

Excitation of Hard Rock Aquifers in Southern Peninsular India Associated with the 2004 Sumatra Earthquake

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Abstract

Emergence of springs at surface or in shallow pits reported from discrete locations during the month of January 2005 in the southern Indian peninsular shield area had been an interesting post geo-hydrological phenomenon to investigate. Such freak incidences at places in the interior parts of a continental shield area were reported for the first time. Its connectivity with the 2004 mega thrust great (Mw 9.3) Sumatra earthquake and its multiple aftershocks are studied and analyzed. Resistivity 2D imaging and its hydrogeological modulations revealed perched aquifer conditions at shallow depth (<10 m). There is no geological or geophysical evidence of structurally controlled upward rise of deep groundwater in the area. Electrical conductivity of the emergent spring water and that of deeper (depth >50 m) groundwater support that the spring water is originated due to local effect by the 2004 mega thrust earthquake. The emergence of spring is attributed to ground movement and squeezing of pores in the saturated zone at shallow depth due the mega thrust Sumatra earthquake.

Key Words: Resistivity 2D imaging, perched aquifer, spring, Sumatra earthquake

Introduction

There are many evidences showing significant changes in geological, geophysical and hydrological parameters in response to major earthquakes at a far distance from the epicenter (Amin and Rama, 1982; Muir-Wood and King, 1993; Montgomery and Manga, 2003). In this paper we have reported the anomalous geo-hydrological changes in the interior of Indian continental shield area after the great Sumatra earthquake on 26th December 2004. This earthquake was followed by the tsunami that had left behind a trail of death, destruction and human misery in many Asian countries. The Sumatra earthquake lasted for about 9 minutes, rupturing nearly 250,000 sq. km. of oceanic rock, a large fraction of it slipping 10-15 m across the fault surface and released as much quantum of energy as all other earthquakes combined over the past fifteen years could have generated (Wilson, 2005). Hundreds of aftershocks M >5.0 are registered during the last few years (Preliminary seismological bulletin, GSI). Earthquake induced water level fluctuations in bore wells provide a means to understand the aquifer characteristics through pore pressure changes once the mechanics governing the earthquake occurrence is adequately understood. Similar to the seismograph, the well aquifer system also consists of a mass (the column of water in the well plus some part of the water in the aquifer), a restoring force (the difference between the pressure head in the aquifer and the displaced water level in the well) and a damping force (the friction that accompanies the flow of water through the well and aquifer) (Cooper *et al.*, 1965).

Earthquake and Hydrology

Earthquakes are regarded as ground shaking due to sudden energy release along active faults in tectonic zones at deeper depths of the crust. In the case of Sumatra earthquake, the rupture length was reported to be one of the largest, extending to a length of about 1200 km. and along a gently curving line, following the Indian plate

boundary in the North-South direction. Anomalous change in groundwater level is one of the most important signatures associated with earthquakes (Ground Shaking). Water level changes take place not only due to earthquakes, but also from various aseismic effects such as barometric pressure change, tidal variations and precipitation influences (Bredohoeft, 1967; Van der Kamp and Gale, 1983). Several observational attempts are made to confirm the fact that there are certain patterns of water level responses to large earthquakes as distant as several hundreds of kilometers. These responses are purely due to seismic waves but unlike seismic waves water level oscillations are monotonic and persist for days or weeks (Roeloffs, 1998) in certain cases. A well known earthquake related water level change was reported in response to the 1989 Loma Prieta, California earthquake, 157 kms northwest of a monitoring well site (Rojstaczer and Wolf, 1992).

Tectonics and Morphological Setting of the Region

Seismotectonics of the Indian shield region is largely contributed by the Himalayan back-thrust and reactivation of the old dormant faults. The central India constitutes of considerable variance in crustal thickness, tectonic history and thermal structure. The concept of Indian peninsula as a stable Archaean shield region has been changed due to low to moderate earthquakes in the recent years. The energy released in these earthquakes is basically a part of intraplate stress arising due to the collision of the northeastward moving Indian plate with the Tibetan plate (Khattri and Tyagi, 1983; Valdiya, 1976). The observational site on the southern Indian shield (Eastern Dharwar Craton) is characterized by sheared and deformed lithosphere (Pandey and Agrawal, 1999). Basically these K-granite plutons are thought to be emplaced as isolated bodies over the Dharwar Craton. Multi-parametric geological, geophysical and GPS studies over Eastern Dharwar Craton brought out a differential up-liftment of the Hyderabad granite pluton and Bangalore Geotectonic Block between Late Archaean and Early Proterozoic (Catherine and Pandey, 2005). Morphotectonic studies, surface and lake sediments radioactivity, heat flow pattern and tremors indicated persistence of Neotectonic activities in the study region (Pandey *et al.*, 2002). The morphotectonic map of the area with study sites is shown in Fig.1.



