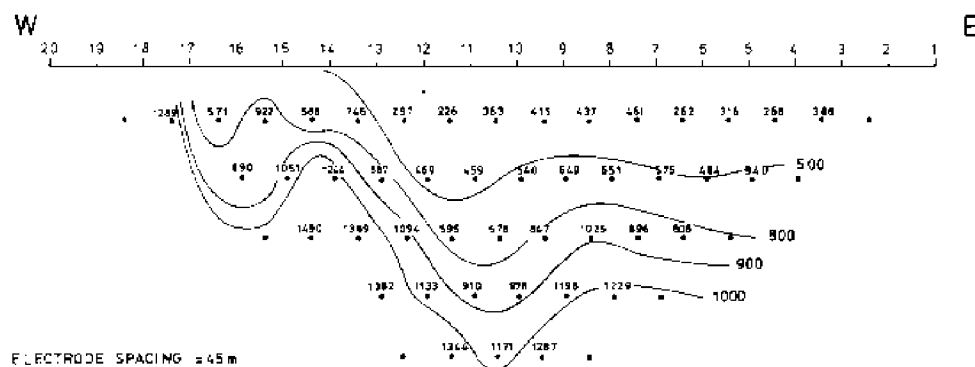


Figure 2. An example of a Wenner pseudo-section.

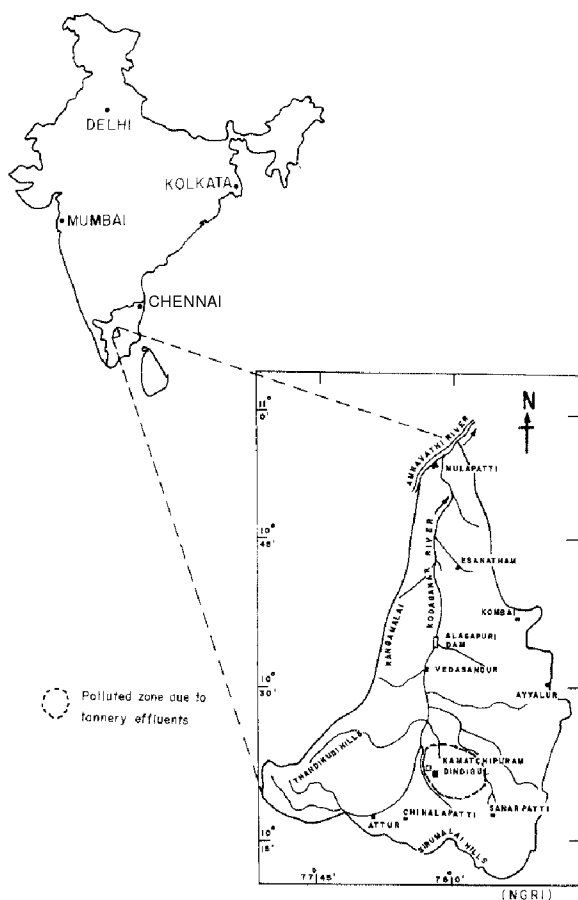


Figure 3. Location of the study area.

they can nevertheless produce spurious resistance readings at any spacing⁴. Their extreme effect is to produce inverted 'V' anomalies across the pseudo-section. The reason why the dipole-dipole array is more sensitive to geological noise is its more complex response to any sub-surface structure.

In order to remove geometrical effects from the pseudo-section and produce an image of true depth and true formation resistivity, the observed data must undergo a form of processing known as inversion. The inversion



Figure 4. Untreated tannery effluents discharged through open channel.

technique recently described by Loke and Barker^{5,6} appears to be a powerful and effective means of processing pseudo-section data to provide a contoured image of true depth and true formation resistivity. It uses a sensitivity matrix of coefficients based on the signal contribution section to form the first model⁴. Then, using a finite difference forward modelling algorithm modified from Dey and Morrison⁷, an iterative least squares optimization technique is applied. An acceptable model is normally arrived at within 5 iterations and the whole process can be carried out in the field on a modern colour notebook computer in less than a couple of minutes.

