A new technique to avoid tilting problems during liquefaction

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Abstract. Soil liquefaction is one of the primary concerns during construction of foundations on saturated sand in seismically active areas. Seismically induced settlement and tilting of structures due to liquefaction have resulted in detrimental consequences. The generation of excess pore pressure is the key to the initiation of liquefaction which mainly occurs due to an earthquake. A series of measures have been tried over time to time to mitigate the effects of liquefaction but till now no effective measure has been evolved to safe a structure founded on a liquefiable soil. The present paper covers an experimental study on a two storeyed frame structure standing on liquefiable soil to show its performance soon after liquefaction. The shape of the footing is changed from conventional to non-conventional footing. Two non-conventional shapes adopted in this study are spherical and trapezoidal in cross-section, designed in such a way that they achieve stable equilibrium under both vertical loads and upthrust generated due to pore-water pressure generation during liquefaction. Series of tests were performed with conventional rectangular footing, spherical shaped footing and trapezoidal shaped footing on a one-dimensional shaker at frequencies of 1 Hz to 5 Hz. Accelerations of the tank were compared with the accelerations imposed over the footings. Displacements were measured from a fixed point using a ruler scale and tilt was measured from comparison of photos taken before and after shaking from a stationary point. It was observed that the vibrations at upper floors are more for conventional footing while vibrations at footing level are more for modified footings. It was also observed that the modified footings floated over the liquefied sand for a longer time and then sank instead of being tilted. The paper concludes that spherical shaped footing is the best alternative to eliminate the tilting problem.

Keywords: liquefaction, trapezoidal, bowl-shaped.

1 INTRODUCTION

As the earthquake triggers on the saturated fine sand or silt, an excess pore water pressure develops in the soil. Due to rapid loading this excess pore pressure is unable to dissipate and the soil starts behaving as a viscous fluid, the shear strength of the soil reduces abruptly, the bearing capacity of the soil suddenly reduces to almost zero. The process is called liquefaction. Due to absence of the bearing capacity of the soil the structure gets tilted due to eccentric loading, for an example, many structures in Adaparazi in Turkey tilted during the August 17, 1999 Kocaeli earthquake (Mw = 7.5) (Bray & Dishti, 2010), structures suffered maximum differential settlement of more than 200mm due to liquefaction in Niigata-ken Chuetsu-Oki Earthquake (Mw=6.5) Japan on July 16th, 2007 (Koichi et al. 2014). Tilting of structures caused irrecoverable damages to the buildings resulting in loss of life and property. There are many theories to calculate liquefaction induced settlements (Tokimatsu & Seed, 1987; Nagase & Ishihara, 1988; Ishihara & Yoshimine, 1992, etc). In order to mitigate the problem of liquefaction, the relative density of foundation soil needs improvement which can normally be achieved through grouting, dynamic compaction, band drains, vibro-compaction, etc. All these mitigation processes are costly, time consuming and require skilled workmanship. The other way to mitigate the problem of liquefaction is to modify the shape of the foundation and apply Archimedes principle so that the building floats on the liquefied soil. The shape of the foundation is, thus, to be modified such that the weight of the building is balanced by the buoyant force and the foundation of the building starts floating like a pontoon with a positive meta-centric height and as the earthquake stops the floating of the building stops and it starts sinking in vertical direction. As there is no tilt in the building due to liquefaction the loss of life and property can be saved.

In the present study, three RCC two-storeyed buildings with the scale ratio of 1:15 (model: prototype) were casted considering three different shapes of footings like rectangular, trapezoidal and bowl shaped. The trapezoidal and bowl shaped foundations were hollow from inside and their design satisfied Archimedes principle. The buildings were successively placed in a steel tank of dimension 1x1x1m which was filled with sand of 50% relative density. The sand was completely saturated by pouring water through perforated pipes placed at four corners of the tank. The process of pouring water was carefully carried out so that the density of soil had a minimum change. The tank was connected to a 1-D shaker. Four accelerometers were used to obtain acceleration time histories at different locations. The building frame was shaken at different frequencies and the acceleration readings were taken at an interval of 0.0001seconds for one minute. The tilt of the building was measured with the comparison of photos taken before and after shaking from a stationary point. The vertical displacements of the bowl and trapezoidal shape footing were measured from a fixed point. Then the tilt and sinking of the different foundations at different frequencies were plotted and compared.

