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Dynamic Behavior of Fibre Reinforced Sand

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Abstract—Fibre reinforcement has more or less established itself as a composite civil engineering material having significant effect in improving the static strength characteristics of granular soil like sand. However, the dynamic behavior of fibre reinforced sand as far as large scale model tests are concerned is rarely discussed in the literature. The present study illustrates the effect of randomly distributed polypropylene fibrillated fibre reinforcement in modifying the dynamic characteristics of locally available sand (Solani River, Roorkee, India). Block resonance tests (BRT) for low-medium strain levels and Cyclic plate load tests (CPLT) for high strain level have been conducted both on un-reinforced and fibre reinforced sand in the laboratory to study its dynamic characteristics. In BRT, the magnitude of resonant frequency and maximum amplitude of vibration of the test block have been recorded at different excitation levels in vertical mode of vibration at a particular percentage of fiber content, thus establishing the effect of dynamic loading or in turn the effect of strain level. The dynamic response was evaluated in terms of coefficient of elastic uniform compression and damping ratio. Where as, in CPLT, settlement and pressure values have been recorded to calculate coefficient of elastic uniform compression at two different strain levels. It was observed that there was no significant effect of fibre reinforcement on the dynamic behavior of sand contrary to the static loading condition.

Keywords—Fibre reinforcement, Block resonance tests, Cyclic plate load tests, Coefficient of elastic uniform compression, Damping ratio.

I. Introduction

Soil reinforcement is one of the techniques of ground improvement and reinforcing materials of various kinds both natural as well as synthetic are in vogue. In this context, randomly distributed fibre reinforced sand (RDFS) i.e. sand reinforced with relatively extensible inclusions (popularly known as ply soil) has opened up new avenues of research and been successfully used as an artificial composite fill material providing solutions to many geotechnical engineering problems satisfactorily. Of course, a number of researchers have studied and substantially contributed in the field of fibre reinforcement in sand, but such studies has been mainly confined to the static loading conditions only. This warrants understanding of the dynamic behaviour of fibre reinforced sand, which other wisely has proved to be a very effective composite material in improving the static strength characteristics of soil. But a very few studies has been undertaken in this direction which primarily comprise of small scale laboratory models tests only viz. Maher and Woods [6] performed laboratory resonant column and torsional shear tests to determine the dynamic response of randomly distributed fibre reinforced sand, Al-Refaei and Al-Suhaibani [1] undertook a study to investigate the resilient behaviour of polypropylene fibre reinforced sand, Li and Ding [5] have conducted experimental investigations and modelling of non-linear elasticity of fibre reinforced soil under cyclic loading at small strains and Consoli et al, [2] have carried out high pressure isotropic compression tests on samples of uniform fine sand at different initial specific volumes reinforced with randomly distributed polypropylene fibres. However, studies of dynamic characteristics by using large scale model tests like cyclic plate load tests (which provide a simple approach for evaluation of elastic constants) or block resonance tests (which simulate more closely field condition for machine foundation) has rarely been discussed in literature. The main objective of the present study is to evaluate the response parameters and dynamic elastic constants of locally available river sand (Solani river, Roorkee, India) with fibre reinforcement using these large scale model tests at a relative density of 30%.

Block resonance tests have been conducted in the laboratory masonry tanks filled with both un-reinforced and fiber reinforced sand at different excitation levels at a particular fiber content (0.5%) for evaluation at low-medium strain level. The cyclic plate load tests have been performed in a laboratory steel tank at the same fiber content for evaluation at high strain levels. In both the cases, similar zone of reinforcement (with respect to projection beyond and depth below the loaded area) has been adopted for the shake of comparison.

I. Test Programme

A. Test Materials

The sand from the local Solani river was used for all the tests and the fibre used was fibrillated polypropylene fibres manufactured by Propex concrete systems, USA. The properties of the sand in un-reinforced condition and as sand fibre composite was determined by standard dry sieving as well as triaxial test as per relevant Indian Standards (Table I&II) & (Fig.1). The salient features and properties of fibres are listed in Table III and Fig.2 shows the view of the fibres. The length of the fibre used was 40mm and fibrillated type, because in literature [7] fibrillated
fibres in the range of 40-60mm length have been shown to
give better results as reinforcement and longer length of
fibre poses difficulty in mixing.

