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Experimental modal analysis of a steel frame structure with SFSI effects

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ABSTRACT

In the present study, a systematic experimental investigation has been carried out on a three-story model steel frame resting on a dry sand bed. A series of 24 tests has been done by varying parameters such as depth of embedment of the footing, relative density of soil, and vertical factor of safety (FOS_v) of the footing. The dynamic characteristics such as natural frequency, mode shapes and damping ratios of the structure are evaluated through an impact hammer test. The experimental results indicate that the fundamental natural period increases about 20% when the structure is rested on the soil bed compared to that of the fixed base structure. The flexible base period is more for the structure rested on loose sand compared to the structure on dense sand. For the structure with same FOS_v, the period increases as depth of embedment increases. Further, the flexible base period is observed to have a decreasing trend with increasing vertical factor of safety of the footing.

Introduction

It has been well established that the estimation of the dynamic characteristics of the structures excluding the soil-foundation-structure-interaction (SFSI) effect is unjustified and detrimental to the actual analysis of the physical phenomenon. Over the years, the dynamic soil-structure interaction has been investigated through analytical or numerical approaches (Bielak (1975), Stewart et al. (1999, 1999), Bhattacharya and Dutta (2004), Khalil et al. (2007), Raychowdhury (2012) etc.) and through experiments on physical and instrumented full scaled systems (Ohtsuka et al. (1996), Algie et al. (2009), Anastasopoulos et al. (2012), Hatzigeorgiou and Kanapitsas (2013) etc.). But the analytical and numerical approaches though elegant in its form are limited to the assumptions made for the analysis and require experimental validations. Hence experimental analysis is an invaluable tool for investigating the soil-structure interaction mechanism. But it is to be noted that, as per authors knowledge, there are only little or no experimental studies performed pertaining to the investigation of period lengthening of the modes or mode shapes of dynamic structure-foundation-soil system with varying depth of embedment of the footing, relative density of soil, and vertical factor of safety of the footing. This systematic experimental parametric analysis is an invaluable tool to identify the main aspects of the interaction behavior and provide a benchmark for the subsequent numerical and analytical studies.

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This paper investigates into the dynamic behavior of a three storey steel framed structure-foundation-soil system with varying structural and geotechnical characteristics. The tests are performed with varying embedment depths (D/B= 0, 0.5, 1) and varying soil relative densities, (R_d= 40% and 80%). To understand the soil-foundation-structure effect on wide spectrum of building types, the structure is loaded with a range of super structural mass (from relatively low FOS_v to high FOS_v). The dynamic characteristics of the structure are evaluated through an impact hammer test, where input excitations are provided using a short sledge impulse hammer. The structural responses are measured through a series of accelerometers instrumented at each floor of the structure. These structural responses are further processed to characterize the dynamic properties of the model such as natural frequency, mode shapes and damping ratios. For all the loading cases, dynamic characteristics of the structure with fixed base are also performed to measure the variation of flexible base period to that of the fixed base period.

Model structure-foundation selection and sand bed preparation

The three-story single bay steel building with shallow foundations resting on loose or dense soil deposit, considered for the present study, is a representative of the large number of low rise buildings in India . The prototype building is designed following the IS 800:1998 and zone III response spectra as per IS 1893:2000. The building has a floor plan of 6 m x 6 m with a story height of 3 m. The prototype structure is designed with Indian standard medium weight beam, ISMB600 I-section (Depth of beam = 600 mm, width of beam = 210 mm, flange thickness = 20.8 mm and web thickness = 12.0 mm) for columns and ISMB500 I-section (Depth of beam = 500 mm, width of beam = 180 mm, flange thickness = 17.2 mm and web thickness = 10.2 mm) for beams. An isolated square footing of size 1 m x 1 m is designed for each column subjected to vertical column load of 134 kN, shear force of 50.25 kN and base moment of 132 kN-m. The footing sizes are purposefully under designed in order to amplify the SSI effects. The prototype-model accordance is developed after Iai (1989), to functionally correlate the prototype response to model response. The geometric scaling factor (β), of 10 is used to perform the experimental study.