2 THEORY

2.1 Design criteria

The foundation of the building was designed according to Archimedes principle i.e. weight of the building should be equal to the buoyant force. The super structure of all the building models were kept identical but the footings were made different. Weights of superstructure and substructure were calculated.

$$W_{building}= W_{super}+ W_{foundation} \quad (1)$$

According to Archimedes,

$$W_{building}= W_{buoyancy} \quad (2)$$

$$W_{buoyancy}= \gamma_{liq}*V_{sub} \quad (3)$$

The liquefied density of soil can be determined by Equation (4) (Sumer et al., 2006),

$$\gamma_{liq}= (G_s+e_{max}) * \gamma_w/(1+e_{max}) \quad (4)$$

$$GM = (I/ V_{sub})-BG \quad (5)$$

Where $W_{building}$= Weight of the building; W_{super}= Weight of the super-structure; $W_{foundation}$= Weight of the foundation; γ_{liq}= unit weight of the liquefied soil; G_s=specific gravity of the soil grains; e_{max}= maximum void ratio of soil; e_{min} = minimum void ratio of soil; γ_{sub}=submerged volume of the foundation; GM = Meta-centric height; I= Moment of inertia of plan about vertical axis i.e. pitching; BG = Distance between centre of pressure and centre of gravity; γ_w = unit weight of water.

From the laboratory tests values of G and e_{max} were obtained and γ_{liq} was calculated from Equation (4). Substituting the value of Equation (1) in Equation (3) ¥$_{sub}$ was calculated. As we know the length of the foundation, the area of submergence was obtained from ¥$_{sub}$/length. Depending upon the shape of the foundation effective depth was calculated. From Equation (5) GM was calculated and for the foundation design, the value of GM>0 was adopted. The pictorial views of the buildings are shown in Figure 1. From the above relationship the meta-centric height in trapezoidal footing was 4.8mm and in bowl footing was 1.5mm.

Figure 1. Pictorial view of (a) rectangular (b) trapezoidal and (c) bowl shaped footing.

3 EXPERIMENTAL SETUP

Index and engineering properties of soil were obtained as shown in table 1.

Table 1. Index and engineering properties of the soil sample.

Properties	Symbol	Value
Specific gravity of soil solid	G_s	2.63
Maximum void ratio	e_{max}	0.866
Minimum void ratio	e_{min}	0.54
Cohesion	c	7.06 Kpa
Angle of internal friction	∅	34.4°
Coefficient of uniformity	C_u	2.03
Coefficient of curvature	C_c	1.52
Classification according to USCS	SP	
Mean particle size	d_{50}	0.27mm

Steel tank of size 1x1x1m was taken and was filled with predetermined weight of sand in stages of 5 cm height. 20 mm diameter bottom closed plastic pipes with perforations near the bottom were placed at the four corners of the tank for saturating the soil. The soil was filled in stages upto a height of 70 cm through rain dropping technique. Then water was added very slowly to the soil through the perforated pipes placed at the four corners of the tank. After saturating the soil in the tank, the rectangular footing was placed at the centre. The steel tank was connected to the 1-D shaker. Four accelerometers were placed at different locations like two on floors of the building frame, one on top of the footing and fourth one on the steel tank. The accelerometers were connected to a data acquisition system which stored the readings of the accelerometers at interval of 0.0001 seconds. Then the building frame was shaken at frequencies 1Hz, 2Hz, 3Hz, 4Hz, and 5Hz. The reading of acceleration and time were taken for one minute and the acceleration v/s time graphs were plotted for each accelerometer at different frequencies. After every shaking the tilt and displacement were measured. Tilt was measured from comparison of photos taken before and after shaking from a stationary point. The vertical displacement was measured from a fixed point on the top of the tank above the centre of the building. After every shaking the building frame was restored in its original position for the next shaking. Similar experiments were conducted for trapezoidal and bowl shaped footings also. Graphs were plotted for tilt and displacement at different frequencies.

