Nordic Hydrology, 14, 1983, 33-40

Breaks in Resistivity Sounding Curves as Indicators of Hard Rock Aquifers

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In a previous paper (Nordic Hydrology, Vol. 12, 1981), the authors have discussed the inadequacies in the technique of resistivity method for location of sites for constructing deep water walls in hard rock areas. It was pointed out that the water bearing fracture zones in the bed rock could not be identified by merely considering geoelectrical parameters such as layer resistivity. An empirical study based on the correlation of minor irregularities or deviations – "BREAKS" – in the normally smooth sounding curves with the actual driller's logs reveals that under normal geo-electric conditions these water bearing zones (hard rock aquifers) are indicated in the curve by a perceptible lowering of apparent resistivity and hence could be used as a guide for locating well sites. As such breaks may also be caused by other conditions such as lateral inhomogeneities, certain methods for distinguishing them are discussed.

Introduction

Geoelectrical parameters such as layer resistivities, total longitudinal conductance etc. are useful in dilineating the weathered and decomposed portion of the bed rock which is usually within a depth of about 30 metres from the ground surface. However, they do not give any indication about the presence or absence of the water bearing zones in the hard rock layer (hard rock aquifers) which is precisely what one has to look for while selecting sites for drilling borewells. In the absence of this very necessary information, namely the location and extent of these fractures which are the main producing zones for borewells in areas underlain by crystalline rocks, the siting of borewells, it appears, is often more a matter of chance than due to any reasonably positive geoelectrical indications.

Over eight hundred vertical electrical sounding (VES) curves from areas underlain by granitic gneisses (Peninsular gneisses of archaean age) of southern India were studied and correlated with the lithological logs of borewells drilled at these sounding sites. Both Schlumberger and Wenner electrode configurations were employed in carrying out vertical soundings and a direct current resistivity meter (Baratan) with a constant current source was used. The drillers' logs provided hydrogeological information such as: borewell depth; casing length; thickness of overburden and weathered rock; depths at which water sources were met with their respective yields and static water levels. The data recorded by the drilling engineers could be taken as reasonably correct since pneumatic down the hole hammer drilling method was employed.

Curve Breaks

The VES data was plotted on double logarithimic paper. The VES curves normally show minor deviations in their slopes which would ordinarily be smoothened out for analysis and interpretation by the curve matching method. Without smoothening the curves and retaining them as they are, terming these deviations as "Breaks", it is noticed that these breaks have some significance and relationship with the existence of hard rock aquifers. Under normal field conditions these breaks in the VES curves could be correlated to source zones in borewells at depths comparable to the electrode separations at which the breaks occur. As this was found to be true in a large number of cases the possibility of using these curve breaks as indicators of hard rock aquifers was examined in detail.

Van Nostrand and Cook (1960) refer to such curve breaks and point out that when they correlate with vertical resistivity contrasts, they may be caused by effects not taken into account in the assumption of an Ohmic flow of current. They also note that "... Although such breaks are completely outside the bounds of present theory, it must be said in defence of the empirical school that some excellent results have been obtained with this method" (Page 86). Amalendhu Roy (1978), in discussing the theorem for direct current regimes points out that a thin conducting horizontal layer buried in an otherwise resistive medium contributes nothing to the measured signal because the potential gradient is zero inside such a body. Thus, by contributing less than normal, a conducting target helps the generation of a negative anamoly or a resistive low. The hard rock aquifers can be considered essentially as horizontal discontinuities on a local scale (Ballukraya et al. 1982, a) in the form of fractures and joints along which weathering of country rock has resulted in highly decomposed material with appreciable clay content.

The resistivity of this layer can be assumed to be infinitely low as compared to that of the overlying and underlying rock material and therefore may cause a resistivity low in the vertical electrical sounding curve.

By carrying out VES profiling, where soundings are taken close to each other, – say 10 to 15 metres apart – along a common azimuth, it is noticed that the hard rock aquifers or more generally the horizontal discontinuities in the bedrock, do cause curve breaks. The breaks due to such horizontal discontinuities are repeated in two or more of these sounding curves at approximately the same electrode separations. Fig. 1 shows such an example where four soundings were carried out close to each other. A clear break is observed in all the four VES curves at electrode separations of $\overline{AB}/2$ = 33 to 36 metres while another break around $\overline{AB}/2$ = 24/27 to 30 metres is seen in two curves. From the driller's log of the borewell drilled near station 4, the presence of two water bearing zones, one at 29 metres (yielding 2.7 m^3/hr.) and another at 35 metres (yielding 13.6 m^3/hr.) are confirmed. Such a correlation was evident in a larger number of VES curves confirmed by drilling data.

