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RESOLUTION OF AN ELECTROMAGNETIC BOREHOLE CONDUCTIVITY LOGGER FOR GEOTECHNICAL AND GROUND WATER APPLICATIONS

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ABSTRACT

A new induction logger, the Geonics EM39, was specifically designed for use in plastic-encased wells drilled for geotechnical and groundwater applications. Such applications require different specifications than those used in the oil industry. Specifically, while insensitivity to the invaded zone need extend only out to a distance of about 10 cm from the well axis, vertical resolution must be of the order of a few tenths of meters. These constraints are met by (1) using a small intercoil spacing of 50 cm and (2) incorporating a single focussing coil. The resulting probe measures the electrical conductivity of the surrounding soil within a distance range from 20 cm to 100 cm from the well axis while being insensitive to conductivity of the borehole fluid and disturbed material situated near the well axis.

The theoretical response of such a probe to an arbitrarily layered earth is easily calculated using a simple computer program. A comparison between calculated and measured responses is given for three case-histories that exhibited clearly defined horizontal boundaries. In the first example (Taylor, Hess and Mazzela, 1989) the probe was slowly immersed in a conductive lake (i.e. a homogeneous half-space). Calculated and measured response as a function of depth were in good agreement.

In the second example a migrating contaminant plume from a landfill located in sand was unexpectedly elevated due to thin layers of clay or silt; comparison of the measured and calculated responses shows that the transition from contaminant to no contaminant occurs over a narrow distance of about 0.2 m to 0.4 m, illustrating the limit of vertical resolution of the instrument. The location of this interface is resolved to within 0.1 m. In the third case history (taken through another contaminant plume migrating from a landfill located in sand) the plume was again unexpectedly elevated, but in this case it also exhibited "fingering". Comparison of the derived geoelectric section with a detailed lithologic log shows that part of the plume layering is associated with recognizable lithologic units but that the rest is due to undetected lithological variation.

The latter two case histories are of more than academic interest: in the first landfill site the presence of the plume was missed by two monitoring wells due to incorrect well depth and/or screen location, and in the second site the plume would have been missed had not the EM39 been used to log the well.

INTRODUCTION

The electromagnetic induction method of remotely measuring the electrical conductivity of the ground is now widely used for mapping groundwater contamination plumes, for groundwater exploration, and for general geological mapping (McNeill 1980). Development of a borehole conductivity probe for monitoring contamination both in the vadose zone and below the water table was a logical extension to the surface geophysical method. Although such devices (known as induction loggers) have been employed in the oil industry for many years (Doll, 1949) those probes are generally not suitable for geotechnical applications, where the principle requirements are:

1. Slim probes, since the boreholes are often only 5 cm in diameter,
2. Moderate depth of exploration, usually a few tens of meters and seldom greater than 200 m,
3. Good vertical resolution so that thin contaminant plumes can be accurately located and their spatial distribution resolved,
4. High sensitivity combined with low noise for measurements in resistive environments and also for detecting the small reductions in conductivity that will occur when passing through contamninant plumes of organic liquids,
5. Excellent stability so that repeated measurements in a monitoring well will detect the small variations in

conductivity with time that arise from changes in the extent of the contaminant plume resulting from reclamation procedures.

The principle advantage of induction electromagnetic (EM) loggers over conventional DC resistivity probes lies in the fact that EM loggers measure terrain conductivity outside of monitoring wells that have been cased with insulating PVC or Teflon tubing. Thus, although induction loggers should be used initially to locate sections of significant ground water contamination in uncased holes to help select the optimum screen placement, their real advantage is that they can be deployed in existing, cased wells to confirm that the screening is correctly placed, and also for subsequent monitoring of contamination levels outside the cased wells to indicate changes in plume morphology with time. Furthermore since they do not require electrical contact with the soil, they are also quite suitable for detecting and monitoring contaminant plumes in the vadose zone.

Like the inductive ground conductivity meter, the borehole induction logger employs a small internal transmitter coil energized with an audio-frequency current to induce the eddy currents (Figure 1) in the soil or rock surrounding the well. These eddy currents generate an alternating secondary magnetic field which can be detected and measured by a small receiver coil located some distance away from the transmitter. If the logger is designed to operate at "low values of induction number" the small secondary magnetic field will be essentially linearly proportional to the electrical conductivity of the surrounding material and the device can be calibrated to read the terrain conductivity directly. Technical details of such a logger are given in McNeill (1986).

INSTRUMENT RESPONSE PARAMETERS

Response as a Function of Radial Distance from Borehole Axis

In the design of an induction logger there is always a compromise between achieving both a large lateral range of exploration in the surrounding soil or rock and, simultaneously, a high degree of vertical resolution. The first requirement is satisfied by large transmitter/receiver coil spacing, whereas the second requires a small intercoil spacing. Analysis of these conflicting constraints showed that optimum intercoil spacing for a borehole logger specifically intended for ground water contamination monitoring was 50 cm. With this relatively short intercoil spacing it was apparent that a centrally located focussing coil must be incorporated to reduce the response from conductive borehole fluid to negligible proportions.

The relative response with radial distance from the well axis resulting from this coil configuration is shown in Figure 2, from which we see that the instrument is most sensitive to material located at a distance of about 30 cm from the axis, but still has appreciable sensitivity out to 100 cm. On the other hand, the sensitivity to material located within 5 cm of the borehole axis is virtually zero, making the instrument blind to the conductivity of borehole fluid in wells of diameter up to 10 cm. Indeed it can be shown (McNeill 1986) that even for a borehole diameter of 15 cm and borehole fluid conductivity one hundred times greater than the surrounding material, the contribution to the instrument reading from the borehole fluid is generally negligible.

Response to a Horizontally Layered Earth

It can be shown that the resolution of the probe to horizontal layering is completely defined by the instrumental response as the probe passes down through an extremely thin (compared with the intercoil spacing) conductive horizontal sheet located in otherwise resistive ground. This instrumental response, illustrated in Figure 3, is somewhat assymetrical due to use of the focussing coil, and has a "full width to half-maximum" of about 65 cm.

In the general case, as the probe passes downwards through a horizontally layered earth the response at any given depth z is the integral from zero to infinity of the instrumental response function shown in Figure 3 multiplied by the actual conductivity distribution with depth. In fact it is a simple matter, using this function, to calculate the response to an arbitrarily (horizontally) layered earth, and a small computer program has been written for this purpose.

The calculated response that would arise as the sonde passes down through the layered earth geometry shown in Figure 4 is also shown on that figure. Two effects are evident: the first is that the sharp boundaries of the theoretical conductivity distribution are smeared out by the averaging introduced by the instrumental response, and the second is that, even though the thickness of the conductive layer is 5 m, this thickness is small enough so that the averaging introduced by the instrumental response also results in an erroneously low value for the apparent conductivity at the anomaly peak. This error, $\Delta\sigma_m$, which is a function of the thickness t of the conductive (or resistive) thin layer, and of the conductivity contrast of the layer with respect to the background conductivity, has been discussed by Taylor et al (1989) and McNeill et al (1988). With reference to Figure 5 it is shown in McNeill et al that, for thick sheets, as long as the thickness is greater than 1.5 m, the error in peak conductivity $\Delta\sigma_m/(\sigma_2 - \sigma_1)$ is less than 20%, and for thin sheets, as long as the thickness is less than 0.75 m, the indicated apparent conductivity is approximately numerically equal to the product of the conductivity contrast, $\sigma_2 - \sigma_1$, multiplied by the sheet thickness t, as indicated on the figure.

For the remainder of this paper we will focus our attention on the first effect described above, viz the smearing of the response at sharp boundaries. Specifically, we first calculate the theoretical response from a step-wise graded boundary, using the program described above, to determine how well we can resolve a sharp boundary. The results of these calculations are then compared with measured data from three case histories.