Location map of electrical imaging technique applied in Dindigul town, and its surrounding area in Tamil Nadu is shown in Figure 3.

The groundwater system in this area was contaminated due to untreated tannery effluents from 85 tanneries. Nearly 100 km² area of agricultural land was affected by the tannery pollution. Flow of untreated effluents is shown in Figure 4 and a contaminated well near the tannery site is shown in Figure 5.

The effluents are collected in Sangaikulam and over flows to Pudhupatty tank (Mangikulam) and then to Kottapatty tank. The outlet of both tanks joins the river Kodaganar.

Table 1. Imaging lines and their locations

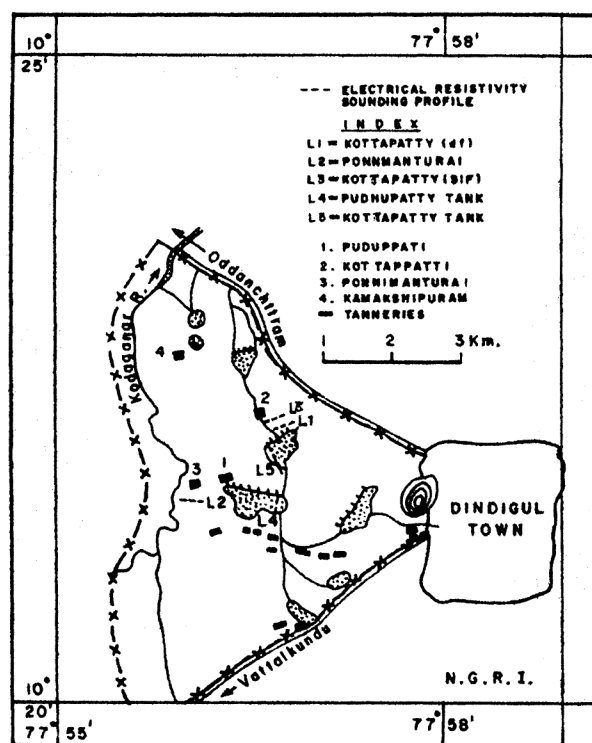
Line	Number of electrodes	Location	Length (m)	Apparent depth (m)	True depth (m)
1	54	Kottapatty (df)	210	17.9	19.8
2	34	Ponnimanturai	165	17.9	19.8
3	45	Kottapatty (sif)	210	17.9	19.8
4	24	Pudhupatty tank	120	17.9	19.8
5	24	Kottapatty tank	120	17.9	19.8

**Figure 5.** A contaminated well in the vicinity of a tannery.

The present study was to delineate the pollutant zone through electrical imaging method. In the Dindigul surveys, the imaging system was used in the manual mode. A single cable with 25 takeouts at 5 m interval was used together with a simple manual switchbox. In order to speed up the surveys and reduce the number of required measurements, all surveys were done using the Wenner array. The cable and switchbox were connected to SSR MPL resistance meter, manufactured in India by IGIS Ltd. Electrodes were 0.5 m long and made of stainless steel; they were planted to a depth of 0.4 m. Each electrode was watered to ensure good contact with the ground. A total of five image lines were measured with the images varying in length from 120 to 210 m. This effectively gave a maximum depth of imaging of 20 m.

A summary of the lines and their locations is given in Table 1 and Figure 6.

Five images were measured at Ponnimanturai and Kottapatty areas situated about 5 km west of Dindigul town. The location of electrical imaging lines around Ponnimanturai and Kottapatty is shown in Figure 6. An attempt was made to get further information on the extent of groundwater contamination due to the leather tanneries. Such imaging is difficult to interpret as the resistivity of

**Figure 6.** Location of electrical imaging lines near Dindigul.

the weathered overburden may vary in response to degree of weathering, saturation and presence of contaminated groundwater.

