in Rhodes, Crete and Hagia Sophia. The binder to aggregate ratio is found to be 1 : 3, which meets the various structural requirements. Further, the presence of low percentage of magnesium enhances the hydrophobic character of the mortar. There is no evidence of cracks in the images of mortar even with various magnification using SEM-EDX studies. The use of sand rather than clay during manufacture was confirmed from XRD. Exercise of hydraulic lime mortar in the historic site was confirmed from TGA/DTG and microscopic studies. This showcases the technological capability and skills present in the preparation of mortar during these ancient civilizations.

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Impact of Earth's crustal tides on groundwater regime in confined sedimentary aquifers of Andhra Pradesh, India

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Signatures of the Earth's crustal tides are recorded in the groundwater regime, particularly in confined aquifers in the form of rise and fall of its piezometric surface. Though this phenomenon is universal, and exists in the entire groundwater regime, the recording at a few places and in some rare situations is doubtful. An attempt is made here to study the conditions required for recording this phenomenon along with its basic principles. The Central Ground Water Board has constructed 115 piezometer wells and monitored piezometric heads with high frequency digital water level recorder. The impact of Earth tide on groundwater regime is clearly recorded at two sites namely, Kothagudem (Khammam district) and Mangapet (Warangal district). The wells at these sites are constructed in the confined aquifer of Kamthi sandstone in Godavari valley which is nearly 200 km inland from the east coast. Analysis of the data reveals that the piezometric level heads fluctuate in a cyclic manner and the variations for each lunar cycle of 13–14 days with high peaks on new Moon and full Moon days. The peaks observed in the piezometric heads gradually decline coinciding with the lunar phase. Distinct changes in piezometric heads are observed for each phase of the Moon in both of the above-mentioned places. An account of impact of lunar and solar attraction forces on piezometric level heads of groundwater, the ideal conditions required for recording this phenomenon along with a comparison of these hydrographs with examples from the literature are provided in the present study.

Keywords: Confined aquifers, crustal tides, groundwater regime, lunar attraction, piezometer wells.

THE attraction of the Sun and Moon on the Earth can be visualized with the naked eye in the form of oceanic tides. Similar tidal waves are also created by them on the Earth's crust and the groundwater undergoes changes along with it. Though the phenomenon is general in nature and occurs in total groundwater regime of the Earth's crust, it can only be recorded in special situations and conditions at a few places.

The Central Ground Water Board (CGWB) in Andhra Pradesh constructed 115 piezometer wells (alluvium – 2,

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Rajahmundry sandstones – 15, Tirupathi sandstones – 8, Gondwana formations, including Kamthi sandstones–15 and in hard rocks – 75) and installed high frequency digital water level recorders (DWLRs). Only in two piezometer wells (Figure 1), the DWLRs could record the Earth's tidal influences on groundwater clearly. It shows that special conditions are required to record this phenomenon, mainly the ideal confining conditions of aquifer to be tapped along with the method of construction of piezometer well and high-frequency monitoring.

In this communication, we discuss the lithology of aquifer zones, the confining conditions that occur, construction mechanism of piezometer wells at two sites in AP, piezometric head data obtained from these wells, the influence of lunar and solar attractions on the groundwater regime and comparison of the hydrographs prepared from the recorded data with earlier examples.

The two piezometer well sites at Kothagudem, Khammam district and Mangapet, Warangal district, AP, are more than 100 km apart. These sites are underlain by Kamthi Sandstone Formation comprising medium to coarse-grained sandstone with intercalations of clay belonging to Gondwana supergroup of rocks, part of Godavari sedimentary basin (Figure 1). Aquifers tapped in the piezometers at Kothagudem (Figure 2) and Mangapet are under confined condition. A layer of about 12 m thick clay from 102 to 114 m bgl (metres below ground level) at Kothagudem and from 71 to 82 m bgl at Mangapet provides considerable confining condition to the underlying aquifer. The aquifer lying below the clay layer from 126 to 132 m bgl and 97 to 103 m bgl was tapped at Kothagudem and Mangapet respectively.

