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Experimental Investigation on Dynamic Characteristics of Structures Founded on a Dispersive Soil

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Key words: Soil-structure-interaction, natural frequency, isolated foundation, soil flexibility, Shedi soil.

ABSTRACT: The objective of this paper is to evaluate the Soil-Structure-Interaction (SSI) effects on the seismic response of structures founded on Shedi soil of Dakshina Kannada. Shedi soil, which is a dispersive type of soil is highly vulnerable to dynamic loading in the saturated condition. Experimental investigations have been carried out on 1:10 scaled single bay three dimensional multistorey building models made of aluminium with its foundation resting on locally available Shedi soil (classifying as sandy silt) and sand in the saturated and dry conditions. The combined system of Soil-Foundation-Structure models is subjected to dynamic loading. The response of the model is measured at each floor level. This structural response is compared with that of a fixed base model to isolate the effect of soil structure interaction. The variations in natural frequency with various parameters such as different types of soil, degree of saturation of soil, number of storeys and the stiffening effect of walls are evaluated. The experimental results are presented and the modifications in dynamic characteristics due to the incorporation of soil flexibility are studied. Free vibration analysis of the three dimensional finite element model of the soil foundation structure system is carried out and the results are compared with the experimentally obtained values.

1 Introduction

In the last three decades, the effect of SSI on earthquake response of structures has attracted an intensive interest among researchers and engineers. Most of these researches focus on theoretical analysis, while less has been done on the experimental study. The interaction among the structure, foundation and soil medium below the foundation alter the actual behaviour of the structure considerably as obtained by the consideration of the structure alone. Flexibility of soil medium below foundation decreases the overall stiffness of the building frames resulting in an increase in the natural period of the system (Bhattacharya.K, 2004).

In the recent decade Japan and America have started to carry out site tests and shaking table model tests on dynamic SSI system. Takahito,et. al (2004) conducted a series of shake table tests on soil pile structure models to study the effect of pore pressure build up. Dynamic centrifuge tests were performed on layered soils to study the effects of localised soil inhomogenity in modifying seismic soil structure interaction in a containment structure(Ghosh.B, 2003,2007). Quite a large number of analytical studies are published on various aspects of soil structure interaction. But more importantly, many theoretical outcomes have not been verified to achieve a general accuracy for practical use. The effect of soil structure interaction is recognised to be important and cannot, in general, be neglected (Wolf, 1985). The current study deals with the soil structure interaction effects of a specific dispersive soil in Dakshina Kannada District ,South India.

2 Test set up

In the present study multi-storey three dimensional single bay frame models with isolated foundation resting on dry and saturated sand and shedi soil are considered.

2.1 Model of structure

A reinforced concrete frame of 3mx1.5m with 1,2,3 and 4 storey with brick infill is chosen as prototype. The clear storey height is assumed as 4m. The model is scaled for 1:10 of the prototype. (Harris.H.G,. 1999), Figure 1(a) shows the typical model of four storey building frame with columns and slabs. The dimensions of the building model and foundation are summarized in Table 1. Stiffener plates are provided in between the floor which acts like a brick infill thereby increasing the lateral stiffness of the building. Depth of foundation is assumed as 100mm below soil surface in model corresponding to the depth of the foundation of 1m in prototype.

2.2 Model of ground

For the investigation, a finite soil mass around the building is modeled by placing soil in a rigid box. The structure is kept over this soil with sufficient embedment depth. The Size of the box used for the ground modeling is 1.5 x 0.96 x 0.9 m in which 600mm of its depth is filled with soil which represents the 15 x 9.6 x 6 m soil on ground. The soil used for modeling of ground is sand and shedi soil with different dry densities and degrees of saturation. The properties of soil used in model and prototype are identical. Physical properties of sand and shedi soil used for the study is tabulated in Table 2.