Thus in Figure 6 we compare the calculated response from stepwise graded boundaries with the calculated response from an abrupt boundary. In Figure 6a the transition in conductivity from 100 to 0 mS/m takes place over a vertical extent of 3 m and we observe that the two measured responses are sufficiently different to allow unambiguous identification of the graded response. Figures 6b and 6c show similar data, except that the boundary width is 1.5 m and 0.75 m respectively. Again the two different boundary types, graded and abrupt, can be distinguished. The results of Figure 6d, however, for a boundary width of 0.38 m, show virtually the same response for both boundary types, from which we conclude that, with an intercoil spacing of 50 cm, it will be impossible to distinguish between a graded and abrupt boundary as long as the width of the former is less than about 40 cm. We note, however, that in all examples shown in Figure 6 it is possible to locate the midpoint of the boundary to within about 10 cm.

We will now compare the results of such calculations with field data.

CASE HISTORY #1
TAYLOR, HESS AND MAZZELA(1989)

Our first case history simply shows the measured and calculated instrumental response as the sonde is lowered from the air (of zero conductivity) into a lake of conductivity 6 mS/m (constant at least for the first few meters of depth). We see in Figure 7 that agreement between the measured and calculated response is good, and also that the signal-to-noise ratio of the measurement is high enough to allow the detection of small differences in the response.

CASE HISTORY #2. - U.S.A

Our next case history concerns a municipal landfill located in an area of relatively silt and clay-free sand. A plan view of the site, indicating the location of two adjacent monitoring wells, 9S and 9D, is shown in Figure 8. The lithologic logs from these two wells are shown in Figure 9, from which we see that sand generally predominates, with occasional silt and clay. We note also the location of the screen in the two wells; in the deeper well (9D) the screen is set at the top of what the lithologic log shows to be the first occurence of predominantly clay.

Results of the EM39 conductivity log of well 9D are shown in Figure 10 (both up and down direction logs are plotted to indicate the repeatability of the measurement technique). We note that the steel casing at the top of the well causes the conductivity log to read incorrectly until it has passed down a distance of about 0.6 m below the casing, beyond which there is no further effect. Once beyond the casing the measured conductivity increases rapidly, reaching a maximum of about 90 mS/m at a depth of 11 m. Using the relationship that, in clay-free sands, an increase of 25 ppm in total dissolved solids (TDS) causes an increase of about 1 mS/m in apparent conductivity (McNeill et al, 1988) we conclude that our 90 mS/m corresponds to a TDS of approximately 2200 ppm, good indication of potential contamination.

At a depth of about 14 m the conductivity starts to fall rapidly; by 16 m the conductivity has decreased to about 10 mS/m, a value typical for silt and clay-free sand. It appears that the bottom of the plume (and, to a slightly lesser extent, the top) are quite abrupt. The multi-layered earth computer program referred to above was employed iteratively to generate the calculated profile of Figure 11 by selecting layers of different conductivities and thicknesses until a good match to the measured data was obtained. Such a procedure, after a little practice, takes about 20 minutes. The resultant geoelectric section in Figure 11 shows that abrupt transitions from 22 mS/m to 76 mS/m at 4.7 m and from 68 mS/m to 7 mS/m at 15 m give a good fit to the measured data.

In Figure 12a we show in greater detail the measured and calculated conductivities at depths from 12 to 18 m. We wish to investigate further the nature of the transition at 15 m and as a first step we introduce, at this depth, an intermediate layer of conductivity 37.5 mS/m (= 7 + (68 -7)/2) and of width 1.30 m. Results of the multi-layered earth calculation for this model, shown in Figure 12b, are in poor agreement with the measured data. The thickness of the intermediate layer is reduced to 0.80 m, and again the results, shown in Figure 12c, show poor agreement. Finally, however, results for a transition layer of width 0.40 m, shown in Figure 12d, are in better agreement with the measured data than the abrupt layer of Figure 12a, from which we conclude that the width of the transition layer is of the order of 40 cm. The location of the transition zone is accurate to within about 10 cm.

Comparison of Figure 9 with Figure 11 shows that the contaminant plume was not detected by either monitoring well. One well is too shallow, the screen in the second well is too deep.

CASE HISTORY #3 - CANADA

Once again this case history involves a municipal sanitary landfill located in a relatively clay and silt-free sand. As a result of contaminant migration into nearby residential wells, several monitoring wells were installed around the landfill site and logged with the EM39. The conductivity and lithological logs from one of these wells are shown in Figure 13. We again note that the steel casing at the top of the well causes the conductivity log to read incorrectly until it has passed down about 0.6 m below the casing, beyond which there is no further effect. Figure 13 shows that above the water table the conductivity varies from 5 to 10 mS/m, typical values for a clean, relatively dry sand. As often happens there is no abrupt change of conductivity on passing through the water table, indicating that there is sufficient moisture in the vadose zone to enhance the conductivity. The water table is poorly defined electrically, even in this granular material, implying that use of surface electrical or electromagnetic techniques to determine the level of the water table would be unsuccessful (seismic refraction is preferred). Once beneath the water table the conductivity increases rapidly but smoothly, reaching a maximum of about 100 mS/m at a depth of 37 m. Again using the relationship that, in clay-free sands, an increase of 25 ppm in total dissolved solids causes an increase of about 1 mS/m in apparent conductivity, we conclude that 100 mS/m corresponds to a TDS of approximately 2500 ppm. In this conductivity log there is no suggestion that the lithological variations exhibited in the driller's log are exerting any influence on the plume morphology.

Consider now the induction conductivity log shown in Figure 14 from another well at the same landfill site. Once again the sand above the water table has low conductivity and the water table is electrically poorly defined. However in this log the plume shows large variations of conductivity with depth, indicating that the plume is "fingered". More seriously, however, at a depth of 25 m the conductivity rapidly decreases to the same low values observed above the plume; the conductivity beyond this depth is again indicative of clay-free, uncontaminated sand. It would be impossible to determine from the lithological log where to set the slotted screen section of the plastic casing so as to intercept the plume; furthermore, variations within the plume itself would make accurate assessment of the total contaminant burden unlikely if the only data available were ground water samples from the well.

The multi-layered earth modeling program was used to generate the curve of Figure 15 which closely matches the measured curve of Figure 14. The geoelectric model that gave the response of Figure 15 is shown in Figure 16, which gives the location, conductivity, and thickness of each of the model layers. Several points are suggested:

(1) Many of the geoelectric model interfaces (i.e. those at a, b and c) coincide with interfaces indicated on the lithologic log. These different materials have been differentiated by the logger on the basis of their different electrical conductivities.

(2) The remainder of the interpreted geoelectric interfaces do not have corresponding interfaces on the lithologic log. The features causing the variations in hydraulic conductivity are too subtle to be discerned on the lithologic log, but are

resolved on the basis of conductivity.

(3) The transition from contaminated to uncontaminated soil at a depth of 25.3 m once again occurs over a vertical distance of a small fraction of a meter. Since the measured data is well matched by an abrupt transition we can assume, from the calculations shown in Figures 6a - d, that the transition width is less than 40 cm.

Clearly, without the induction log, accurate setting of the monitoring well screen and correct sampling of the ground water would be most unlikely.

CONCLUSIONS

It was stated in the Introduction that one of the requirements for an induction logger designed to be used for ground water contamination studies was a high degree of vertical resolution so that thin or variable contaminant plumes could be accurately defined and precisely located. In this paper we have shown two case histories, in both of which contaminant plumes exhibited abrupt transition zones at both the top and the bottom, and in one of which the plume also exhibited a good deal of fingering, thus establishing that such situations do exist in the real world.

It was shown that a simple multi-layered earth program (which uses the low induction number approximation) gave good agreement with measured data as the EM39 sonde was lowered into a lake. This simple test is sufficient to show that agreement between the modelling program and experiment will be satisfactory for all layered-earth conductivity configurations. The modelling program was then used to accurately match theoretical models with the two plume responses. In both cases it was established that the transition zone at the base of the plume was of the order of, or less than, 40 cm in vertical extent. Furthermore in the last case history the geoelectric section derived from the measured conductivity log was in good agreement with some of the interfaces indicated on the lithologic log, and in other instances the geoelectric log suggested interfaces that were undetected on the lithologic log.

