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Time lapse monitoring of the vadose zone response of a granitic aquifer in experimental hydrogeological park: a case study in south India[1]

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Abstract

Introduction: The faults and fractures of the granite are, according to their position in relation to the plane of deformation, hypothetically interpreted as tension and shear faults. The faults in shear position are supposed to be tight and have very little groundwater. The tension faults, on the other hand, are supposed to be open and to be capable of a high yield of groundwate. The electrical conductivities of rocks and soils are highly dependent of the water saturation. Variations in electrical resistivity are monitored by time lapse electrical resistivity tomography (TLERT) during a long duration pumping test.

Rocks such as granite and schist are generally poor aquifers because they have a very low porosity. However, if these rocks are highly fractured, they make good aquifers. A well is a hole drilled into the ground to penetrate an aquifer. Normally such water must be pumped to the surface.

Material and methods: Climate of South India is mostly tropical. The study of climate is very important from many aspects. It is predominantly important for crops, tours, vegetation etc. Henceforth necessary to understand the working and eating habits, also. In fact the study of climate is correlated to Topography and Temperature of the region. In fact the region has a tropical climate and depends on monsoons for rainfall. This region includes Karnataka, inland Tamil Nadu and western Andhra Pradesh.

Most importantly it gets between 400 and 750 millimetres (15.7 and 29.5 in) of rainfall annually . The summers are hot and dry . But the winters are cool with temperatures around 20-24°C (68-75°F).

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This experiment is carried out in the Experimental Hydrogeological Park (EHP) located in Choutuppal, 45 km south-east of Hyderabad. Vadose zone of EHP comprises an uppermost thin layer of red soil (<1m), sandy regolith (1m-3m), saprolite (3m-15m), and then the fissured granite. The pumping test lasts for 5 days and the piezometric variations are between 13 m and 18 m during pumping in CH03 borehole. This fissured granite is characterized by an important horizontal fracture density controlling the flow. An East West profile was laid with 48 electrodes and 3 m spacing interval. CH03, pumping well, was in the center of the profile covering 8 observation wells in both directions. 27 time-lapse datasets were inverted using Res2Dinv adopting least square inversions. The inverted resistivity datasets seem to be correlated with weathered profile and the variations of resistivity may be correlated with variation of hydraulic head. The variations of resistivity are more important close to CH03 and decreases with distance away from it. This behavior is coherent with the depression cone created by the pumping. Moreover, resistivity variations in the vadose zone highlight an influence of the pumping on the water content evolution of this zone. The observed heterogeneous response seems to be correlated with the geological media heterogeneity. TLERT appears to be a powerful tool to follow dynamic behavior of both saturated level and vadose zone for a given event. Grounwater punping monitoring helps to the water content evolution and groundwater productivity.

Results: The different distribution pattern of resistivity during and after the pumping are noticed. There is no occurrence of rainfall event during the experiment and the watershed. However, there is a temporary storage tank towards the eastern end of the profile, constructed for storing the water. This tank has no effect on the percolation, but the saturation effect is observed the surficial level. A very sharp breakup is seen after almost 40hr of pumping. This sharp boundary or may be fracture is strongly observed upto 20m depth.

Conclusion: Subsurface hydrology of the granitic terrene is studied, monitored and analyzed by a simpler approach of TLERT. The inverted resistivity datasets successfully correlates with the hydraulic head data measured at the water table at the same timings. This research, intended to examine the validity of time-lapse electrical imaging has been extremely successful, showing that repeat measurements of resistivity recorded at the surface can accurately delineate changes in saturation in the subsurface. The observed heterogeneous response seems to be correlated with the geological media heterogeneity. The precise location of a fracture can be determined with this non-invasive and quick method in the presence of significant vertical flow. Vadose zone connectivity in terms of pathways in both horizontal as well as vertical directions. It helps in reducing the uncertainty in the model parameters.

Keywords: Granitic Aquifer, Groundwater Productivity Vadose Zone, Time Lapse Electrical Resistivity Tomography.