Depth of Investigation

The depth of investigation for the purpose of estimating depth to aquifers from breaks in VES curves is taken as half the current electrode separation ($\overline{AB}/2$) as is the practice in many empirical evaluations. The depth of investigation in general is that depth from which a dominant portion of the measured signal is generated for a given electrode separation. It is often noticed that the theoretically computed layer thicknesses do not correlate with the actual field conditions in hard rock areas. The empirical method of relating geological controls with salient points in the sounding curves to determine layer thicknesses is quite useful. The transition from overburden to rock layer is generally indicated by an inflection point (minima) in the sounding curves. It is interesting to note that the current electrode separation at which the inflection occurs is about twice the depth to rock layer in majority of cases, that is, the depth of investigation can be said to be more or less equal to half the current electrode separation. Though this generalization is theoretically inexact, it forms a very useful thumb-rule for practical purposes in areas underlain by crystalline formations. Four sounding curves with their respective lithologs are given in Fig. 2 to illustrate the validity of this empirical relation. Three of the curves show breaks which can be correlated to waterbearing zones. The fourth without any break was nearly dry. However, it must be noted that under certain geoelectrical conditions this may not hold good; also, the relation was examined in the case of Schlumberger and Wenner electrode configurations only. Since theoretical computations also do not always give satisfactory results, it is convenient to use this approximation in field.

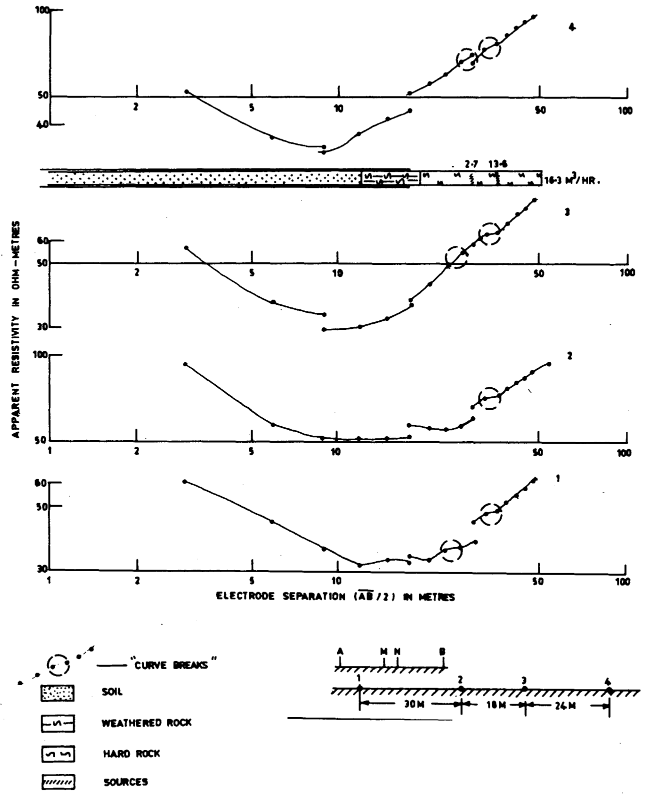

Fig. 1. Curves of VES-profiling showing curve breaks as indicators of hard rock aquifers.

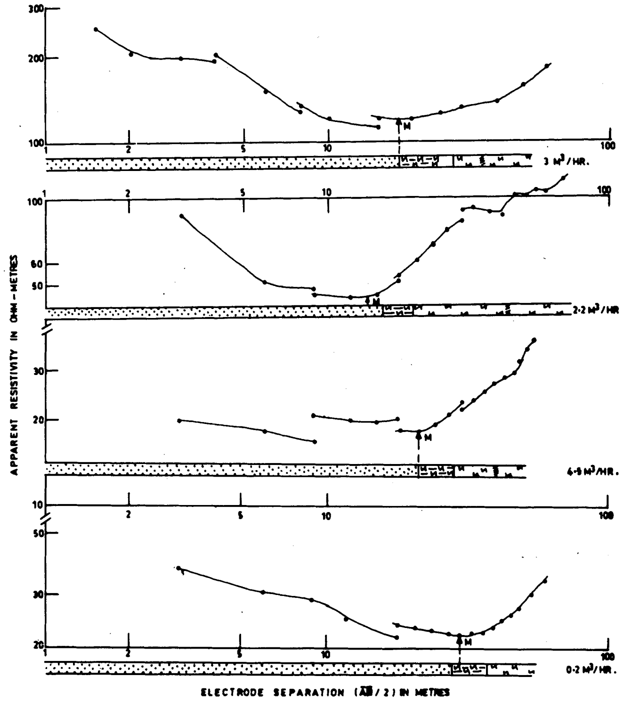

Fig. 2. VES curves and borehole sections – relating inflection points with lithological change – curve breaks indicating aquifers.

