

# Visualization of Liquefaction in Soils with PWP Measurements by Tapping



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## 1 Introduction

Following large earthquakes, liquefaction-induced failure in many geo-structures remains major interests for geotechnical discipline, and various post-failure case studies are available in the literature. With the advent of computer simulation, dynamic shake table-mounted centrifuge tests, laboratory physical scale model tests, and in situ tests, attempts are made to the development of constitutive and numerical modeling tools to characterize the liquefaction-prone soils (Perlea & Beaty, 2010). The computational work reported in Boulanger and Ziotopoulou (2015), Manzari et al. (2018) has revealed that practicing engineers need simple yet elegant field tools to ascertain the liquefaction initiation and subsequent onset of lateral spreading leading to mass-scale failure of geo-structures. The lessons learned from Liquefaction Experiment and Analysis Projects (LEAP) on Ottawa sand (F-65) were that (1) only a few of the available numerical techniques are reliable for liquefaction prediction and (2) there is a wide variability in many of the centrifuge tests (Perlea & Beaty, 2010). It noted that rounded soil particles of uniform size are usually susceptible to liquefaction. While well-graded granular soils, due to their stable configuration, are relatively less prone to liquefaction, the natural silty sands which are deposited in a loose state, are more prone to shear contraction. Clayey soils are resistant to the relative movement of particles during cyclic shear loading and hence are not prone to liquefaction. Non-plastic silts do not create adhesion and hence do not provide appreciable resistance to particle rearrangement and liquefaction. Sandy soils with appreciable fines content may be inherently collapsible, perhaps because of the greater compressibility of the fines between the sand grains.

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The occurrence of earthquakes is inevitable in the Himalayas and almost after eight decades Nepal has been shaken by M7.9 earthquake on 25 April 2015 followed by a series of large aftershocks that rocked the entire northern and northeastern India. The M6.4 Sonitpur (29 April 2021) earthquake in the state of Assam, India, affected several buildings in the Guwahati, which is more than 100 km away and caused several trails of liquefaction in the riverside areas of the Brahmaputra. Likewise, the country has experienced several devastating inter-plate as well as intra-plate earthquakes during the last 125 years, with heavy liquefaction-induced destruction in the hilly terrains. The liquefaction effects were widely observed following the 1934 Bihar–Nepal in India, the 1948 Fukui Earthquake in Japan, the 1964 earthquakes in Niigata, Japan, and Alaska, and more so due to Bhuj (2001), Kashmir (2005) earthquakes. Earthquake causes soft sediments that tend to amplify and prolong shaking duration. Hence, continued interests in the small-scale physical modeling as well as recreating in situ of stress and strain during the onset of liquefaction have been underway since the 1964 Niigata earthquake.

During an earthquake, seismic energy passes from the focus to the sub-structure through which it is transmitted to the superstructure. Excess pore pressure generation in the saturated fine-grained soil deposits has been used to characterize the liquefaction potential. Liquefaction phenomena are the consequence of earthquake-induced excess pore water pressure in the soil. This phenomenon is uncertain and varies with the change in drainage, soil consistency, grain size distribution, earthquake duration, amplitude and frequency of shaking, distance from the epicenter, location of water table, and permeability of soil layer (Chang et al., 2007; Perlea & Beaty, 2010; Rathje et al., 2005). A procedure based on field penetration resistance and cyclic stress resistance has been developed using PGA which assesses the initial liquefaction of soil, now being used widely all over the world (Seed & Idriss, 1971; Seed et al., 1983). A number of case histories of liquefaction-induced ground deformation and their effects on constructed facilities are well recorded in the state-of-the-art reports (Dobry, 1995; Dobry & Abdown, 1998; O'Rourke et al., 1989). The initial excess pore water pressure plays a role in the nonlinear, dynamic response of granular soils. The pore-pressure generation characteristics from field reconstituted specimens are presented. The pore pressure patterns at various strain levels, the observed stages, and pore pressure generation curves are obtained (Jiaer et al., 2580). The semi-empirical liquefaction procedures can be evaluated effectively by providing the in situ pore pressure generation and dissipation behavior of liquefying soils. The liquefaction potential for Delhi and Northeastern India has been evaluated based on the field SPT test data and shear wave velocity survey using different models (Chang et al., 2007; Rathje et al., 2005).