Table 1. Dimensions of building frame

	Prototype	Model
Type of material	Concrete	Aluminium
Room dimension (L × B)m	3 x 1.5	0.3 × 0.15
Slab thickness (mm)	127	12.7
Column (B × D)(mm)	100 × 200	25 × 6
Young's modulus (kN/m^2)	25×10^6	69×10^6
Stiffener plate A (mm)	-	150 x 160 x 2
Stiffener plate B (mm)	-	312 x 160 x 2
Total mass at floor level (kg)	1675	3.086
Isolated foundation (Steel)	1000 x 1000	100 x 100

Table 2. Physical properties of soil

Description	Values	
Soil type	Sand	Shedi soil
Natural moisture content %	-	26.70
Insitu bulk density (kN/m^3)	-	18.37
Dry density (kN/m^3)	-	14.50
Degree of saturation %	-	92.85
Specific gravity	2.81	2.57
60% grain size ,D60 (microns)	0.7	58
30% grain size ,D30 (microns)	0.4	4.1
10% grain size ,D10 (microns)	0.3	1.3
Coefficient of curvature Cc	0.76	0.22
Coefficient of uniformity Cu	2.33	44.61
OMC %	-	22.5
Maximum Density at OMC (kN/m^3)	-	15.7
Voids ratio at OMC	-	0.60
Maximum dry density (kN/m^3)	15.96	-
Minimum dry density (kN/m^3)	13.34	-
Maximum voids ratio e_{max}	1.066	-
Minimum voids ratio e_{min}	0.728	-

2.3 Measurement

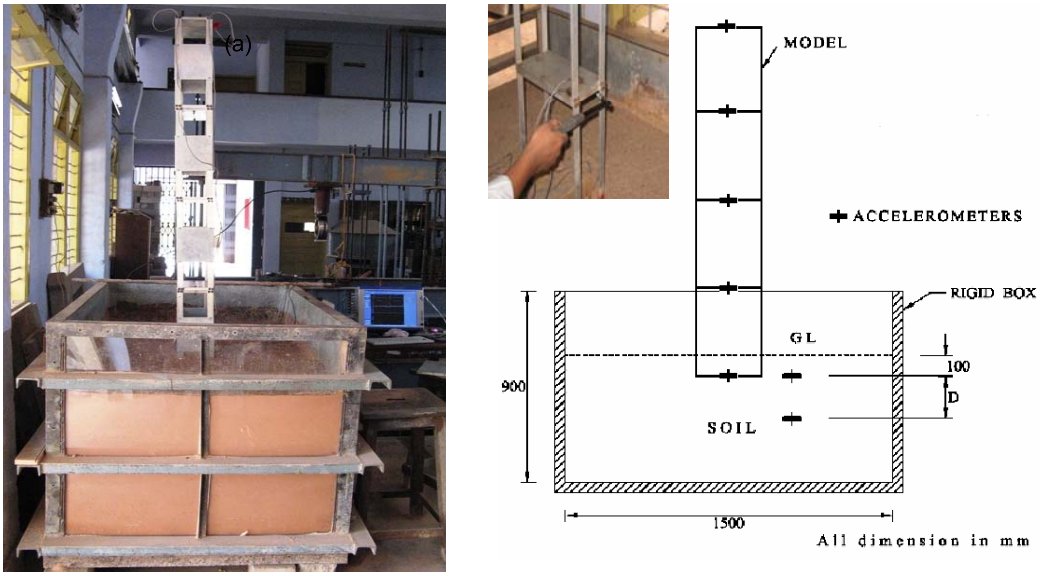
Accelerometers are placed in soil to measure the shear wave velocity and on building model for measuring the response. Figure 1(a) gives general view of the experimental set up and soil model. The locations of recording devices in the structure are shown in Fig. 1 (a) and the locations of recording devices in the soil are shown in Fig. 1 (b). DEWESOFT and SMART OFFICE softwares are used for measuring the response and modal analysis. DEWESOFT is used for data acquisition from the building model by measuring FRF (Frequency response function) and SMART OFFICE is used for modal analysis.

2.3.1 Measurement of soil shear wave velocity

A weighted wooden timber impacted at the end with a hammer blow provides an energy source that is rich in the type of energy required to excite the particular wave of interest, the S-wave. Shear wave velocity is measured in soil layer by using two accelerometers placed horizontally in the soil bed at known distance (Kramer.S.L., 2003)as shown in the Fig. 1 (b). Knowing the time lag between the wave arrival times on two accelerometers t (sec) and distance between the accelerometers D (m), velocity of the wave V_s can be computed.

$$V_s = \frac{D}{t} \tag{1}$$

$$G = \rho \cdot V_s^{\,2} \tag{2}$$



(b)

Figure 1 (a) General view of experimental setup (b) Experimental setup of building model supported on soil and Impact using impact hammer (inset)

$$G = \frac{E}{2(1+\nu)} \qquad (3)$$

Where, E, G and ν are the modulus of elasticity, the shear modulus and Poisson's ratio of soil.