Finally, in the first contaminant case history, the fact that the plume was elevated by a substantial distance above the first obvious aquitard (as determined from drilling) resulted in inaccurate screen location and an undetected plume, which would have been detected had the well been logged with the EM39. In the second contaminant case history, had the screen been installed without running a conductivity log it is almost certain that this plume would have been missed as well.

ACKNOWLEDGEMENT

We are grateful to Gartner Lee Limited of Markham, Ontario, for allowing us to publish the induction logger case history of Figures 13 to 16.

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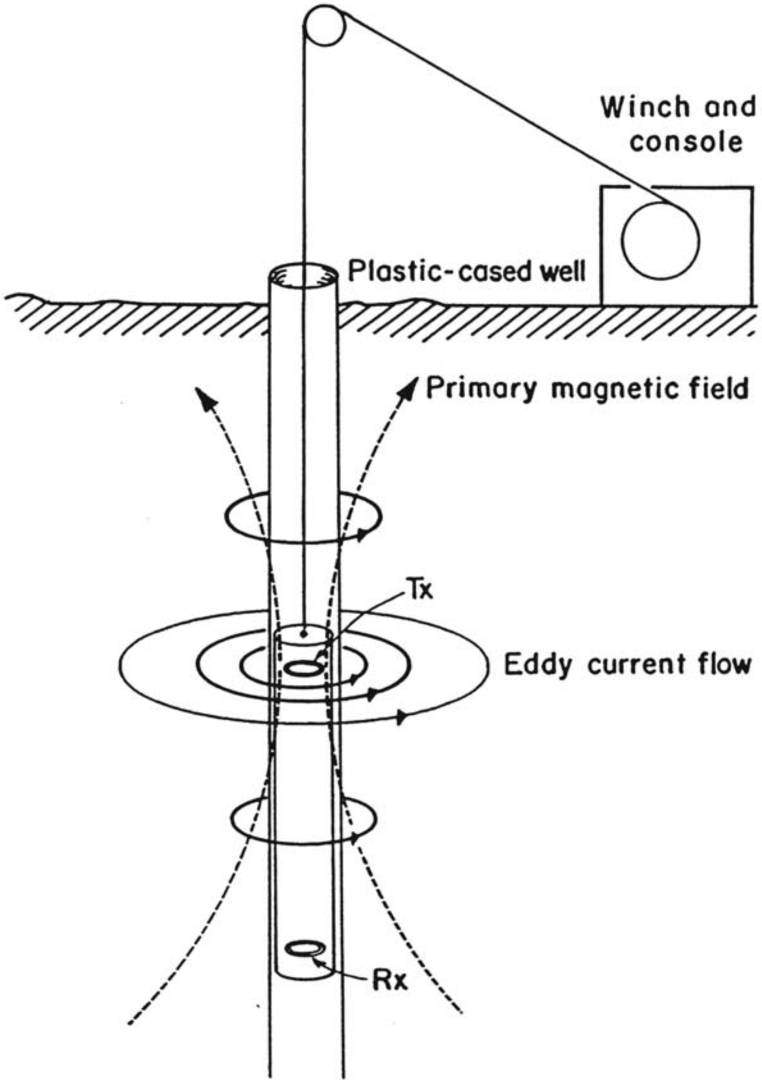


Figure 1 Borehole induction logger, showing current flow.

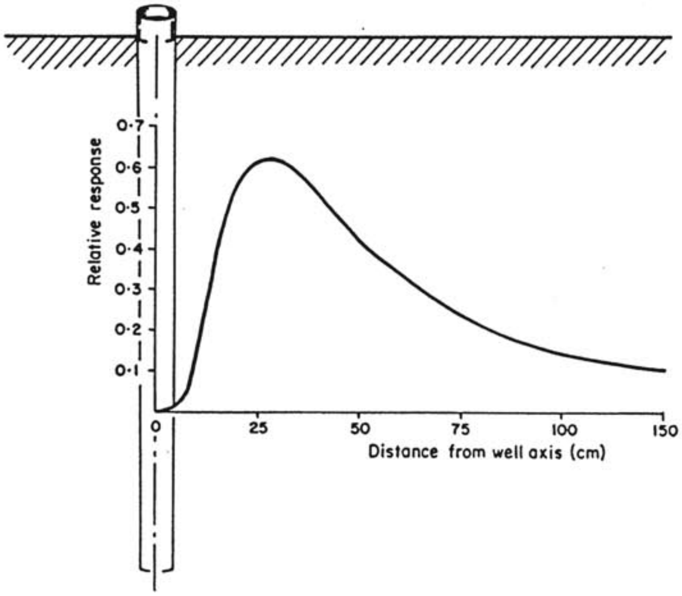


Figure 2 Relative response with radial distance from borehole axis.

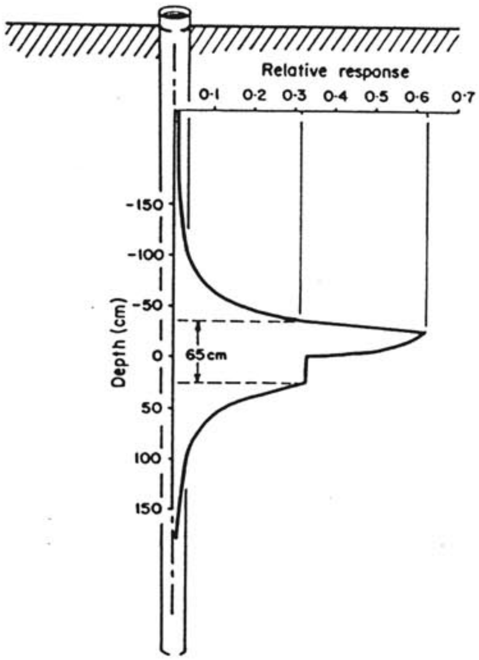


Figure 3 Relative response with vertical distance above and below sonde center.

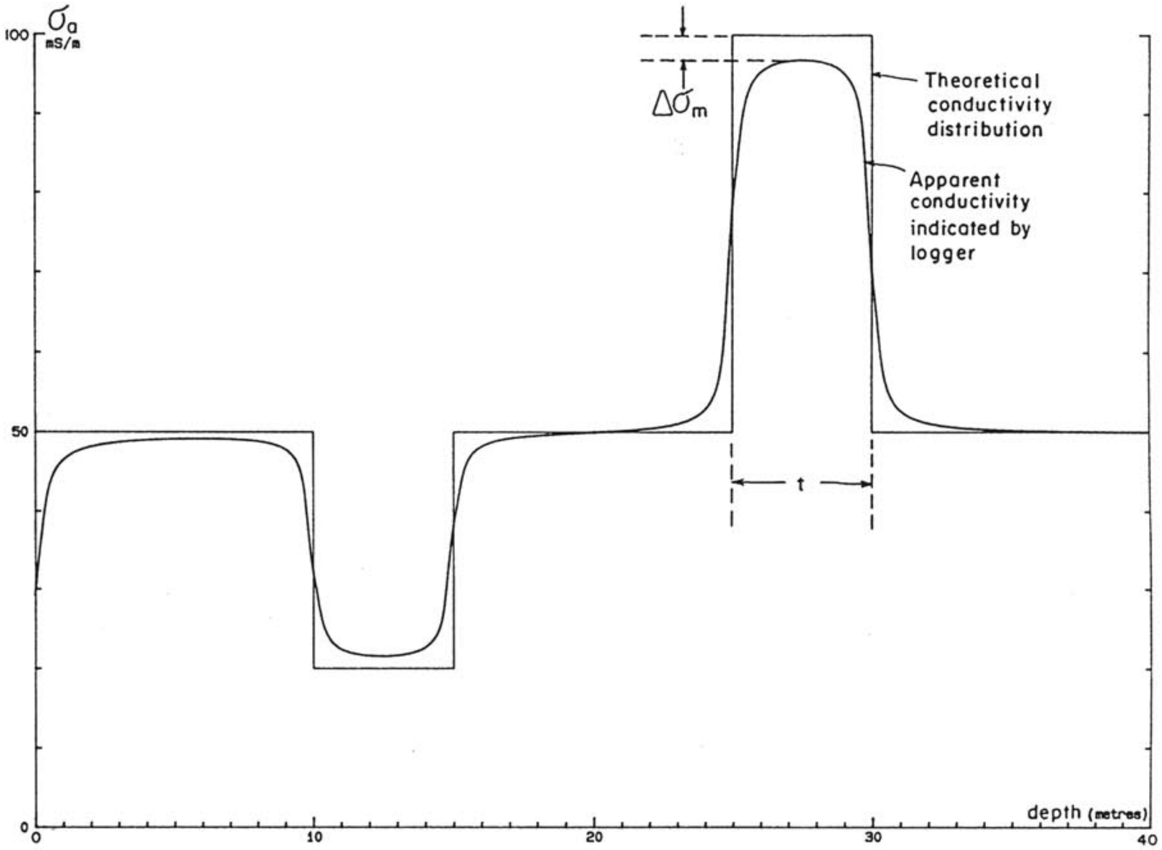


Figure 4 Calculated response as a function of depth for a theoretical layered-earth distribution.