Slotted pipes of 6 m length along with blank pipes were lowered, gravelled against the slotted portion and filled with clay against the blank. The discharge of the wells was around 1 l/s/well. Piezometric heads were observed using pressure transducers and recorded in digital format with 6 h time interval. Recording of high-frequency piezometric head data helped in understanding the effect of various factors, including the lunar and solar attractions on the groundwater system.

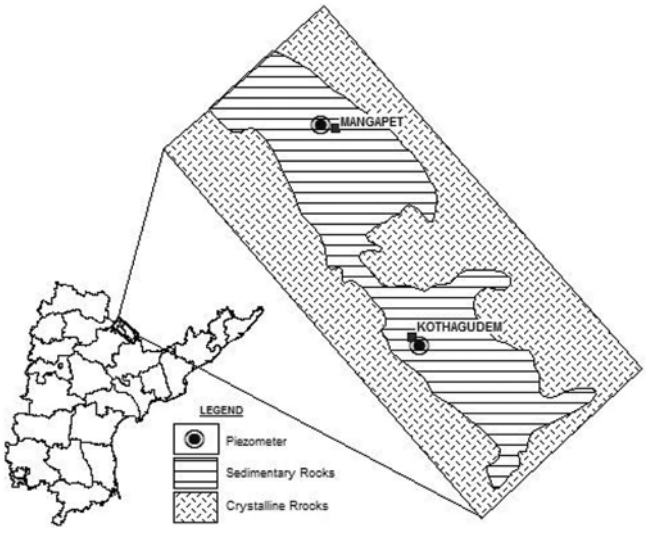

Figure 1. Location of piezometer wells.

The effect of gravitational force of the Moon, the only natural satellite at a mean distance of 384,000 km from the Earth has been studied. The moon moves round the Earth once in 27.3 days passing through different phases. The oceans and the Earth's crust are influenced by lunar gravity. However, because the land is rigid compared with the oceans, the 'tides' in the body of the Earth's crust are much smaller than those in the oceans. The fluid in the oceans is much more easily deformed and this leads to significant tidal effects. In addition to the gravitational force of the Moon, differential gravitational force of the Sun also influences the tides to some degree.

The effect of the Sun on Earth tides is less than half that of the Moon. The enhancement in tides of the Earth is also different because the Sun and Moon are lined up on opposite sides (full lunar phase) as well as the same side (new lunar phase) of the Earth. The coincidence of low water with the transit of the Moon can be explained by reasoning that at this time tidal attraction is maximum; therefore the overburden load on the aquifer is reduced, allowing it to expand slightly, whereas the high piezometric head is the result of aquifer compaction.

Todd[1] observed regular semidiurnal fluctuations of small magnitude in piezometric surface of confined aquifers located in Iowa City at great distances from the ocean. These fluctuations result from Earth's tides, produced by the attractions exerted on the Earth's crust by the Moon and to a lesser extent by the Sun (Figure 3)[1].

Karanth[2] described that tides of the Earth which are caused due to the forces exerted on the Earth's surface by the Sun and the Moon, may produce fluctuations in water level in artesian wells. Figure 4 shows a hydrograph prepared from the water-level record (well of 189 m depth) of Veerapandipurdur in Noyil basin, Tamil Nadu.

Marechal *et al.*[3] measured fluctuations in water level in a well constructed (173 m depth) in an unconfined crystalline aquifer (granitic terrain) located at the National Geophysical Research Laboratory (NGRI), Hyderabad. Figure 5 shows that tides of the Earth are responsible for observed daily and semi-daily period of fluctuations in the water table.