## 2 Seismic History of Delhi

The National Capital of India, Delhi, has a long history of being vulnerable to earthquake hits (Iyengar & Ghosh, 2004; Agarwal and Chawla, 2006). The first known earthquake jolted the city around 893AD (Oldham, 1883), and the first earthquake

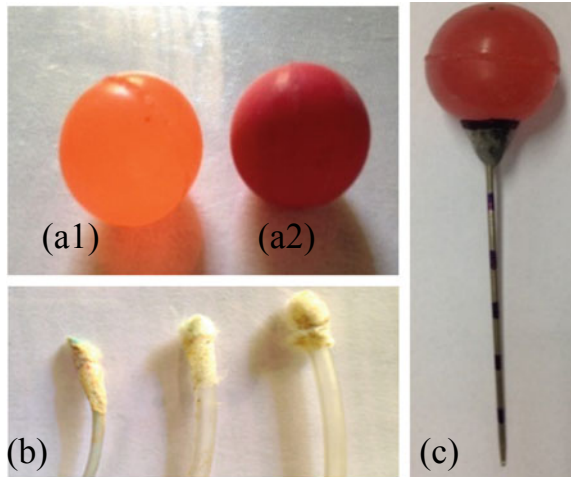
was recorded on 6 July 1505. The first documented earthquake of 6.5 magnitude hit the city on 15 July 1720 (Iyengar, 2000). Besides a number of earthquakes near and far from the city had also caused great damage. These earthquakes are Mathura (1803 and 1842), Kangra (1905, M8.1), Khurja (1956, M6.7), Moradabad (1966), Uttarkashi (1991), Chamoli (1999), Bhuj (2001), and Kashmir (2005). More records on large Himalayan earthquakes, which caused great damage to the capital city are found in Iyengar (2004), Perlea and Beaty (2010), Rajendran and Rajendran (2005), Iyengar (2000). Qutub Minar, a famous landmark in Delhi also faced severe damages from time-to-time earthquakes. Mathura Earthquake on 25 August 1803 had caused great damage to Qutub Minar, documented by Nazir Akbarabadi, 1740–1803, in his Urdu poem *Bhucal-nama* (Iyengar & Ghosh, 2004). As per Indian Seismic Code, India, has four macro zones (IS 1893: 2002). As this zonation is primarily based on the historical occurrences of the earthquake in the last 600 years, there is significant variation in the intensity of ground motion, which depends largely on the geological properties, as well as the magnitude of earthquake. Microzonation of a few Indian cities, including Delhi, Guwahati, Kolkata, etc., has been completed and similar studies of the most seismically vulnerable cities are in progress.

Delhi being situated on the right bank of the Yamuna River and bounded by Indo-Gangetic alluvial plains in the north- and east-faced severe threats of liquefaction. The soil types consist of low plastic silt, sandy silt, fine sand, clay with low and medium plasticity, and alluvium. The earthquakes being amplified by alluvial soil, the Yamuna River bed section is more vulnerable to liquefaction even under small and moderate earthquakes. The Trans-Yamuna area of Delhi is prone to liquefaction damages based on M7.2 earthquakes. More than 80% of the soil have potential to liquefy. The aim of this paper is to examine the chances of liquefaction of Yamuna River sandy silt by experimenting with two bottles and creating thereby dynamic excitation into the loose specimen by manual tapping *vis-à-vis* measuring the changes in the excess PWP as compared to eight more soil specimens under similar test conditions. Experimental visualization of the rise in corresponding water level with respect to three sizes of drain pipes has been carried out in a large container.