Surveys in the shallow basement areas suggest that the regolith (weathered overburden) be characterized by resistivities in the range 50 to 200 Ωm . In the region of the leather tanneries, the regolith is thought to be much thicker and may be as much as 100 m in thickness. In this case, the resistivity of shallow regolith might be expected to have weathered to a greater degree and therefore exhibit a resistivity of slightly less than 50 Ωm . If it is assumed that the water table is not far below the surface and that the regolith is largely saturated, resistivities much below 25 Ωm might well indicate groundwater contamination.

The first line was measured across fairly dry fields at Kottapatty (Figure 7). Figure 7a shows that the top 12–15 m of regolith has resistivity of less than 10 Ωm with the top 5 m having a resistivity of less than 4 Ωm .

Therefore, it appears that here the soil is strongly contaminated.

An image line was measured near Ponnimanturai, across an area where resistivity soundings had previously been made and where the villagers claimed that groundwater had been contaminated. The imaging line was chosen in an elevated place in the village. Though the villagers claimed that the entire area had been contaminated, it was observed during the recent field work that the wells falling in the drainage of Pudhupatty tank had been contaminated with total dissolved salts (TDS) more than 3500 mg/l. TDS of drinking water supply close to river Kodaganar is about 1500 mg/l. Figure 8 shows that there is little indication of strong contamination, as the resistivity of much of the sub-surface falls within the range expected for uncontaminated ground, i.e. greater than 50 Ωm . However, towards the right end of the line, the surface resistivity falls to just less than 25 Ωm and could indicate a slight contamination. It is found through field investigations that just 500 m north of electrical imaging line (low-lying area) the TDS level is more than 3000 mg/l).

Three lines were measured fairly close to each other near Kottapatty. The first one was measured across a variety of fields, some of which were being irrigated from a well dug half way along the line. Figure 9 shows that there are signs of contamination as the resistivity of the regolith drops to less than 25 Ωm over much of the line. Bedrock appears to be relatively shallow with high resis-

tivities of more than 200 Ωm being encountered at depths of 15 to 20 m.

Figure 10 shows the image measured directly at the base of the Pudhupatty tank, a large holding reservoir into which polluted water from the tanneries is discharged. At the time of the survey, the tank was dry and its surface appeared to comprise thin salty clay. Here the sub-surface was characterized by low resistivities, with values of less than 10 Ωm being seen at the surface and values of less than 50 Ωm being apparent down to depths of 15 m or more. A recent survey (April 2001) shows that the surface water at Pudhupatty tank contains 15000 mg/l of TDS, which indicates high contamination of groundwater in that village.

Line 5 is almost a continuation of Line 4, but into the adjacent overflow of Kottapatty tank. The surface water in this tank also had high TDS of 12000 mg/l during April 2001. This is the main source of contamination to pollute groundwater as seen in Figure 11. The low resistivity at the surface reflects the presence of a thin layer of surface clay and contamination. However, the resistivity increases rapidly with depth, suggesting that contaminated water has not affected the sub-surface to the extent seen in the adjacent tank.

Groundwater in and around Dindigul town was contaminated due to untreated tannery effluents discharged on the unlined canals. Five Wenner-array profiles were used to measure the apparent resistivity of sub-surface soil. Imaging produced under that condition is difficult to interpret, as the resistivities of the weathered overburden