4 EXPERIMENTAL RESULTS AND DISCUSSION

Dynamic tests were performed on building frames to check the stability of the foundations during liquefaction. Figures 2 to 6 show comparison of acceleration-time histories of different types of foundations at operational frequency 1Hz to 5Hz. Tables 2 to 4 show the peak acceleration (PA) at different levels of the building frames for frequencies of 1Hz to 5Hz. Figure 7 shows the comparison of PA at footing level of different shaped footings at operating frequencies from 1Hz to 5Hz. From figure 7 it can be seen that the PA of trapezoidal shaped footing is the highest at higher operating frequencies. From figures 2 to 4 it is seen that the trapezoidal and bowl foundation vibrated about the mean position during shaking and attained some stationery position at the end of shaking. It was also seen that after shaking the soil got liquefied and excess pore water pressure was dissipated in the form of accumulation of water on the top of soil surface (figure 13). The bowl shaped footing and the trapezoidal shaped footing sank in the liquefied soil but remained to its original position without any tilt as seen in figure 13. The rectangular foundation got tilted after shaking as seen in figure 14.

Figure 8 shows the comparison of PA at bottom floors of different shaped footings at 1Hz to 5Hz. From this figure it is clear that the PA of bottom floor of bowl shaped footing is higher than that of rectangular or trapezoidal shaped footings.

Figure 9 shows the comparison of PA at top floor of different shaped footings at 1Hz to 5Hz. From the figure it is seen that PA at the top floor of rectangular shaped footing is the highest of all the three types.

Figure 10 shows the comparison of PA at different levels of the building frame with rectangular shaped footing at different operating frequencies 1Hz to 5Hz. Figure 11 shows the comparison of PA at different levels of the building frame with trapezoidal shaped footing at 1Hz to 5Hz. Figure 12 shows the comparison of PA at different levels of the building frame with bowl shaped footing at 1Hz to 5Hz. Thus it is seen that the vibrations

at top floor are maximum for conventional rectangular shaped footings whereas the vibrations near the footing are maximum for nonconventional trapezoidal or bowl shaped footings. At 4Hz, the PA of at different levels for all the building frames are maximum showing that some sort of resonance occurs at this frequency.
Tilting of different foundations under different operating frequencies is shown in figure 15. It is observed that the rectangular footing tilted to 16° from the vertical axis at 5 Hz operating frequency. Although tilting was minimum for bowl and trapezoidal shaped footings but both the footings sank to the liquefied soil after vibration. The bowl shaped footing sank up to 13mm in vertical direction after shaking at 5 Hz as shown in figure 16.

Table 2. Peak Acceleration different shaped foundation at 1Hz to 5Hz.

Frequency	Rectangle	Trapezoid	Bowl
1Hz	0.0369g	0.0174g	0.0188g
2Hz	0.0587g	0.0782g	0.0793g
3Hz	0.0934g	0.1097g	0.0919g
4Hz	0.136g	0.1616g	0.1353g
5Hz	0.1189g	0.1459g	0.1166g

Table 3. Peak Acceleration of bottom floor of different shapes of foundation at 1Hz to 5Hz

Frequency	Rectangle bottom floor	Trapezoid bottom floor	Bowl bottom floor
1Hz	0.0564g	0.0296g	0.0584g
2Hz	0.0902g	0.0941g	0.1464g
3Hz	0.1201g	0.1133g	0.1374g
4Hz	0.3307g	0.2237g	0.2988g
5Hz	0.1977g	0.1611g	0.2276g

Table 4. Peak Acceleration of top floor of different shapes of foundation at 1Hz to 5Hz