The new and full Moon days during 2003 along with exact timings of each phase are given in Table 1. These data are correlated with the hydrographs prepared from the piezometric head data for the entire year of 2003 recorded in the piezometer well at Kothagudem (Figure 6 *a*) and for August to October 2003 at Mangapet (Figure 7 *a*). The hydrograph prepared from the piezometric head data recorded at Kothagudem piezometer well exhibits a unique pattern in the fluctuation of its head. There are around 24 spindles followed by 24 quiet periods (two

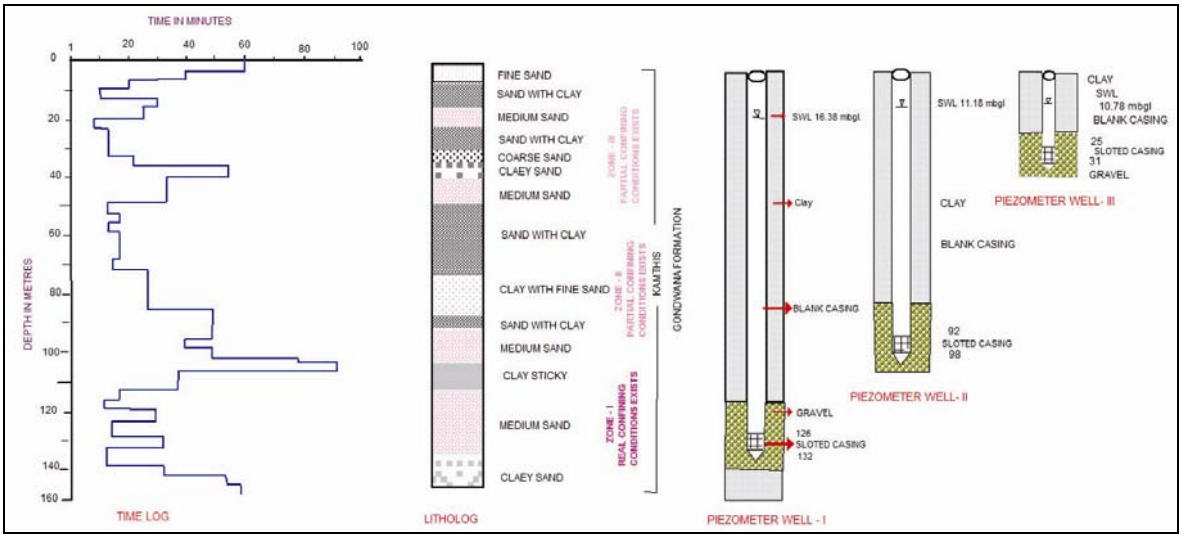

Figure 2. Time log, litholog and construction details of piezometer wells at Kothagudem, Khammam district, Andhra Pradesh, India.

