Imprint of 26 December 2004 Sumatra earthquake in aquifers of Hyderabad granite pluton

There have been many reports of earthquake-induced groundwater anomalies.1 A convincing explanation arrived on earthquake-induced hydrological changes is that they are caused by changes in hydrostatic pressure due to earthquake-induced changes in crustal volumetric strain.2,3 Any quantitatively measurable change in an environmental parameter that occurs before the main shock is thought to be linked to the preparation process of the main shock and is regarded as a precursor.4 Change in water level in deep wells is recognized by the IASPEI (International Association of Seismology and Physics of Earth’s Interior) as a precursor in earthquake studies. This explanation has been offered over several decades and there have been reports of quantitative analysis of earthquake-induced groundwater anomalies and crustal volumetric strain changes. One of the recent devastating events in the history of mankind and near the Indian subcontinent was the Sumatra earthquake of 26 December 2004 and the consequent tsunami, which had caused mass destruction and property damage all along the east coast of the Indian subcontinent. The effects before and after the Sumatra earthquake were clearly registered in hydrographs of wells located over Hyderabad granite pluton. Here we present the micro-level impressions registered in hydrograph of a deep bore-well located in the National Geophysical Research Institute (NGRI) campus, Hyderabad, supported with records of other bore-wells located more than ~100 km away from the NGRI well site.

A battery-powered pressure transducer [IN-SITU, Minitroll Water Logger, USA], was installed at 20 m depth in a bore-well (~80 m deep) located in the NGRI campus, for monitoring the aquifer response to precipitation and ground motion due to earthquakes since December 2003. Geophysical logging of the well has shown a fractured aquifer zone under confined conditions at 55–60 m. Electrical logging with the lithologue of the bore-well is shown in Figure 1. The pressure transducer was subjected to different sampling time intervals (from few seconds to 1 h) for optimization of sampling with less extraneous noise influence on the hydrograph. The effect of semi-diurnal tides5,6 is seen prominently at every six hourly interval on water levels.

Daily hydrograph records were analysed with seismograph records (Seismometer KS-2000M) of NGRI seismic observatory to understand the behaviour of water level during seismically active time periods. Response of water level in wells to earthquake is found to be influenced by factors such as magnitude, focal depth, distance from epicentre, depth of well and aquifer condition (confined or unconfined), hydrologic environment, etc.

The observational site on the southern Indian shield (Eastern Dharwar Craton) is characterized by sheared and deformed lithosphere.7 Basically, these K-granite plutons are thought to be emplaced as isolated bodies over the Dharwar Craton. A multi-parametric geological, geophysical and GPS study over Eastern Dharwar Craton has brought out a differential upliftment of Hyderabad granite pluton and Bangalore geotectonic block between Late Archaean and Early Proterozoic periods.7 Morpho-tectonic studies, surface and lake sediments, radioactivity, heat flow pattern and tremors indicated persistence of neotectonic activities in the study region.8 The morpho-tectonic map of the area with study sites is also shown in Figure 1.

The world’s most powerful earthquake of magnitude 9.3 had struck on 26 December 2004, near the west coast of northern Sumatra Island at 00:58:53 UTC or 06:28:53 IST. The cause was attributed to be thrust faulting on the boundary of the Indian–Burman plates. The accumulated stress due to ongoing subduction of the Indian plate beneath the overriding Burma micro-plate and release of strain was the cause of the Sumatra earthquake.9 The fault displacement analysis implies that fault rupture propagated to the northwest from the epicentre. The Sumatra earthquake generated a giant wave (tsunami) which propagated across the Indian Ocean. The tsunami struck the Indian coast at around 8:50 h IST in Chennai and 9:10 h IST in Visakhapatnam10. The tsunami caused severe destruction along the east coast and parts of west coast of India, killing thousands of people and causing heavy loss of property.

The daily hydrograph records for the months of December 2004 and January 2005 were subjected to wavelet-spectral analysis for removal of tidal effects. December being a non-monsoon month, the water level had surprisingly shown a gradual rise from the early hours of 25 December 2004, which persisted till 2 January 2005. Micro-analysis of hydrograph data of 26 December 2004 has shown a 4 mm amplitude of sudden variation in water level at 6:42:40 IST or 01:14:40
UTC lasting over 2 min at 40 s sampling interval. The hydrograph is shown in Figure 2 (inset). The time correlation of well hydrograph and seismic records revealed that arrival of surface wave was recorded after 14 min of actual earthquake time at both locations. Thus, the time lapse in registering the surface wave motion effect on water level by 1 min at Hyderabad, means the distance travelled would be around 3400 km, assuming an average surface wave velocity of 3.5 km/s, which is probably assumed by modellers. Since we know the exact distance between the epicentre and Hyderabad (2460 km), and elapsed time of arrival of surface wave, the calculation of velocity yielded a value of 2.5 km/s. The lower order of velocity obtained may be attributed to the travel of surface wave across the ocean and ocean bottom sediments.

