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GROUND RESPONSE ANALYSIS OF GANGA SAND THROUGH SHAKE TABLE EXPERIMENTS

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ABSTRACT

It is well-known that local site conditions greatly influence the acceleration amplitude and frequency characteristics of the seismic waves during an earthquake. An appropriate ground response analysis is therefore crucial for development of realistic site-specific design spectra, estimation of dynamic shear stress-strain behaviour, liquefaction potential, and so on. The present study focuses on dynamic response analysis of local Ganga sand through performing a number of shake table experiments using a flexible laminar container. Moreover, ground response analysis has been carried out using 1-D equivalent linear model through SHAKE 2000. Comparisons between the analytical and experimental results are done to calibrate and validate the analytical model parameters.

INTRODUCTION

Ground shaking resulting from earthquake constitutes the major cause of destruction to the built-in environment around the world. During a seismic event, the local site conditions greatly influence the seismic wave characteristics such as the acceleration amplitude and the frequency content. Hence over the years, the researchers have developed quantitative methods to predict the influence of local site conditions on strong ground motions. The knowledge from an appropriate ground response analysis is crucial for developing site-specific design spectra, estimating the dynamic shear stress and strain of the soil, evaluating the liquefaction potential and so on. In recent decades, several researchers (Schnabel et al. (1972), Ishibashi and Zhang (1993), Finn et al. (2003), Jishnu et al. (2013) etc) have conducted theoretical ground response analysis on various soils to quantify the nature of propagation of the seismic waves through the soil. Experimental studies like Lu et al. (2002), Li et al. (2011), Turan et al. (2009) etc performs a series of shake table test on laminar shear box to understand the dynamic response of various soil deposits. For an effective understanding of the dynamic soil behaviour of a particular soil deposit, a comparison of the experimental and analytical studies is very much important.

The present study focuses on dynamic response analysis of local Ganga Sand through performing a number of shake table experiments using a flexible laminar container as well as an analytical 1-D ground response analysis involving an equivalent-linear dynamic approach using SHAKE 2000. It may be noted that although some element level tests on Ganga sand has been performed by some previous researchers, but comprehensive dynamic characterization using shake table experiment coupled with equivalent-linear analysis has not been done before. Therefore, the

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outcomes of this study is expected to a enhance our understanding on the dynamic response of this soil as well as the seismic behaviour of infrastructures built upon this type of soil deposits.

GEOTECHNICAL PROPERTIES OF GANGA SAND

Ganga sand which covers a wide area of Northern India is considered for the study. Table 1 presents the physical properties of the sample soil. As per IS 1498-1970 (Unified Soil Classification System), the Ganga sand is classified as a poorly graded sand with low fine content. The minimum and maximum void ratio ranges from 0.712 to 0.936. The present study considers a loose soil deposit, with 30% relative density.

Table 1. Properties of Ganga Sand

Physical properties	Values
Specific Gravity	2.7
Clay content	1.68 %
Silt content	12.92 %
Sand content	85.4 %
Maximum void ratio, $e_{\max}$	0.936
Minimum void ratio, $e_{\min}$	0.712
Cohesion, c (kg/cm^2)	0.128
Angle of internal friction, φ (degree)	12
Natural density of soil (g/cc)	1.3

SIMILARITY RULE

Several researchers such as Iai (1989), Lu et al. (2002), Lin and Wang (2006), Turan et. al (2009) etc, have well established the similitude rules for 1-g soil models. The present study utilizes the similitude rule established by Iai (1989) where the scaling problem is defined in terms of geometry, density and strain scaling factors. The model developed by Iai (1989) assumes a continuous soil medium and maintains the equilibrium at low strain deformations, which adheres to the nature of the present study. Table.2 provides the scaling relationship between the prototype and the model. The geometric scaling factor, β of 200 is used in the present study. The similitude conversions are summarized in Table 3.