The model structure-foundation system fabricated for the study is a three storey single bay steel moment resisting frame with rigid beam column joints. The structure has a storey height of 30 cm and bay width of 60 cm. The beams and columns are square solid mild steel sections with dimensions 10 mm x 10 mm and 12 mm x 12 mm respectively. The columns of the superstructure is supported by isolated square footings of size 10 cm x 10 cm x 1 cm resting on loose (R_d=40%) or dense (R_d=80%) sand deposit. Sand paper was placed underneath the footing to achieve a near realistic foundation-soil interface roughness (with a coefficient of friction, ν = 0.65). The superstructure mass (1 cm thick steel plates and lead blocks) is installed in each storey in such a manner that the center of mass is maintained at the same level.

Dry quarzanium sand, the uniformly graded industrially manufactured sand, with uniformity co-efficient C_u=2.0, co-efficient of curvature C_c=0.826 and effective size D_{10}=0.35 mm is used for the study. The material and strength property of the quartzanium sand is characterized through a series of laboratory tests. Quartzanium sand, with specific gravity (Gs=2.57) provides a dry density ranging between 13.2 kN/m^3 to 15.1 kN/m$^{3.}$ A series CU triaxial tests are performed with the dry quartzanium sand at low confining pressures (0.05 kg=cm^2, 0.1 kg=cm^2 and 0.2 kg=cm^2)

and shearing at a strain rate of 0.005 mm/min to determine the soil friction angle (ϕ). For 40% and 80% relative densities, sand provides a friction angle of 26.5^o and 32^o respectively.

The study involves a total of 24 load cases, where the single footing load varies from 94.4 N to 319.3 N. The mass of the structural model (and hence the FOS_v) is varied by adding and removing the steel plates. For various embedment depth (D/B=0,0.5,1) , the ultimate footing load as calculated from Meyerhof bearing capacity equation varies from 178.6 N to 353.1 N for loose sand (R_d = 40%) whereas for dense sand (R_d = 80%), ultimate footing load varies from 251.9 N to 579.9 N. Table 1 summarizes the range of FOS_v considered in the study.

Table 1. Range of vertical factor of safety (FOS_v) of the footing considered in the study

Relative density	**D/B ratio**	**Ultimate load (N)**	**FOS_v**
R_d = 40%	0	178.6	1.04 – 1.89
	0.5	265.8	1.03 – 2.82
	1	353.1	1.37 – 3.74
R_d = 80%	0	251.9	1.05 – 2.67
	0.5	416.0	1.03 – 4.41
	1	579.9	2.04 – 6.14

The sand is layered inside the container through a well established rainfall pouring technique by hand hopper to maintain the desired relative density (loose sand bed with Rd=40% and dense sand bed with Rd=80%). To obtain a uniform soil bed with a particular soil density, the hand hopper is swung back and forth like a pendulum, keeping a constant height of fall that provides a uniform deposition over the layers. The height of fall to achieve the relative density for the dense and loose sand is calculated after shubham et al. (2014), which was established through a series of pluviation tests. In order to assure the uniformity of sand deposition while filling, the dynamic cone penetrometer is employed at different location long the horizontal direction.