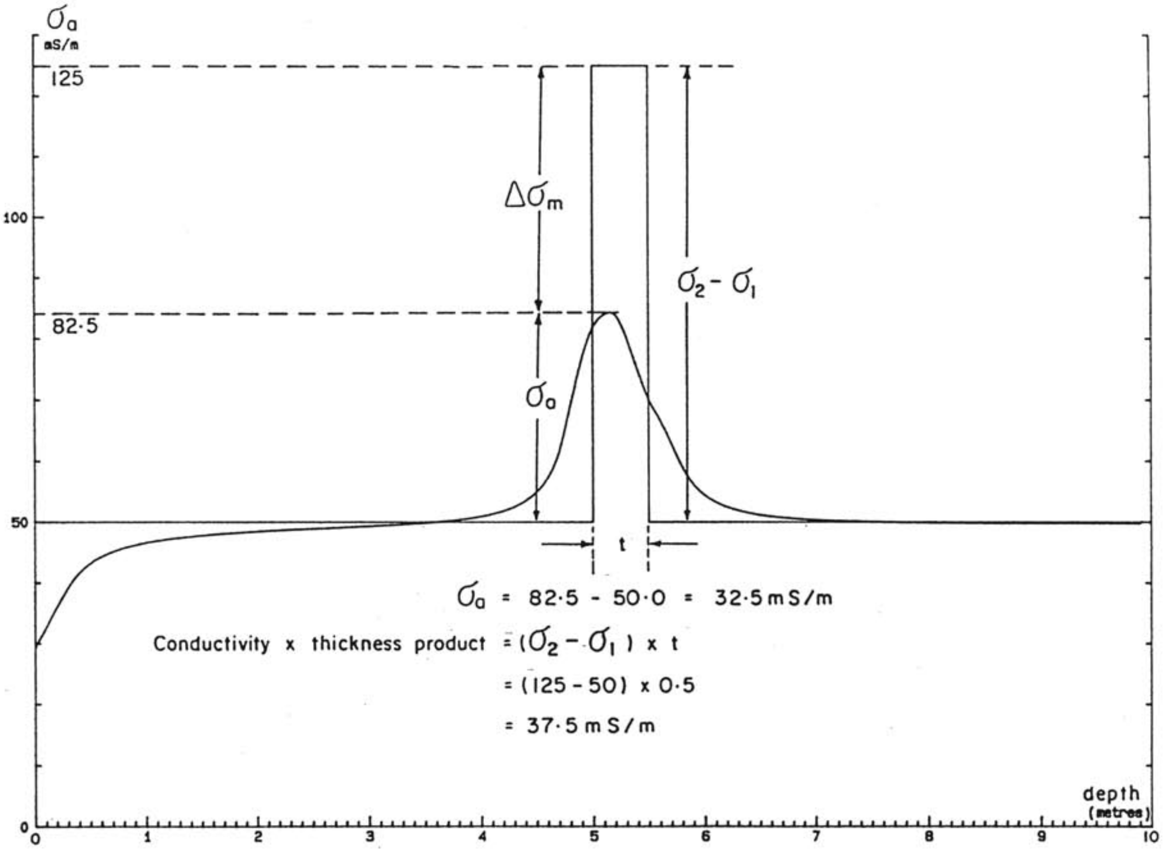
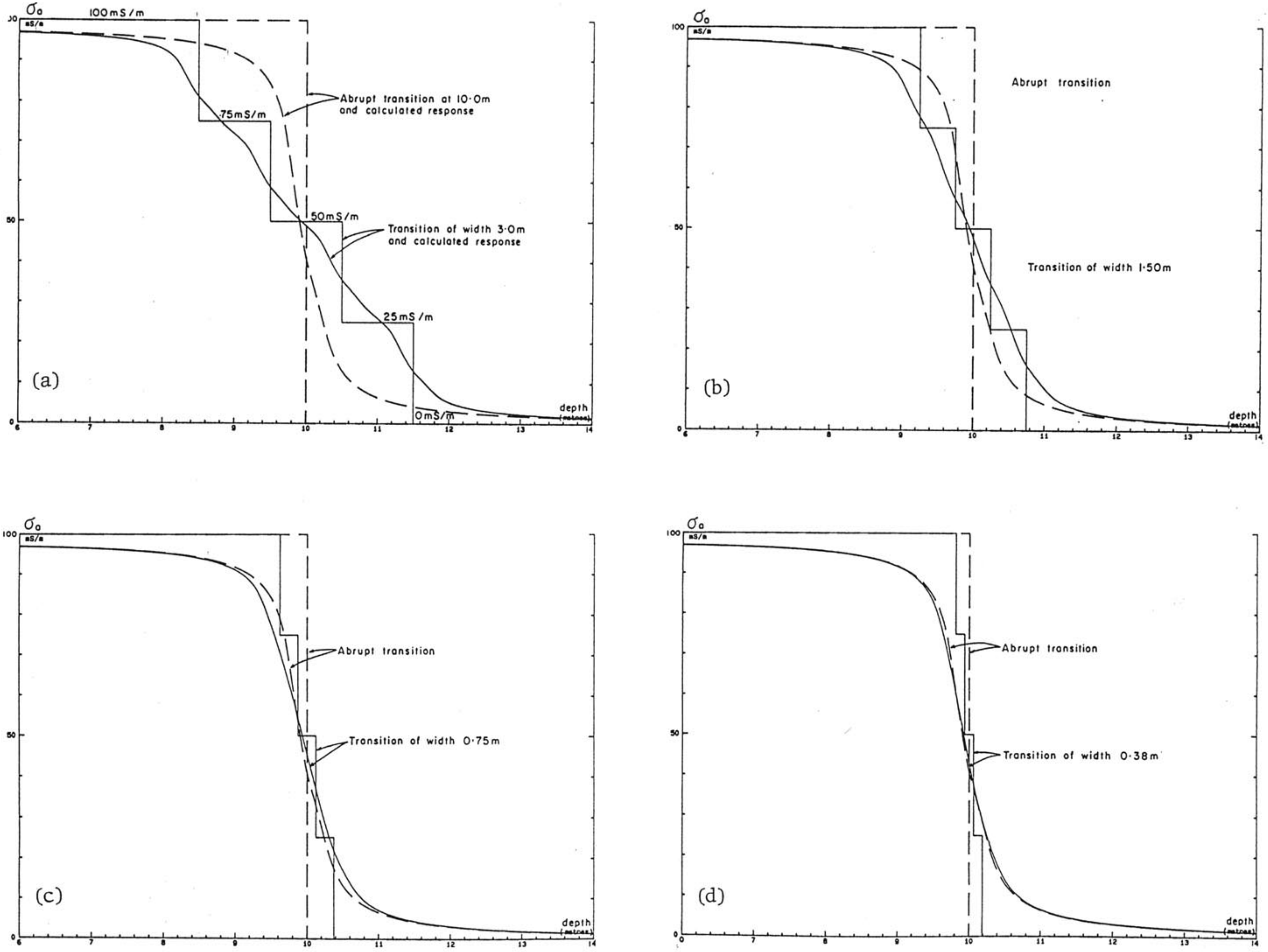


Figure 5 Calculated response as a function of depth for a thin conductive layer.



