Experimental Study of Soil Amplification and Soil-Pile-Structure Interaction Performing Shake Table Test

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Abstract. In the present study, the shake table tests were performed to investigate the amplification behavior of cohesion-less soil column. The soil columns were subjected to dynamic load of sinusoidal base excitation with varying the frequencies and amplitudes. In the experimental setup, a scale down model was designed consisting of four aluminum piles with pile cap, embedded in the soil sample. Three accelerometers were placed in different depths inside the soil column and one was placed at pile cap. It was observed that the acceleration responses of soil got amplified in upward direction in the soil column. The response of acceleration at pile cap level also got amplified in comparison to the base excitation due to soil-pile-structure interactions. However, it is observed that the amplification of acceleration responses depends upon the frequencies and amplitude of the base excitations. Additionally, in order to observe the amplification characteristics of soils, the simulation study using DEEPSOIL software tool for a selected site with a analogous case study was performed.

Keywords: Soil-Amplification· Shake Table Test· Pile Foundation· Soil-Pile-Structure Interaction· Ground Response Analysis

1 Introduction

Civil engineering structures such as tall buildings, chimneys, nuclear facilities and industries are supported on a foundation system. The pile foundation system is more preferred if the soil at the top layer possesses lower bearing capacity in comparison to the anticipated load of superstructures. During earthquakes the bed rock stratum gets excited depending on various seismic characteristics like magnitude of earthquakes. As the excitation moves from bed rock stratum towards the foundation system it propagates through the soil mass and its characteristics get changed. The excitation of superstructure are dependent on excitation of bed rock stratum, near field soil and type of foundation system. The complete phenomena are known as soil-pile-structure interaction.

The behaviour of structures during earthquakes depends upon the ground response which in turn depends profoundly on local soil condition. The local modification of a wave motion between bed rock and soil outcrop depends upon the geotechnical parameters of bed-rock, nature and profile of deposited soil above the bed rock. The schematic representation of the same is shown in Fig.1.

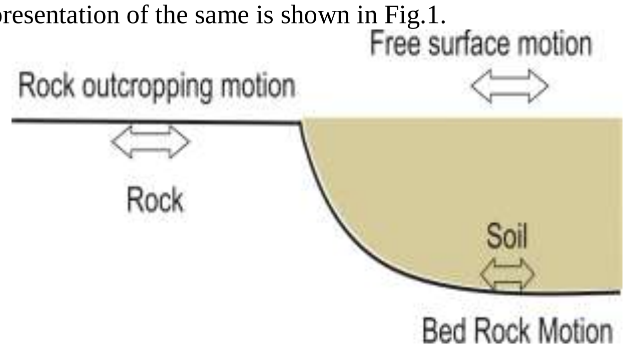

Fig. 1. Motion at bed rock, free surface and rock outcropping

The frequency content and amplitude of earthquake motion at bed-rock level get amplified during its upward propagation through the soil layers. The various parameters affecting the amplifications are densities of soils, rigidity, soil thickness as well intensity of seismic motion. It is also very important to note that the relationship between the predominant period of supporting soil and period of vibration of structure plays an important role in study of the seismic response of structures.

During earthquake in Gujarat (2001), it was observed that several buildings structures of height between a certain range got collapsed but buildings of lesser and higher heights than that range were not affected. It is also reported in literature that during the Caracas (Venezuela) earthquake (1967), extensive damage occurred to buildings of 4-5 storeys that were supported on soil up to bed-rock depth less than 100 m. Whereas the sites at which alluvium soil depth was more than 150 m the building of over 14 storeys suffered extensive damage. The response of the structure supported on soil mass influenced the way in which seismic waves were modified during upward transmission through the soil deposited on bed-rock. Soil amplification also may get influenced by the presence of structures on it.

Hence it is required to investigate the performance of foundation systems and soil amplification for construction of seismic resistance superstructures. The objective of the present study is to investigate soil amplification of soils and responses of pile foundation system using shake table test. Due to the limitation of the full-scale prototype test, a scale down model was tested under similar experimental conditions. This will be utilized for prediction of actual behaviour of full-scale prototypes. Additionally, in order to observe the amplification characteristics of soils, the simulation study using DEEPSOIL software tool for a selected site with a analogous case study is presented. The brief literature survey, mathematical model, methodology used, results are presented subsequently in this paper.