2.3.2 Measurement of response using impact hammer and modal analysis

Model consists of 1, 2, 3 and 4 storey building with floor slabs and isolated foundation. To measure the dynamic response, one point in the building model is taken as an impact node. The response at various other points to a given impact at the impact node are recorded to get the dynamic characterestics of the system. Serially placed 9 points on each of the slab surface are taken as the response nodes. For this each floor slab is divided into 4 equal sections by bisecting the sides and the corner nodes are marked as response nodes. At the foundation level 4 nodes at the bottom of column are considered. Using impact hammer an impact is given at the centre node of shorter side in the first floor in x direction and the response of the model is measured at all the response nodes using tri-axial accelerometers placed at each node. This data is acquired using data acquisition system and this measured data is frequency response function (FRF). The records of 5 consecutive uniform impacts are averaged for FRF and analyzed. Natural frequency and damping are noted.

3 Experimental procedure

Single bay three dimensional building frames with 1, 2, 3 and 4 storeys with stiffener plates in between each floor with isolated foundation is fixed to a rigid platform and the response of the structure to the impact from an impact hammer is noted as explained in 2.3.2. Same structures supported on soil strata of dry and partially or fully saturated soil are considered for analysing the effect of soil stiffness. Experiments are repeated on bare frame models without the stiffener plates to study the effect of infill on the dynamic characteristics of buildings.

3.1 Effect of stiffness of soil

The soil container is filled to 200 mm depth with sand of 100 percent relative density. Above this sand a top layer of 400mm is filled with sand either of 65, 80 or 90 percentage of relative density. These are designated as Sand – x where x denotes the percentage of relative density (ie. Sand-65). The foundation level of the building model is kept at 100 mm below the soil surface equivalent to depth of embedment. The structure considered is of 1, 2, 3 and 4 storeys with stiffener plates. The response of the structure is measured as explained in 2.3.2. Natural frequency and damping are noted from the modal analysis of the building supported on sand. Sand is saturated to 15% by adding water and mixing properly and filled full in the container with uniform layers of 200 mm and compacted to required density (Sand (sat 15))and the structural response of model placed over the saturated sand is measured and analyzed and frequency and damping of the structure is noted.

Locally available shedi soil with different dry densities is placed in top layer of 400 mm over a bottom layer of 200 mm of shedi soil of 100% compaction (Shedi I,Shedi II and Shedi III)and dynamic response of the structure is measured and analyzed. Shedi soil is saturated to 65% and 100 % and filled full in the box and compacted in layers of 200 mm(Shedi (sat 65), Shedi (sat 100)). The structure is placed over this soil and response is measured and analyzed.

The different types of soils and their properties are listed in Table 3 for dry and saturated conditions, based up on density, modulus of elasticity, Poisson's ratio, water content and degree of saturation.

Table 3. Properties of soil

Soil classification	Soil type	Density (kN/m^3)	Distance (mm)	Shear Velocity (m/sec)	Shear modulus G (kN/m^2) $\times 10^4$	E (kN/m^2) $\times 10^4$	Poisson's ratio (ν)
Sand	Sand - 65	14.94	200	32.26	1.55	4.04	0.3
	Sand - 80	15.36	200	40.40	2.51	6.52	0.3
	Sand - 90	15.65	200	51.95	4.22	11.0	0.3
	Sand -100	15.96	200	62.31	6.19	16.1	0.3
	Sand (sat 15)	15.92	300	22.52	8.08	2.10	0.3
Shedi soil	Shedi - I	13.57	200	32.63	1.44	3.76	0.3
	Shedi - II	14.12	200	39.06	2.15	5.60	0.3
	Shedi - III	14.42	200	56.82	4.65	12.1	0.3
	Shedi (sat 65)	17.74	200	37.31	2.47	6.42	0.3
	Shedi (sat100)	18.92	320	26.00	1.25	3.25	0.3

3.2 Effect of infill

Models of 1 to 4 storeys with isolated foundation with out infill (stiffener plates) are also considered in the study. The supporting soils considered are, sand with 80% relative density (sand – 80) , sand with 15% saturation sand (sat 15) , and dry shedi soil shedi I, shedi (sat 65) and shedi (sat 100)with 65% and 100% saturation . The response of the structures is measured and analyzed.