### 3 Experimental Investigations

Considering the significance of various laboratory and field studies done since the 1964 Niigata Earthquake, it has no doubt that pre–during–post liquefaction aspect requires more precise yet field-sensitive characterization. To this extent, several physical model test has been performed using shaking table (Perlea & Beaty, 2010; Prasad et al., 2004; Youd & Holzer, 1994; Kramer, 1996). In this study, the following aspects have been incorporated: Use of sandy silty soil in water container that will be able to recreate soil layer in the loosest possible state, which is one of the prerequisite for creating liquefaction; Checking the embedment depth of physical model subjected to excitation by finger-tapping; Effect of continuous vibration versus Initial (loosest) condition; Physical objects are placed inside the soil in such a manner that even little

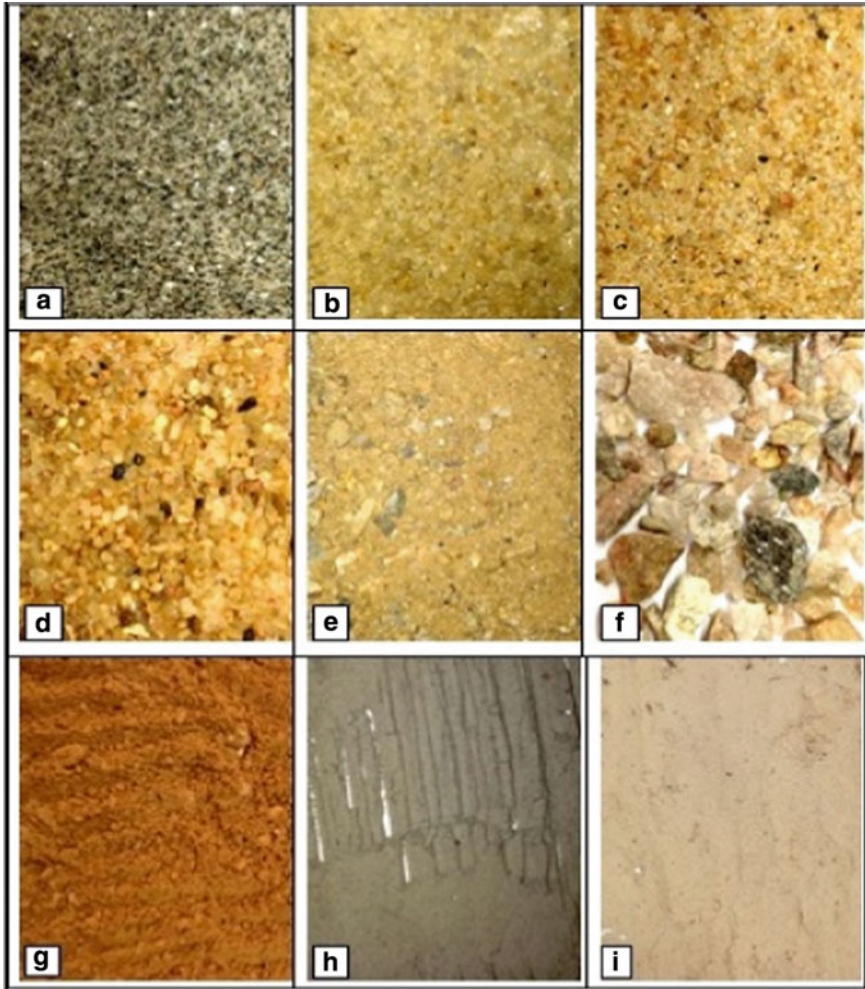
**Fig. 1** **a1** Rubber ball lighter than water: **a2** Ball heavier than water being used as underground model utilities **b** Three different plastic tubes with their ends masked with cotton piezometer. **c** Lighter ball pierced with a needle being used as overground model structure



tapping or vibration will be enough to create changes in the density of loose specimen; Measuring relative variation of PWP inside the soil specimen during liquefaction, which is otherwise not possible by existing methodologies, where PWP transducers are placed usually at the specimen boundaries; Use of particular size of stand pipe which will not disturb the grain structure much for the exact capturing of excess PWP; Visualization of liquefaction effect on model objects, e.g., floating of submerged ones and large settlement of building (Fig. 1); Effect of manual tapping (low energy impact) on a small container model on nine different types of soil, including fly ash, clay, stone dust, where liquefaction usually don't occur; The nine different sample (Fig. 2) collected from North and Northeast India are investigated to find the vulnerability of liquefaction and comparing it with fine sand of the Yamuna River, Delhi (Fig. 3). Experiment on a large container signifies relative measure of excess PWP with respect to height.