Table 2. Similitude relationship between the prototype and the model (after Iai, 1989)

Length	β	Time	$\beta^{0.5}$
Mass density	1	Frequency	$\beta^{-0.5}$
Strain	1	Acceleration	1
Stress	β	Shear wave velocity	$\beta^{0.5}$
Force	β^2	Bulk modulus	β

Table 3. Similitude relationship of Ganga sand between prototype and model

Physical parameter	Model	Prototype
Soil depth (m)	0.15	30
Strain	1	1
Acceleration (g)	0.2, 0.36, 0.54	0.2, 0.36, 0.54
Average shear wave velocity (m/s)	16.89	239

EXPERIMENTAL SET-UP AND INSTRUMENTATION

A series of shake table tests are carried out with a flexible laminar box to investigate the ground response of Ganga sand for various excitation amplitudes. The scaled model flexible laminar box consists of five horizontal square shaped lamina of size 300mm x 300mm x 27 mm. Each lamina is supported individually by six low-friction roller bearings (three per side) which are guided through a guide channel. Multiple roller bearings considerably reduce the friction between the lamina. The guide channels are connected to the external frame which transfers the weight of the lamina away from the shake table.

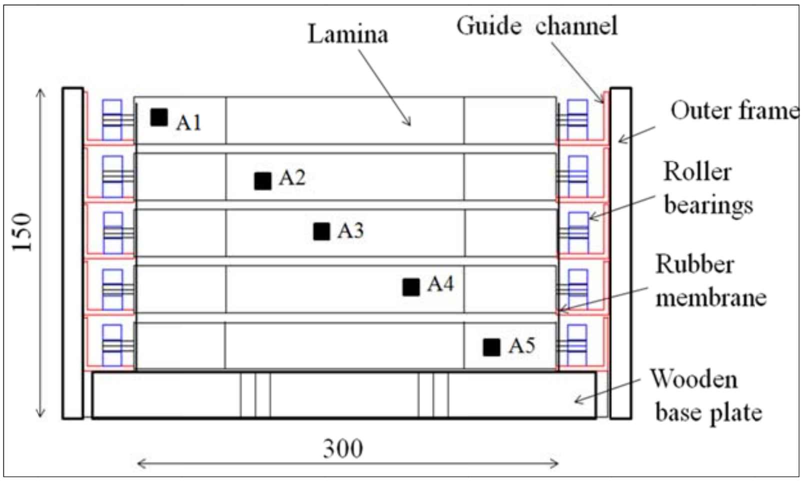


Figure 1. Side view of the flexible laminar container used in the shake table test

The complete laminar box is assembled by stacking five individual laminas creating a 150mm high, 300mm long and 300mm wide box. A clearance of 3mm is provided between the individual lamina which establishes individual movement of the lamina. The roller bearing system restricts the movement of the container to the direction of the motion of the shake table. Fig. 1 provides the side view of the flexible laminar container used in the shake table test.

In order to place the soil inside the flexible laminar box, a wooden base plate of size 300 mm x 300 mm x 5mm is bolted to the top of the shake table. The top of the wooden base plate is epoxied with course sand to minimize the sliding movement at the soil -base plate interface. The interior of the flexible laminar box is lined with thin rubber membrane to prevent the soil spill out through the gaps between the lamina. The compression modulus of the rubber membrane is .04N/mm and thickness of the membrane is 0.3mm which provides minimum interference with the flexibility of the box

The small uniaxial shaking table at Indian Institute of Technology, Kanpur comprises 150 mm x 150 mm table that displaces laterally using electrical actuators controlled by digital control module. The tests are carried out for frequencies ranging from 1 Hz to 5 Hz