2 Literature survey

Site effects are usually termed as ground response characteristics and more commonly described as amplifications. Zheng and Tamura (1992) studied effects of incident angles on soil amplification [1]. Different methods of soil amplification analysis were studied by Schnabel et al. 1972 [2], Idriss and Seed 1974 [3], Tezcan and Ipek 1977 [4]. Various studies were also carried out to determine the site response of various locations. Site response for Goa city was studied by Naik and Choudhury [5]. Desai and Choudhury carried out 1-D Equivalent linear ground response analysis for NPP and port in Mumbai region [6]. Equivalent linear ground response analyses were performed by Gupta et al. [7] for some cities in Haryana using spectrum compatibility acceleration time history. Site response analysis with 1-D equivalent linear and non-linear ground response was carried out by Kumar et al. for Guwahati city using DEEPSOIL [8]. Jishnu et al. performed 1D and 2D ground response analysis in term of pore pressure development, liquefaction development and post liquefaction settlement for different locations in Kanpur city to study the behaviors of soil subjected to strong ground motion [9]. Whiteman et al. studied ground motion amplification study [10]. Nath et. al. presented effects of bedrock depth on site classification [11]. Earthquake response analysis of sites in the state of Haryana was studied by Puri et al. using DEEPSOIL Software [12]. Phanikanth et al. presented equivalent-linear seismic ground response analysis of typical sites in Mumbai [13].

3 Mathematical modelling

The relationship between the predominant period of supporting soil and the period of vibration of structures plays an important role in the study of the seismic response of structures. Considering travelling of shear waves vertically upwards through a single layer of depth 'H' above bed rock, the predominant period of horizontal vibration of soil is given by Eqn. (1).

$$T_n = \frac{4H}{(2n-1)v_s} \tag{1}$$

where, n represents various modes of vibration and v_s is shear wave velocity.

Peak acceleration value (PGA) at bedrock and soil transform factor is required for calculation of Dynamic Amplification Factor (DAF). The steps involved in evaluation of DAF and responses at soil surface are presented in flowchart form in Fig. 2.

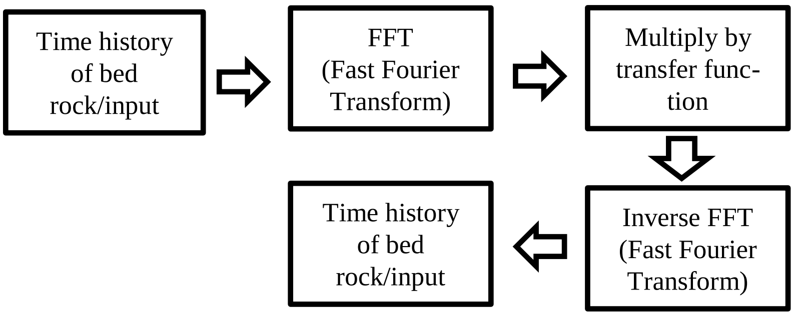

Fig. 2. Steps involved in calculation of ground responses from bed rock level to ground surface

Considering uniform undamped soil on rigid rock and choosing two points both at the top and bottom of the soil layer, the transfer function is evaluated as Eqn. (2).

$$F_1(\omega) = \frac{1}{COS(\omega H/v_s)} \quad (2)$$

where 'w' is circular frequency of ground shaking, 'H' is depth of soil layer and 'v_s' is shear wave velocity in the soil medium.

The modulus of the transfer function is the amplification function. Considering uniform damped soil on rigid rock and choosing two points both at the top and bottom of soil layer the transfer function is evaluated as Eqn. (3).

$$F_2(\omega) = \frac{1}{COS[\omega H/v_s(1+i\xi)]} \quad (3)$$

Soil amplification (A) relationship for different types of soil based on shear wave velocity value of soil are expressed as Eqns (4) & (5).

$$A = 68 v_{s_{30}}^{-0.60} \left(v_{s_{(30)}} < 1100 \frac{m}{s}\right) \quad (4)$$

$$A = 1 \; (v_{s_{(30)}} > 1100 \; m/s) \quad (5)$$

where 'A' is soil amplification and $v_{s_{(30)}}$ is the average shear wave velocity (SWV) in upper 30m depth of soil. As per NEHRP, SWV(v_s) assigned to the sub-surface at any specific site is calculated using Eqn. (6).

$$v_{s_{(30)}} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{v_{si}}} \quad (6)$$

where 'v_{si}' is the SWV of any layer in m/s and 'd_i' is the thickness of any layer between zero meter and 30 meter.