The hydrograph record of reported timing of tsunami hit along the eastern coastal belt was stripped from the continuous records and analysed for studying the effect. The strip of hydrograph record considered for qualitative analysis between 08:44:40 and 10:14:40 h IST period is shown in Figure 2 (inset). The signature of tsunami on water level was well registered by a quiescent prelude followed by turbulence. The quiet period between 08:44:40 and 09:19:20 is the first of its kind in the hydrograph record so far gathered. It coincides with recession of sea observed prior to the tsunami. Perturbations observed between 09:19:20 and 10:00:40 h coincide with the hit time of tsunami on the east coast. According to the tidal records of Survey of India and its notification, the tsunami that hit at Vizag by 09:10:00 h was considered for analysis as it is near Hyderabad compared with other tidal stations. The disturbance observed on hydrograph lags nearly by 10 min with the hit time of the tsunami. Considering the longitudinal position of Vizag with respect to Hyderabad and being situated at 5° eastwards, the time variation would be around 10–12 min ahead of Hyderabad time. This means the recorded disturbance is delayed approximately by 20 min. The observed disturbances on the hydrograph associated with the tsunami and time delay of its arrival in the interior continental part warrant further analysis.

The unfiltered hydrograph of NGRI well from 24 December 2004 to 14 of January 2005 is shown in Figure 2. The observed rise in water level from 25 December 2004 to 2 January 2005, and a decline beyond 2 January during non-monsoon period, collectively indicates the effect of the Sumatra main earthquake and aftershocks. The rise in water level is about 90 mm. In order to confirm our observation, continuous water-level data of forty wells in Mahabubnagar district, Andhra Pradesh were collected from State Groundwater Department and analysed. Similar rise in water level during this period was observed only in four out of forty bore-wells. These are the four wells which had shown semi-diurnal tidal effects and tapping confined aquifers. The hydrograph of one of the wells located at Rajapur village is shown as an example in Figure 3.

Over the past several decades, monitoring of hydrological response to earth-
Figure 2. Hydrograph record (unfiltered) for the period 24 December 2004–14 January 2005 along with strip of hydrograph of 26 December 2004 depicting Sumatra earthquake and consequent tsunami impact.

Figure 3. Hydrograph of a bore-well located at Rajapur village, Mehboobnagar district, Andhra Pradesh.

Quakes has been able to quantify the changes in both surface water and groundwater levels in wells. Studies indicated that mild earthquakes of around $M_w$ 3 could effect groundwater, such as in wells, as far as about 10 miles from the epicentre. The effects of magnitude 9 quake could be observed in a well more than 6000 miles away, as in the case of 1964 Alaska earthquake\textsuperscript{13} that registered $M_f$ 9.2. The present observation of 2004 hydrograph data reveals that the change in hydrostatic pressure from the early hours of 25 December 2004 may have been caused due to the stress release before the major activity in the Sumatra–Indonesia subduction zone on 26 December 2004. Similar pressure effects were observed from other
Swarm cells of slime molds in sexual conjugation from sixty-five million year old sediments, Madhya Pradesh, India

Swarm cells of slime molds (Myxomycetes) in solitary or conjugating stages are reported from the Decan intertrappean beds (Maastrichtian) of Padwar, Madhya Pradesh, India.

Sexual intercourse enhances the gene pool of the future generations, which is manifested in the innovation of new characters to cope with the external and environmental pressures. The sexual organs being delicate and the time of conjugation short-lived, it is indeed rare to get this stage in the fossil state. However, some sixty-five million year old slime molds could be recovered from the Decan intertrappean bed at Padwar near Jabalpur, Madhya Pradesh, while in copulation.

Slime molds are generally placed under the fungi by mycologists, while zoologists place them in the order Myxogastreales, subclass Mycetozoa and phylum Protostolomata. Though inconspicuous in appearance, slime molds have many stages of life cycle, comprising three types of uninucleate cells, among which one is flagellate, one multinucleate somatic phase, a resistant stage and finally a reproductive phase.

The slime molds were recovered from a dry dug-out well at Padwar. The well is approximately 9 m deep and has basaltic rocks at the base and top. The basal basalt is overlain by about 1.5 m thick grey-carbonaceous/limy shale, which is covered by more than 3 m thick volcanic ash bed. An approximately 2 m thick grey-carbonaceous shale layer is sandwiched between the ash bed and the upper basaltic rock (Figure 1). The intertrappean sediments were deposited in water bodies formed due to the obstruction of drainage channels, during the dull period of Decan volcanism.

The palynological assemblage of the clastic sediments has been divided into a lower Aquilapollenites bengalensis zone and an upper algae-dominant zone.

The presence of Azolla cretacea Stanley, Aridacarpites aridae (Miner) Potonié, Gabonisporites vignouxiotis Boltenhagen and Aquilapollenites bengalensis Baks and Deb in the lower zone indicates a Maastrichtian age for the sediments. The slime molds recorded here come from the highly carbonate-rich samples (P2–P4) of the A. bengalensis zone (Figure 1). These comprise solitary swarm cells, swarm cells in sexual conjugation, spores and zygospores; however, only swarm cells are reported here. These palynomorphs were recovered by means of maceration of the samples by commercial nitric acid (40%), followed by a wash of potassium hydroxide solution (5%).

Swarm cells are biflagellate and common in the samples. Two types of swarm cells are observed. In the first type, flagella are about 200 μm long, narrow,


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