Settlement of a Square Footing on Dry Sand Bed Reinforced with Stone Columns under Seismic Conditions: Effect of Frequency

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Abstract. Effect of frequency of input motion on settlement behaviour of a square footing on the sand bed with stone columns as inclusion has been studied by means of an experimental study. A model of reinforced dry sand bed using a large laminar shear box on the shaking table has been developed. The laminar box has inner dimensions as 1000 mm × 1000 mm × 1000 mm (length × width × depth) and consists of 23 hollow aluminum layers. These layers are placed over one another with linear roller bearings between them allowing the relative motion of the layers. The shaking table facility has only horizontal degree of freedom for simulating the motion associated with seismic vibrations. Frequency of input motion has been found to have significant influence on the settlement of the footing. It has been observed that for unreinforced case, i.e., without provision of stone columns, the slope of displacement vs. time curve changes drastically along with the magnitude of settlement with reduction in the frequency of input motion. In case of few tests on reinforced conditions, the reduction in settlement has been found to be of the order of about 62% as frequency changes from 1.73 Hz to 1.23 Hz.

Keywords: Laminar box, horizontal motion, shaking table, stone columns.

1 Introduction

These days, use of stone columns is not new to improve the ground and this technique finds application in various areas such as roads and highways, railways, ports and airports, storage tanks, chemical plants, land reclamations, and residential buildings. Although these are mainly adopted in case of saturated cohesive soils, however, few studies also mention about their effectiveness in densification of loose sands. Raju and Daramalinggam [1] studied different ground improvement techniques and their suitability for different soil conditions. Usefulness of the ground treatment with stone columns were illustrated for improvement in load carrying capacity and reduction in settlement of foundations for most of the structures. Lot of literature is available pertaining to the foundations on stone column treated ground [2-9]. However, very few studies dealt with the performance of footings on stone columns treated ground under the dynamic loadings. Some of such studies include Adalier [10], Chen et al. [11], Krishna et al. [12], Bouassida and Hazzar [13], Han [14], Ashour [15], Fahmi et al. [16]. Most of these studies dealt with cyclic loading and used rigid tank for preparation of the physical model of footings on reinforced beds. Rigid tanks have related issues such as boundary effects and side friction between soil and the tank. Some of the experiments have been conducted using laminar box by Maheshwari et al. [17]. However, the current work focuses on the effect of frequency of input motion on the response of a square footing resting on dry sand bed with stone columns inclusion.

2 Materials and method

2.1 Experimental set-up

A shaking table facility with only horizontal degree of freedom has been developed in the Geotechnical Engineering laboratory of IIT Roorkee, in order to simulate the seismic excitation. For varying the frequency of the input motion, an arrangement has been manufactured which could simulate three values of frequency viz. 1.23, 1.5 and 1.73 Hz. The payload capacity of the developed table is 8 t and it can simulate the acceleration range from 0.05g to 1g. The facility can have maximum displacement in horizontal direction as ± 75 mm.

In order to prepare the model of sand bed, a laminar box is preferred over the rigid tank to overcome the problems of boundary effects and side friction. The box has 23 aluminum layers separated by roller bearings facilitating the relative motion between the layers. The set-up has been depicted in Fig. 1.

2.2 Instrumentation

Physical models of footing on dry sand bed with stone columns inclusion have been prepared inside the laminar box and to measure the vertical settlement of the footing, a displacement transducer has been used. An arrangement of slider and roller has been designed to monitor the vertical settlement under horizontal motion and the same has been mounted on the footing. A data acquisition system with 10 channels has been used to record the settlement. This could sample at a sampling speed of 1000 samples/sec.

2.3 Materials used

Poorly graded sand has been used to prepare the sand bed while well graded stones of sizes between 4.75 mm to 10 mm have been adopted for making the stone columns. The sand has following index properties: Specific gravity: 2.57; D_{50}: 0.28 mm; maximum and minimum unit weight: 16.43 & 13.82 kN/m^3, respectively.

Fig. 1. Developed facility of shaking table with laminar box

2.4 Model preparation and testing procedure

The size of the footing has been taken as 300 mm and all the models have plan dimensions as 1000 mm × 1000 mm. Extent of treatment by stone columns of 50 mm diameter has been kept as 800 mm. After placing the aluminum frames up to 200 mm height, a polythene sheet has been placed to the inner side of the box so that the sand filled inside the box does not flow from the gap between the two frames. The sand has been filled with the desired relative densities. For the construction of stone columns, help of PVC pipes has been taken. Stone columns have been installed in triangular fashion and filled in these pipes with unit weight of 19.62 kN/m^3 in three layers. The pipes have been withdrawn slowly after placement of the stone layer. This procedure has been repeated till the complete bed was constructed. The loading has been applied using dead weights through the square plate. The model has been subjected to the horizontal motion for 30 sec and vertical settlement-time history has been recorded.

