Effect of Saturation on Stiffness of Finite Sand Stratum Under Vertical Vibrations

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ABSTRACT

The presence of a rigid base at shallow depth increases the stiffness of the overlying soil stratum affecting the resonant frequency and the corresponding displacement amplitude of the foundation-soil system. Further, infiltration of water to such deposits makes the overlying soil to become saturated and adds to the complexity of the problem. Vertical vibration tests were conducted using model footings of different size and mass resting on the surface of finite dry and saturated sand layer of different height to width ratios underlain by rigid concrete base. The equivalent stiffness of the finite sand stratum is determined using available theoretical equations in the literature both under dry and saturated conditions using the measured values of resonant frequency and the corresponding maximum displacement amplitude. The test results revealed that the stiffness of foundation-soil system reduces due to saturation, when compared for the case of the results obtained on finite dry sand stratum, consequently reducing the resonant frequency and increasing the maximum displacement amplitude.

1. INTRODUCTION

The stiffness (or spring constant) is an important parameter required for the dynamic analysis of foundation-soil system. It can be estimated using the stiffness formulae derived from the theory of elasticity; using the elastic constants obtained from different static or dynamic testing; tables and charts correlating the sub grade modulus and stiffness obtained from small scale plate load tests subjected to repeated loading as well as small scale vibration tests. It is established that the stiffness of the underlying soil depends on several factors viz., initial static stress, contact area of the foundation base, magnitude of the dynamic stress increment, variation of shear modulus, nonhomogeneity of soil including the effect of layering and saturation. Among these factors, the study on the effect of saturation of soil and the soil nonhomogeneity on the dynamic stiffness are very scarce in literature.

The soil in natural state can occur in a state with a hard rock at shallow depth or consisting of different layers with different soil properties. Presence of a rigid rock or a hard stratum within the depth of influence of static and dynamic loading is one of the common features that occur in the natural deposits. Also, many soils exhibit an increase in shear modulus with increase in depth. Bycroft (1956) and Wartburton (1957) have studied the vertical response of a circular footing underlain by a rigid base. Gazetas and Roesset (1979) have developed a solution for the vertical response of a strip footing resting on the surface of elastic soil layer overlying a rock. Many investigators have also studied the effect of various factors on the stiffness of the underlying soil and have suggested several methods of estimating the same (Reissner 1936, Barkan 1962, Novak 1970, Prakash and Puri 1981, Sridharan and Nagendra 1981, Gazetas 1983, Nii 1987, Baidya 1992, Baidya and Sridharan 2002). Baidya and Muralikrishna (2001) presented an expression for equivalent stiffness for the stratum underlain by a rigid layer using lumped parameter model in a form shown in Eq.(1a) and (1b) as below:

\[ k^*_{r} = \pi G r_o \left( F \right) \left( \frac{H}{r_o} \right)^{H/2} \]  

\[ F = \left\{ \frac{(1-\mu/2)}{\tan^{-1}(H/r_o)} \right\} - 1/4 \left[ (H/r_o)^2 / (1+(H/r_o)^2 \right]^{3/2} \]  

where, \( k^*_{r} \) = equivalent stiffness for the stratum underlain by a rigid layer, \( G \) = the shear modulus of the material, \( H \) = the thickness of the finite stratum, \( r_o = \) equivalent radius of the footing, and \( F = \) non-dimensional depth factor given by.

Gazetas (1983) also presented an expression for the vertical equivalent static stiffness of a finite layer underlain by rigid layer in the form of an empirical equation derived from the
results of Kausel et al. (1974) as given below:
\[ k_{v}^* = 4Gr \left[ 1 + 1.28r_{o}/H \right]/(1-\mu) \] ..(2)
where, \( k_{v}^* \) = the vertical equivalent static stiffness, \( G \) = the shear modulus of the material, \( H \) = the thickness of the finite stratum, \( r_{o} \) = equivalent radius of the footing, \( = (A/\pi)^{0.5} \), \( \mu \) = Poisson’s ratio of soil, and \( A \) = contact area of the foundation.

It is clearly evident from the Eq. (1) and (2) that the presence of rigid bedrock at a shallow depth increases the static stiffness of the rigid surface foundation. The present investigation is aimed at, to determine the effect of saturation and location of rigid concrete base on the dynamic stiffness of foundation-soil system by conducting vertical vibration test on model footings resting on the surface of finite dry sand stratum as well as on finite saturated sand stratum underlain by rigid concrete base. Laboratory investigations by Barkan (1962) reported that the Poisson’s ratio of soil does not depend on moisture content. The saturated density of soil thus has been considered for calculation purpose along with a value of 0.33 for Poisson’s ratio, both for saturated sand and dry sand.