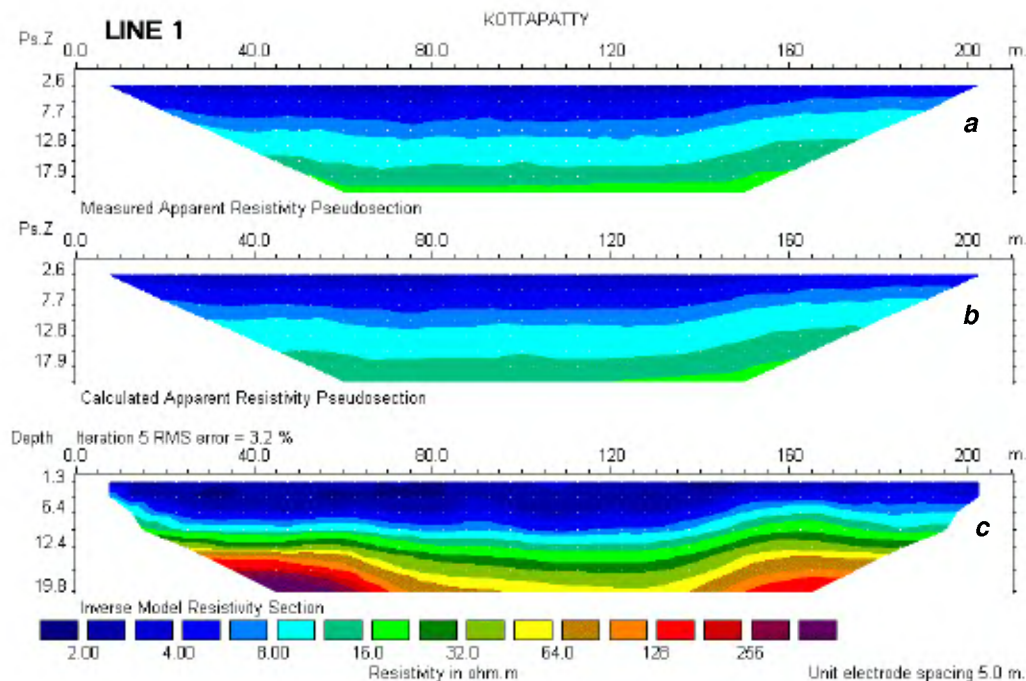


Figure 7. Electrical image along Line 1 over Kottapatty dry field (*a*), Observed data plotted as a coloured pseudo-section, Ps.Z, pseudo depth; (*b*), Pseudo-section computed from the model, and (*c*), Image or model showing the true depth and true formation resistivity.

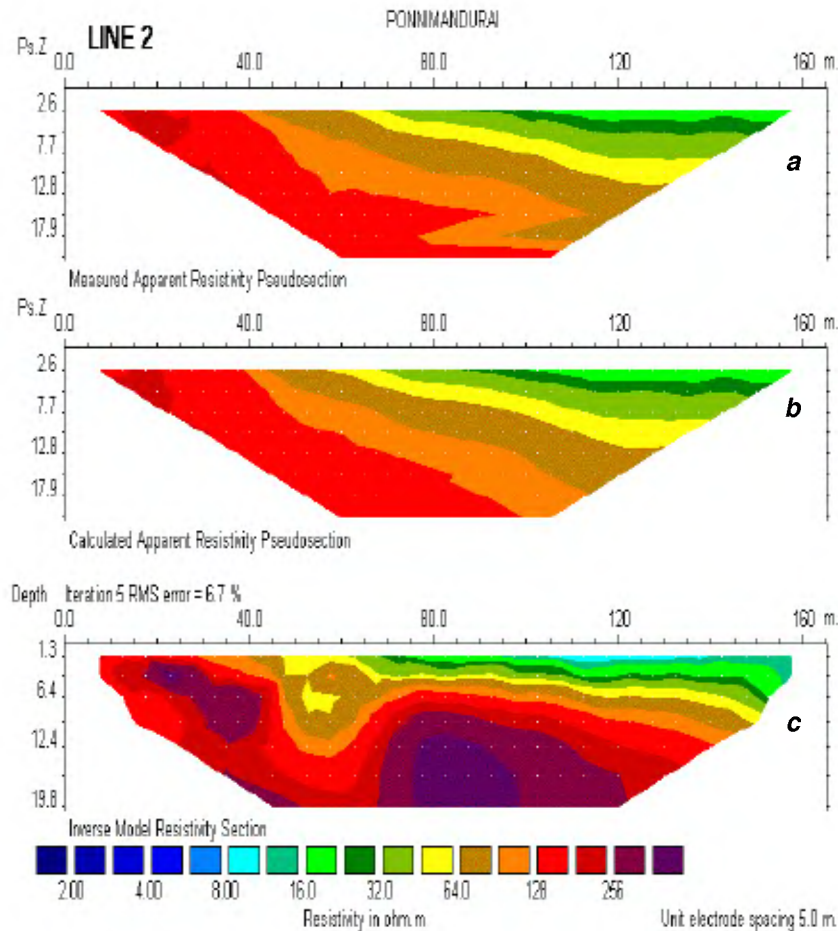


Figure 8. Electrical image along Line 2 near Ponnimanturai.