4 Methodology

In the present work, shake table tests were performed to study the soil responses and soil amplifications at different locations along the depth when subjected to dynamic loads. The interaction of soil pile and structure was also studied. Further, a simulation model was developed to study the soil amplification identifying a selected site in Mumbai region using DEEPSOIL software tool for similar experimental conditions. The behaviors of soils in geotechnical engineering and responses of structures in civil engineering are generally studied by either developing numerical modelling or by conducting laboratory tests such as shake table test.

4.1 Experimental test

In-situ tests or real situation tests in civil engineering with exact and true-site conditions are difficult to perform. In the present study, soil amplification was studied by performing shake table test. The box container filled with soil samples was subjected to sinusoidal base excitations of different amplitudes and frequencies to mimic the earthquake like dynamic load condition to carry out investigations.

The payload capacity of shake table with 25 MT was used for the current experimental investigation. It consists of shake table platform of size 1.5 m length and 1.2 m width. Apart from shake table platform, it consists of linear rail guide, actuator assembly unit, hydraulic power pack, PC based assembly, control system and software as shown in Fig. 3. Actuator is a linear motion device which gives a controlled motion. Hydraulic power pack is to supply required flow and pressure for actuator to carry out various tests. Shake table platform is supported on linear rail guide system which facilitates the movement of table in only horizontal pre-defined directions and prevents motion in unwanted degree of freedoms.

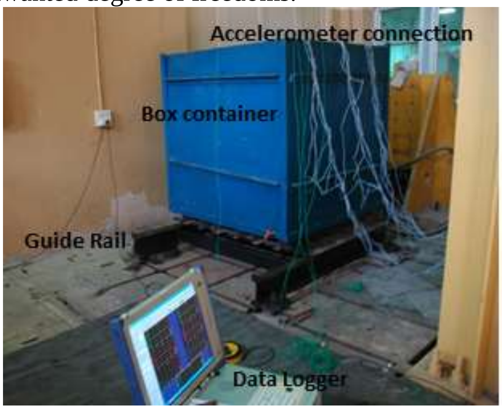

Fig. 3. Shake table experiment set up showing shake table, box container, datalogger

The detailed specification of shake table and actuator used for test is presented in Table 1.

Table 1. Specification of shake table and actuator

Parameters	Details
Motion	Horizontal
Maximum Pay Load Capacity	25 *MT*
Top table size	1.5 *m x* 1.2 *m*
Frequency range	0-20*hz*
Amplitude	±50 *mm*
Motor rating	10HP, 3phase, 440v, inputs

Cohesion-less soil sample was used for test and filled in the box container made of steel. Geofoam of thickness 50 *mm* was glued all along the solid box container to mitigate rigid box boundary conditions as shown in Fig.4.

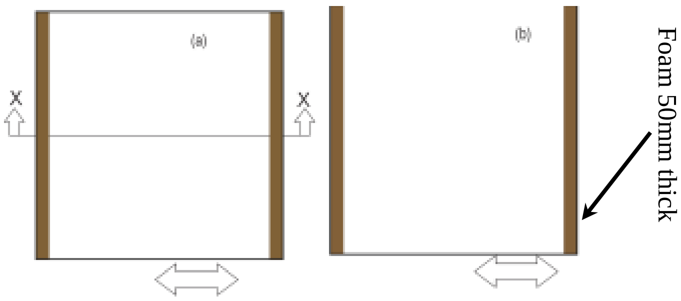

Fig. 4. (a) Plan view and (b) sectional view of rigid box container with Geofoams

Scaled down model consisting of 4 piles with pile cap was placed inside the soil sample as shown in Fig. 5. The placement of accelerometer at various depth in soil sample along with scale down model are presented. Three accelerometers marked as A_1, A_2, and A_3 were placed at different locations in soil and the one accelerometer marked as A_4 was placed on the pile cap as shown in Fig. 6.

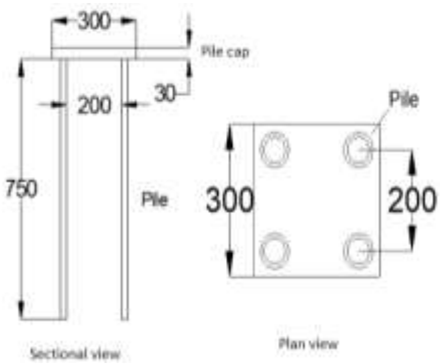

Fig. 5. Schematic diagram of pile group with pile cap (all dimensions are in mm)