Fig.1: Location map of the investigation sites with its morpho-tectonic settings.

The 2004 Sumatra Earthquake

The world's most powerful earthquake of Mw 9.3 had struck on 26th December 2004 near west coast of northern Sumatra Island. The cause was attributed to be thrust faulting at the boundary of the Indian-Burmese plates. The accumulated stress due to ongoing subduction of Indian Plate beneath the overriding Burma micro-plate and release of strain was the cause of Sumatra earthquake (Purnachandra Rao and Kalpna, 2005). The fault displacement analysis implies that fault rupture propagated to the north from the epicenter. The post-effect of the Sumatra earthquake was generation of giant sea waves (*Tsunami*) and its propagation across the Indian Ocean. Tsunami struck the Indian coast and caused severe destruction along the east and parts of west coast of India, causing heavy loss of property and casualties.

Hydrological Response to Earthquakes

Hydrogeological responses to earthquakes are well known phenomena for both near field and far field earthquake sources. Water wells becoming turbid, dry or begin to flow, increase in discharge of springs and forming of new springs have been reported as observations of post earthquake effect. Studies have also indicated that mild earthquakes of M 3 could generate effects on ground water, such as in bore-wells; as far as about 10 miles from the epicenter and effects of magnitude 9 quake could be observed in wells of more than 6000 miles away, as in the case of 1964 Alaska earthquake that registered M 9.2 (Montgomery and Manga, 2003). The observation of 2004 hydrograph data of a well in Hyderabad (NGRI Campus) exhibited the change in hydrostatic pressure from 25th Dec'04 early hours onwards, which is attributed to the stress release before the main shock in the Sumatra-Indonesia subduction zone on 26th Dec'04 (Muralidharan *et al.*, 2005). Similar effects of hydrostatic pressure changes were observed from other places located over Hyderabad granite pluton. These site records were cross-correlated with respect to time and magnitude of water level change. The effects were of the same order in all the well hydrographs.

Emergence of springs at surface or in shallow pits during the month of January 2005 in Ranga Reddy district of Andhra Pradesh was reported in local newspapers (Deccan Chronicle dated 01.02.2005) as a probable post-effect of Sumatra Earthquake of 26th December 2004. However, in a sub-normal rainfall year of 2004, spring emergence at discrete places called for an understanding of the process and causes in interior continental part of southern India, necessitated geophysical and hydrological reconnaissance surveys around these sites, namely Devanur and Mukundapur villages (Fig.1), using resistivity tomography and by water sample collection from all the nearby wells at these sites. Brief report on the outcome of the survey and the inference drawn for the probable cause of spring emergence are presented below.

Resistivity Imaging at Devanur Site

One of the reported sites of spring emergence was near the Devanur village in Ranga Reddy District of Andhra Pradesh and the location of spring emergence is at the foreshore area of an ancient irrigation tank. Discussion with the local villagers yielded information on oozing of water on the surface was first noticed on 16th January 2005 and out of curiosity, the villagers dug out the soil down to 20 to 30 cm and by seeing unusual water seepage in the pits, they linked the incidence to the effects of the 2004 tsunami earthquake which was later reported to the local News Papers. It was an interesting incident to note from such an area where the monsoon over the past few years was below

normal. Due to vagary nature and consecutive failure of monsoon, the inflow to the tank reduced over the years, and remained dry. The seepage pits reported were aligned in perpendicular direction (NE-SW) to the main tank axis and at the mouth of feeder stream channel that brings the runoff water to the tank. In order to understand the cause of emergence of spring, resistivity method was adopted to map the sub-surface nature of the area. Multi-electrode Imaging System with 2 m electrode spacing ($a=2\text{m}$) was deployed in WNW-ESE direction perpendicular to the direction of pits alignment. The center of the image profile was over a pit having water during the time of survey. The sub-surface resistivity image obtained after data processing is shown in Fig.2a.