2. MATERIALS AND METHODS

Material Used
The sand used in the present investigation was locally available river sand, whose properties were determined as per Indian Standards and are as described in Table 1. The rigid concrete base of 300mm thickness and of M20 grade was cast and cured at the testing site which is used to simulate the presence of a rock stratum occurring in nature, the location of which is represented by different height to width ratio of the finite sand stratum. For tests on saturated sand, a network of perforated PVC pipes of 12mm diameter were made abutting the top of the rigid base and connected to a water inlet, through which water was allowed to flow in the upward direction, maintaining uniform and laminar flow conditions. Saturation was achieved by submerging the sand overnight for 12 Hours. Excess water at the surface was removed using sponge and water level in the tank was kept in flush with top surface of sand. Soil samples at different locations (both from the surface of sand as well as below the surface of sand) and at different time intervals during the experimental program were removed, to determine the degree of saturation, \( S_r \) corresponding to various height to width ratios of the compacted sand. Results of several such measurements showed that the degree of saturation achieved was well above 96%.

Test Tank
A test tank of plan size having internal dimensions 1.6 m x 1.6 m and of height 1.2 m with vertical sides simulating a test pit, was constructed at the testing site situated near the Geotechnical Engineering Laboratory of the Bangalore University Campus, using solid concrete blocks after removing the top loose soil to a depth of 300mm in the natural ground formation and compacting the soil at the site so as to minimize the relative displacements below the rigid concrete base. Based on the maximum size of the model footings used, the size of the test tank was optimized in order to minimize the boundary reflections. A small opening of about 500mm x 600mm was made on one side of the test tank to facilitate easy fixing of the flexible shaft connecting the oscillator (source of vibration mounted on the model footing) with the D.C. motor.

Table 1: Properties of Sand Used

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Particulars</th>
<th>Specific gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coefficient of curvature (Cc)</td>
<td>1.4</td>
</tr>
<tr>
<td>2</td>
<td>Grain size analysis</td>
<td>Coarse sand (%) 0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium sand (%) 60.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fine sand (%) 37.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Silt and clay (%) 1.31</td>
</tr>
<tr>
<td>3</td>
<td>Co-efficient of uniformity(Cu)</td>
<td>2.6</td>
</tr>
<tr>
<td>4</td>
<td>Coefficient of curvature(Cc)</td>
<td>1.4</td>
</tr>
<tr>
<td>5</td>
<td>Maximum Dry Density, ( (\gamma_d)_{max} \</td>
<td>18.3 kN/m³</td>
</tr>
<tr>
<td></td>
<td>Minimum Dry Density, ( (\gamma_d)_{min} \</td>
<td>14.6 kN/m³</td>
</tr>
</tbody>
</table>

Two series of reinforced model footings of square shape and of different thickness using M20 grade cement concrete were cast and cured. Table 2 shows the specification of the model footings used in the present experimental investigation. The mass of footings were so fabricated that, each series of model footings generated almost equal intensity of static contact pressure at its base so as to avoid any consequential effects of variation in contact pressure during vibration.

Table 2: Specifications of Model Footings Used

<table>
<thead>
<tr>
<th>Series Index</th>
<th>Size ([L \times B \times H])</th>
<th>Total Mass Including Oscillator Assembly ((kN))</th>
<th>Static Weight ((kN))</th>
<th>Average Static Pressure ((kN/m²))</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI(A)</td>
<td>200x200x100</td>
<td>1.276</td>
<td>3.0</td>
<td>106.9</td>
</tr>
<tr>
<td>SI(B)</td>
<td>200x200x200</td>
<td>1.408</td>
<td>1.1</td>
<td>110.0</td>
</tr>
<tr>
<td>SI(C)</td>
<td>200x200x300</td>
<td>1.693</td>
<td>1.1</td>
<td>110.8</td>
</tr>
<tr>
<td>SII(A)</td>
<td>300x300x100</td>
<td>1.431</td>
<td>3.0</td>
<td>49.23</td>
</tr>
<tr>
<td>SII(B)</td>
<td>300x300x200</td>
<td>1.739</td>
<td>52.66</td>
<td></td>
</tr>
<tr>
<td>SII(C)</td>
<td>300x300x300</td>
<td>1.861</td>
<td>54.66</td>
<td></td>
</tr>
</tbody>
</table>
Methodology