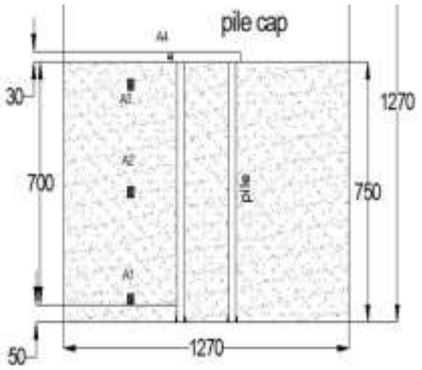

Fig. 6: Schematic diagram of Accelerometer location inside the box container filled with soil and at pile cap (all dimensions are in *mm*)

Cohesion less soil was used as soil sample in the present work to study the soil amplification. Aluminium hollow circular cross sectional pipes as shown in Fig. 5 were used to fabricate the scaled down model of group of pile. The outer diameter of aluminium hollow pipe was 25.5 *mm* with the wall thickness of 1.2 *mm*.

Acceleration data were observed and recorded by suitable data logger. The sampling frequency during the test was of 500 *Hz*. The acceleration nomenclatures and their respective locations in soil and on pile cap are given in Table 2.

Table 2. Nomenclature and location of accelerometers during shake table test

Sl. No.	Accelerometer number/ nomenclature	Location
1	A-11255/A_1	650 *mm* from soil surface
2	A-11233/A_2	375 *mm* from soil surface
3	A-11251/A_3	100 *mm* from soil surface
4	A-11241/A_4	Pile cap

Shake table test was performed by subjecting the base excitation of different frequencies and amplitudes. The table can give sinusoidal motion whose amplitude and frequency can be set for desired '*g'* value for experiments. A typical base excitation of shake table is presented in Fig.7.

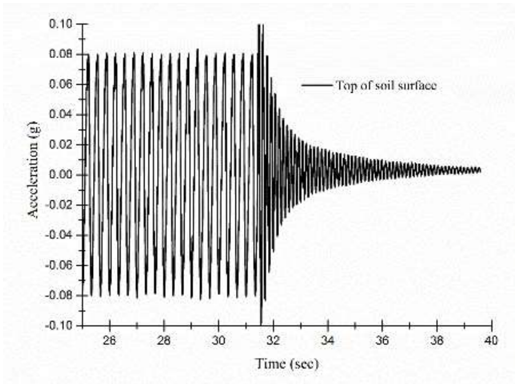

Fig.7. A typical **input b**ase motion of shake table of 0.08 *g* and 3 *Hz*

Base Excitation of different acceleration can be generated as follow;

$$x = A \sin \omega t \quad (7)$$

$$\dot{x} = \omega A \cos\omega t \quad (8)$$

$$\ddot{x} = -\omega^2 A \sin\omega t \quad (9)$$

$$\ddot{x} = (2\pi f)^2 \frac{x}{1000} \quad (10)$$

With frequency of 2hz and amplitude of 10 mm

$$\ddot{x} = (2\pi 2)^2 \frac{10}{1000} = 1.577 mcec2 = 0.16g$$

Similarly, with frequency 4*hz* and amplitude 20*mm*

$$\ddot{x} = (2\pi 4)^2 \frac{20}{1000} = 12.62 mcec2 = 1.28g$$

To generate various base excitations, different frequency and amplitude combinations that were set during the experiments have been presented in Table 3

Table 3. The details of test matrix

S. No	Test Name	Frequency (*Hz*)	Acceleration at Base (*g*)	Acceleration at top (*g*)	Amplification at soil top	Acceleration at pile cap (g)	Amplification at pile cap
1	Test 1	3	0.075	0.08	1.230	NA	-
2	Test 2	4	0.075	0.12	1.411	0.14	1.647
3	Test 3	5	0.075	0.08	1.431	0.9	1.384
4	Test 4	5	0.150	0.22	1.467	0.27	1.800
5	Test 5	3	0.100	0.20	1.250	0.15	1.875
6	Test 6	4	0.250	0.20	1.330	0.25	1.666
7	Test 7	5	0.250	0.25	1.388	0.3	1.667
8	Test 10	7	0.100	0.30	3.000	0.35	3.500

9	Test 11	10	0.080	0.18	2.000	0.24	2.667
10	Test 12	12	0.150	0.16	1.142	0.22	1.571
11	Test 13	8	0.100	0.22	2.200	0.27	2.700

4.2 Numerical modelling

In the present study, soil amplification and site response have also been studied at a selected site in Mumbai region with the help of DEEPSOIL software using geotechnical parameters from geotechnical investigations [14]. Geotechnical and geological data of soils are evaluated by geotechnical investigations of the site. Bore holes were drilled and standard penetration test (SPT) were conducted at approximate 1.5 m interval along the depth during drilling process as per IS 2131-1981 (Reaffirmed 1997) [15]. Cross hole test was also conducted as per ASTM D4428/D448M [16]. The typical geological formation existing in the area is indicated as in Fig. 8 for the soil profile. For the case study, Chi-Chi earthquake (1999) & Kobe Earthquakes (1995) acceleration time histories shown in Fig. 9 are considered to understand the soil amplification and site response.