Field Layout

While carrying out vertical soundings the emphasis is on a proper field layout of electrode spacings as with large electrode spacing expansions the breaks may get masked. An ideal expansion of electrodes will be in steps of four or six metres, i.e. $\overline{AB}$ = 4, 8, 12, 16, 20, 24 ... 72, 76, 80 metres and so on with appropriate potential electrode separations. The Schlumberger electrode configuration is best suited for the purpose of studying the curve breaks as the data obtained is relatively free from the effects of lateral heterogeneities. Electrode arrays where potential electrodes are shifted to expanded separations for each measurement during a sounding (e.g. Wenner) are not suitable for the curve break study as a certain amount of error creeps in due to lateral anamolies and also from possible inaccuracies in the placement of potential electrodes which often cause false breaks in VES curves. As majority of productive aquifers in the hard rock areas of southern India are within a depth of 60 metres from ground level, the maximum current electrode separation needed is only about 150 metres ($\overline{AB}$ = 150 m).

Lateral inhomogeneities in field such as a high resistivity dyke-like body, boulders, zones with significant changes in the thickness of weathered and decomposed rock etc. present within the electrode spread zone may also cause the formation of breaks in VES curves and hence it is necessary to differentiate them from breaks due to genuine horizontal discontinuities which are probably water bearing. When the breaks are due to horizontal discontinuities, they repeat in the sounding curves essentially at the same electrode separations in two or more curves of closely spaced soundings as in Fig. 1, whereas breaks caused by lateral inhomogeneities or dipping discontinuities will be at different electrode separations, the shifting of breaks directly related to the distance between the sounding station and the resistive body. Fig. 3 is an example where three soundings were carried out at stations 1, 2 and 3; 6 and 12 metres apart respectively. It is seen that the break at electrode separation $\overline{AB}/2$ = 33 to 42 metres in the VES curve of station 1 is shifted to $\overline{AB}/2$ = 15 to 24 metres in the curve of station 3, thus being offset by the respective differences in the distance between the sounding stations. It is clear that a lateral inhomogeneity, probably a dyke or a vertical fractured zone with a lower resistivity is present 33 metres away from station 1. The break in the VES curve is thus undoubtedly the result of the presence of this dyke-like body. Under certain geoelectrical conditions, the slope of the VES curve may also get affected due to the presence of a highly resistive lateral inhomogeneity resulting in an inclination of a part of the curve being more than 45°.

Radial soundings are also helpful in identifying breaks due to lateral heterogeneities. Soundings are carried out in four or more directions of electrode spread, but with a common centre. The breaks caused by a horizontal discontinuity may be seen in all the sounding curves, whereas those caused by lateral heterogeneities will be present in some of the curves only and that too at different electrode separations.

False curve breaks may also be formed when random magnitudes of input current are used during a sounding. This is probably due to possible non-ohmic flow of current which may manifest itself under certain geoelectrical conditions, with the result, the measured resistances may be different for varying current magnitudes for a given electrode separation (Ballukraya et al. 1982, b). The need to maintain a constant current input is therefore emphasized for the success of curve break method of identifying hard rock aquifers. Its advantages in identifying lateral anamolies as well have been discussed by the authors in the above mentioned paper.

Correlation

188 Schlumberger VES curves were examined to verify the curve break concept. A graph plotted for aquifer depths versus half the current electrode separation ($\overline{AB}/2$) at which the breaks occur in the respective sounding curves (Fig. 4) shows an excellent correlation with a correlation coefficient of 0.94. Incidentially, this also supports the assumption regarding the depth of investigation as being about half the current electrode separation in Schlumberger configuration. Sounding curves identified as affected by lateral inhomogeneities were not considered as they tend to be distorted. Curve breaks which were not confirmed by aquifers in the borewells were also ignored. This anamoly is probably due to the location of aquifer a few metres away from the borewell site or negligible discharges from fractures when encounted and probably due to effects of lateral inhomogeneities too. However, such anamolies are comparatively few, less than 20 percent of the investigated VES curves. The presence of vertical joints, inaccurate signal measurements, variations in the magnitude of input current, inaccuracies in current electrode spacing measurements etc. may also contribute to breaks on sounding curves.