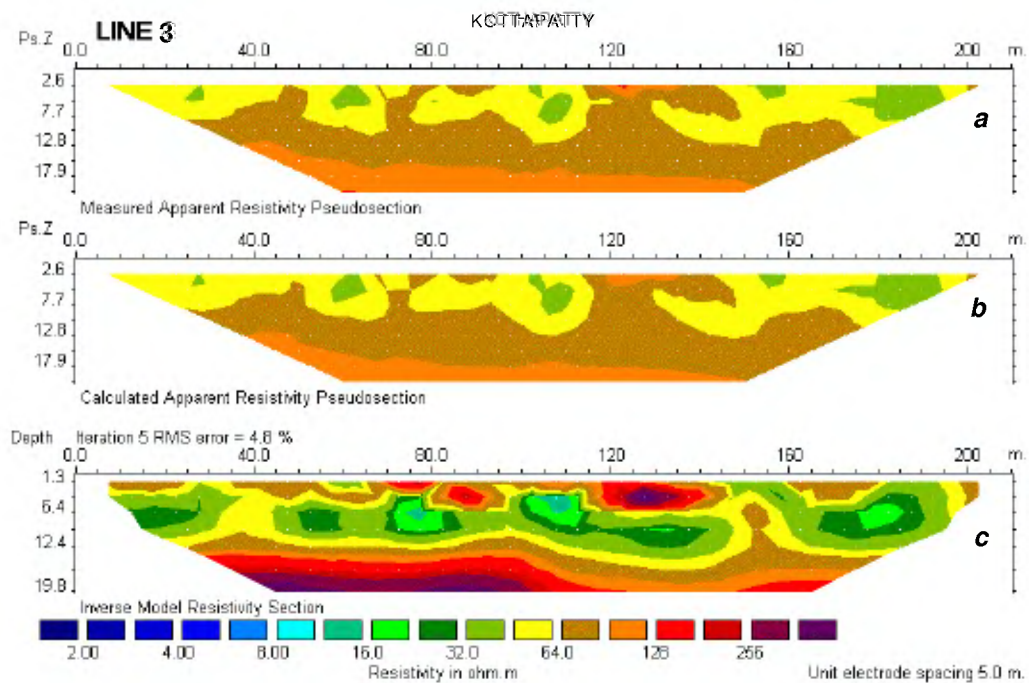


Figure 9. Electrical image along Line 3 near the Kottapatty semi-irrigated field.

may vary due to degree of weathering, saturation and presence of contaminated water. In general, surveys in the shallow basement areas suggest that the weathered overburden is characterized by resistivities in the range of 50 to 200 Ωm , whereas in the neighbourhood of tanneries, it is expected to occur as a relatively thick layer of contaminant zone. In that case, the resistivity of shallow regolith might be expected to be less than 50 Ωm . Since the water

table is shallow and the regolith is largely saturated, any resistivity much below 20 Ωm will indicate groundwater contamination, in absence of any clay material. Out of the five profiles, four have shown that the top 10–15 m of regolith has resistivity of less than 10 Ωm , with top 5 m having a resistivity of less than 4 Ωm . This has clearly indicated that the soil is strongly contaminated. One profile has shown low resistivity at the low topography part