The test results observed during shake table test are presented and discussed in following section (Section 5.1). The observation of site response performing DEEPSOIL analysis is discussed in section 5.2.

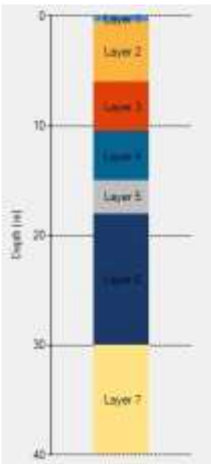

Fig.8. Soil profile considered for site response analysis.

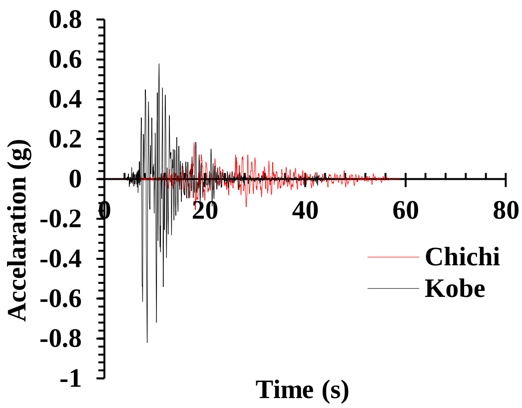

Fig.9. Input time history in case of Chi-Chi earthquake and Kobe Earthquake

Cross hole seismic test was also carried out to observe various geotechnical parameters as presented in Table 4.

Table 4. Cross bore hole test results and evaluated geotechnical parameters of soils

Depth (*m*)	**Average V_p (*m/s*)**	**Average V_s (*m/s*)**	**Vp (*m/s*)**	**Vs (*m/s*)**	**Poisons ratio**	**Young's Modulus (*Gpa*)**	**Shear modulus (*Gpa*)**	**Bulk modulus (*Gpa*)**
0.5	736	210	436	210	0.35	0.19	0.07	0.21
				1.00m				
1.5	750	342	920	451	0.34	1.00	0.37	1.02
3.0	980	492						
4.5	1029	519						
6.0	1528	768						
				5.25m				
7.5	1510	759	1589	801	0.32	3.54	1.29	3.27
9.0	1591	804						
10.5	1727	873						
				11.25m				
12.0	2198	1200	2876	1633	0.27	18.00	7.27	12.85
13.5	2854	1628						
15.0	3576	2072						
				15.75m				
16.5	4053	2377	4202	2420	0.24	38.72	15.23	25.18
18.0	4351	2462						
				18.75m				
19.5	5218	2760	5445	2850	0.29	64.28	23.28	51.80
21.0	5423	2841						
22.5	5468	2892						
24.0	5535	2842						
25.5	5500	2825						
27.0	5481	2899						
28.5	54450	2888						
30.0	5482	2857						
				30.75				
31.5	5819	2945	5815	2948	0.33	67.06	25.20	64.36
33.5	5872	2945						

34.5	5805	2923
36.0	5819	2952
37.5	5763	2956
39.0	5805	2983
40.0	5823	2931

5 Results

The results obtained from experimental investigation using shake table test and simulation studies using DEEPSOIL software tool are presented in this section

5.1 Shake Table test

During shake table test acceleration time histories in soil samples were observed at different three locations by placing accelerometers (A11255/A_1, A11233/A_2 & A11251/A_3) as shown in Fig. 6. However, A11233/A_2 was unable to provide the data due to sensor malfunction. In addition to this, another accelerometer (A11241/A_4) was placed on pile cap as shown in Fig.6. The soil sample along with model pile was subjected to sinusoidal base excitation by varying the frequencies and amplitude. The amplification factors (responses in term of acceleration) at soil surface and pile cap level at different frequencies and amplitude are tabulated in Table.3. In the present test, it is observed the amplification factor at soil surface level is in the range of 1.23 to3.00 and at pile cap level is in the range of 1.384 to 3.50 for different frequencies and amplitude. A typical time history of acceleration response with frequency 5*Hz* is presented in Fig.10. A significant amplification in the magnitude was recorded as signal is propagated from bottom to top.