2.5 Law of similitude

Tests have been conducted at 1*g* on the models prepared on reduced scale and the similitude law as proposed by Iai [18] has been adopted with geometrical scale factor of 10.

3 Results and Discussion

The chosen input parameters for studying the effect of frequency of input motion on settlement response of a square footing are as follows: peak ground acceleration (PGA): 0.2*g* & 0.3*g*; frequency: 1.23, 1.5, & 1.73 Hz; spacing to diameter ratio of stone columns: 2, 2.5, & 3; relative density (*RD*) of sand bed: 30% and 50%; applied vertical load: 75, & 90 kg.

The vertical settlements are only because of horizontal motion and initial settlement due to static vertical load has not been included.

Figure 2 depicts the influence of frequency on settlement response of square footing for *d* = 50 mm, PGA= 0.3*g*, *Q* =75 kg and *s/d* = 2.5. Both the values of relative densities of 30% and 50% have been considered and tests have been conducted at three values of frequency (1.23, 1.5 and 1.73 Hz). For a relative density of 30%, the final vertical settlement has been found to reduce by 36% as frequency reduces from 1.73 Hz to 1.23 Hz. However, corresponding reduction of about 7% has been observed for 50% relative density of sand bed. At higher relative density of sand bed, frequency does not show significant effect. This may be attributed to the fact that at higher relative density, the sand bed reinforced with stone columns achieves its maximum dry density in 30 s of test duration for all the values of frequencies and therefore not much effect of frequency is observed. However, at lower value of relative density, the frequency of input motion significantly affects the settlement response of the footing.

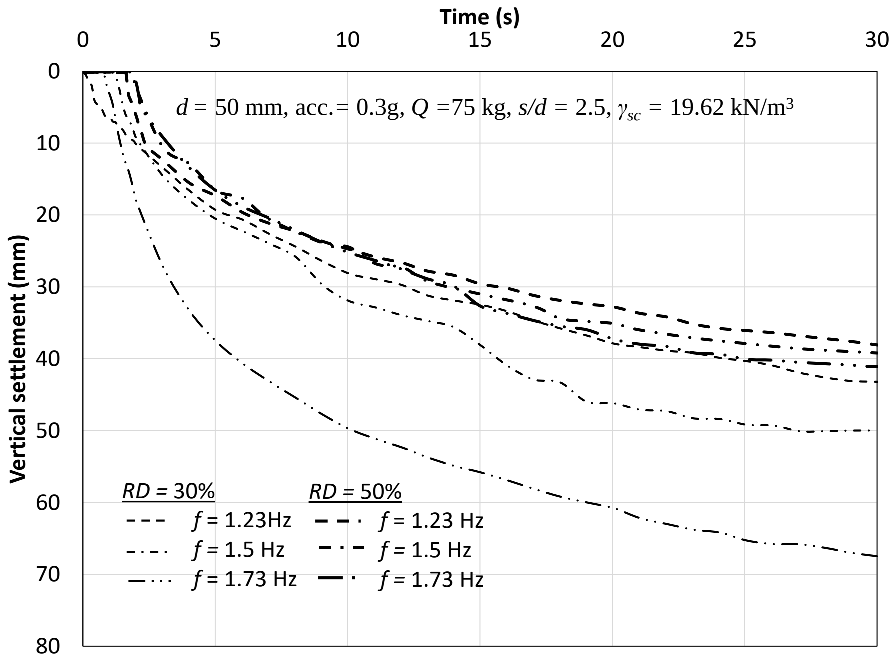

Fig. 2. Influence of frequency for both values of relative density

Further, few typical results pertaining to two limiting values of frequency have been reported to show the influence of frequency on response of footing under seismic conditions. Figure 4 shows the effect of frequency on settlement response of footing for applied load level of 75 kg. The PGA and relative density has been considered as 0.2*g* and 50% respectively. It is to be noted that for unreinforced case, i.e., without provision of stone columns, the slope of displacement vs. time curve changes drastically along with the magnitude of settlement with reduction in the frequency of input motion. A reduction in frequency of input motion results into reduction of vertical settlement of the footing which has been found to be 62%, 24%, 41% and 44% for unreinforced case, *s/d* equals to 2, 2.5 and 3 respectively.