Figures 6a-d Calculated response as a function of depth for a series of step-wise graded conductivity distributing.

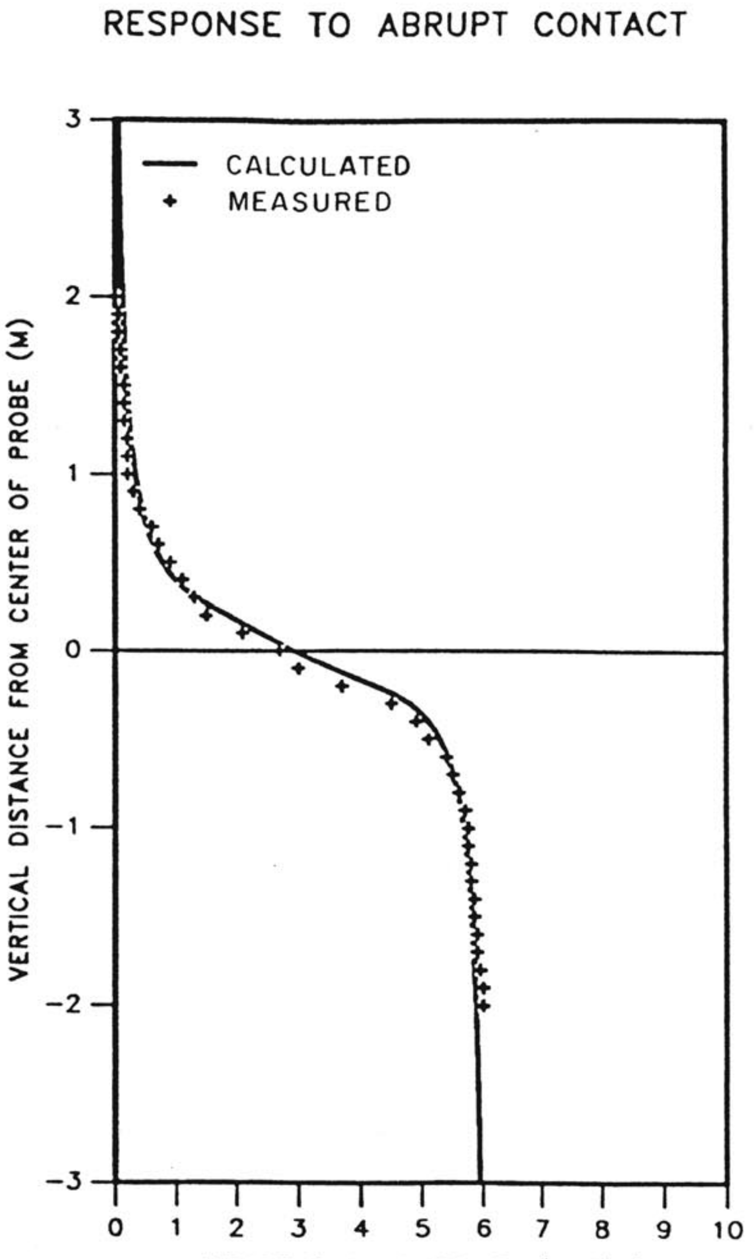


Figure 7 Comparison of calculated response with measured response when passing through an abrupt transition (after Taylor et al, 1989).

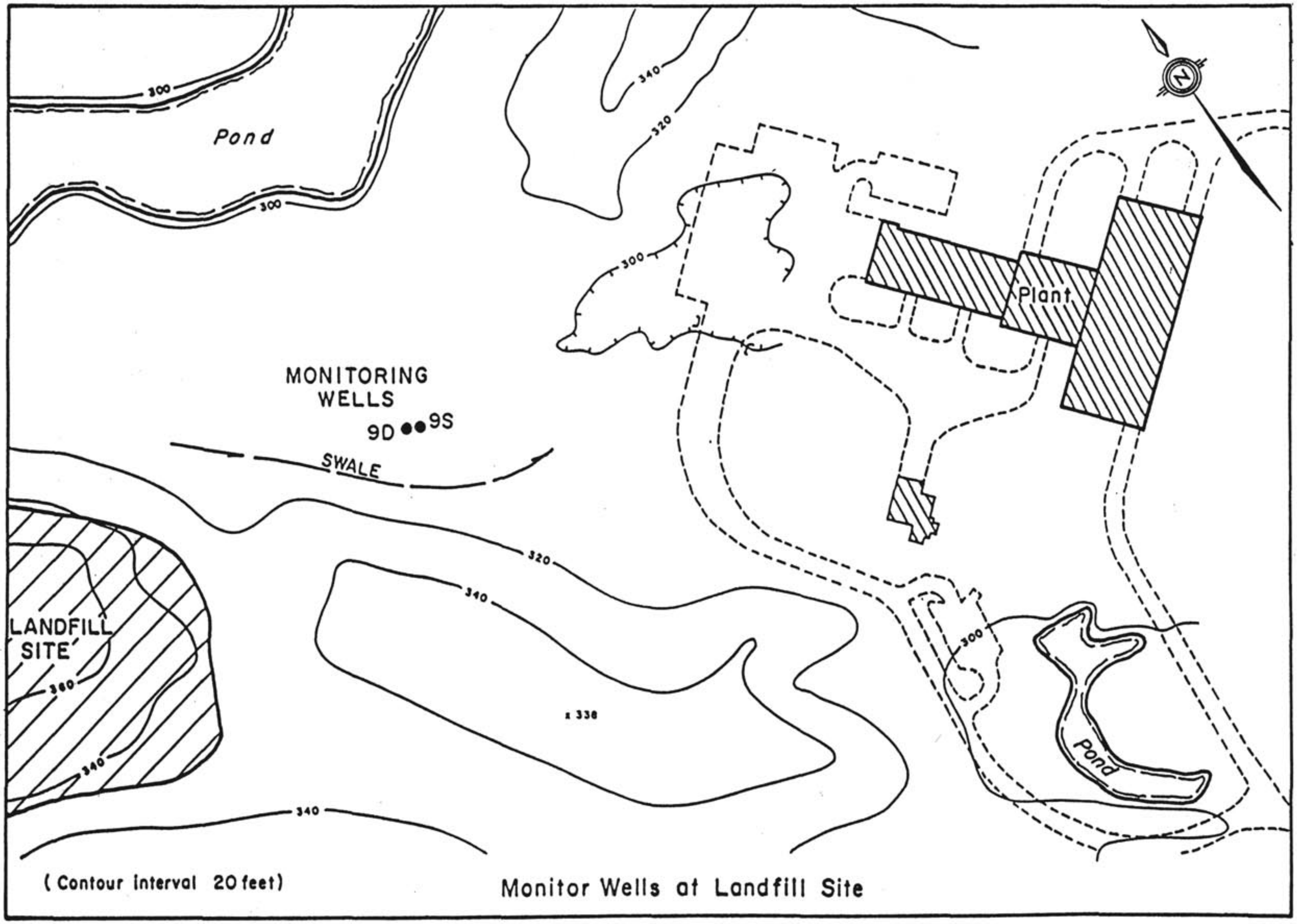


Figure 8 Site plan of landfill showing location of monitoring wells.