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>Property/Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Soil classification</td>
<td>SP(Poorly graded sand)</td>
</tr>
<tr>
<td>2.</td>
<td>Effective size (Dn)</td>
<td>0.165mm</td>
</tr>
<tr>
<td>3.</td>
<td>Average Grain Size (D50)</td>
<td>0.27mm</td>
</tr>
<tr>
<td>4.</td>
<td>Coefficient of Uniformity (Cu)</td>
<td>1.8</td>
</tr>
<tr>
<td>5.</td>
<td>Coefficient of Curvature (Cc)</td>
<td>1.09</td>
</tr>
<tr>
<td>6.</td>
<td>Mean Specific Gravity(G_s)</td>
<td>2.63</td>
</tr>
<tr>
<td>7.</td>
<td>Minimum voids ratio(e_min)</td>
<td>0.536</td>
</tr>
<tr>
<td>8.</td>
<td>Maximum voids ratio(e_max)</td>
<td>0.865</td>
</tr>
<tr>
<td>9.</td>
<td>Angle of internal friction(Φ) at Φ = 30°</td>
<td>32°</td>
</tr>
</tbody>
</table>

Table : Physical & Mechanical properties of Solani Sand

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>% fibre content</th>
<th>Cohesion c</th>
<th>Angle of internal friction Φ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>0.5</td>
<td>43 kN/m²</td>
<td>38.04°</td>
</tr>
<tr>
<td>2.</td>
<td>1.0</td>
<td>104 kN/m²</td>
<td>38.04°</td>
</tr>
<tr>
<td>3.</td>
<td>0.5</td>
<td>120 kN/m²</td>
<td>38.04°</td>
</tr>
<tr>
<td>4.</td>
<td>0.5</td>
<td>104 kN/m²</td>
<td>38.04°</td>
</tr>
</tbody>
</table>

TABLE II. Shear Parameters of Sand Fibre Composite

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Particulars</th>
<th>Description/Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Material</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>2.</td>
<td>Type</td>
<td>Fibrillated</td>
</tr>
<tr>
<td>3.</td>
<td>Shape</td>
<td>Flat-narrow</td>
</tr>
<tr>
<td>4.</td>
<td>Colour</td>
<td>White</td>
</tr>
<tr>
<td>5.</td>
<td>Sp.Gravity</td>
<td>0.91</td>
</tr>
<tr>
<td>6.</td>
<td>Tensile Strength</td>
<td>4.55 x 10^5 kPa</td>
</tr>
<tr>
<td>7.</td>
<td>Youngs Modulus</td>
<td>48.26 x 10^5 kPa</td>
</tr>
<tr>
<td>8.</td>
<td>Elongation at break</td>
<td>20%</td>
</tr>
<tr>
<td>9.</td>
<td>Length Evaluated</td>
<td>40 mm</td>
</tr>
</tbody>
</table>

Table III. Properties of Fibre Used As Reinforcement

B. Test Specimens

All the tests (both reinforced and un-reinforced) were performed at the relative density of 30% to evaluate the effect of fibre reinforcement as it is more effective in loose state. The fibre reinforced specimen was prepared by spreading sand and calculated quantity of fibre (at a fibre content of f = 0.5%) on the floor and hand mixing the two so as to provide a uniform mix. The sand or the sand fibre composite was deposited inside test tanks in layers of small thickness. Aluminium frame partitions were used to provide RDFS in restricted zones within which the composite materials were placed and compacted to the required density after which the partitions were gradually taken out.

Fig 1. Grain Size Distribution Curve for Solani sand

Fig 2. View of Fibrillated Polypropylene Fibres

C. Test Set-up and procedure

Block resonance tests-The block resonance tests were performed in a laboratory masonry tank of 1.6m x 1.2m x 1.2m with the provision of chain pulley arrangement for lifting the test block assembly. Forced vibration tests were conducted by exciting the test block (made up of M20 grade of concrete of size 800mm x 400mm x 400mm) by a mechanical oscillator (1800 kgf capacity) run by D.C. motor (3 H.P.) and the frequency and the amplitude of vibration were measured by acceleration pick ups (TML make, 2g capacity) suitably mounted on blocks and recorded through NI DAQ data acquisition system. The force level of excitation was varied by varying the eccentricity settings of the oscillator and for each time, the block was placed over freshly prepared specimen of sand or RDFS by lifting the block-oscillator-motor assembly. The tests were conducted as per I.S. 5249:1992. The test set up is shown in Fig. 3.
Cyclic plate load tests- A rigid steel tank of size 1.2m x 1.2m x 0.6m fabricated under an elevation adjustable loading frame of 100 kN capacity and a mechanical jack was used for performing cyclic plate load tests. The tests were performed on prepared sand or RDFS sample with a steel square footing of size 200mm x 200mm x 25mm thick machined to smooth faces. The load on the test footing was applied by the mechanical jack and measured through calibrated proving rings of required capacity fitted with plunger through ball and socket arrangement. The settlement of the test footing was measured by four dial gauges mounted on vertical studs fixed to the corners of the plate. The top of the sand or RDFS sample was properly levelled on which the footing was placed in position for testing and the load was applied in increments and released by rotating the handle of the jack. The tests were conducted as per the I.S. 1888:1982[3] & I.S. 5249:1992[4]. The test set up is shown in Fig. 4.