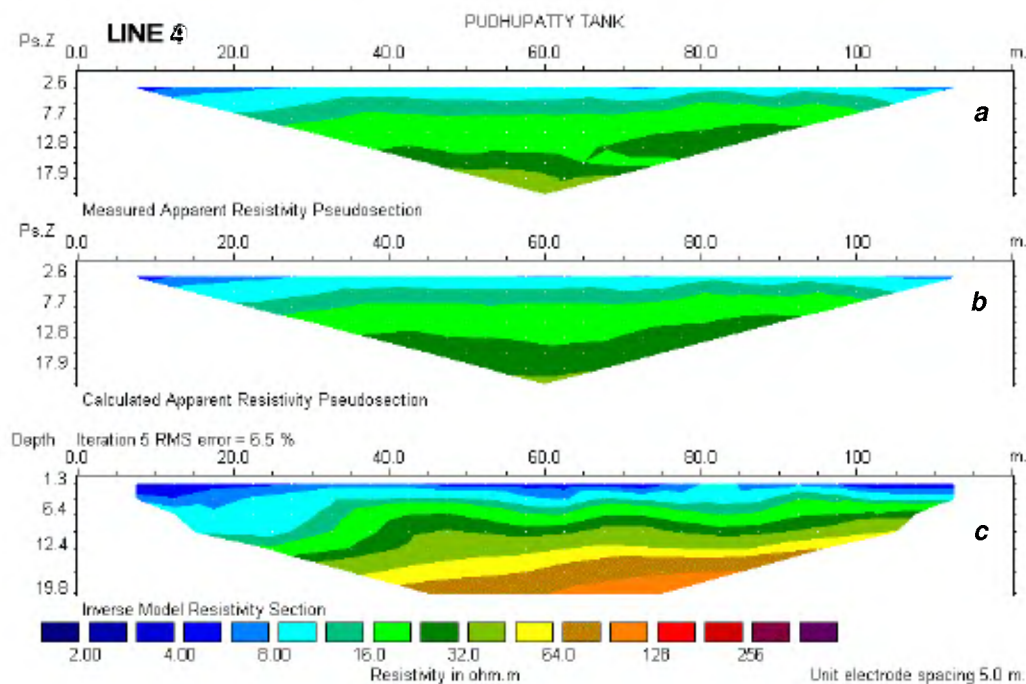


Figure 10. Electrical image along Line 4, Pudhupatty tank.

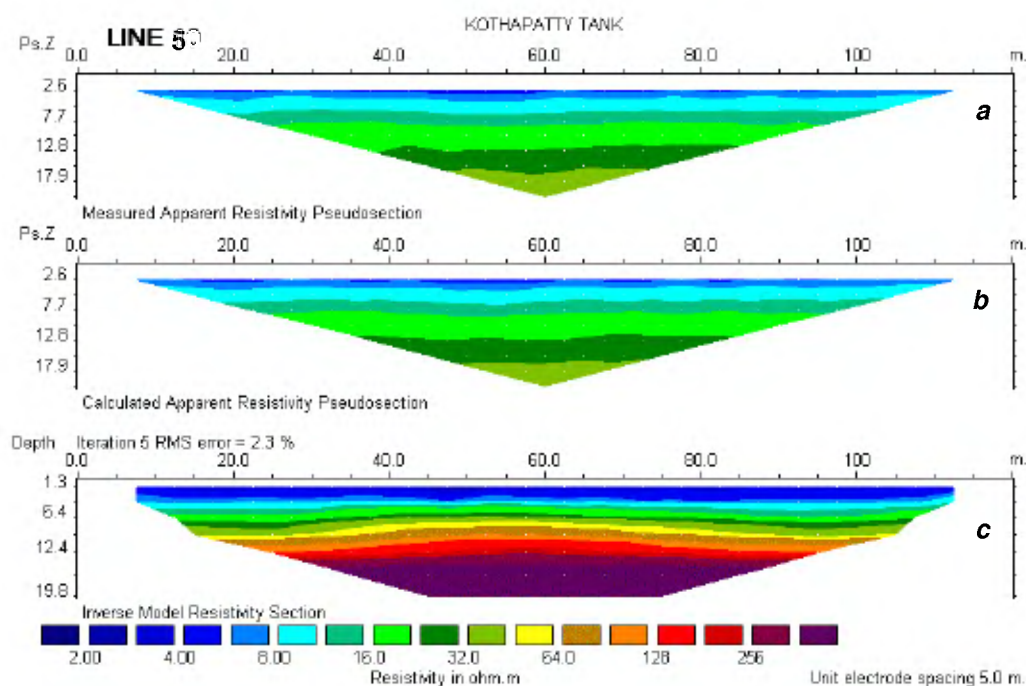


Figure 11. Electrical image along Line 5, Kottapatty tank.

of the profile, and resistivity of above 100 Ωm in the elevated area which is not contaminated. Thus, this technique provides useful and interesting information about the polluted zone.