4 Modal analysis of models using FEM

Three dimensional finite element model of the integrated soil foundation structure system is generated in ANSYS based on the experimental model dimensions. Building models are modelled with fixed base and with support on soil. Two noded 3D beam elements with 6 degrees of freedom (DOF) at each node, is used in 3 dimensional building frame model. Slabs are modelled with 4 noded shell elements with 6 DOF at each node. Isolated foundations are modelled with shell element. The soil mass below the foundation is discretised with 8 noded solid brick elements with 3 DOF at each node. The boundary nodes of soil are assumed to be restrained against rotation and translation. Modal analysis is carried out to calculate the natural frequency and mode shapes of the structure. Block Lanczos method is used for modal extraction. Natural frequencies of the models are noted for support on soil and for fixed base condition.

5 Results and discussions

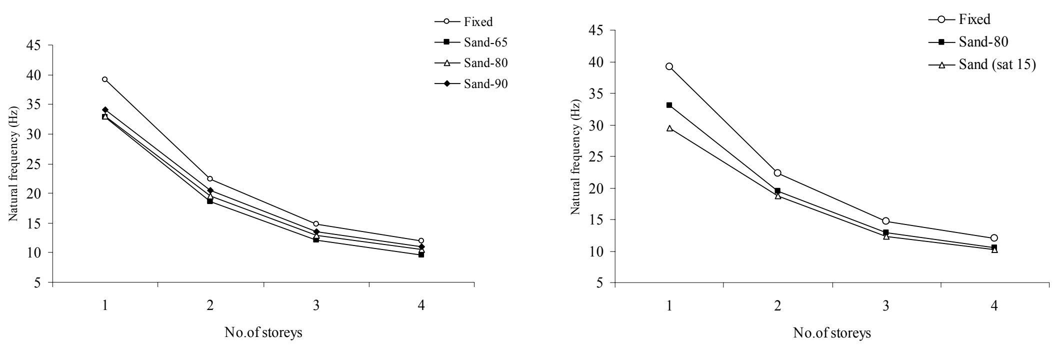
In the present study modification of natural frequency of multistorey structures supported on different types of soils is analyzed. Layered soil strata of sand and shedi soil with different relative density and saturated conditions are considered for the study.

5.1 Building supported on sand

Variation of natural frequency and damping for the building models due to effect of soil flexibility is tabulated in Table 4 for dry and saturated sand. Variation of natural frequency of building model is shown in Fig. 2 and it is observed that the frequencies of building model in stiff soil is higher than that of the soft soil and the natural frequency of the integrated system is lower than that of a fixed base assumption. System damping is higher for soft soil and varies with the number of storeys. The structure founded on saturated sand has the lowest frequency with a 24.73% variation and highest damping observed for a single storey building as compared to the fixed base structure. The percentage variation of natural frequency is more for a single storey building for all types of sand.

Table 4. Natural frequency (f) and damping (ξ) of building models on sand for various modes

BASE CONDITION	MODE	No. OF STOREYS							
		1		2		3		4	
		f (Hz)	ξ (%)	f (Hz)	ξ (%)	f (Hz)	ξ (%)	f (Hz)	ξ (%)
Fixed	1	39.18	2.52	22.38	2.87	14.76	4.43	11.99	4.27
	2			67.86	1.84	48.42	3.34	40.10	2.43
	3					77.10	1.52	68.13	1.80
	4							86.12	1.10
Sand-65	1	32.76	8.88	18.65	7.95	12.10	7.39	9.59	7.66
	2			61.35	2.55	44.04	3.24	35.74	2.97
	3					72.45	2.10	63.69	1.62
	4							82.70	1.26
Sand-80	1	33.03	4.47	19.50	6.87	12.84	6.82	10.49	6.23
	2			58.95	3.16	44.09	3.11	36.84	3.77
	3					70.67	2.27	61.71	1.54
	4							81.72	1.63
Sand-90	1	34.02	6.76	20.49	7.45	13.54	6.69	11.08	9.92
	2			59.41	2.67	43.87	3.39	36.33	2.87
	3					71.27	1.43	62.02	1.76
	4							81.88	1.09
Sand (sat 15)	1	29.49	10.24	18.77	5.17	12.25	8.12	10.15	8.71
	2			62.51	2.07	44.37	2.58	37.12	2.60
	3					74.66	1.17	64.91	1.74
	4							84.45	1.37