Fig 3. Details of Test Set up for Block Resonance Test

D. Tests performed

Block resonance tests- Vertical vibration tests were performed on sand sample without and with fibre reinforcement varying parameters like force level (which in turn implies the strain level) by three settings of eccentricity values of oscillator (\( \varepsilon = 7.5^\circ, 15^\circ, 22.5^\circ \)). Fibre reinforcement were provided in a restricted zone below the test block such that projection of the reinforced zone beyond edges of the block were B/2 and the depth of reinforcement below the block = B, where B= width of the test block. This dimension of reinforcement zone was selected from the consideration of effective stress bulb below the test block. Thus in total six number of block resonance tests were conducted at low-medium strain level.

Cyclic plate load tests- Cyclic plate load tests were carried out on a 200mm square footing at the relative density of 30% on both un-reinforced and fibre reinforced sand. In this case also a similar zone of reinforcement was provided below the test footing (steel plate) such that the projection of reinforced zone was equal to half the width of the footing and the depth of reinforcement equal to width of the test block. Thus in total two number of cyclic plate load tests were performed at high strain level.

III. Experimental Observation

A. Block resonance test-The test data i.e. values of frequencies and amplitudes recorded from the tests were plotted in the form of amplitude vs. frequency graphs from which the resonant frequency and the corresponding maximum amplitude values were determined as shown in the Fig. 5(a&b) & Table-IV.
TABLE IV. ANALYSIS OF VERTICAL RESONANCE TEST DATA

B. Cyclic plate load tests-

From the test data i.e. values of pressure and settlement recorded both during compression and rebound phase of the tests were plotted in the form of pressure vs. settlement curves [Fig. 6(a&b)] and subsequently as pressure vs. total settlement curves [Fig. 7(a&b)] and pressure vs. elastic settlement curves [Fig. 8(a&b)]. From the pressure vs. total settlement plots, the ultimate bearing capacity and the corresponding settlements were noted.

I. ANALYSIS OF RESULTS AND DISCUSSIONS

The results of the experiments were analysed to evaluate relevant dynamic properties/parameters such as coefficient of elastic uniform compression \( C_u \) and damping ratio \( \zeta \) of un-reinforced as well as fibre reinforced sand.

A. Block Resonance Tests

The damping ratio was calculated by the band width method as applicable for frequency dependant excitation for forced vibration case and the values of coefficient of elastic uniform compression was calculated from the formula

\[
C_u = 4\zeta^2 f_{nd}^2 (M/A)
\]

from the known values of \( f_{nd} \), \( M \), and \( A \), where \( f_{nd} \) = damped natural frequency, \( M \) = mass of block, oscillator and motor, \( A \) = base area of the block. The confining pressure correction and area correction (for a pressure of 10 kN/sqm and area of 10 sqm) have been applied for standard reporting as \( C_{10/10} \). The stain level was calculated by dividing the maximum amplitude by the width of the test block.
It is observed from the plots and tables that there is slight decrease in resonant frequency and increase in maximum amplitude values with the increase in strain level for both un-reinforced and reinforced sand. It indicates softening behaviour with the increase of strain level. Again from Table IV, the damping ratio \( \dot{i} \) was found to increase with the strain level both for un-reinforced and fibre reinforced sand. The rate of increase of damping ratio with strain level is less for reinforced sand than for the un-reinforced sand. However, both for un-reinforced and fibre reinforced sand, as the strain level increases, the value of \( C_u \) decreases.