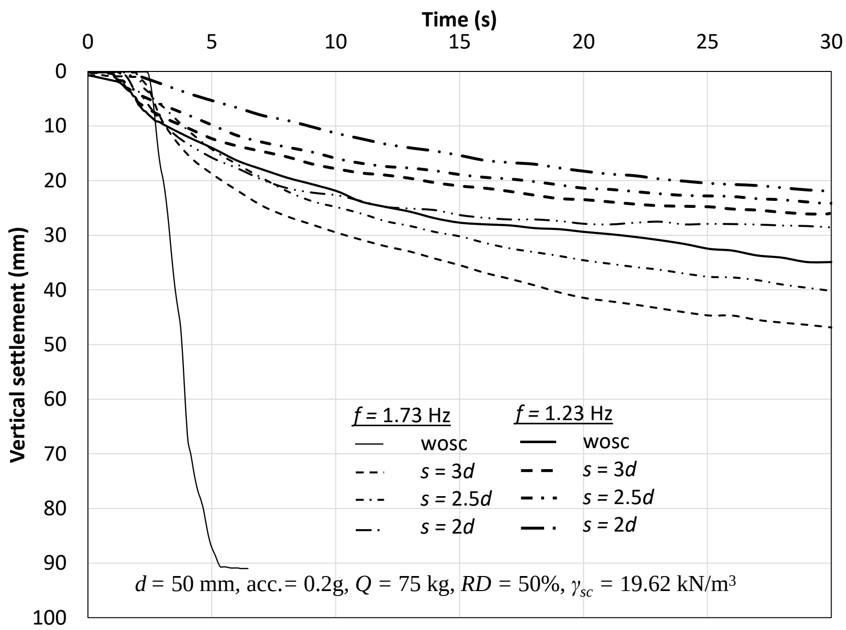

Fig. 3. Influence of frequency: *RD* = 50%; applied load = 75 kg; PGA = 0.2*g*

The effect for higher value of applied load of 90 kg has been shown in Fig. 4 and similar trend has been observed. Reduction in vertical settlement of the footing corresponding to reduction in frequency from 1.73 Hz to 1.23 Hz has been observed to be 44% for both *s/d* equals to 2, 2.5. The corresponding reduction for unreinforced case and for *s/d* = 3 has been found to be 38% and 55% respectively.

The corresponding plots exhibiting the influence of frequency on settlement of footing for lower relative density of 30% have been shown in Figs. 5 and 6 for applied loads of 75 and 90 kg respectively. Similar pattern of results has been obtained. Fig. 5 shows a reduction of about 28%, 34% and 41% for *s/d* values of 2, 2.5 and 3 respectively corresponding to 75 kg of applied load level. When the load level is increased to 90 kg, the corresponding reduction has been observed to vary between 51% and 56% for different configurations of stone columns (Fig. 6).