1. Introduction

Timing and spatial pattern of recharge or pumping in the unsaturated zone is very complex to monitor. Time Lapse Electrical Resistivity Tomography (TLERT) is primary geophysical method which allows for long-term quasi-continuous and spatially extensive data for monitoring the saturated and unsaturated zone. Many workers (Daily *et al.*, 1992; Zhou *et al.*, 2001; Dutta *et al*., 2006) have experimented in different ways to detect the temporal changes in the moisture content in the unsaturated zone. Arora & Ahmed (2011) have monitored the long-term effects of recharge at a fixed location under different meteorological conditions which enabled to improve the understanding recharge mechanisms though the vadose zone.

The TLERT data set provides an excellent opportunity to verify our current understanding of physical processes during the pumping of the aquifer. TLERT method is reliable to observe water table fluctuations even in zones were few boreholes are available but also appears to be able to record variations of water content in the vadose zone. The heterogeneities observed with electrical profiles can be geological heterogeneities. In the present work, the variability of moisture content is determined by the variability of electrical resistivity measurements through TLERT during a long time pumping test. The electrical conductivities of rocks and soils are highly dependent of the water saturation. The resistivity method has additional benefits in the monitoring of groundwater conditions as it is non-invasive and provides continuous spatial information, properties lacking from all traditional hydrogeological monitoring techniques. However, interpretation of resistivity data can be ambiguous, as many subsurface models of resistivity distribution can give rise to similar results measured at the surface. A means of negating the need for a definitive interpretation of resistivity data is to examine only the changes in resistivity over time. This concept of time-lapse electrical imaging involves repeat measurements of resistivity at a time interval appropriate to the rate of change of subsurface conditions expected at the study site. The electrical resistance tomography (ERT) technique was used to characterize and monitor the unsaturated zone of the hard rock area of two watersheds in South India. One of the first hydrogeophysical applications of cross hole ERT was to study vadose zone (i.e., unsaturated zone) dynamics (Daily *et al*., 1992). General aspects of DC resistivity are well covered in the literature (Ward & Hohmann, 2002; Binley, 2015; Arora & Ahmed, 2011; Singha *et al*., 2015; Arora *et al*., 2016; Alamry *et al*., 2017).

There must be galvanic contact between the electrodes and the surroundings. Therefore, it is necessary to backfill the boreholes to ensure good contact in vadose zone studies (Binley, 2015). The best noise estimates in ERT surveys are obtained by comparing reciprocal data points, i.e., with current and potential electrodes interchanged (LaBrecque & Yang, 2000). Resistivity volumetric measurements indicates the volumetric moisture content. Owing to this property, resistivity volumetric measurements are of much greater importance for hydrological studies of the vadose zone. The primary objective of this study is to study the qualitative variations of saturation as a function of resistivity variations in the unsaturated zone due to the hydrological behavior of water table.

2. The Study Area

This experiment is carried out in the Experimental Hydrogeological Park (EHP) located in Choutuppal, 60 km south-east of Hyderabad (Figure 1). The area is gently sloping towards north-east and is covered by sparse vegetation. It is mostly constituted to Archaen orthogneissic granites (pink granite), which outcrops at several locations along the western limit of the park. The experimental park has been developed in weathered and fractured Archean granite and consists of 28 drilled borewells at variable depth. This crystalline aquifer system is poorly fractured with few permeable fractures at different depths. The shallowest fracture zone is localized at the top of the fractured granite, around 15-20 m deep below the ground surface. Few of the permeable fracture zones were identified at deeper depths in neighboring wells, but there exists only one deep fracture zone around the public well CH03. Compartmentalization of the hard rock aquifer system is established in such deeper flowing fracture zone, but it looses connectivity with the surrounding compartments.

Vadose zone of EHP comprises an uppermost thin layer of red soil (<1m), sandy regolith (1m-3m), saprolite (10m-15m), and then a fissured layer until the bedrock (42m). The pumping test lasts for 5 days and the piezometric variations are between 12 m and 18 m during pumping in CH03 borehole. This fissured granite is characterized by an important horizontal fracture density controlling the flow.