With the introduction of reinforcement, the resonant frequency decreases and maximum amplitude values increases in comparison to un-reinforced sand (Table IV). For un-reinforced sand \( (f_c=0\%) \), at the eccentricity values of \( \dot{e} = 7.5^\circ, 15^\circ \) and \( 22.5^\circ \), the values of damping ratio were 0.082, 0.095 and 0.110 respectively. But due to the 0.5% reinforcement of zone dimension \((L+B) \times 2B \times B\), the values of damping ratio were 0.080, 0.089 and 0.107. Thus it is evident that the effect of reinforcement is to decrease the damping ratio but the decrease is not very significant. This may be attributed to the slippage of sand particles or less friction at the surface of fibres due to the effect of vibration.

Due to 0.5% reinforcement, the values of \( C_{u10/10} \) decreases from \( 1.419 \times 10^4 \) to \( 1.379 \times 10^4 \), \( 1.289 \times 10^4 \) to \( 1.183 \), and \( 1.189 \times 10^4 \) to \( 1.075 \times 10^4 \) at the eccentricity level of \( \dot{e} = 7.5^\circ, 15^\circ \) and \( 22.5^\circ \) respectively. Therefore, the effect of reinforcement is to reduce the value of \( C_u \) which may be attributed to the low modulus of fibre material used for the reinforcement.

### A. Cyclic plate load tests

Since the pressure settlement curves show a continuously increasing gradient without indicating any clear-cut failure point, the ultimate bearing capacity was obtained as the load causing a settlement of 10% of footing width. The slope of the pressure vs. elastic settlement plots gives the coefficient of elastic uniform compression \( C_u \), which was corrected for a standard value \( C_{u10/10} \) of confining pressure of 10kN/sqm and area of 10 sqm. Strain level was calculated by dividing the settlement by the width of the test plate/footing.

The ultimate bearing capacity of the un-reinforced sand was 57 kN/sqm corresponding to the settlement of 20mm [Fig. 7(a)]. When the sand is reinforced with 0.5% fibre of zone dimension \((2B \times 2B \times B)\), the ultimate bearing capacity was found to be 128 kN/sqm and the settlement corresponding to the ultimate bearing capacity of un-reinforced sand is 13.3mm [Fig. 7(b)], thus indicating an increase in bearing capacity by 2.25 times and decrease in settlement by 0.34 times. The corresponding strain levels were \( 2.05 \times 10^{-3} \) and \( 5.025 \times 10^{-3} \) respectively. Due to 0.5% reinforcement the \( C_u \) values decreased from \( 100.26 \times 10^3 \) kN/cum for un-reinforced sand [Fig. 8(a)] to \( 93.09 \times 10^3 \) kN/cum for fibre reinforced sand [Fig. 8(b)]. Thus the value of \( C_u \) decreases with the reinforcement. This could again be attributed to the low modulus of the fibre material.

Again after area and confining pressure correction for standard reporting (Table V), for un-reinforced sand the values of \( C_{u10/10} \) are \( 0.802 \times 10^4 \) kN/m\(^3\) and \( 0.522 \times 10^4 \) kN/m\(^3\) at strain levels of \( 1 \times 10^{-3} \) and \( 3 \times 10^{-3} \) respectively which after reinforcing with 0.5% fibre (of zone dimension \( 2B \times 2B \times B \) i.e. projection of \( B/2 \) beyond the edges of the test footing and depth equal to the width of the test footing) the values of \( C_{u10/10} \) are \( 0.797 \times 10^4 \) kN/m\(^3\) and \( 0.519 \times 10^4 \) kN/m\(^3\) at the corresponding strain levels. Thus the values of \( C_{u10/10} \) do not vary appreciably for the range of strain levels considered and the decrease in the value of the coefficient of elastic uniform compression is further less at higher strain levels.

### V. CONCLUSIONS

The major conclusions based on this study can be summarised as follows:-

- With fibre reinforcement, the resonant frequency decreases and maximum amplitude increases.
- Both the damping ratio \( \dot{i} \) and the coefficient of elastic uniform compression \( C_u \) decreases with the introduction of fibre reinforcement but this decrease is not significant.
- The static bearing capacity increases and the settlement values decreases by fibre reinforcement.
- Strain level has a decreasing effect on the value of \( C_u \), but this is not appreciable.

Therefore, in seismically active zones and for the structures likely to be subjected to vibrations, the RDFS is to be cautiously and judiciously used taking into consideration the increase in amplitude or decrease of \( C_u \) values after weighing against the improvement of performance in static case.
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