Frequency	Rectangle top floor	Trapezoid top floor	Bowl top floor
1Hz	0.0918g	0.0359g	0.0619g
2Hz	0.1465g	0.1206g	0.1637g
3Hz	0.2094g	0.2045g	0.1974g
4Hz	0.5808g	0.3483g	0.3449g
5Hz	0.2771g	0.2332g	0.2474g

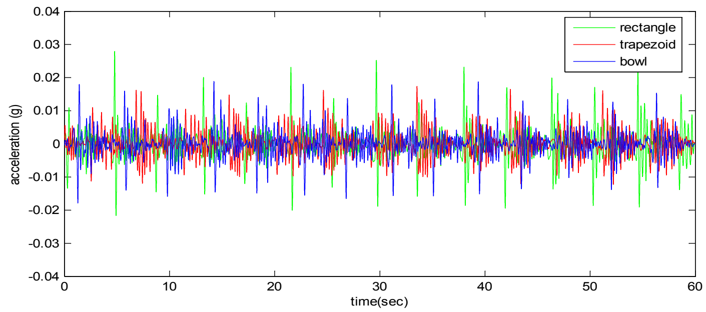

Figure 2. Acceleration v/s time graph of footings at 1Hz.

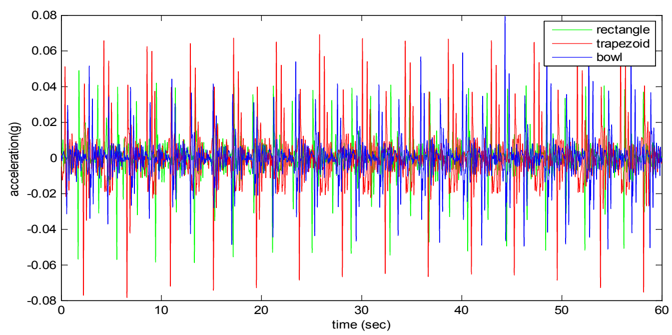

Figure 3. Acceleration v/s time graph of footings at 2Hz.

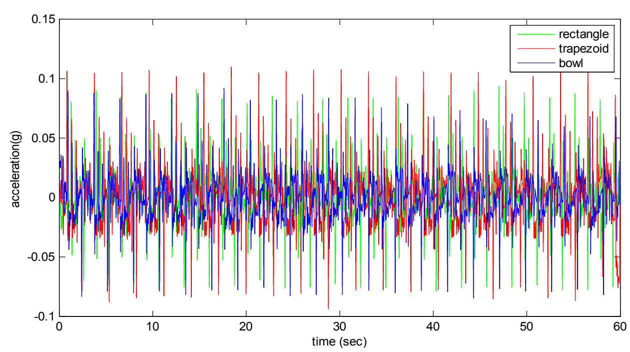

Figure 4. Acceleration v/s time graph of footings at 3Hz.

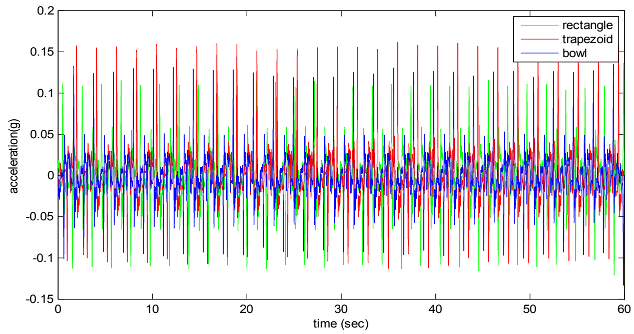

Figure 5. Acceleration v/s time graph of footings at 4Hz.

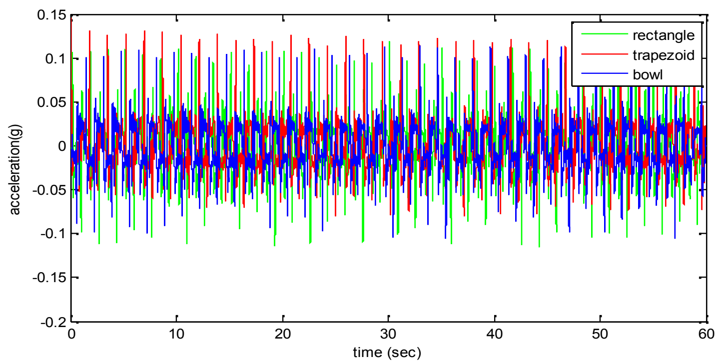

Figure 6. Acceleration v/s time graph of footings at 5Hz.