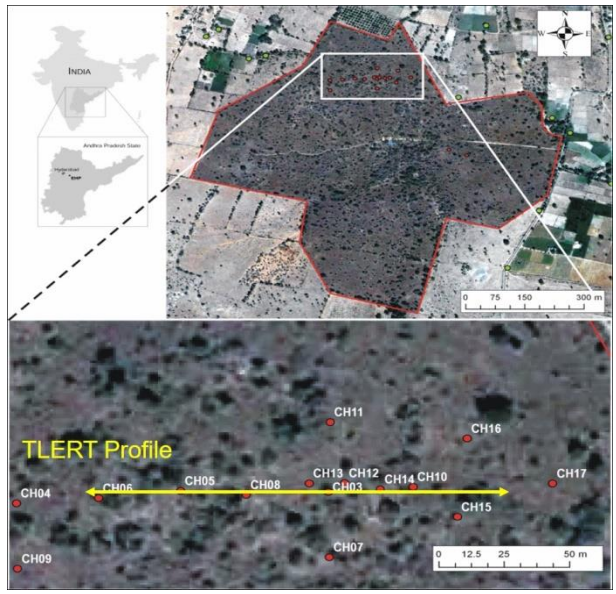

Fig. 1. Location of the EHP within the Choutuppal campus of National Geophysical Research Institute (NGRI, Hyderabad); the project wells are indicated by red circles

3. Experimental Observations

The EHP is a part of international network of experimental parks in Europe and Asia. Most of the data is taken from the published reports of the network, except the geophysical experiments undergone.

4. Hydrogeological Experiments

The long duration pumping test was carried out in EHP during 5 days with CH3 in pumping well. A network of seventeen observation boreholes was taken in place and the recording of variation of hydraulic head was during each 40 seconds. The recovery was measured at the same interval of time during 2 weeks after stop pumping (Figure 2). The drawdown inside pumping well was 5 meters and the quasi-steady state was not acquired. The figure 2 shows the variations in the water level measured in the main pumping well and also the adjacent borewells which falls along the resistivity profile undertaken. It is continuous measurements at different timings. The deepest peak in water level is attained at the main pumping well CH03 after 92hr and 19 minutes after the starting of pumping test experiment. Whereas the shallowest water table occurs in CH16 after the same duration.

The weathering thickness is poorly correlated with the observed well transmissivity: wells located in a thicker profile may have low transmissivity (e.g., CH06, CH05) and wells located in the thinner portion may exhibit higher transmissivity (e.g., CH03). As per the injection test performed by team IFCGR, the Transmissivity in CH03 is 2.1E-04 when interpreted by Theis method. Also the hydraulic conductivity calculated is 8.5E-06 in the same well.

The lithology of well CH03 is as below:

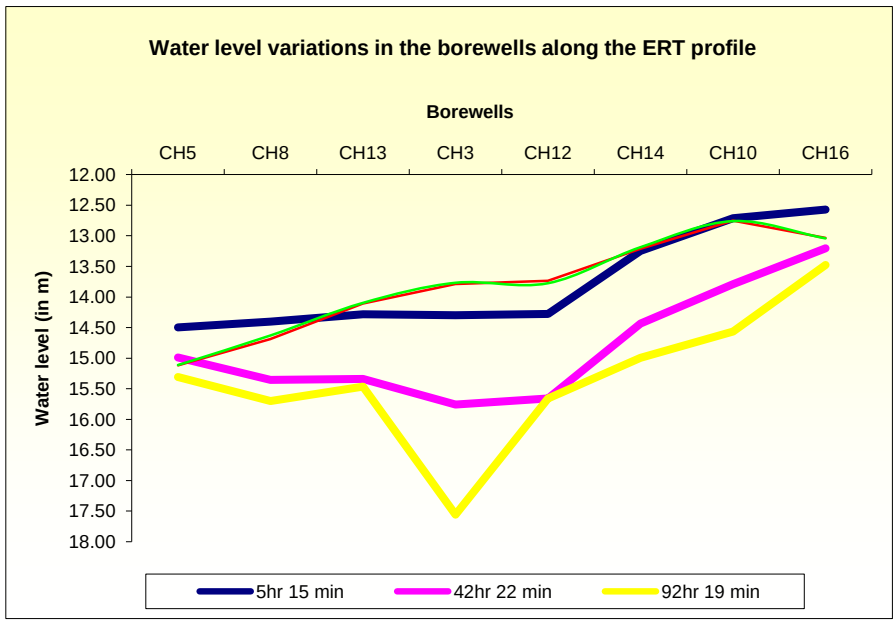

Fig. 2. shows the water level variations in the wells falling along the TLERT profile