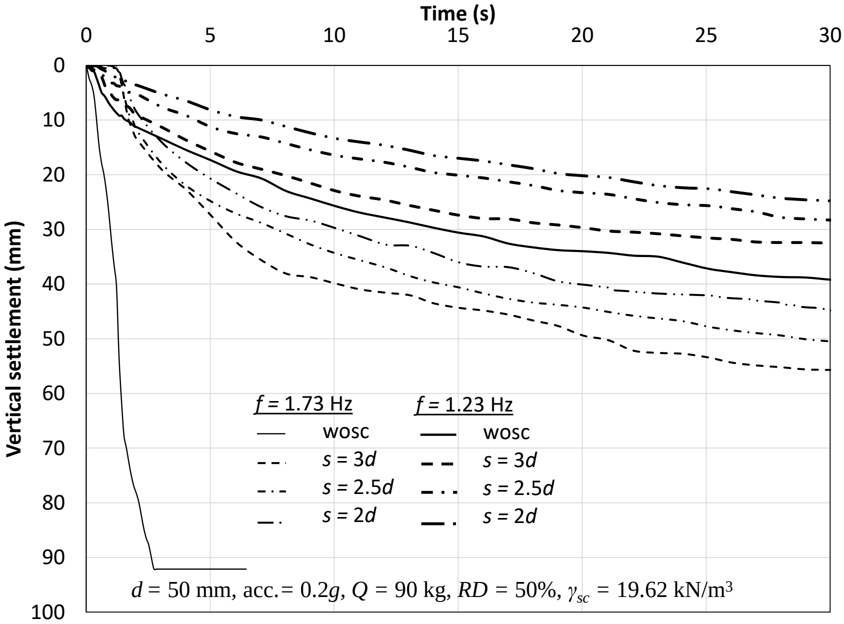

Fig. 4. Influence of frequency: *RD* = 50%; applied load = 90 kg; PGA = 0.2*g*

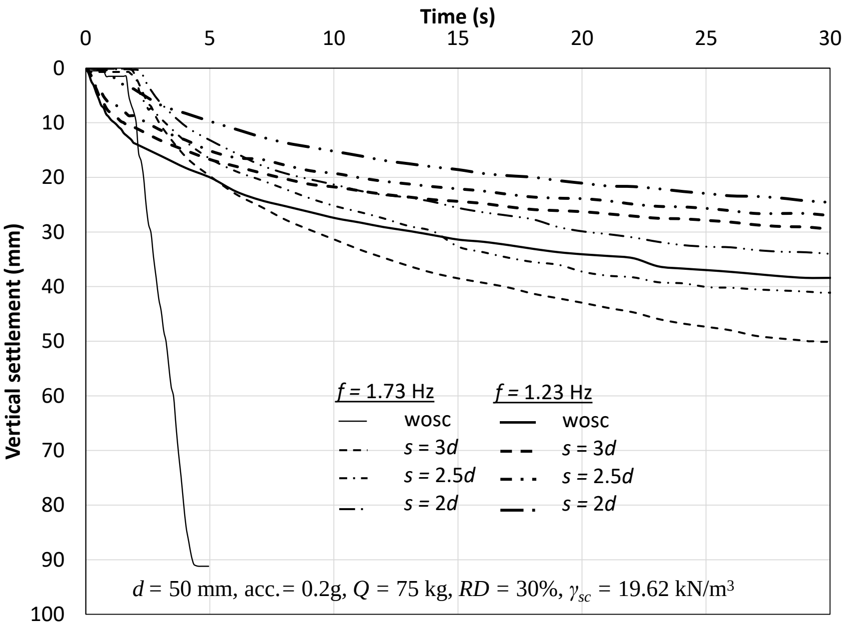

Fig. 5. Influence of frequency: *RD* = 30%; applied load = 75 kg; PGA = 0.2*g*

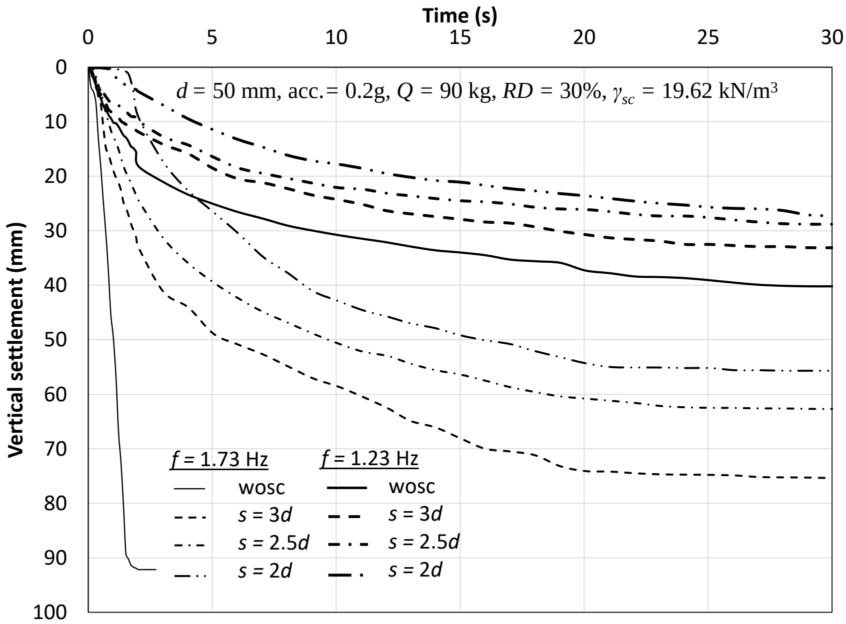

Fig. 6. Influence of frequency: *RD* = 30%; applied load = 90 kg; PGA = 0.2*g*

The effect of frequency of input motion on settlement response of footing has been shown in Figs. 7 and 8 for applied load of 75 kg and 90 kg respectively. The relative density for these tests has been considered as 50% and the tests have been conducted at PGA of 0.3*g*. For 75 kg load level, the settlement at 30 s has been found to reduce by about 11%, 7% and 18% for *s/d* values of 2, 2.5 and 3 respectively (Fig. 7) as the frequency reduces from 1.73 Hz to 1.23 Hz. However, the corresponding reduction for 90 kg load has been found to be about 23-26% (Fig. 8).