Conclusions

One must, however, be aware of certain limitations in the method while applying it for the purpose of identifying hard rock aquifers. It can be applied with confidence for shallow investigations, generally upto about 50 metres from ground surface. Beyond this depth it may be ineffective as a thin low resistivity layer present at greater depths may not influence the sounding curve sufficiently so as to be recognized. Also in hard rock areas being highly heterogeneous, lateral inhomogeneities may cause or mask breaks and differentiating these from breaks due to horizontal discontinuity becomes extremely difficult beyond a certain electrode separation. However, since most of the aquifers in the area of interest are encountered between 20 and 50 metres, this method has been successfully

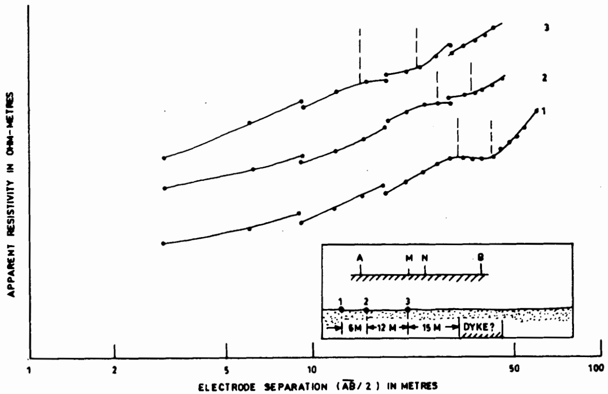

Fig. 3. Curves of VES-profiling showing breaks caused by a lateral inhomogeneity.

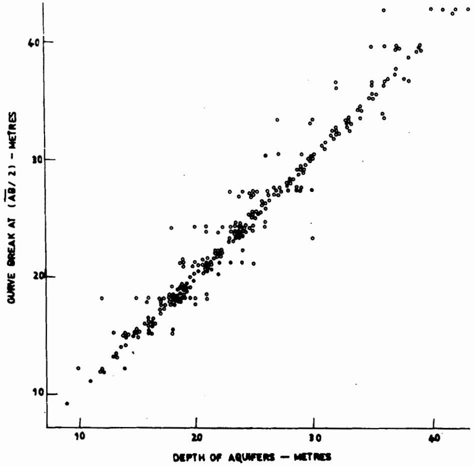

Fig. 4. Aquifer depth versus curve break plot.

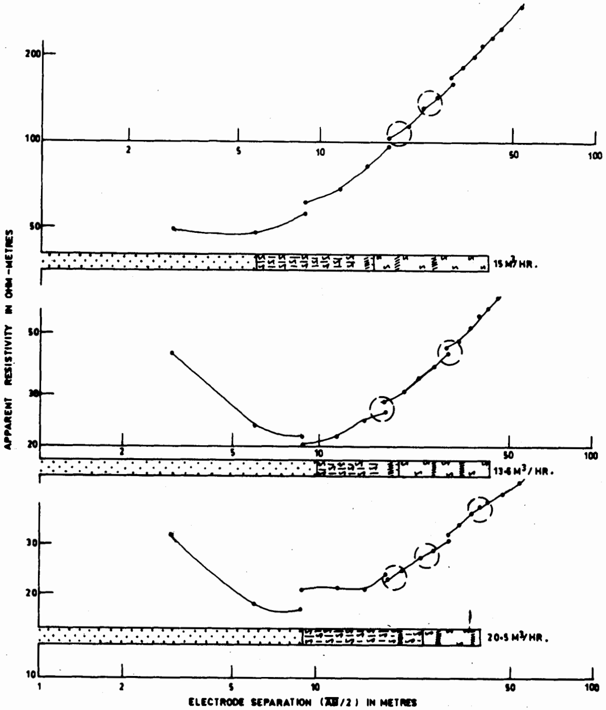

Fig. 5. VES curves with breaks and borehole sections showing aquifers.

employed in groundwater investigations.

It must be emphasized that the technique is a purely empiricial exercise and a certain degree of discernment, judgement and hydrogeological knowledge of the area is necessary for a proper evaluation of data by the curve break method. In the absence of any other positive method for identifying hardrock aquifers, it is felt that this technique will be an useful tool for locating borewell sites in areas underlain by crystalline formations, more so because it has been proved in field with successful results. Three such cases from an area underlain by granitic gneisses near Banglalore, south India, are given in Fig. 5.

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First received: 28 May, 1982
Final version received: 10 January, 1983

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