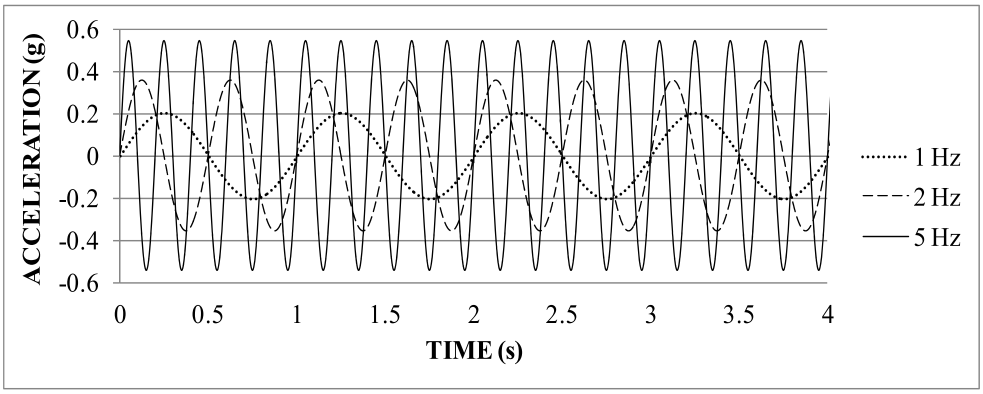


Figure 2. Acceleration time history plot of input motion for (a) 1 Hz, (b) 2 Hz (c) 5 Hz

A series of five accelerometers (A1 to A5) were attached to each individual lamina of the flexible box. The accelerometer A6 attached to the shake table measures the input motion of the wave. The locations of the accelerometers are as shown in Fig. 1. These individual accelerometers, A1 to A5, measure the acceleration of the individual layers. A series of shake table tests with various input accelerations are carried out to investigate the non-linear dynamic behaviour of the Ganga sand. Fig. 2 provides the acceleration time history of input motion for 1 Hz, 2 Hz and 5 Hz.

1-D GROUND RESPONSE ANALYSIS

The study adopts the 1-D ground response analysis, which applies equivalent linear dynamic approach using the commercial software SHAKE2000. Equivalent linear dynamic analysis counters the non-linear behaviour of soil using equivalent rigidity modulus and damping ratio with the developed level of strain.

The SHAKE2000 computes the response associated with the vertical propagation of the shear wave emerging from a rigid base and travelling through a linear viscoelastic system. For the present analysis, the bed rock motion is assumed to be at the top surface of the shake table and the shear waves propagates through a multitude of horizontal soil layers of Ganga sand of equal thickness. The overall depth of 15cm is divided into 5 horizontal layers of 3 cm thickness.

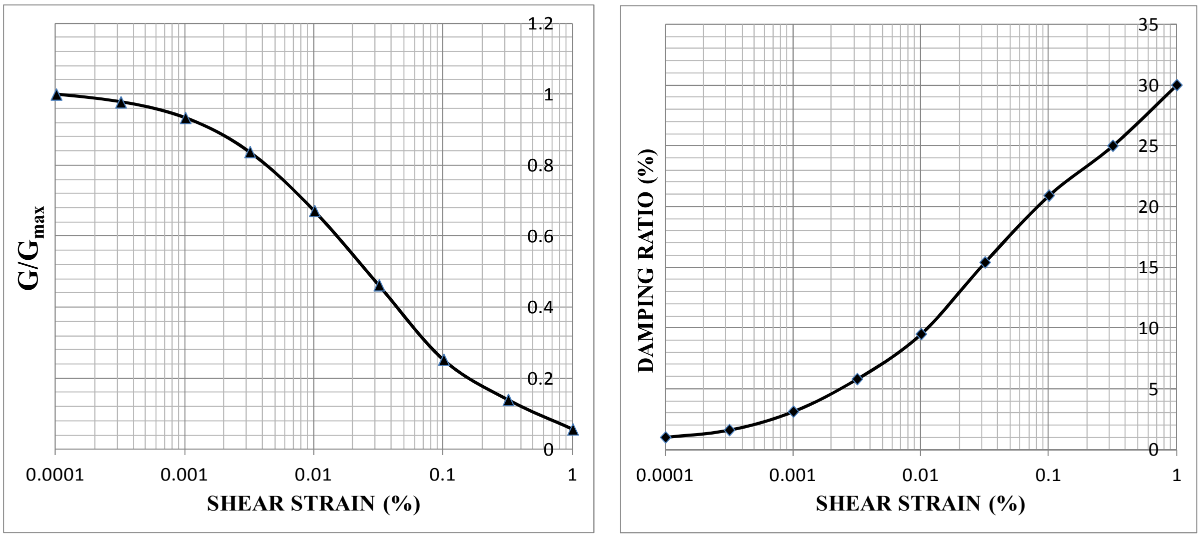
The maximum shear modulus, G_{max} of the Ganga sand was determined regarding the low confining pressure σ_c after Kanatani et al. (1994) through:

$$G_{\max} = \frac{840(2.17-e)^2\sqrt{\sigma_c}}{1+e} \text{ kg/cm}^2 \qquad (1)$$

where σ_c is the effective confining pressure and e is the void ratio.

In the equivalent linear approach, in order to determine the shear modulus and the damping ratio, that are consistent with the level of strain induced at each level, an objective function of strain level is established. The Fig. 3 provides the variation of modulus reduction, G/G_{max} and damping ratio of Ganga sand with the shear stain considered for the analysis.

The shear wave of varying frequency such as 1 Hz, 2 Hz and 5 Hz is provided as the input bedrock motion to study the non-linear dynamic behaviour of the Ganga sand.



(a) (b)

Figure 3. Variation of Shear strain (%) with (a) G/G_{max} and (b) damping ratio used in SHAKE 2000 analysis.

INTERPRETATION OF EXPERIMENTAL DATA

The present study utilizes the wave motion amplification factor, the variation of shear stress and power magnitude of the Fast Fourier Transforms to interpret the ground amplification and dynamic response of the Ganga sand.

The wave motion amplification factor at any depth z of soil deposit on the flexible laminar box is expressed as:

$$\rho_{amp}(z) = \frac{\left(\ddot{U}_{soil}(z)\right)_{\max}}{\left(\ddot{U}_{input}(z)\right)_{\max}} \tag{2}$$

where ρ_{amp} is the amplification factor and $\ddot{U}_{soil}(z)$ and $\ddot{U}_{input}(z)$ are the soil and input wave accelerations at any depth z respectively.

The Ganga sand in the flexible laminar container in the present study assumes a shear beam model deformation during excitation after the works done by Zeghal and Elgamal (1994), Elgamal et al.(1995), Li et al. (2011) etc,. When the soil deposit is assumed as a shear beam, the shear stress developed in the soil at any depth z is determined from the acceleration measurements at that particular depth by integrating the equation of motion as:

$$\tau(z,t) = \int \rho \ddot{U}.dz \tag{3}$$

where $\tau(z,t)$ is the shear stress at any particular depth z at time t, $\ddot{U}$ is the acceleration measurements at depth z and ρ is the mass density of Ganga sand.

Using the first order approximations between the acceleration measurements of low frequency shear deformation modes, that are dominant in the flexible laminar container, Eq.(3) is modified to determine the shear stress at any particular depths as :

$$\tau(z,t) = \tau_{i-1}(z,t) + \rho \frac{\ddot{U}_{i-1} + \ddot{U}_i}{2} \Delta z_{i-1}, \quad i=2,3,\ldots. \tag{4}$$

where i refers to the depth of the i^{th} accelerometer as in Fig. 4, Δz_i is the spacing interval between the accelerometer.

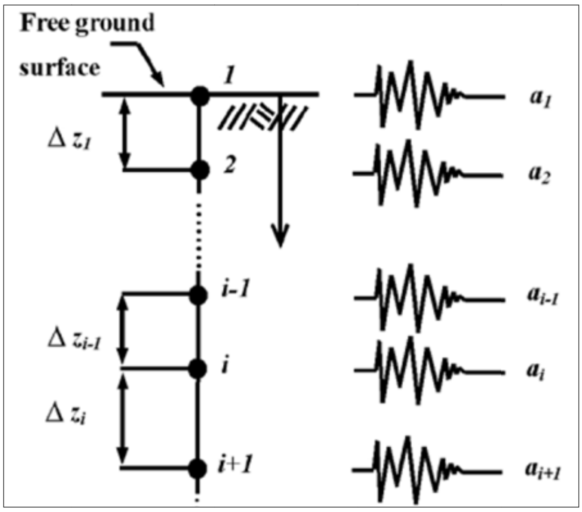


Figure 4. Accelerometer array and soil discretization used for calculating shear stress in the soil (Li et al., 2011)