Similarly, tests have also been conducted at 30% relative density. Other input parameters have been taken as: PGA = 0.3*g* and *d* = 50 mm. For both the load levels of 75 kg and 90 kg, the effect has been seen and shown in Figs. 9 and 10 respectively. The settlement has been observed to experience a reduction with reduction in frequency of input motion which has been found to be about 30-36% for all the three spacing of stone columns for both levels of applied load.

These figures depict that frequency has significant influence on settlement response of the footing. However, this influence has been found to be more for lower relative density.

4 Conclusions

Extensive experimental study has been undertaken to understand the effect frequency of input motion on the settlement response of a square footing placed over stone columns reinforced dry sand.

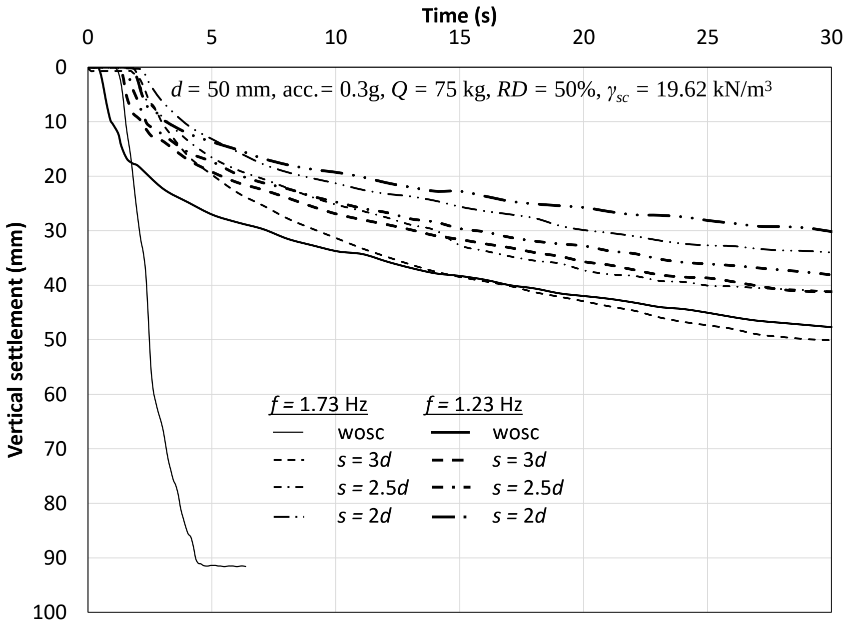

Fig. 7. Influence of frequency: *RD* = 50%; applied load = 75 kg; PGA = 0.3*g*