#### 4 Creating Liquefaction Effect by Tapping

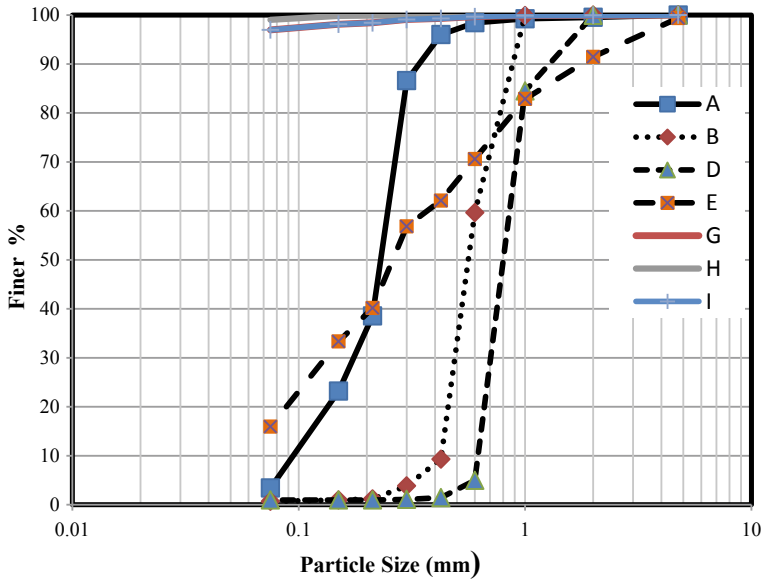
The main aim of this preliminary stage of experiment is the visualization of vibration effect on loose saturated sand in terms of a relative measure of PWP increase; in synchronization with the liquefaction effect on underground objects such as sewerage pipeline, tunnel, manhole cover, earthfill dam, tilting of buildings as well as capturing excess PWP through an open standpipe placed inside soil specimen. Simplified experimental devices explaining the reason for liquefaction by tapping and measuring excess PWP, which is otherwise being done PWP transducer in laboratory. Measuring the relative increase in the density of loose sand as an input energy is applied vis-a-vis impact on the settlement of overground object. Easy process for reconstituting of test specimen ensuring minimum variation in the initial condition before applying tapping energy.



**Fig. 2** A close view of the nine soil specimens, **a** The Yamuna River sand, Delhi **b** The Gomoti River sand, Tripura **c** Kolkata medium sand, **d** Khowai coarse sand, Tripura **e** Badarpur well-graded sand, Delhi, **f** Pebbles, **g** Clay, **h** Fly ash, **i** Stone dust

### 4.1 The Present Investigation

Visualizing liquefaction effect by manual finger tapping, respectively, on 500 ml bottle without PWP measurement, 2000 ml bottle with PWP measurement (keeping bottle cap closed and open), and on 5 L container with three different pipe diameters. Excess PWP being measured in terms of an increase in the water column on the standpipe, which is placed inside the soil specimen. Effect of number of tapping on the gradual increase in the settlement of loose soil at varying initial height. Measurement



**Fig. 3** Grain size distribution curve for the seven different soil specimens

of the liquefaction effect on the embedded and overground objects (Fig. 1), for which amount of settlement is being recorded. Deciding the pipe diameter to be used for the next series of experiments, in which water level fluctuation due to the finger Tapping as input source of dynamic excitation by earthquake are being noted. As the aim of the current experimentation is to visualize the phenomena of liquefaction-induced failure (Fig. 4), the exact amount of energy input by index finger-tapping was not accounted for. As long as the liquefaction event as shown in Fig. 1, is recreated in the series of model experiments by using the same set of small and large bottles and characteristic differences of the same are noted in the nine different types of soils, the exact measurement of input energy to the equivalent earthquake energy is not of prime concern.

## 5 Discussions

The main inspiration for the laboratory simulation is to recreate the situation shown in Fig. 4. The underground sewerage pipelines got uplifted due to the buoyancy effect. The soils of various consistencies are shown in Fig. 5 and as the size of the bottle is small, spherical rubber balls are used as representative underground utilities.