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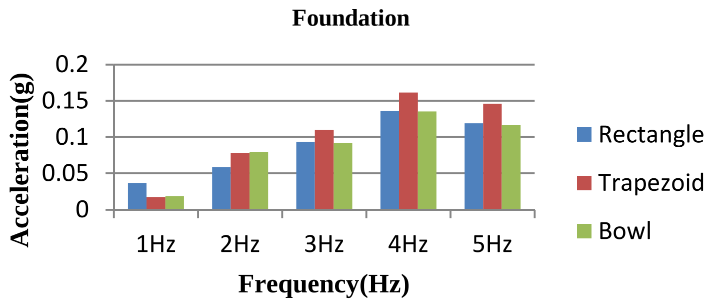

Figure 7. Comparison of Peak accelerations at footing level of different shaped footings

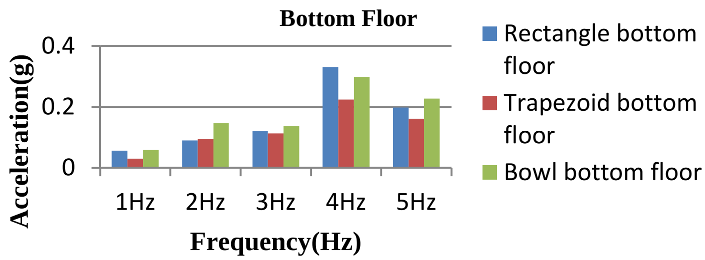

Figure 8. Comparison of Peak accelerations at bottom floor of different shaped footings at different frequencies.

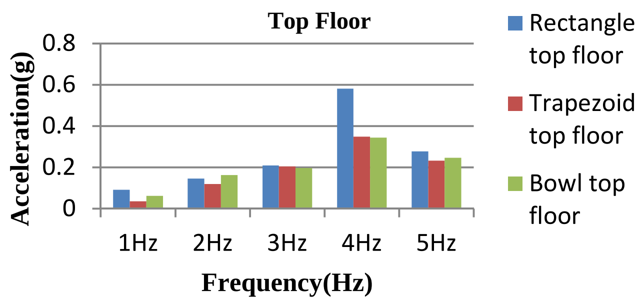

Figure 9. Comparison of Peak accelerations at top floor of different shaped footings at different frequencies.

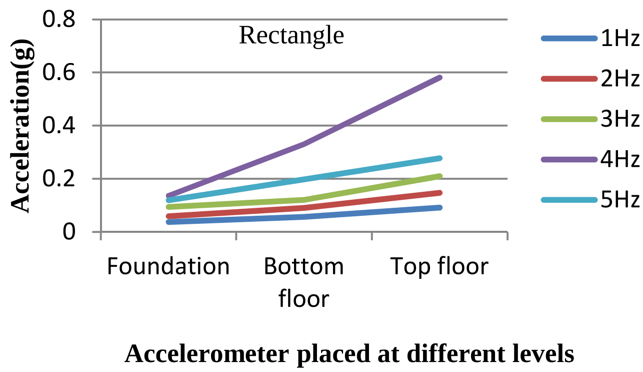

Figure 10. Comparison of Peak acceleration of rectangle foundation at different floor levels at variable frequencies.