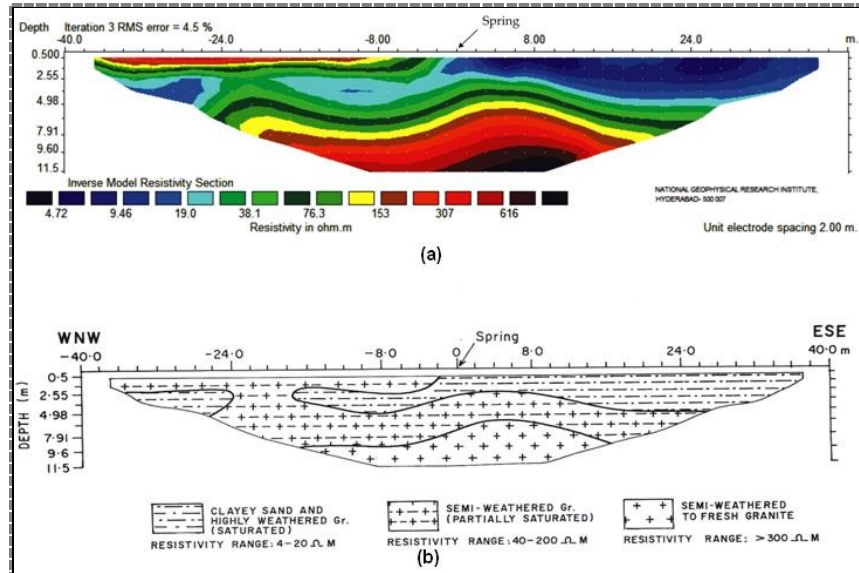


Fig.2: (a) 2D resistivity tomography pseudo-section along a profile at Devanur spring emergence site. (b) Subsurface hydrogeological section of the resistivity profile survey at Devanur spring emergence site.

The resistivity section of an 80 m long traverse exhibited a three layered sub-surface formation, of which the top layer with a resistivity range of 4 to 20 Ohm-m extends to a depth of about 5 m clearly depicting a highly conductive nature of the formation and higher degree of saturation. A middle layer with 40 to 200 Ohm-m resistivity followed the top conductive layer from 5 m to 10 m depth marking the semi-weathered part of granite with less saturation. The third geo-electric layer with a resistivity range of 300-650 Ohm-m representing the hard granite found to be occurring below 10 m depth throughout the section. The resistivity imaging results have been modulated to the existing hydrogeological conditions of the site and a section was prepared to understand the prevailing condition. The hydrogeological representation of resistivity image obtained at this site is shown in Fig.2b. The influence of an outcrop of weathered granite seen on the western part of the profile line is getting reflected clearly in the resistivity image by a high resistive zone at shallow depth itself. The eastern side of the profile having the reported spring site reflected a high conductive clayey sand layer with increase in thickness to 5 m on eastern side of the profile. The resistivity range of 4-20 Ohm-m indicates that the geo-electric layer consists of probably clayey sand at the top and followed by highly weathered granite with high degree of saturation. As it is not expected to have such a thick silt deposits in the foreshore area of a tank, it can be visualized that the bottom of the first inferred hydrogeological layer may probably consist of highly weathered granite with saturation as it is reflected with resistivity of 20 Ohm-m.

The hydrogeological layer that follows the first layer from a depth of 5 to 10 m is inferred to be semi-weathered granite with less degree of saturation characterized with

resistivity range of 40-200 Ohm-m. A dried nature of a dug well at the time of survey towards NW of the profile line having a depth of 9-10m in the semi-weathered granite located at a distance of 40 m from the center of the image profile affirmed the inferences. The third layer was assumed to be of semi-weathered to fresh granite without saturation, represented by resistivity of more than 300 Ohm-m.

The resistivity imaging and hydrogeological studies collectively indicated that the spring emergence at Devanur site could be due to the formation of pseudo-perched condition of an aquifer system at very shallow depth. The resistivity range obtained for the top layer clearly indicates that the formation is admixture of clay and highly weathered granite materials. The rainwater percolated during the monsoon of 2004 probably saturated the soil zone. Due to poor rainfall during later monsoon months, the percolated water front has not further moved into deeper zones under the normal process of natural recharge. The dried nature of dug well near the site at the time of spring emergence at very shallow level should of localized and not of regional phenomenon. As the resistivity imaging studies did not revealed any signatures of structural features at the site spring emergence, upward movement of ground water from deeper horizons to shallow levels is being questionable. Also, the very low order of electrical conductivity of 200 to 275 micro-mhos of the seepage pit water indicate that the water is not from deeper groundwater source as the electrical conductivity of groundwater source collected from boreholes of 60 m depth was measured to be varying from 800 to 880 micro-mhos. Reoccupation of the same site with the resistivity imaging profile in the month of February 2007 for validating the sub-surface feature seen with same electrode spacing of 2 m confirmed the persistence of shallow highly saturated soil zone without any spring emergence in spite of being normal rainfall year of 767 mm.