Set-up, instrumentation and testing

The experiment is carried out in a rigid rectangular tank, 1.6 m long, 1.2 m wide and 0.6 m high. As shown in Figure 1, the model structure-foundation system is installed on the prepared sand bed with adequate depth (H=6B) and with adequately large distance (L=4.5B) from the tank walls to minimize the superfluous boundary effects. The model structure-foundation system is carefully lowered atop the leveled soil bed at the desired depth, with minimal disturbance, enabling its accurate positioning. The spirit levels are used to check the horizontal alignment of the system and thereby ensure the absence of any initial inclination of the super- structure. The external mass (1 cm thick steel plates and lead blocks) to obtain the required FOS_v are carefully mounted in each floors with least possible disturbance to the model foundation-soil system. As illustrated in Figure 1, the structure is instrumented with three uniaxial PCB piezotronics accelerometers (4 terminals, 18-30 Volt DC operated with 100 mV/g sensitivity), A1, A2 and A3 to the bottom, middle and top floor respectively. The study adopts ICP impulse force test hammer to obtain the modal characteristics of the model structure-foundation-soil system. The impulsive testing of the dynamic behavior of the set-up involves striking the top floor of structure with the force instrumented hammer and subsequently measuring the response through the series of accelerometers (A1 to A3) mounted at each floors. The axis of accelerometer is aligned horizontally to the direction of impact. The impact hammer with quartz force sensor mounted on the striking end converts the impact force into electrical signals to process in the FFT analyzer. The data acquisition system (Agilent Dynamic Signal Analyzer) converts the impact force and accelerometer response in time domain to the frequency domain to generate the Frequency Response Function (FRF's) for the particular impact force. A total of three experiments are carried out, maintaining a coherence value of 1 between the trials. The peaks from the average FRF's of the three trials (processed in Me'scope software) provide the natural frequencies and mode shapes.

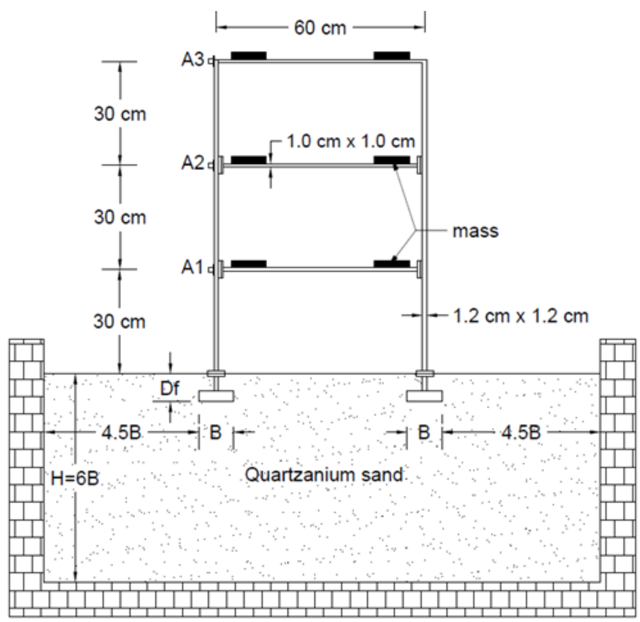


Figure 1. Experimental set-up and instrumentation

Experimental results and discussion

In order to determine the variation of the modal response of the structure-foundation soil system from the structure with fixed base, a series of tests are performed in the model structure with its base tightened to the floor. The mass is mounted to each floor to generate the same footing load as provided in Table 1. The figure 2(a) provides the comparison of mode shapes for the first mode of fixed base model structure with that of model structure-foundation-soil system with different foundation and soil configurations. Both the fixed base model structure and the model structure-foundation-soil system are loaded with mass to provide the footing load of 94.4 N. Similarly Figures 2(b) and 2(c) respectively provide the mode shapes for the two higher modes. It's observed through Figures 2(a) to 2(c), that the variation of mode shapes of the SSI base model to that of the fixed base model is predominant for the first 2 modes and variation becomes significantly lower for the higher mode. It's inferred that the rigidity provided by the foundation base through various foundation and soil condition relates to the deviation of the SSI base mode shapes from the fixed base mode shapes.