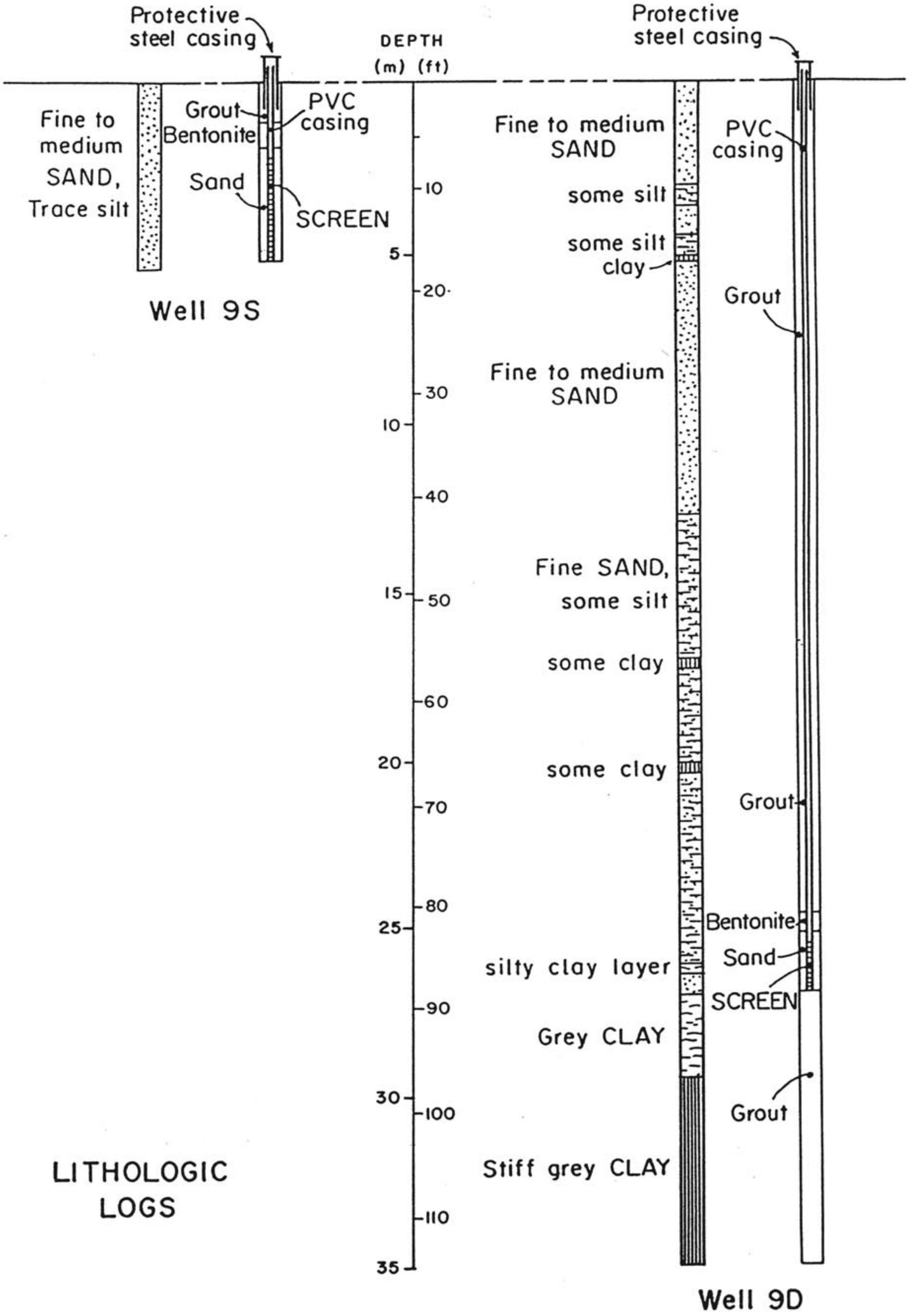


Figure 9 Lithologic logs from wells 9S and 9D.

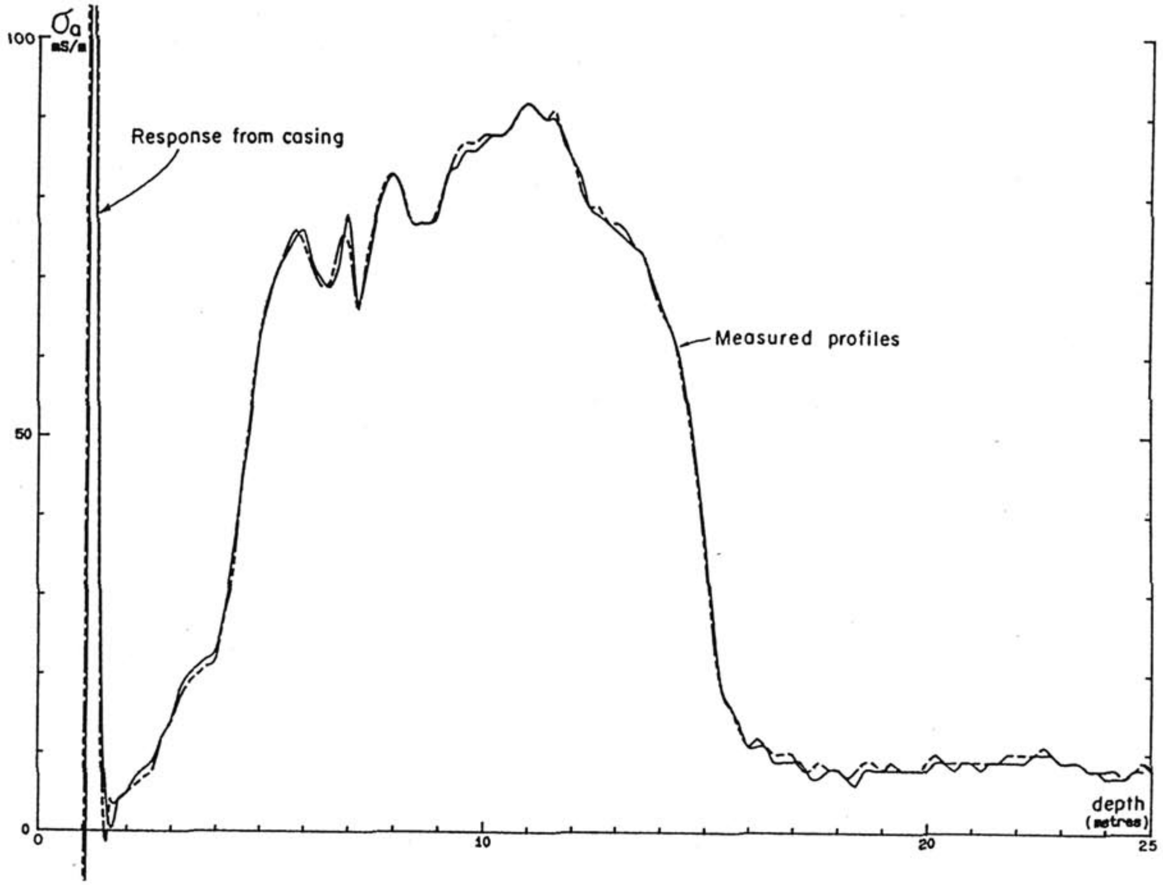


Figure 10 Measured responses (up and down directions) from well 9D.