Resistivity Imaging at Mukundapur Site

The emergence of spring reported from another site near Mukundapur village in the same district was noticed in the form of more wetness in rain fed agricultural field before harvesting itself. After harvesting, in the month of January 2005, they dug a pit at the place of more wetness and found that the groundwater was oozing and flowing out of the pit. As the water was continuously coming out of the pit, the villagers attributed the observation to be the effect of the 2004 tsunami earthquake and reported to the News Papers. The location of the site is on a sloping ground (*agricultural terraces*) of a broad valley. The area is underlined by granites similar to that of the Devanur site. A stream channel was noticed on the downstream of site. The excavated pit was at the edge of an agricultural field at higher elevation. The geomorphologic condition suggested that the site was having a good catchment area on the upstream with a topographical slope of roughly about 5-10%.

Resistivity tomography survey was carried out at this site keeping the orientation of the profile (N-S) parallel to the field terrace border. The orientation was chosen so that the study is made perpendicular to the general groundwater flow direction. The center of the profile line was shifted by 17 m towards north of the spring emergence site due to site constraints. The profile length of 80 m was laid with the electrodes placed at 2 m interval. The processed image obtained for the study profile is shown in Fig.3a.

The hydrogeological interpretation of the resistivity image obtained to a depth of 11.5 m revealed that the sub-surface nature of the investigated area can be grouped into three layered structure similar to that of the Devanur site. The top layer of conductive nature extending to a depth of 5 m with a resistivity range 6-30 Ohm-m was found to be uniformly present through out the study traverse line. However, a bowl shaped anomalous zone was reflected just at/near the location of spring site. This layer followed by a semi-weathered formation with a resistivity range of 50-230 Ohm-m forming the

middle layer extending to a depth of 8-9 m. The third layer with resistivity more than 300 Ohm-m marked the basement.

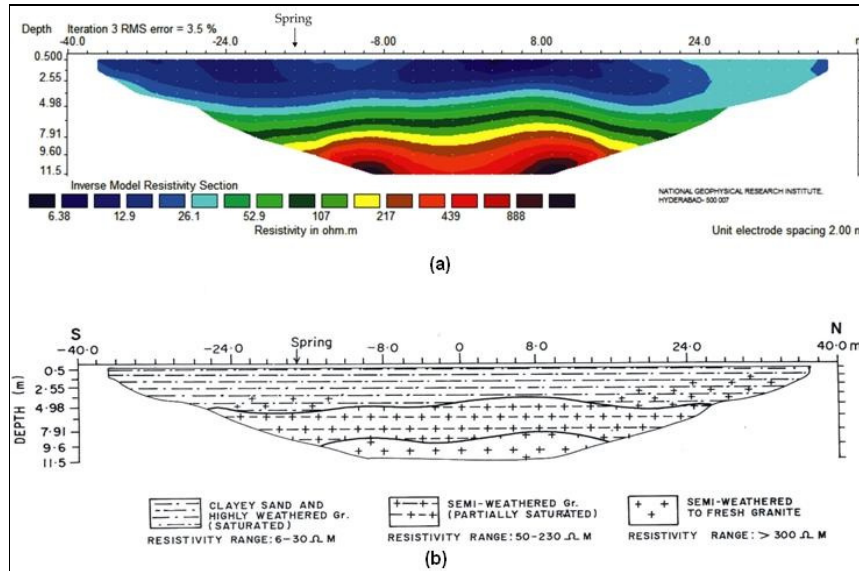


Fig.3: (a) 2D resistivity tomography pseudo-section along a profile at Mukundapur spring emergence site. (b) Subsurface hydrogeological section of the resistivity profile survey at Mukundapur spring emergence site.

Similar to the Devanur site, a section was constructed transforming the resistivity imaging results into a hydrogeological representation and shown in Fig.3b. The top layer extending to a depth of 5 m throughout the section is attributed to clayey sand layer at shallow and highly weathered granite, at the bottom part with high degree saturation. However, on the northern side of the section, this layer is with very less topsoil as evidenced in the field with exposure of highly weathered granite. This was well supported by higher resistivity over this area when compared to the areas on the southern side for the same hydrogeological layer. A semi-weathered granite layer with partial saturation follows this highly conductive top layer and its thickness extends to a depth of 8-9 m. The third layer is deciphered to be semi-weathered to fresh granite layer representing the basement. The high order resistivity of more than 300 Ohm-m for this layer indicates that the rocks are compact and devoid of saturation.