(a) Dry Sand (b) Saturated Sand

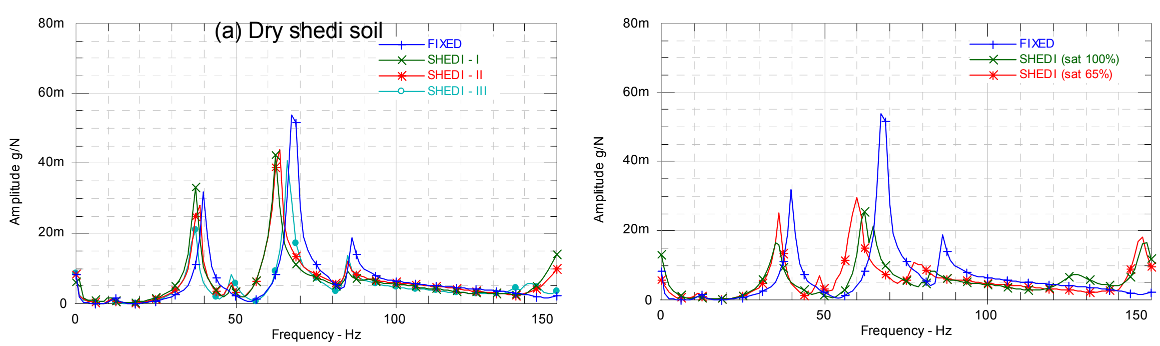
Figure 2 Variation of fundamental natural frequency of building model supported on sand

5.2 Building supported on shedi soil

Variation of natural frequency and damping of building models resting on dry and saturated shedi soil for various modes is tabulated in Table 5. Figure 3 shows the frequency response function for a four storey building model supported on dry and saturated Shedi soil. It is observed that the fundamental natural frequency varies according to shear wave velocity of the soil. It is seen that the damping of the structure gradually decreases with increased density or compaction for dry soil but increases with degree of saturation of saturated shedi soil. The natural frequency of the structure on fully saturated shedi soil is the lowest among the various soil types with different compaction and saturation. Saturated Shedi soil acts stiffer than saturated sand resulting in a higher frequency for the structure.

Table 5. Natural frequency (f) and damping (ξ) of building models on shedi soil for various modes

BASE CONDITION	MODE	No. OF STOREYS							
		1		2		3		4	
		f (Hz)	ξ (%)	f (Hz)	ξ (%)	f (Hz)	ξ (%)	f (Hz)	ξ (%)
Fixed	1	39.18	2.52	22.38	2.87	14.76	4.43	11.99	4.27
	2			67.86	1.84	48.42	3.34	40.10	2.43
	3					77.10	1.52	68.13	1.80
	4							86.12	1.10
Shedi - I	1	34.37	6.39	18.22	8.33	12.94	6.87	9.47	7.74
	2			58.91	3.63	45.12	2.82	37.60	2.67
	3					71.79	1.55	62.75	1.55
	4							84.49	1.59
Shedi - II	1	37.50	5.54	19.05	7.00	13.22	5.93	10.16	7.45
	2			62.16	1.73	46.61	2.52	38.42	2.38
	3					72.02	1.54	63.68	1.60
	4							84.84	1.21
Shedi - III	1	38.18	4.42	20.07	6.42	13.53	5.81	10.50	7.14
	2			62.60	3.63	45.62	2.50	37.12	2.89
	3					75.84	1.38	66.54	1.57
	4							84.27	1.31
Shedi (sat 65)	1	36.39	4.62	20.02	10.24	13.87	5.61	11.43	7.80
	2			61.79	2.10	44.59	2.28	36.83	2.52
	3					70.98	1.96	60.44	1.68
	4							78.14	1.40
Shedi (sat 100)	1	33.38	6.73	16.98	13.38	11.92	7.03	9.58	13.72
	2			54.13	5.61	43.12	4.02	35.78	3.43
	3					73.99	1.99	62.02	1.85
	4							82.04	1.96



(b) Saturated shedi soil

Figure 3. Frequency Response Function for four storey building model supported on Shedi soil

5.3 Effect of infill

The variation of natural frequency and damping of building models with out stiffeners resting on various types of soil is tabulated in Table 7. If the effect of infill wall stiffness is neglected the structures show very low frequency as compared to that with infill stiffener. Similar trend in variation of natural frequency as observed for the structures with infill is seen due to soil structure interaction but the percentage decrease of frequency is more than 53% compared to that of the structure with infill stiffness. The single storey building model shows reduction of natural frequency of more than 63.72% in all soil types.