Calculated weight of sand was poured into the test tank in layers of thickness of 100 mm to maintain a uniform condition. Each layer was compacted to maintain uniform density of 17 kN/m³ so that the desired relative density of 70% was achieved. For compaction, a square steel plate of 400mm width and 10mm thickness was placed on sand and was tampered by uniformly distributed 16 blows of a 4.5 kg compaction rammer falling through a height of 457.2 mm. Several trials were made to know the unit weight $\gamma$ of the sand and the corresponding relative density ($D_r$) achieved, before starting the test. After filling sand in the test tank, the precast concrete model footing was placed concentrically and the Lazan oscillator assembly along with the static weight in the form of steel plates were placed on top of the model footing so that the whole setup acts as a single unit, with the center of gravity of whole system and that of the footing to lie in the same vertical line. A piezoelectric type vibration pickup was placed on top of the footing to measure the displacement amplitude and was connected to ‘Data Acquisition System (DAS)’ using a low noise cable provided for the purpose. The oscillator was then run slowly by the motor using the speed control unit after setting the desired force rating in the oscillator. The model footings were subjected to vertical mode of vibration at four selected force ratings of 0.016 N-sec², 0.024 N-sec², 0.032 N-sec² and 0.039 N-sec² and the thickness of sand over the rigid concrete base was varied to have height to width ratios ($H/B$) of 0.5, 1.0, 2.0 and 3.0, where $H$ is the height of sand stratum over the finite base and $B$ is the width of the model footing under consideration.

The frequency in Hertz and the corresponding amplitude of vibration were recorded at regular intervals. Sufficient time gap between two successive measurements was allowed to have a stable reading. Finally the frequency versus amplitude curves was plotted for each of the different tests. Four different force ratings were used in order to simulate different intensities of dynamic excitation. The frequency corresponding to the maximum displacement amplitude was taken as the resonant frequency. Tests were repeated under similar conditions over finite saturated sand stratum, in order to compare and contrast the effect of saturation the dynamic response of footings

3. RESULTS AND DISCUSSIONS

Using the shear Modulus $G$ corresponding to $H/B$=3.0, the equivalent stiffness of the finite saturated sand stratum has been evaluated using Eq.(1) and Eq.(2), by taking $\mu$=0.33 for saturated sand.

Effect of Mass of the Foundation

Figure (1) shows a typical variation equivalent stiffness for model footing of series SI. With increase in the mass ratio, the equivalent stiffness does not decrease significantly for a footing with higher mass ratio when compared with a footing with lower mass ratio. This is due to the fact that very little in-phase soil mass is under vibration below the higher mass ratio series of model footings because of its smaller contact area when compared with footing having lower mass ratio and larger contact area.

![Fig. 1: Variation of Equivalent Stiffness with Mass-Ratio of Series SI Resting on Finite Saturated Sand Stratum](image1)

Influence of Contact Area of the Footing

Figure 2 shows the influence of contact area of the footing on the equivalent stiffness of the foundation-soil system with increase in $H/B$ ratio for both the cases. It can be seen that, larger the contact area, higher will be the equivalent stiffness at a constant $H/B$ ratio and at constant force rating applied-for both the cases of finite dry sand and finite saturated sand.

![Fig. 2: Variation of Equivalent Stiffness of Series SI and SII at a Constant Force Rating of 0.016 N-sec²](image2)

The contact area and the force rating significantly affect the equivalent stiffness of the FSS. Figures (3) and (4) substantiate clearly the above mentioned facts. For a given $H/B$ ratio and force rating, equivalent stiffness corresponding to model footing resting on finite dry sand stratum is larger than the one resting on finite saturated sand stratum. Lower the $H/B$ ratio, higher is the equivalent stiffness obtained for both the cases of finite dry sand and finite saturated sand stratum.

Hence, the analysis of dynamic response of the foundations requires a realistic estimation of equivalent stiffness by considering the various factors that affect it, including the soil nonhomogeneity and the effect of soil moisture.
4. CONCLUSIONS

The results of the experimental study and comparison of results between model footings resting on finite dry sand stratum and finite saturated sand stratum underlain by the rigid concrete base showed that:

i. The equivalent stiffness of finite dry sand stratum is comparatively higher than that obtained for finite saturated sand stratum.

ii. The effect of saturation is thus to reduce the stiffness, correspondingly decreasing the resonant frequency of finite saturated sand stratum.

iii. Increase in the contact area increases the equivalent stiffness corresponding to a constant H/B ratio and at constant force rating applied for both the cases of finite dry sand and finite saturated sand.

iv. Increase in force rating decreases the equivalent stiffness for both the cases.

REFERENCES