The resistivity imaging and other hydrogeological observations at the Mukundapur site brings out the plausible reasons for the emergence of spring may be attributable to the presence of conductive formation at shallow depth with saturation may be the source for the spring. The bowl shaped anomalous zone at the spring emergence location is probably due to excavation and filling with sediments. Recharge from the upland area might have helped in increase in water accumulation of water at this site due to the presence of terrace cue nearby. Presence of conductive layer throughout the section at shallow depth with saturation supports the movement of water from the upland area as a sheet flow following the topographical slope and the terrace cut surface boundary near the site favored the emergence of spring. The electrical conductivity of spring water of 163 micro-mhos exhibits the recent origin. The electrical conductivity of groundwater of the region of 700 of a well near the stream on the downstream and 2270 micro-mhos of village hand pump on the upstream clearly points out that the spring water is not from deep groundwater source. The practice of keeping the agricultural field dry before harvesting supports that the water emerged as a spring is probably due to the movement of upland monsoon recharge as a sheet flow under the influence of topographic slope.

Conclusion

The hydrogeological conditions and resistivity imaging at the two sites in Ranga Reddy district of Andhra Pradesh points out that the emergence of spring was of localized nature. However, the mobilization of water and emergence of spring might have been caused due to ground movement associated with the 2004 Sumatra earthquake and hundreds of aftershocks. Continuous monitoring at these two sites by having few observation wells of shallow depth for next hydrological cycle is required to better understand the subsurface mechanism.

References

- Amin, B.S. and Rama (1982) A search for correlation between seismicity and radon anomaly in hot springs. *Earth Planetary Sciences*, v. 91(1), pp.15-19.
- Bredohoeft, J.D. (1967) Response of well-aquifer systems to earth's tides. *J. Geoph. Res*, v.72, pp. 3075-3087.
- Catherine, J.K. and Pandey, O.P. (2005) Differential uplift Between Hyderabad and Bangalore Geotectonic Blocks of Eastern Dharwar Craton, South India. *Geology*, v.65, pp. 493-496.
- Cooper, Hilton H. Jr., Bredohoeft, John D., Papadopoulos, Istavros S. and Bennett, Robert R. (1965) The response of well aquifer system to seismic waves. *J. Geoph. Res*, v.70, pp.3915 – 3926.
- Khattari, K.N. and Tyagi, A.K. (1983) The Transverse tectonic features in the Himalaya. *Tectonophysics*, v. 96, pp.19-29.
- Montgomery, David R. and Manga, Michael (2003) Stream flow and Water Well Responses to Earthquakes. *Science*, v. 300, pp.2047-2049.
- Muir-Wood, R. and King, G.C.P. (1993) Hydrological signatures of earthquake strain. *J. Geophysical Research*, v. 98, pp. 22,035–22,068.
- Muralidharan, D., Andrade, Rolland, Laxminarayana, G., Swathi, T. and Swetha, T. (2005) Imprint of 26th December 2004 Sumatra Earthquake in Aquifers of Hyderabad Granite Pluton. *Current Science*, v. 89(7), pp.1083 - 1086.
- Pandey, O.P. and Agrawal, P.K. (1999) Lithospheric mantle deformation beneath Indian craton. *Geology*, v.107, pp.683-692.
- Pandey, O.P., Agrawal, P. K. and Chetty T. R. K. (2002) Unusual lithospheric structure beneath the Hyderabad granitic region, Eastern Dharwar Craton, South India. *Phys. Earth Planet. Int.*, v.130, pp.51-69.
- Preliminary seismological bulletin for seismic events recorded and registered at broad band seismic observatory, Nagpur, Maharashtra, India, for Sumatra earthquake of 26th December 2004 and the aftershocks. GSI; Broad Band Seismic Observatory, Nagpur.
- Purnachandra Rao, N. and Kalpna, G. (2005) Deformation of the subducted Indian Lithospheric slab in the Burmese Arc. *Geoph. Res. Let*, v.32, pp.1-5 LO5301.
- Rojstaczer, Stuart and Wolf, Stephen (1992) Permeability changes associated with large earthquakes: An example from Loma Prieta, California. *Geology*, v.20, pp. 211-214.
- Roeloffs, Evelyn A. (1998) Persistent water level changes in a well near Parkfield, California, due to local and distant earthquakes. *J. Geoph. Res*, v.103, pp. 869-889.
- Valdiya, K.S. (1976) Himalayan transverse faults and folds and their parallelism with subsurface structures of north Indian plains. *Tectonophysics*, v.32, pp. 353-386.
- Van der Kamp, G. and Gale, J.E. (1983) Theory of Earth tides and barometric effects in porous formation with compressible grains. *Water Resources Research*, v.19, pp. 538-544.
- Wilson, Mark (2005) Modeling the Sumatra-Andaman Earthquake reveals a complex, non-uniform rupture. *J. Geol. Soc. India*, v. 66(4), pp.499 – 503.

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