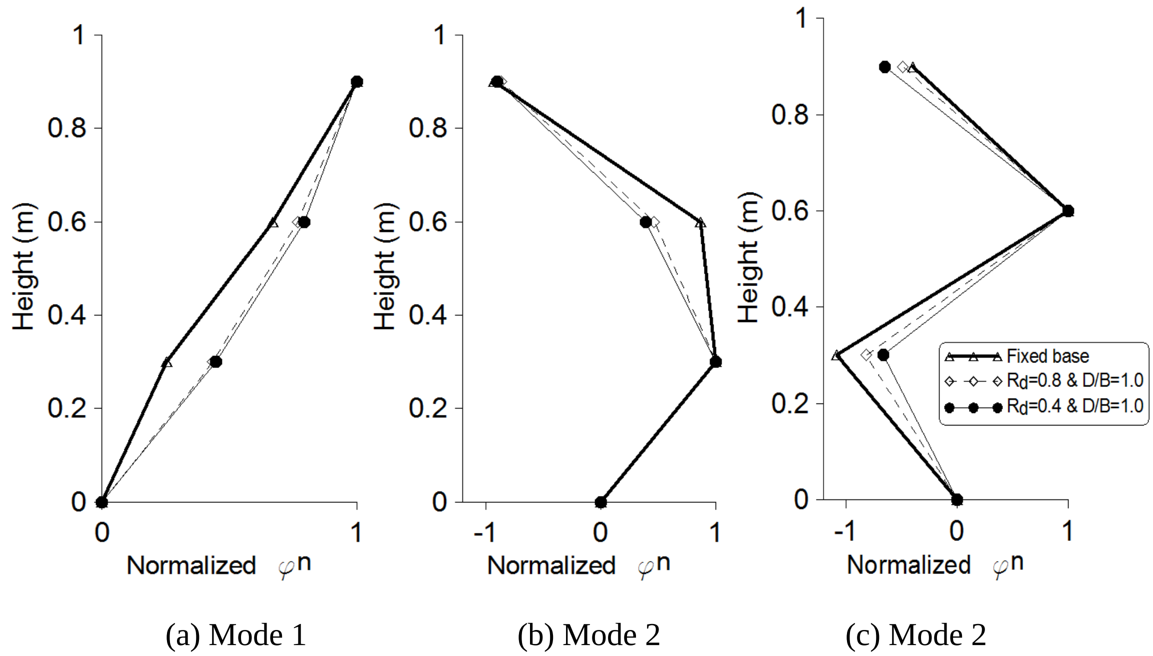
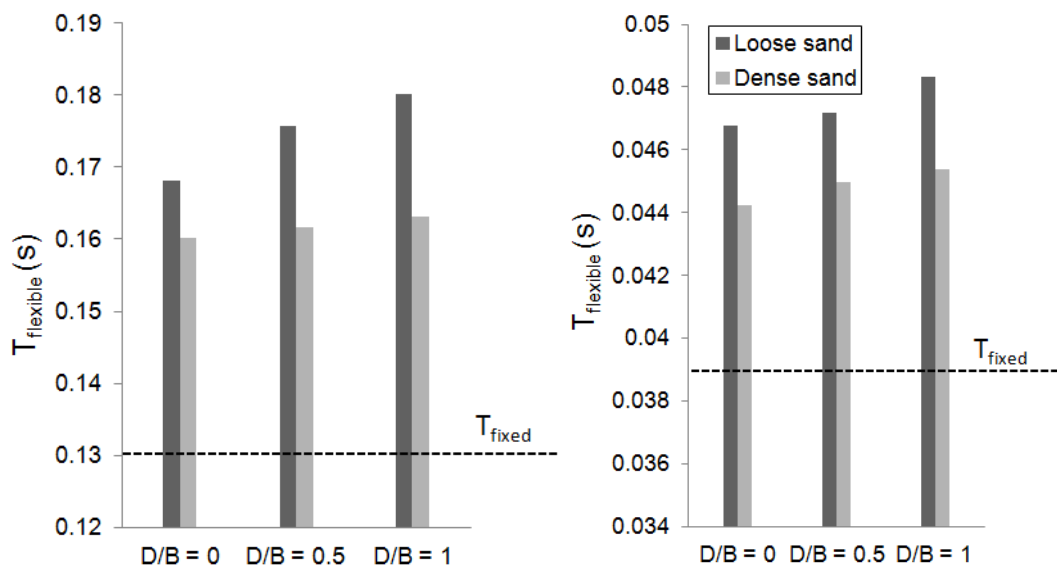


Figure 2. Comparison of fixed base and SSI base normalized mode shapes at (a) mode 1 (b) mode 2 and (c) mode 3 for the structure with footing load of 94.4 N.