Table 7. Natural frequency and damping of building models without stiffener

BASE CONDITION	MODE	No. OF STOREYS							
		1		2		3		4	
		f (Hz)	ξ (%)	f (Hz)	ξ (%)	f (Hz)	ξ (%)	f (Hz)	ξ (%)
Fixed	1	13.84	3.56	8.18	5.85	5.73	8.08	4.84	8.27
	2			21.20	2.41	16.84	2.84	14.60	3.29
	3					23.95	2.08	21.32	2.32
	4							26.20	1.85
Sand-80	1	10.12	4.65	7.01	6.93	5.21	7.69	4.12	7.83
	2			21.12	3.13	16.60	3.65	14.16	4.01
	3					23.20	2.98	21.37	2.10
	4							26.61	1.69
Sand (sat 15)	1	10.70	6.39	6.55	8.64	4.87	21.43	4.12	12.61
	2			20.18	3.05	15.55	3.76	13.41	4.32
	3					23.51	2.16	20.87	2.66
	4							25.95	1.97
Shedi – I	1	12.51	6.21	7.85	7.77	5.55	6.86	4.06	11.70
	2			20.93	3.00	15.95	4.12	13.92	4.52
	3					23.89	2.16	21.49	2.49
	4							26.18	1.94
Shedi (sat 65)	1	11.96	5.01	6.42	5.29	5.13	6.12	4.83	8.23
	2			20.93	2.8	15.95	3.16	13.92	2.65
	3					23.89	2.01	21.49	1.78
	4							26.18	1.56
Shedi (sat 100)	1	11.61	6.73	6.99	9.24	5.58	14.35	3.99	13.54
	2			19.99	3.64	15.43	4.40	13.38	4.78
	3					23.64	2.20	21.08	2.56
	4							25.96	1.92

In general it is observed that the natural frequency of the structure increases with increase in soil stiffness and the percentage of this variation depends on the number of storeys and soil stiffness. The variation of damping varies with soil stiffness, the maximum increase is observed in building model resting on soft soil and it is seen that this increase in damping gradually reduces with increase in soil stiffness.

It is also observed that soil stiffness is affected due to increase in water content. Soil stiffness decreases as the saturation is increased and hence natural frequency of the building model resting on this saturated soil is lower compared to dry soil.

There is a maximum reduction of 69 % in the natural frequency of the single storey building model without stiffeners when compared to building model with stiffeners in saturated soil. This indicates that infill stiffness is worth considering in the seismic analysis of buildings.

5.4 Comparison of experimental and numerical results

The experimental and numerical results for the first mode are tabulated in Table 8. In order to evaluate the experimental and numerical results both natural frequencies for all the models in each support condition are correlated and the coefficient of correlation obtained is more than 0.99 in all cases.

Table 2. Comparison of experimental and Numerical results

BASE CONDITION	Experimental				Numerical				Correlation coefficient r
	No. OF STOREYS				No. OF STOREYS				
	1	2	3	4	1	2	3	4	
	f (Hz)	f (Hz)	f (Hz)	f (Hz)	f (Hz)	f (Hz)	f (Hz)	f (Hz)	
Fixed	39.18	22.38	14.76	11.99	40.64	25.78	17.47	14.15	0.9982
Sand-65	32.76	18.65	12.10	9.59	35.52	19.63	12.82	10.15	0.9998
Sand-80	33.03	19.50	12.84	10.49	36.62	20.60	13.63	10.87	0.9997
Sand-90	34.02	20.49	13.54	11.08	37.41	21.33	14.27	11.44	0.9995
Sand (sat 65)	29.49	18.77	12.25	10.15	33.00	17.77	11.28	8.89	0.9965
Shedi - I	34.37	18.22	12.94	9.47	35.30	19.23	12.66	10.02	0.9990
Shedi - II	37.50	19.05	13.22	10.16	36.31	20.11	13.39	10.65	0.9987
Shedi - III	38.18	20.10	13.53	10.50	37.50	21.27	14.36	11.52	0.9995
Shedi (sat 65)	36.39	20.02	13.87	11.43	36.20	20.24	13.33	10.60	0.9994
Shedi (sat 100)	33.38	16.98	11.92	9.58	34.71	18.99	12.31	9.71	0.9979

6 Conclusion

An experimental investigation to study the dynamic characteristics of building on a dispersive soil - Shedi soil of Dakshina Kannada - is carried out. The study as a whole shows the significance of dynamic soil structure interaction on behavior of building with isolated foundation resting on soil medium. The study highlights the effect of change in soil stiffness and the effect of stiffeners of building on natural frequency and damping of the building. It is observed that saturated Shedi soil is stiffer than saturated sand resulting in a higher frequency for the structure.

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