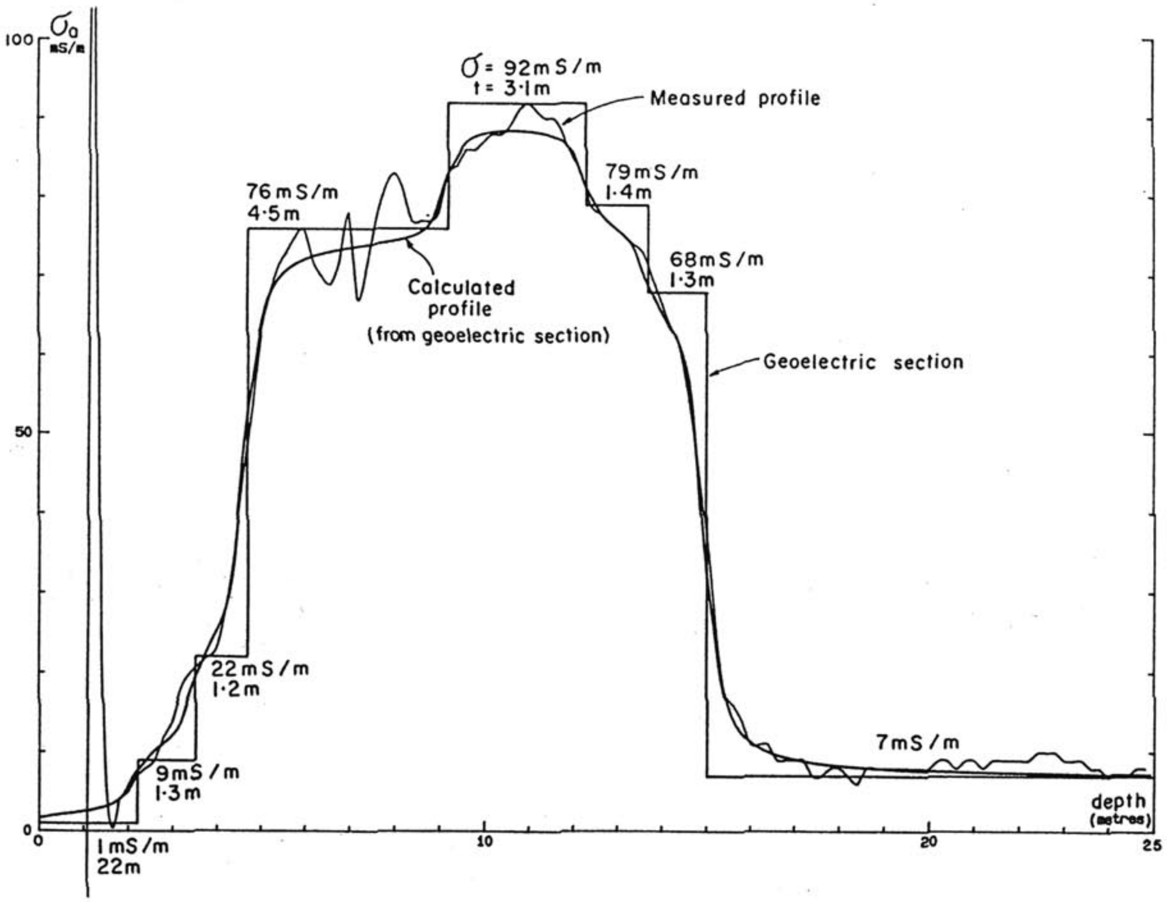
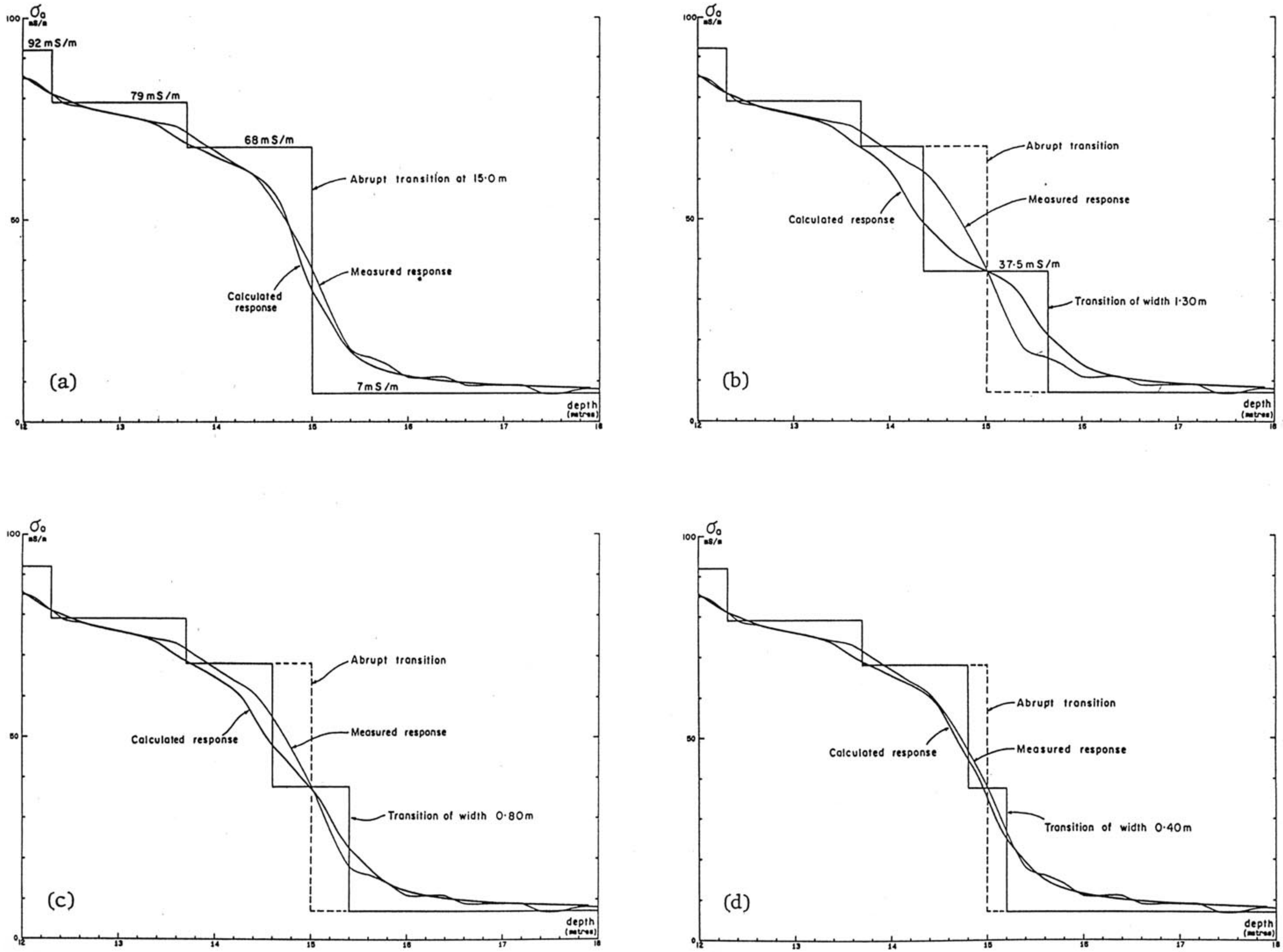


Figure 11 Comparison of measured response with response calculated from the indicated geoelectric section.



Figures 12a-d Comparison of measured response with response calculated from a series of step-wise graded conductivity distributions.

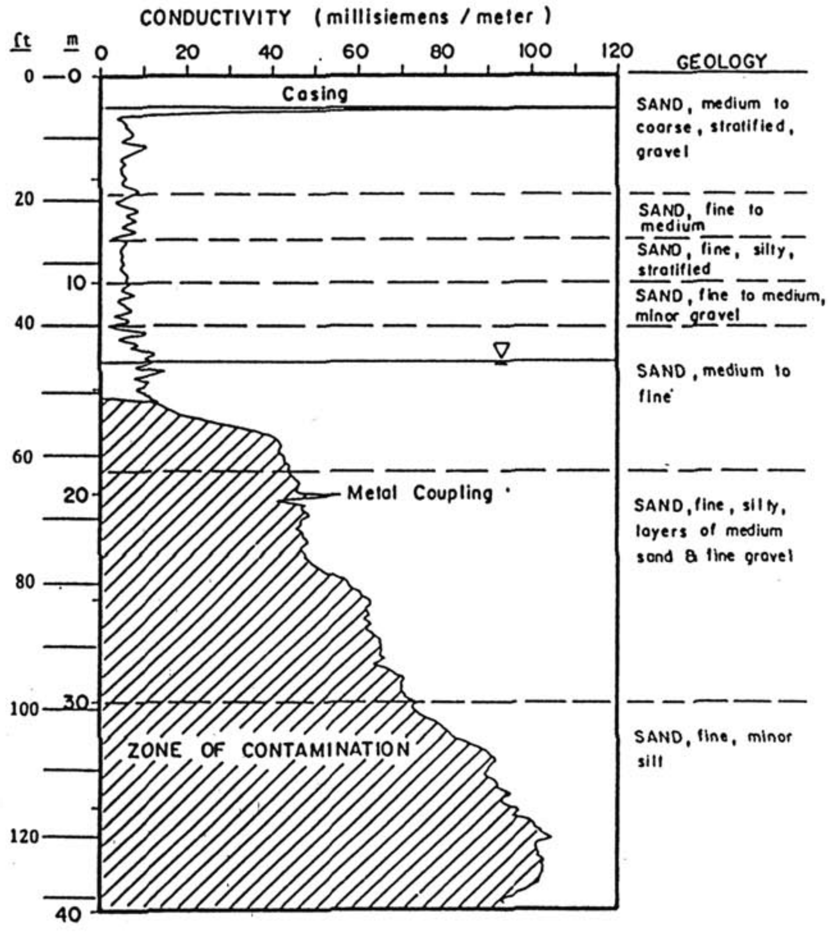


Figure 13

Measured response and lithologic log from first monitoring well.