Height variation (densification) of loose sandy soil (initial height indicated in each case) due to Tapping by Index finger, showing liquefaction in Yamuna and Gomoti sand and lesser in Kolkata sand but no liquefaction is observed in Khowai, Badarpur sand, Badarpur pebbles, clay, fly ash, and stone dust, thus signifying the difference



**Fig. 4** Upliftment of Manhole due earthquake-induced liquefaction



**Fig. 5** Nine Soil specimens in 500 ml bottle subjected to finger tapping as external excitation

between fine, medium, and coarse sands, while subjected to dynamic force. No PWP measuring device was installed in the small 500 ml container but tapping did not show visually the buoyant effect of 20 mm dia object placed inside in each case. Equivalent thickness of the sand due to 20 mm dia ball is than 1.5 mm. Specimen height showed an insignificant variation compared to the Yamuna fine sand.

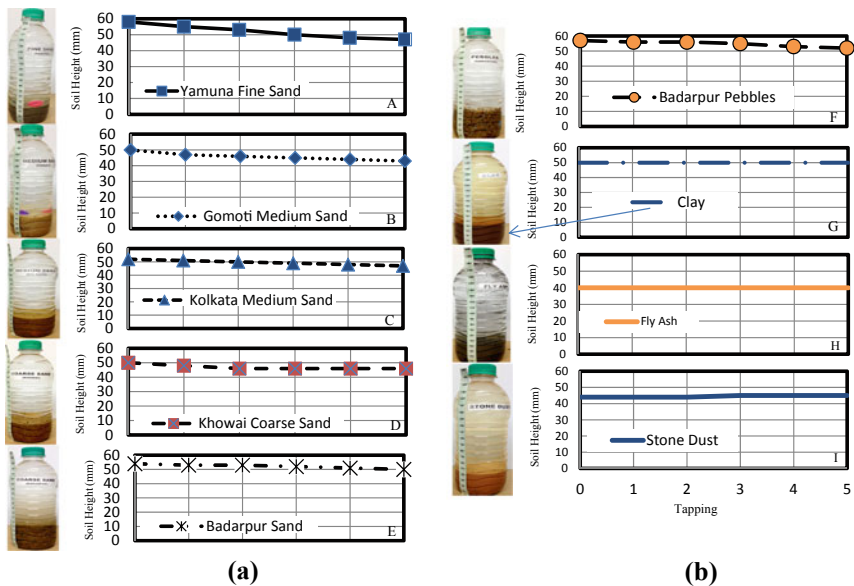
Relative changes of excess PWP, which are expressed in terms of water column above static height of water in a 2 L container, are captured by Open Stand Pipe and it is plotted against the No. of tapping. The variation in the water ht. versus No. of tapping curve is the indicative of liquefaction occurrence checked in the Yamuna sand ht of 90 mm, 120 mm, 150 mm, and the Gomoti sand of 130 mm ht., respectively. During liquefaction, the embedded round object (Fig. 1a) moved up and floating

object (Fig. 1c) moved down. This is the case observed in Fig. 4 due to earthquake-induced liquefaction. As the sand specimen was made at the loosest possible state, the experiment showed a significant reduction in height as number of tapping increased. Specimen height and water column in the 1 mm diameter standpipe were taken at every stage of tapping.

Test condition is same as Fig. 7 but with bottle cap open (Fig. 8) as in the 500 ml bottle experiment (Fig. 6). Out of nine soils, only two of them showed liquefaction, subsequent tests on the 2 L bottle were done for the Yamuna sand and Khowai sand only. Excess PWP showed orderly reduction as number of tapping increased.

In Fig. 9a, the test setup is shown. (I): Test on the Yamuna Sand in 5 L container with pipe dia 1 mm(II), 2 mm(III), 2.5 mm(IV). Variation water ht. was recorded using colored ink. Here tapping was done through a hammer. As evident water column variation is relatively more at the initial number of tapping. There is also residual confining pressure marked in the standpipe. Out of three different sizes of the standpipes, distinct measurements in 1 mm dia pipe were seen. Therefore, all other series of experiments were done with 1 mm pipe.