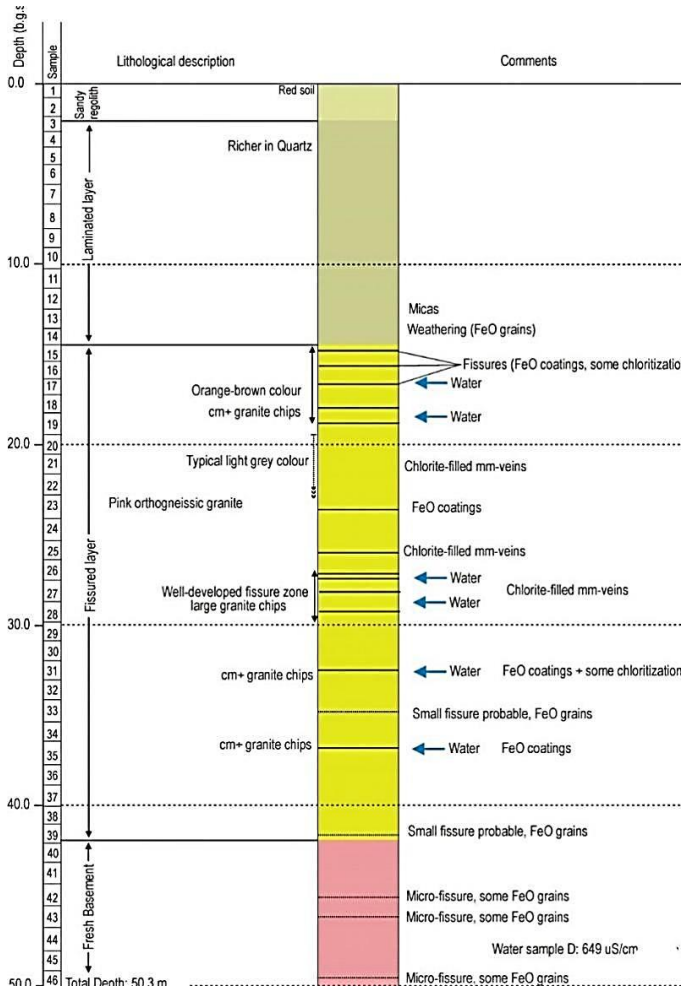

Fig. 3. shows the lithology of drilled well (CH03) [courtesy: H+ network on EHP, IFCGR]

5. Time Lapse Electrical Resistivity Tomography

Electrical Resistivity Tomography is a multi-electrode method in which the electrode arrays provide a two-dimensional vertical image of the sub-surface. The current and potential electrodes are maintained at a regular fixed spacing from each other and are progressively moved along a profile at the surface. At each step, one dataset is recorded. The set of all these measurements at this first inter-electrode spacing gives a profile of resistivity values. The inter-electrode spacing is increased then by a factor n=2, and a second measurement line is done. This process (increasing the factor n) is repeated until the

maximum spacing between electrodes is reached. It is to be noted that the larger the n-values, the greater the depth of investigation.

As the distribution of the current also depends on the resistivity contrasts of the medium, the depth of investigations deduced from the spacing is called the "pseudo-depth". The data are then arranged in a 2D "pseudo-section" plot that gives a simultaneous display of both horizontal and vertical variations in resistivity. Depending on the respective position of the potential electrodes and on the current electrodes, several array configurations can be defined: Wenner, Wenner-Schlumberger, dipole-dipole, pole-pole or pole-dipole arrays are the most commonly used. Depending on the array configuration, the geometrical factor K will differ, Seaton & Burbey (2002) reported that the array configuration has a substantial influence on the resolution, sensitivity and depth of investigation. This is taken into consideration to map the unsaturated zone, in the subsequent part.

The best noise estimates in ERT surveys are obtained by comparing reciprocal data points, i.e., with current and potential electrodes interchanged (LaBrecque & Yang, 2000). In case the electrodes are wrongly placed along the profile or the model is coarsely discretized, there is a possibility of getting a dataset with root mean square error (rms) > 5%. A reduced error is possible by the correct laying of the profile and only if two finite elements are placed between the laid electrodes (LaBrecque & Yang, 2000).