The root mean square (rms) of the power magnitude of the Fast Fourier Transforms reflects the amplification of the input signal. The peaks in the Fast Fourier Transform spectra reflect the resonance frequency of the wave.

RESULTS AND DISCUSSION

The accelerometers A1 to A5 located at varying depths, as shown in the Fig. 1, records the acceleration time history responses of the Ganga sand along that particular depth. For the data processing, the acceleration time recordings are sequentially filtered using a 10th order low pass Butterworth filter (with a cutoff frequency of 10 Hz) and 4th order high pass filter to eliminate the minor contributions of high and low frequency stresses in the acceleration recordings.

Fig.5 provides the variation of wave motion amplification factor as derived in Eq.(2) which characterize the wave motion amplification through different layers of the Ganga sand. The wave motion amplification factor compares the peak ground acceleration of the sinusoidal acceleration time histories measured in the shake table to those peak accelerations from accelerometer reading in A1 to A5. The peak accelerations of the input time histories are approximately 0.2g, 0.36g and 0.54g. Fig. 5 shows that, the input wave motion with various peak accelerations (0.2g, 0.36g and 0.54g) was amplified by around 20%, 40% and 65% respectively as the wave reaches the top surface of the Ganga sand. Result shows that the amplification factor of the soil is dependent on the frequency of the input wave. Increasing in the shaking intensity increases the amplification factors. As compared to soils in previous studies (Lu et al, 2002, Turan et. al, 2009 etc,), the Ganga sand shows larger amplification at higher frequency.

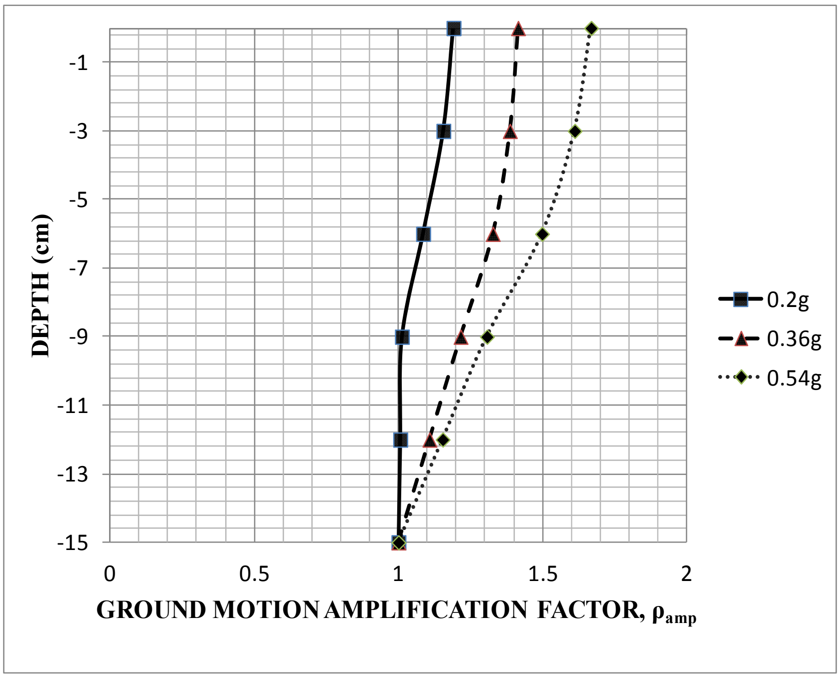


Figure 5. Variation of ground motion amplification factor of Ganga sand for various input excitations

The Fig. 6 and Fig. 7 shows the variation of shear stress over time developed at the center of the flexible box (location of A3 accelerometer) for various input wave intensities. The variation of the shear stress with time at any particular location of the flexible box is calculated using Eq. (4). Results shows that at lower excitation intensities, 2 Hz, the peak value of shear stress varies from 0.035 kPa to 0.293 kPa over an excitation period of 80 seconds whereas at higher excitations, 5 Hz, the peak value of shear stress varies from 0.057 kPa to 0.51 kPa over the same period of time. This infers that Ganga sand offers a higher hysteretic damping at higher excitation frequency and lower hysteretic damping at lower excitation frequency.