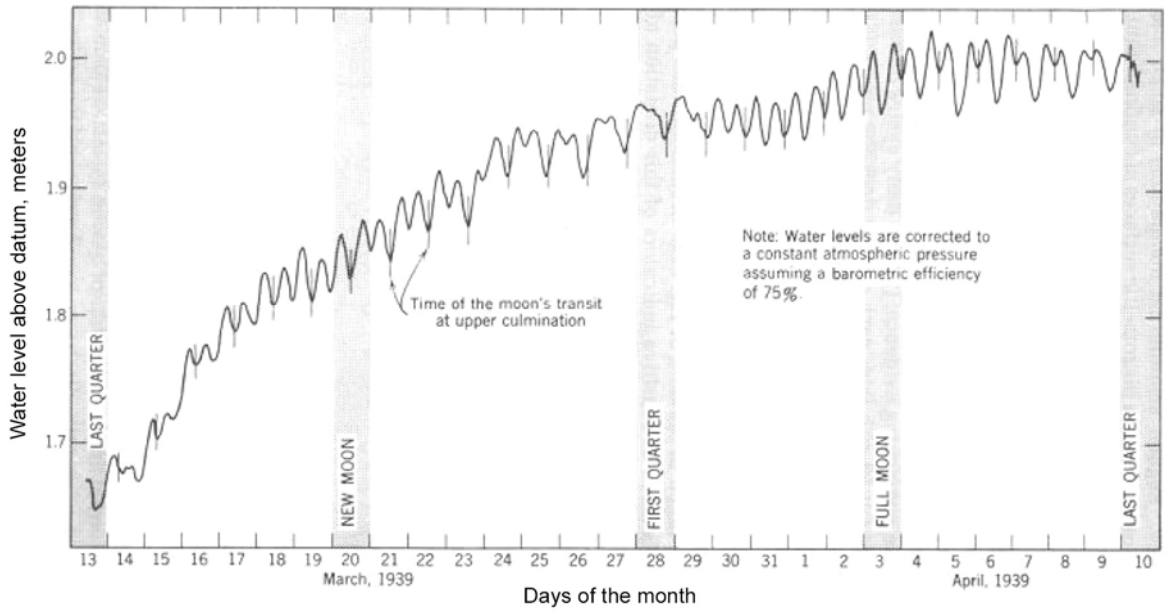

Figure 3. Water-level fluctuations in a confined aquifer produced by Earth tides[1].

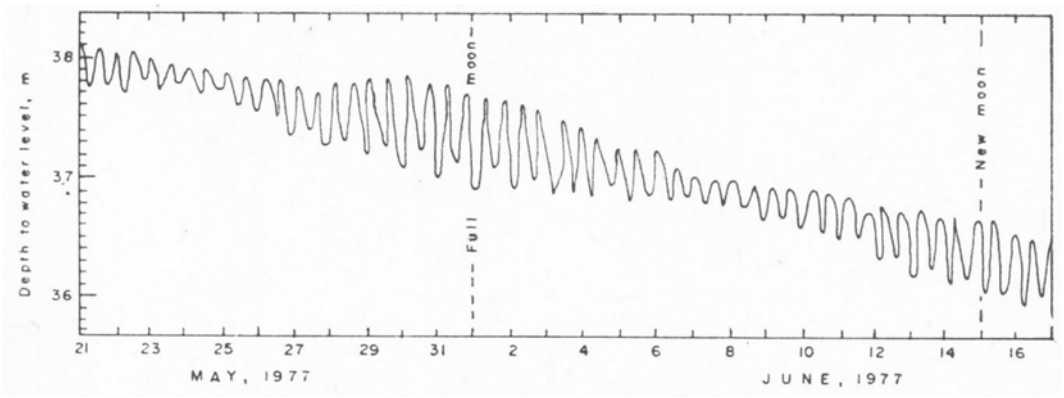

Figure 4. Hydrograph of a well at Veerapandipurdur, Tamil Nadu.

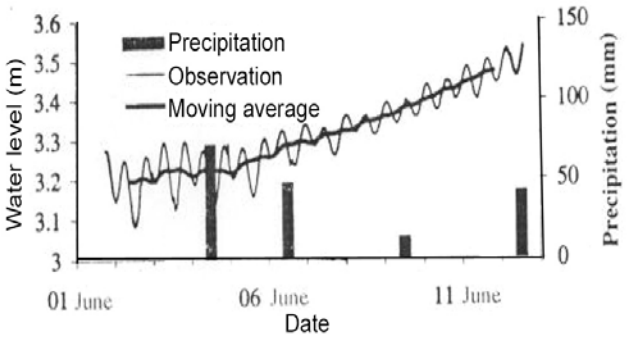

Figure 5. Hydrograph of a well at NGRI, Hyderabad[3].

Table 1. Details of lunar phases

Date/month of new and full Moon phases during 2003	Time (h)
New Moon	
3 January	02.00
1 February	18.00
3 March	08.00
2 April	01.00
1 May	18.00
31 May	09.00
30 June	01.00
29 July	12.00
27 August	23.30
26 September	10.00
25 October	17.00
24 November	05.00
23 December	14.00
Full Moon	
18 January	16.00
14 February	23.00
18 March	14.00
17 April	00.30
16 May	10.00
14 June	08.00
13 July	11.30
12 August	23.30
10 September	23.30
10 October	12.00
9 November	06.00
9 December	02.00

spindles/quiet periods in each month) coinciding with the new, full and intermittent lunar phases of the year.