Electrical Resistivity measurements were carried out at EHP to model the possible geological heterogeneities as well as fractures in the sub-surface. The one time ERT inverted model shows an increase in resistivity with depth that more or less follows the weathering profile. In hard rock areas, the low resistivity values less than 500 ohm-m correspond to saprolite whereas the resistivity greater than 500 ohm-m indicates the granitic bed rock. The resistivity model clearly brings out the interface between saprolite and granites as shown in the Figure 4. In Figure 4, the resistivity variations clearly indicate that the thickness of the saprolitic layer varies from place to place.

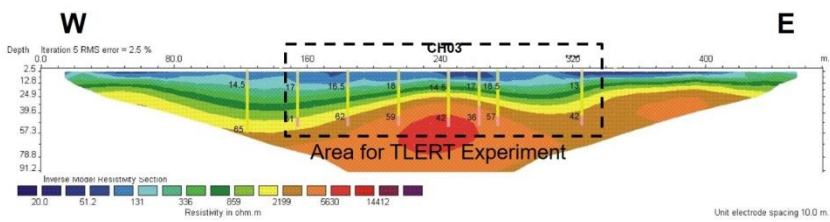

Fig. 4. showing the resistivity variation along the E-W profile in the EHP

6. Results and Discussion

As shown in Figure 5, there are the time-lapse imaging results recorded during the stages of pumping test. The images can be interpreted as a series of steady state stages during the pumping test. The dataset provides an excellent opportunity to verify our current understanding of physical processes during the pumping of the aquifer. An East West profile was laid with 48 electrodes and 3 m spacing interval. CH03, pumping well, was in the center of the profile covering 8 observation wells in both directions. 27 time-lapse datasets were inverted using Res2Dinv adopting least square inversions. In this figure 4 tomograms are shown T1 (at the onset of pumping), T2 (the day when pumping stopped) and T3 (after the recovery). The resistivity data which is between 17 position of electrodes and 36 position of electrodes is of utmost importance as variations in values shows considerable changes in the resistivity of the medium. The main interest is in the vadose zone characterization which is up to the depth of 14 m. The dotted pink line shows tentative piezometric level in the pumping well. The increase in resistivity seen on the side lobes of the images are artifacts of the inversion process, as no data exist in these areas.

The difference in resistivity were calculated and plotted after the start of pumping test as shown in Figure 6. The different distribution pattern of resistivity during and after the pumping are noticed. There is no occurrence of rainfall event during the experiment and the watershed. However, there is a temporary storage tank towards the eastern end of the profile, constructed for storing the water. This tank has no effect on the percolation, but the saturation effect is observed the surficial level. The maximum resistivity value was observed at the center at the depth of 16m beneath the borewell CH03 due to the granitic bedrock. The resistivity anomaly shows the increase towards north-west direction of the profile and later in subsequent profiles the anomaly rifts into two parts. A very sharp breakup is seen after almost 40hr of pumping. This sharp boundary or may be fracture is strongly observed upto 20m depth.