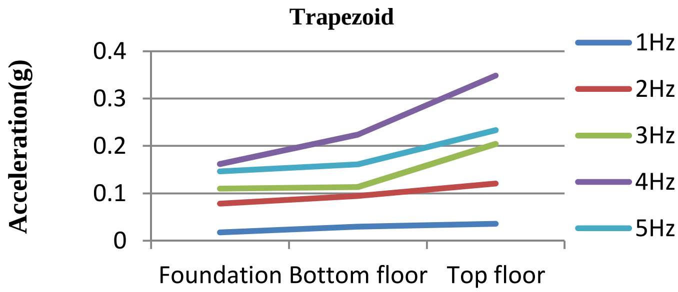

Figure 11. Comparison of Peak acceleration of trapezoidal shaped foundation at different floor levels at variable frequencies.

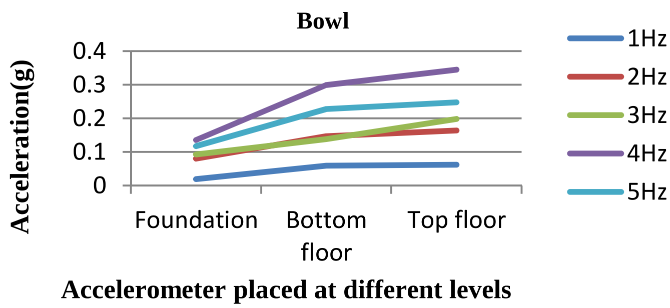

Figure 12. Comparison of Peak acceleration of bowl shaped foundation at different floor levels at variable frequencies.

Figure 13. Building on bowl shaped footing before and after liquefaction.

Figure 14. Tilt of rectangular shaped building frame after shaking.

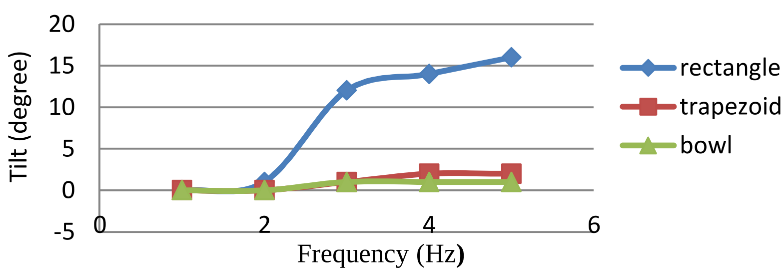

Figure 15. Comparison of tilt of different footings at different frequencies.

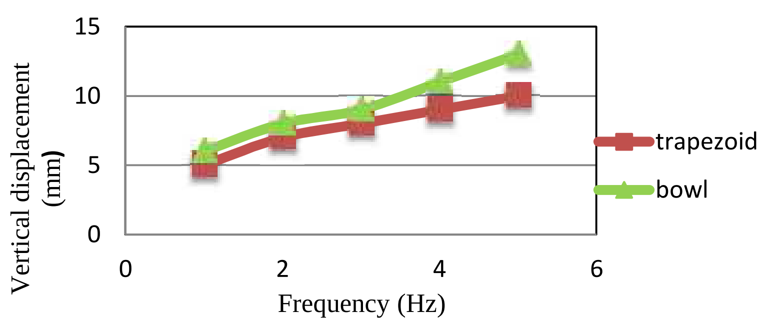

Figure 16. Comparison of vertical displacements of trapezoidal and bowl footings

5 CONCLUSIONS

Following conclusions are drawn from the present study:

1. Archimedes principle can be applied to a foundation system to eliminate tilting during liquefaction.
2. Out of the three shapes of footings, namely, conventional rectangular, non-conventional bowl shaped and non-conventional trapezoidal shaped, the bowl shaped one shows a minimum tilt followed by the trapezoidal shaped foundation under one dimensional shaking.
3. The peak acceleration at foundation is maximum in trapezoidal shaped foundation.
4. The peak acceleration at bottom floor is maximum in bowl shaped foundation.
5. The peak acceleration at top floor is maximum in rectangular shaped foundation.
6. The two storeyed building frames experience resonance effect at 4Hz operating frequency.
7. The bowl shaped footing shows maximum vertical sink followed by the trapezoidal shaped foundation under one dimensional shaking.

Thus the bowl shaped foundation can be used for mitigating the tilting problems during liquefaction, thereby saving life and property.

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