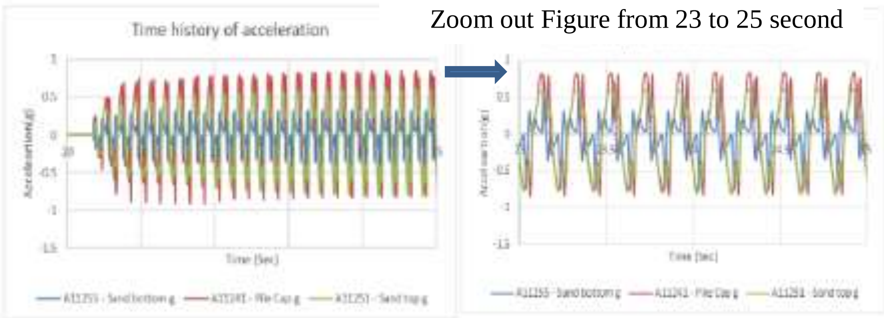

Fig.10. A typical representation of amplification of acceleration (a) from 20 to 25 second along the depth of soil and at pile cap at frequency 5 *Hz* (b) Zoom out responses from 23 to 25 second

5.2 Response Analysis from DEEPSOIL

The ground response at the surface is obtained from input of two-different earthquakes such as Chi-Chi earthquake (1999) & Kobe Earthquakes (1995) as discussed in Fig. 9. The site response from the two-earthquake motion can be observed in the response spectrum in terms of pseudo-spectral acceleration (PSA) explained in Fig.11. It is observed that the amplification in the magnitude is observed up to 0.5 s significantly, however, there is no amplification beyond time period of 0.5 s.

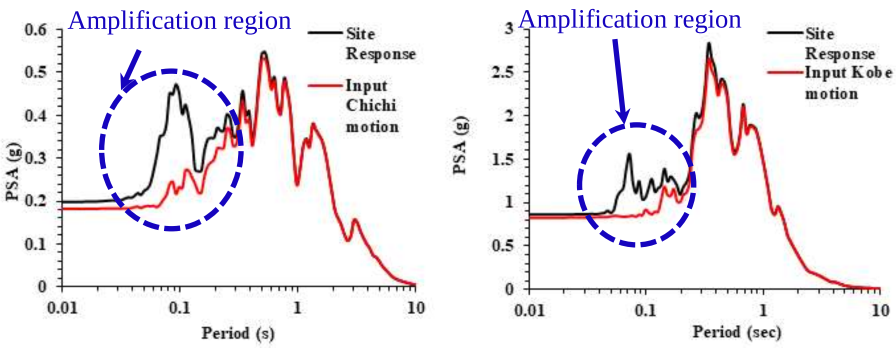

Fig. 11. Site response from the two-earthquake motion

6 Discussion and Conclusions

Present study explained the insight of soil excitation amplification with the help of shake table test. It is observed that there is amplification in soil responses from bottom towards top of the soil layer. The observed responses at pile cap also get amplified which shows the soil-pile structure interaction. It is observed that the amplification of magnitude is increased by factor of 1.23 to 3.0 at soil surface level and of 1.384 to 3.50 which is a strong function of excitation frequency. In other words, the amplification factor is depended on the base excitation, amplitude and frequency. Soil response at a specific site in Mumbai has also been studied with the help of DEEPSOIL software using two different earthquakes such as Chi-Chi earthquake and Kobe Earthquake as input base excitations. The study using DEEPSOIL also demonstrated a similar amplification trend. Hence, it can be concluded that amplification factors must be considered and due importance should be given during analysis and design of structures resting on different profile of soil and rocks. From site response analysis, it has been observed that the site in Mumbai amplify the ground motion significantly, thus, site specific response must be developed and adopted during design. Further, the results presented here can be used dynamic analysis and design of structures in Mumbai area with similar geological profile and characteristics. In the present shake table test the relative density of soil samples were approximately 60%, hence the results of present study is limited to cohesionless soil of medium dense. For cohesive soil like clay the results cannot corelated. Additionally, this study is only limited to dry soil therefore, it is difficult to make analogy with submersed soil. The site response depends upon the site location, soil profile and engineering properties, hence the DEEPSOIL study results in present study can be limited to same soil profile and properties.

Acknowledgement

The authors wish to acknowledge HBNI and BARC for providing technical support and test facility for the study.

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