The cycle of piezometric head fluctuation patterns of a month (18 October–17 November 2003) is compared with different phases of the Moon. The high fluctuation pattern is in the shape of a spindle and maximum at its centre coinciding with the dates of either new Moon or full Moon days. The subsiding/low fluctuations are at both the ends coinciding with the transition stage of the Moon, i.e. presence of the Moon at right angles to the Sun–Earth line (Figure 6 *b*). From the first quarter to waning crescent, the fluctuation of piezometric head is around 1–2 cm. It gradually increases and reaches its maximum fluctuation of 6 cm towards new Moon's day of 25 October. Further, the fluctuation continuously decreases towards waxing crescent and then starts increasing from last crescent, waxing gibbous and finally to its maximum by full Moon's day on 9 November 2003. The fluctuation attains its maximum of 6 cm during a period of 9–10 days and a maximum of 3 cm for the contiguous period of 4–5 days. The lowest fluctuation of 0.5 cm is observed in the first quarter phase of the Moon. The two high and low fluctuation patterns continue in a cycle of 13–14 days. The highest amplitude of fluctuation of piezometric head is observed when the Sun and the Moon are lined up on the same side of the Earth on new Moon's day and slightly less fluctuation is observed when the Sun and the Moon are lined up on opposite sides of the Earth on full Moon's day (Figure 6 *b*). When the Moon is in transitional phase, the effect is least on the piezometric head producing little fluctuation. Similar fluctuation pattern is also observed at Mangapet piezometer site (Figure 7).

The phenomenon of lunar and solar attractions on piezometric surface/water level was observed by Todd[1] and Karanth[2] in confined aquifers and Marechal *et al.*[3] in unconfined aquifers. The hydrographs recorded by them show that the fluctuations during full Moon days are more than those during new Moon days, Marechal *et al.* recorded hydrograph for 13 days only. The present study reveals that the phenomenon of lunar and solar attractions on piezometric surface can be recorded in confined aquifers only. The hydrographs presented in the examples cited from the literature are prepared from the piezometric head data collected from deep wells (Todd mentioned it as confined aquifer, Karant mentioned it as artesian wells and the depth mentioned by them is more than 175 m in each case). Compared to the hydrographs recorded by Todd (Figure 3), Karanth (Figure 4) and Marechal *et al.* (Figure 5), the hydrographs recorded in the present study (Figure 6) explain the variations of piezometric head for each lunar phase in a better way. It can also be seen that the fluctuation during new Moon day is more than that during full Moon day, which correlates with the fact that the attraction of Sun and Moon is more on the Earth on new Moon day. Thus, the present hydrographs are useful for studying the impact of lunar and solar attractions on piezometric heads.

The piezometric head/surface in the wells tapping a confined aquifer overlain by thick impermeable layer is sensitive to the changes in gravitational attraction forces of the Moon and the Sun, and exhibits distinct fluctuation patterns. The fluctuation of piezometric head is maximum on new Moon days, slightly less on full Moon days and is low or insignificant when the Moon is in transition stage. This phenomenon can be recorded when the real confining conditions are tapped in the piezometer wells along with high-frequency monitoring. The hydrographs in the present study clearly show the influence of the Moon and