The imaging over the contaminated areas, although providing interesting information, can only be interpreted qualitatively. As discussed above, the interpretations are ambiguous and can only be improved with other control information from boreholes or chemical sampling. None of the five images measured across the contaminated sites show any strong lateral change in resistivity and it must be admitted that similar information could be obtained with resistivity sounding. A few soundings over the area can indicate likely sites for low resistivity regolith and heavy contamination.

The imaging technique has proved to be a powerful one in groundwater contamination studies. Electrical images provide a more detailed view of the sub-surface structure than can be obtained using other geophysical techniques and therefore lead to a better understanding of the local hydrogeology.

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Response of the Bay of Bengal to Gopalpur and Paradip super cyclones during 15–31 October 1999

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Response of the Bay of Bengal to two tropical cyclones, i.e. Gopalpur and Paradip super cyclones, during 15–31 October 1999, is studied using a stationary mooring buoy for marine meteorological observations. The National Institute of Ocean Technology (NIOT, Chennai) has deployed this buoy at 13°N, 87°E, by fixing various meteorological instruments and sensors to acquire sea surface temperature (SST), air temperature (Ta), wind speed (Ws), wind direction (Wd) and ocean currents (Cs) using remote sensing technique through INSAT-1D satellite at an interval of 3 h. The results of the analysis of the above parameters have shown clearly a response (SST difference between before and after formation) of about 0.7°C for the Gopalpur cyclone and 0.9°C for the Paradip cyclone. Ta has shown rapid variations following the rapid movement of cloud decks across the buoy during the cyclone period. The observed changes in the wind speed and direction are in concurrence with analysed mean sea level pressure oscillations. Finally, this study recommends more buoy-based marine meteorological observations over this region and the neighbouring areas, where the tropical cyclones generally occur and subsequently hit the Coromandal coast.

DURING the post-monsoon season in October 1999, two severe cyclones had formed over the Bay of Bengal with

their centres at 13.8°N, 92.8°E (03 UTC 15 October) and 12.5°N, 98°E (12 UTC 25 October) respectively, during the period from 15 to 19 October and 25 to 31 October. Both these tropical cyclones moved in a north-westerly direction and crossed the Coromandal coast of India at Gopalpur and Paradip in sequence. The important features to be noted about these two cyclones are as follows. (1) The incipient development of the above two cyclones took place over an area where tropical cyclones rarely originated in October; the actual location is 10–13°N, 85–90°E (ref. 1). (2) These systems moved very fast over the ocean and slowed down just prior to the landfall. (3) Following slowness, these systems further intensified into very severe cyclones, with a core of hurricane winds. However, the second cyclone had become a super cyclone just prior to the landfall and stagnated over the coastal region for about two days. (4) Both these systems brought great disaster to the people of Orissa.

During the month of October, cyclones generally originate over an area between 10–15°N and 85–90°E (refs 1–3). These systems generally move in a west-north-westerly direction and cross Tamil Nadu–Andhra coast, but some systems occasionally recurve northwards near 13°N, 86.5°E and move in a north or north-easterly direction and hit the Bangladesh coast subsequently³. It is well known that the meteorological observations over the Bay of Bengal during the season of tropical cyclones are sparse and paucity of data persists. The main reason for this, obviously, is due to the disastrous conditions that prevail in the cyclone field and none dare to venture into it. Nevertheless, there are a few occasions where some observations in the cyclone field have been reported elsewhere^{4,5}. These observations generally confine to a small period and area of opportunity.

In the present study, an opportunity has arisen to examine a case study of a couple of tropical cyclones in the Bay of Bengal using meteorological observations of a buoy, DS-3 (13°N, 87°E) deployed by the National

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