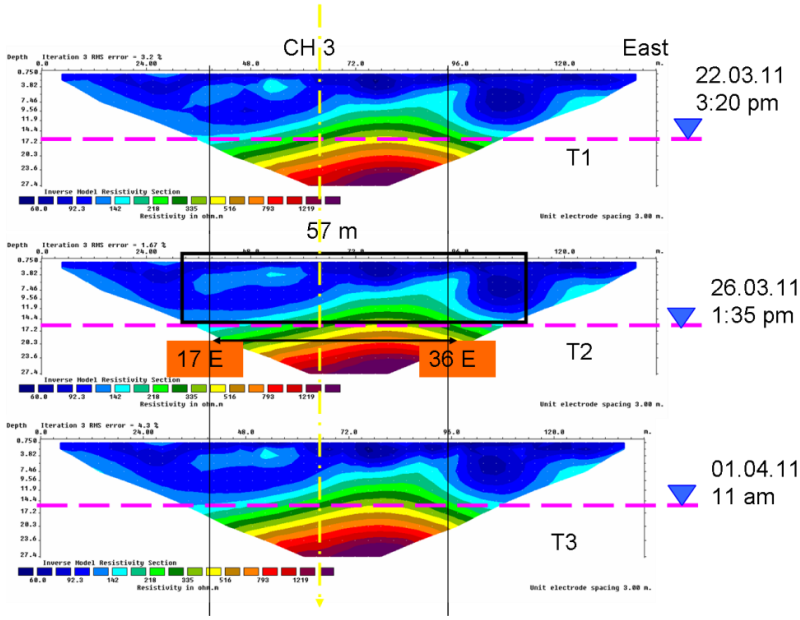

Fig. 5. TLERT tomograms acquired at the onset of pumping test (T1), the day when pumping stopped (T2) and after the recovery (T3)

It is found that there is a significant anomaly corresponding directly to the drawdown cone, as shown in series of Figure 6. In the first 32hr of pumping, the regions of resistivity increase were only in the vadose zone above a depth of 15m. As shown above region with a resistivity increase higher than 7ohm m appeared at a depth of 7m to 10 m between 70m and 75m along the profile and very near to the pumping well. After 40 hr of pumping, we discovered a clear cone-shaped anomalous region below the pumping well.

When correlated with hydrogeological lithology, it is evident that the bottom of the saprolitic later is closely connected with the upper part of the granite and the interface cannot be deduced very clearly. Whereas if there is a movement to the deeper layers, the effect of compartmentalization if clearly observed as the vertical divide is beautifully identified. The south-east to north-west trending anomaly brings out the segmentation of the aquifer and supports that the deeper fracture zones are not continuous. This dewatering effect out of pumping will bring a change in the hydraulic parameters of the soil. In turn these will help in improving the conceptual model of the area. This is very important particularly in a changing climate environment (Al-Gamal, 2021).

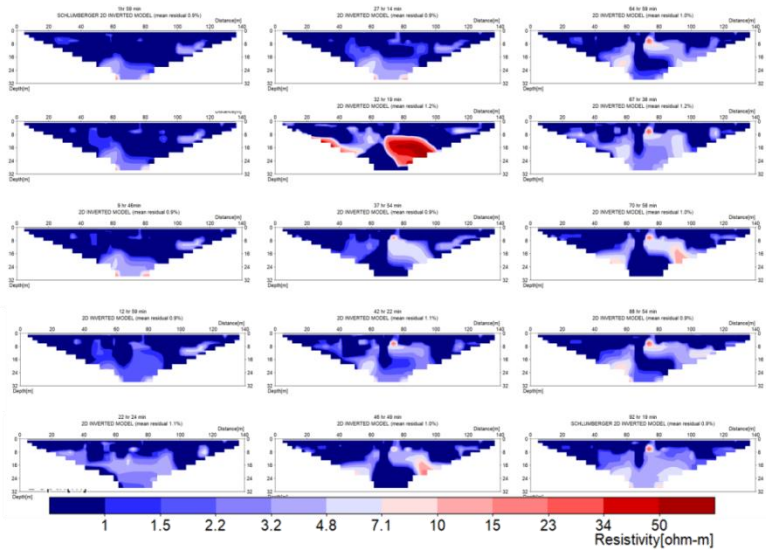

Fig. 6. The selected resistivity-difference images collected at different durations after the start of pumping test

7. Conclusion

Vadose zone of the granitic terrene is studied, monitored and analyzed by a simpler approach of TLERT. The inverted resistivity datasets successfully correlates with the hydraulic head data measured at the water table at the same timings. The variations of resistivity are more important close to CH03 and decreases with distance away from it. This study, intended to examine the validity of time-lapse electrical imaging has been extremely successful, showing that repeat measurements of resistivity recorded at the surface can accurately delineate changes in saturation in the subsurface. The observed heterogeneous response seems to be correlated with the geological media heterogeneity. The precise location of a fracture can be determined with this non-invasive and quick method in the presence of significant vertical flow. Vadose zone connectivity in terms of pathways in both horizontal as well as vertical directions. This study helps in reducing the uncertainty in the model parameters.

8. Aknowledgements

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