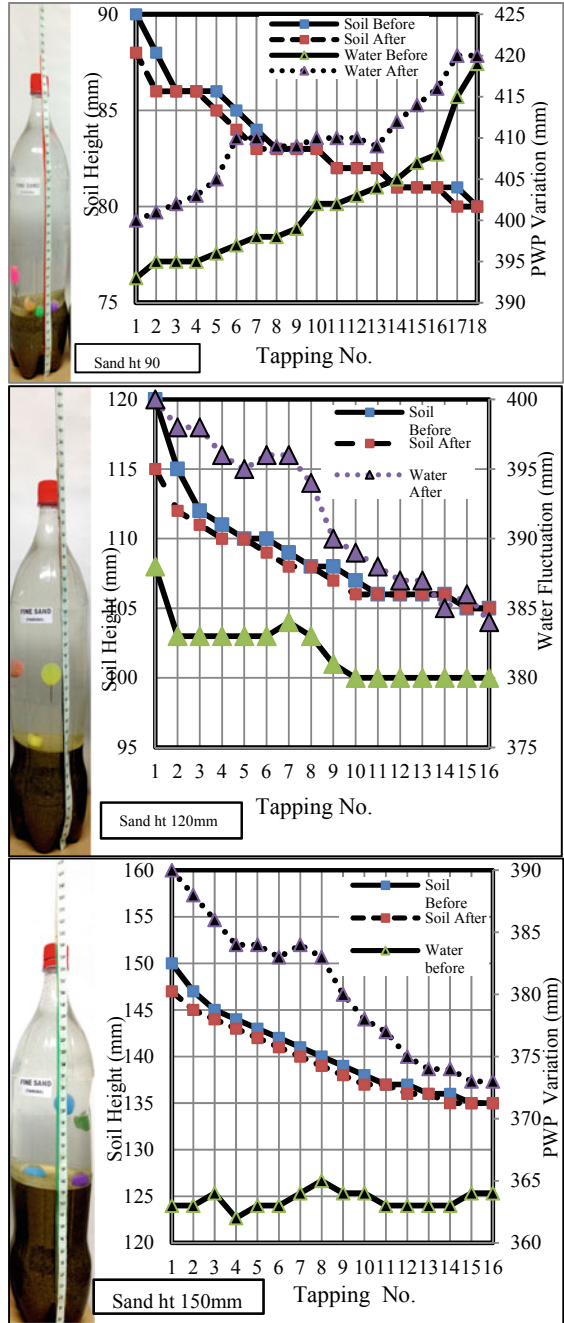
Experiments on large containers gave a more realistic nature of the liquefaction phenomena. Out of nine soil specimens, the Yamuna River fine sand, Delhi, is highly liquefiable. Based on a series of tests on bottles filled up with different types of soils, both visualization of the liquefaction phenomena and measurement of excess PWP have been explained in this paper. The visualization of the liquefaction process, which is mainly due to external forces causing the saturated sandy silty soil to loose shear strength, has been captured by a Piezometer of 1 mm internal diameter standpipe



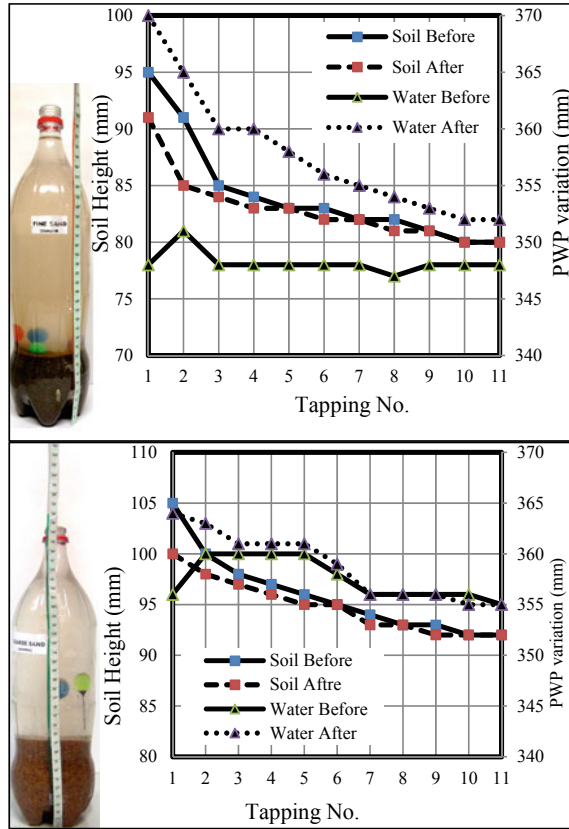
**Fig. 6** a Soil height versus Tapping energy count No. in 500 ml bottle. b Soil height versus Tapping energy count No. in 500 ml bottle