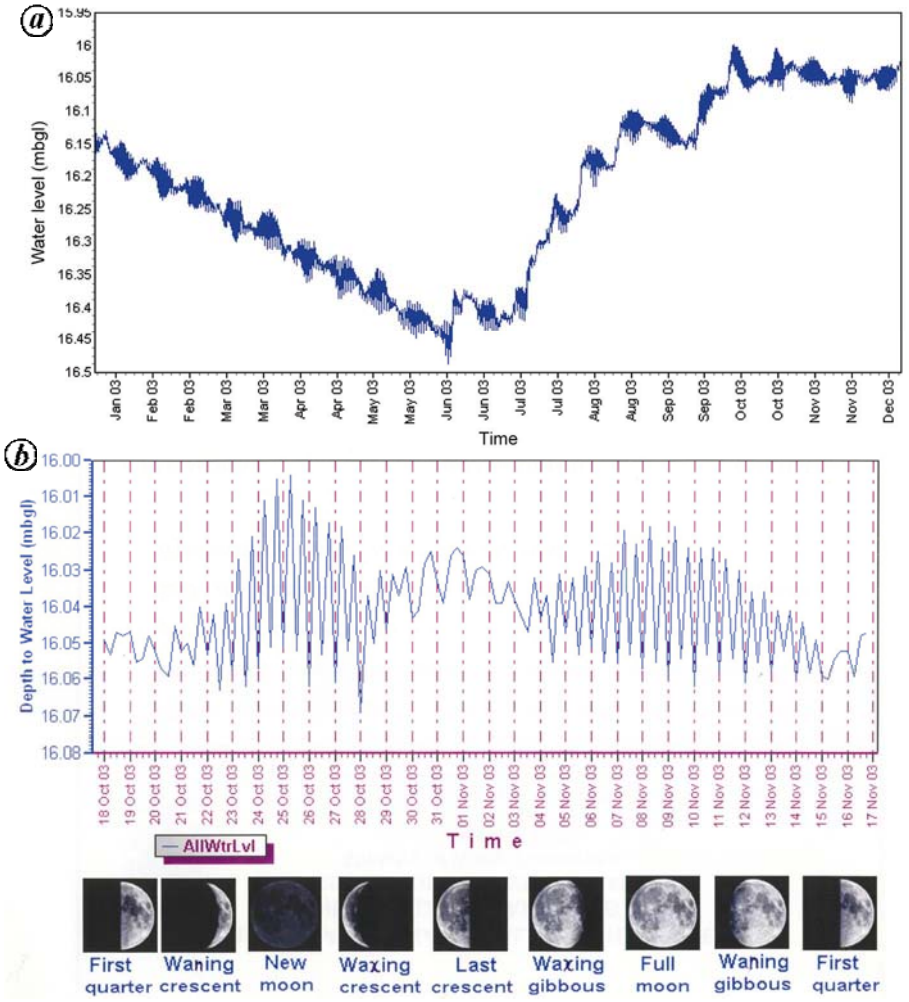

Figure 6. ***a***, Hydrograph recorded at Kothagudem (2003), Khammam District, Andhra Pradesh, India. ***b***, Hydrograph recorded and comparison of piezometric head with different phases of Moon at Kothagudem.

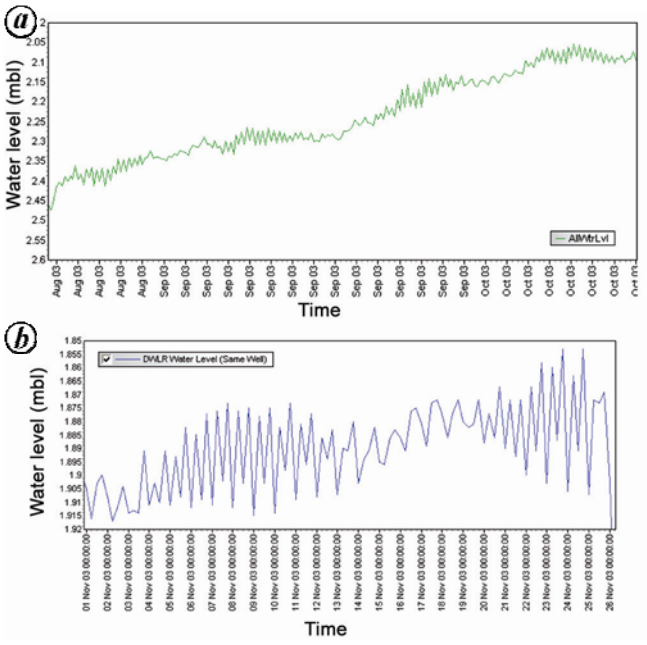

Figure 7 ***a***, ***b***. Hydrographs recorded at Mangapet peizometric well, Warangal district, Andhra Pradesh, India.

the Sun on Earth tides and in turn on the groundwater regime. These hydrographs will prove useful for a better understanding of the solar and lunar attractions/crustal tides of the Earth on the groundwater regime.

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