Figures 3 and 4 summarize the variation of the period of the model structure foundation system for different foundation and soil configurations. In all the cases, the curve shows a logarithmic trend with period of the model structure-foundation soil system decreasing with increase in FOS_v. As expected, the heavily loaded structure (with low FOS_v) shows lower period compared to the lightly loaded structure (with low FOS_v). For the model structure-foundation system supported on loose sand bed (R_d=40%) with various footing configurations, the period varies between 0.265 s to 0.168 s for the fundamental mode whereas the period varies between 0.076 s to 0.047 s for the second mode. As for the model structure-foundation system supported on dense sand bed (Rd=80%) with various footing configurations, the period varies between 0.245 s to 0.156 s for the fundamental mode whereas the period varies between 0.069 s to 0.0423 s for the second mode. This trend of decrease of period of the model structure foundation-soil system with the increase in soil relative density is due to higher angle of internal resistance (ϕ) of sand providing higher rigidity to the soil.

In order to quantify the influence of the soil-structure interaction (SSI) effect on the model structure for different foundation cases (varying D/B ratio and relative density), the experimental modal analysis is performed with both fixed and flexible base foundation mounted with same footing load (94.4 N). The SSI base period of the model structure-foundation system in loose and dense sand bed is compared in Figure 5. It is observed that, the period increases with increase in D/B ratio. Contrary to the concept that, as D/B ratio increases, the period of the structure decreases, is not withstanding. This is due to the fact that, the additional footing embedment length added to the superstructure increases the effective height of the overall structure. The additional rigidity provided by higher D/B ratio (increased passive resistance) is not sufficient

enough to counter the increased slenderness of the structure. This behavior is predominant in similar model studies due the scale effect. As shown in Figure 5(a), for the first mode, as the embedment depth increases, the period varies from 0.168 s to 0.18 s for loose sand whereas the period varies from 0.16 s to 0.163 s for dense sand. As for the second mode, Figure 5(b) shows that, as the embedment depth increases, the period varies from 0.0468 s to 0.0483 s for loose sand whereas the period varies from 0.044 s to 0.045 s for dense sand. The experimental results indicate that the fundamental natural period increases about 20% when the structure is rested on the soil bed compared to that of the fixed base structure.



(a) Mode 1 (b) Mode 2

Figure 5. Comparison of SSI base period of the model structure-foundation system in loose and dense sand for (a) Mode 1 and (b) Mode 2 for same loading conditions.

Conclusions

In the current study, a systematic investigation of the dynamic characteristics of the model-structure-foundation-soil system is performed with varying depth of embedment of the footing, relative density of soil, and vertical factor of safety (FOS_v) of the footing. On the basis of the experimental and numerical results obtained from the present investigations, the following conclusions can be drawn:

(a) Variation of mode shapes of the SSI base model to that of the fixed base model is predominant for the first 2 modes and variation becomes significantly lower for the higher mode.

(b) The flexible base period is observed to have a decreasing trend with increasing vertical factor of safety of the footing.

(c) The flexible base period is more for the structure rested on loose sand compared to the structure on dense sand. It is noted that, the fundamental period varies between 0.265 s to 0.168 s in loose sand whereas the fundamental period varies between 0.245 s to 0.156 s in dense sand bed.

(d) For the same loading, the period of the model structure-foundation-soil system increases with increase in D/B ratio. This is due to the fact that, the additional footing embedment length added to the superstructure increases the effective height of the overall structure. The additional rigidity provided by higher D/B ratio (increased passive resistance) is not sufficient enough to counter the increased slenderness of the structure.

(e) The experimental results indicate that the fundamental natural period increases about 20% when the structure is rested on the soil bed compared to that of the fixed base structure.

It should be noted that, though the model testing performed herein for the study do not represents the true replica of the prototype structure-foundation-soil system, it provides an adequate model which could predict the response within a reasonable domain.

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