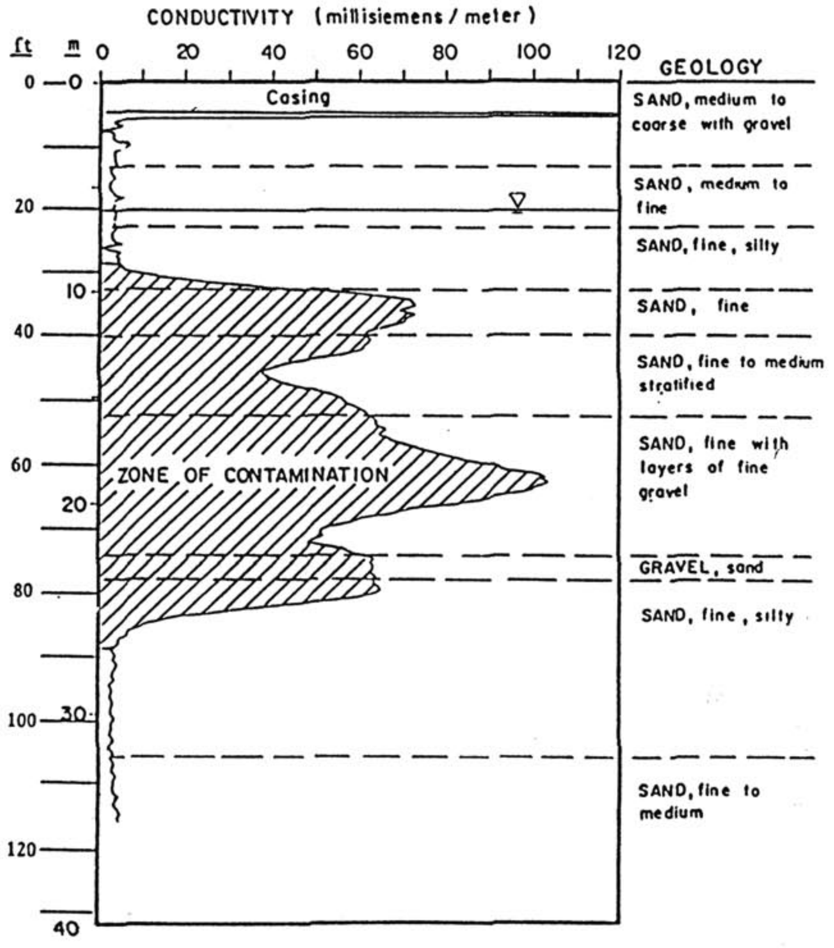


Figure 14

Measured response and lithologic log from second monitoring well.

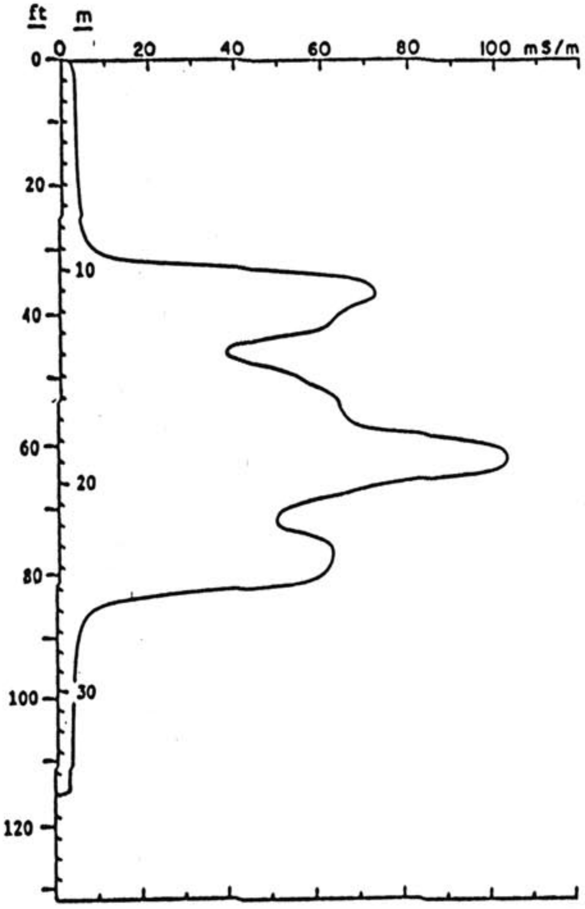


Figure 15

Calculated response from the geoelectric section shown in Figure 16. Compare with the measured response of Figures 14, 16.

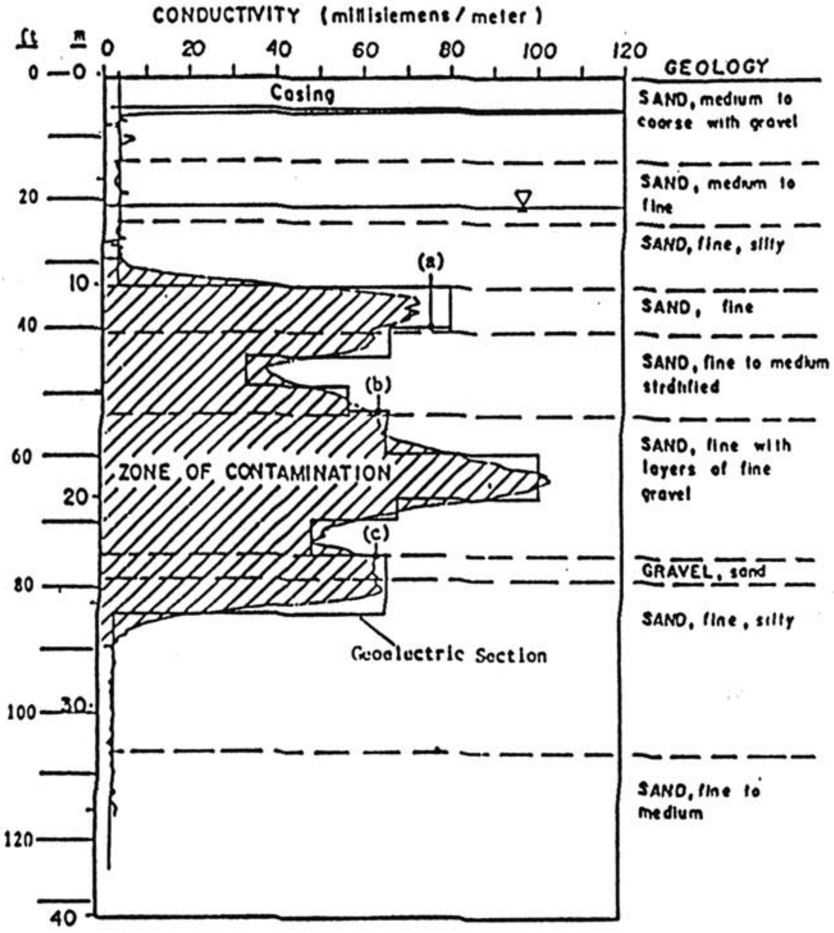


Figure 16

Comparison of geoelectric section and lithologic log from second monitoring well.