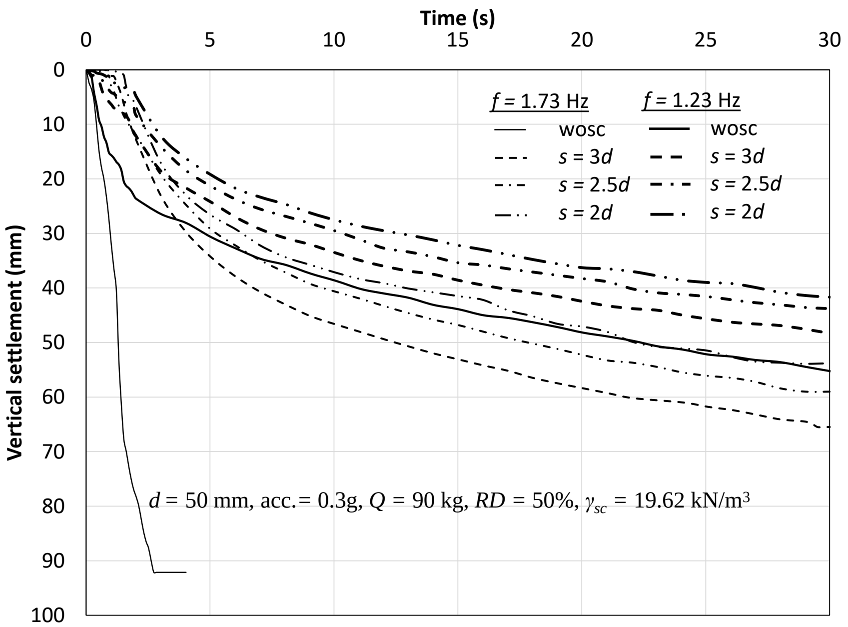

Fig. 8. Influence of frequency: *RD* = 50%; applied load = 90 kg; PGA = 0.3*g*

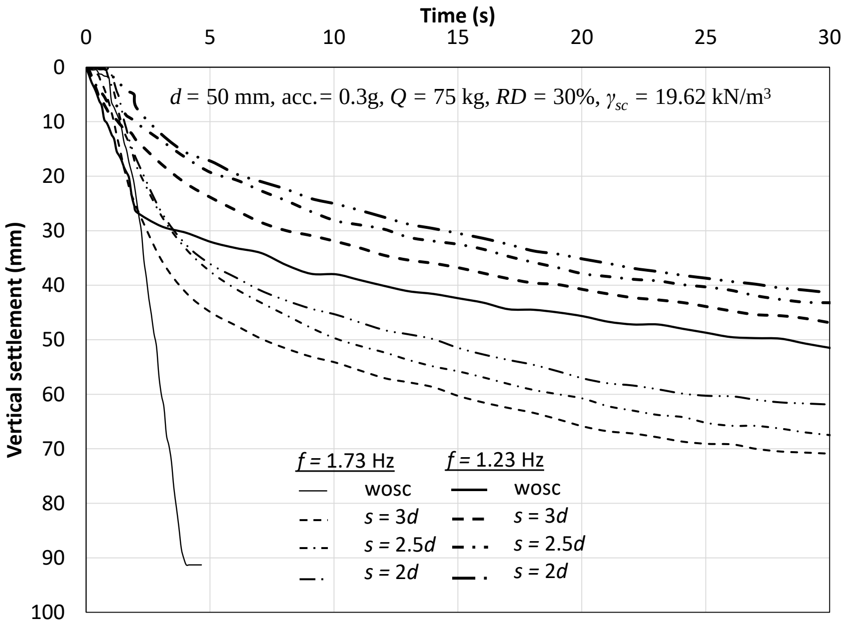

Fig. 9. Influence of frequency: *RD* = 30%; applied load = 75 kg; PGA = 0.3*g*

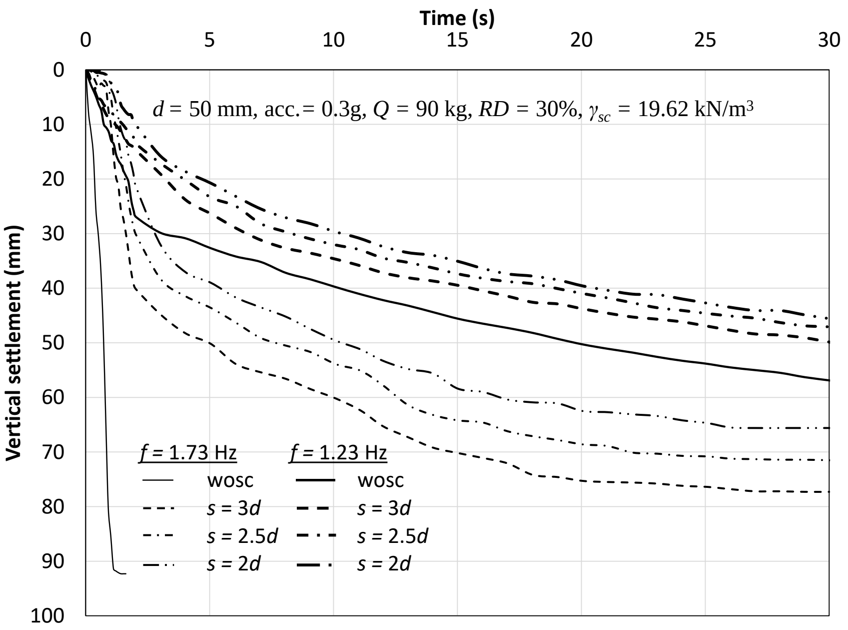

Fig. 10. Influence of frequency: *RD* = 30%; applied load = 90 kg; PGA = 0.3*g*

Frequency of input motion has been found to be significantly influencing the response of footing. It has been observed that for unreinforced case, i.e., without provision of stone columns, the slope of displacement vs. time curve changes drastically along with the magnitude of settlement with reduction in the frequency of input motion. In case of few tests on reinforced conditions, the reduction in settlement has been found to be of the order of about 62% as frequency changes from 1.73 Hz to 1.23 Hz.

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