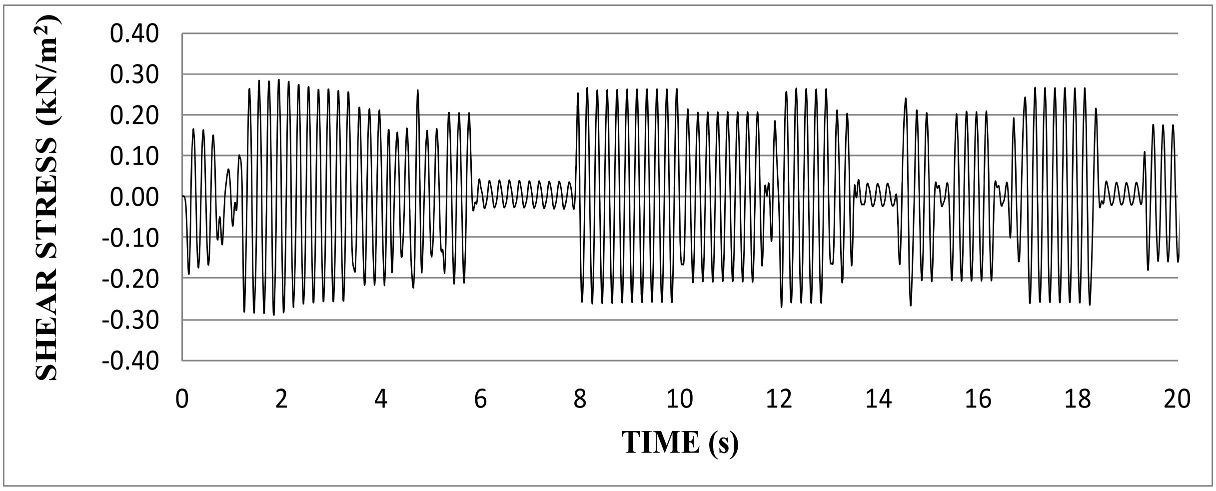


Figure 6. The shear stress time history developed in the Ganga sand for an input excitation of 2 Hz