**Fig. 7** Soil Height and PWP Variation versus no. of tapping (closed cap condition)



**Fig. 8** Soil Height & Water Fluctuation versus no. of tapping (Open Cap Condition)

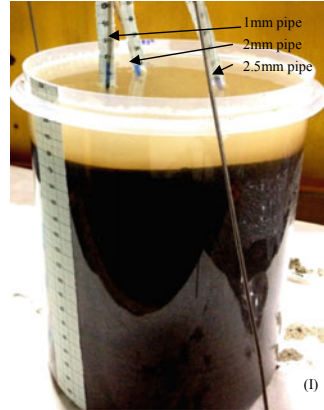


with its tip filled with cotton foam. The experiments were quick and repetitive, thus eliminate errors in sample preparation. Simulation of underground utilities and overground buildings in a liquefiable soil has been done by 20 mm diameter rubber ball affixed with a needle. Capturing the upward movement of the balls and downward movement of the needle fixed ball vis-à-vis instant jumping of water level in the standpipe is some of the unique experimental findings. The results show that out of nine types specimens tested, the Yamuna River sand in Delhi and the Khowai River sand in the state of Tripura, India, are highly liquefiable and PWP variation during dynamic excitation has been measured and simulated during experiment.

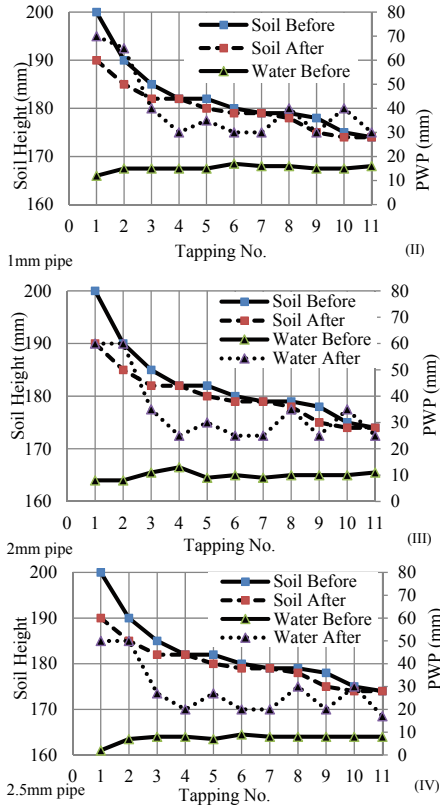
## 6 Conclusions

Visualization of the liquefaction process, which is mainly due to external forces causing the saturated sandy silty soil to loose shear strength, has been measured by simple experiments. The simplicity of the experiments in bottles and buckets vis-à-vis the liquefaction phenomena being evaluated in sophisticated laboratory tests are

**Fig. 9 a** Soil height and Water Fluctuation versus no. of tapping. **b** Soil height and Water Fluctuation versus no. of tapping



(a)



(b)

explained. the use of 1 mm diameter open pipe as an equivalent Cassagrande-type piezometer has been very elegant to capture PWP changes during liquefaction. While doing tests in 500 ml and 2 L bottle, its easier to prepare and recreate specimens in the loosest state. Therefore, experiments were quick and repetitive. Several sets of tests were done in order that there is little or no variation in the tapping energy input. Installation of the standpipe at the bottom of 2 L bottle is a simple technique that ensured capturing PWP changes within the specimen, which is otherwise not feasible in routine liquefaction devices. Simulation of underground utilities and over-ground buildings in a liquefiable soil has been done by 20 mm diameter rubber ball affixed with a needle. Capturing the upward movement of the embedded spheres and downward movement of the needle fixed sphere vis-à-vis instant jumping of water level in the standpipe is the unique experimental findings as reported in this paper. Measurement of excess PWP was possible by these simple experiments and the same is evaluated for nine soil specimens under similar test conditions.

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