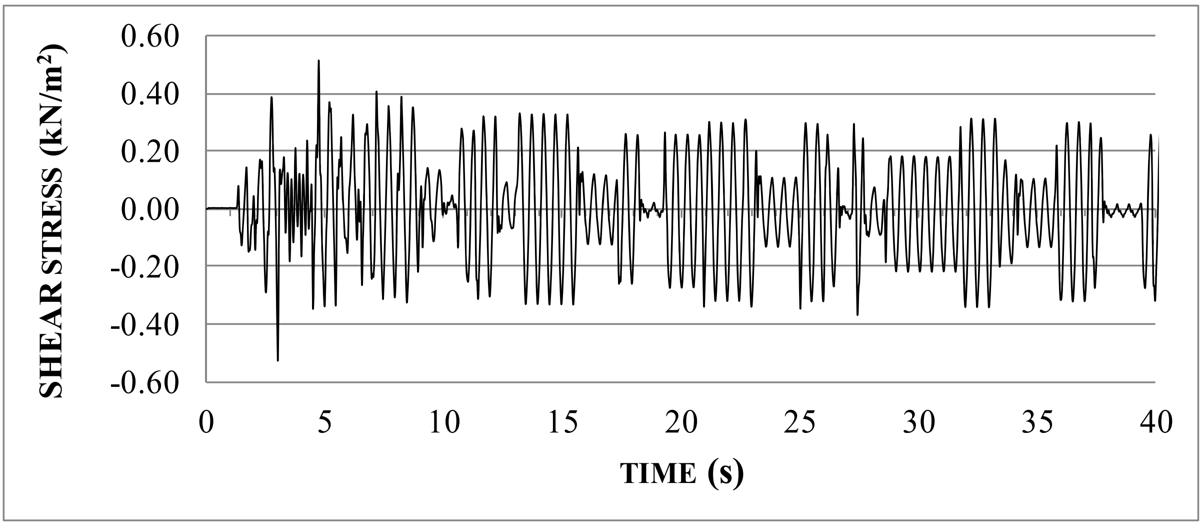


Figure 7. The shear stress time history developed in the Ganga sand for an input excitation of 5 Hz

The amplitude excitation of the input wave due to the dynamic characteristics of the Ganga sand can also be extracted from the power magnitude spectrum. Fig. 8 and Fig. 9 show the comparison of the power spectra for the input and surface wave for the excitation acceleration of 0.36g and 0.54g respectively. The Fast Fourier Transforms of the input and surface waves are developed from acceleration recordings of A6 and A1 accelerometers (Fig. 1). The peaks in the Fast Fourier Transform spectra reflect the dominant frequency of the wave. The power spectrum shows the frequency of the dominant wave as 2 Hz and 5 Hz for the input wave excitation of 0.36g and 0.54g which matches with the input frequency of the wave. The power spectra developed from accelerometer A1 (free surface motion) shows a small shift of dominant frequency as that of the input motion. Result shows that though the dominant frequency of both the free surface motion and the input wave motions are almost the same, the power magnitude of the free surface wave is amplified considerably as compared to the input wave. In Fig. 8, for an excitation acceleration of 0.36g, the power magnitude of the input wave and free surface wave is 0.085 and 0.289 respectively. Similarly in Fig. 9, for an excitation acceleration of 0.54g, the power magnitude of the input wave and free surface wave is 0.067 and 0.195 respectively. Result shows the Ganga sand provides amplification in the power magnitude of the dominant frequency of the surface wave by about 240% and 190% for the input excitation of 0.36g and 0.54g respectively.

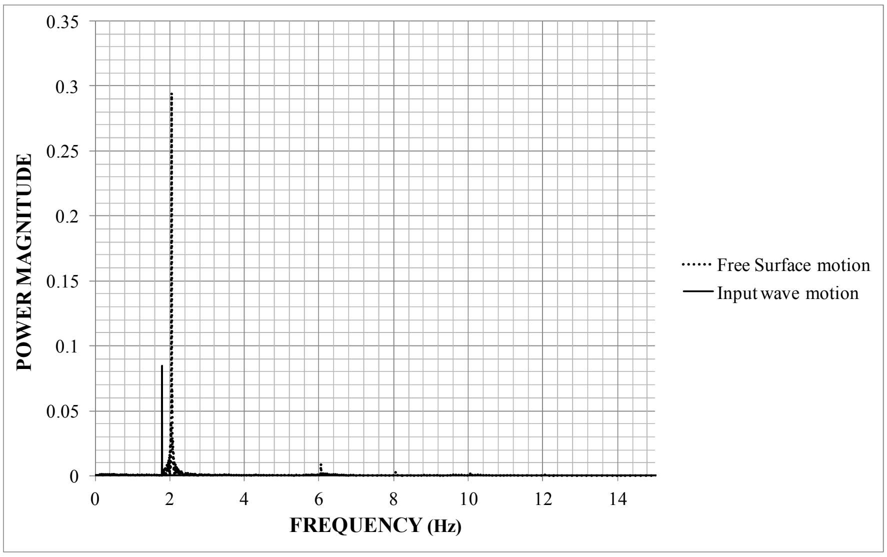


Figure 8. The power spectra plot for the input wave and the free surface motion for an excitation acceleration of 0.36g

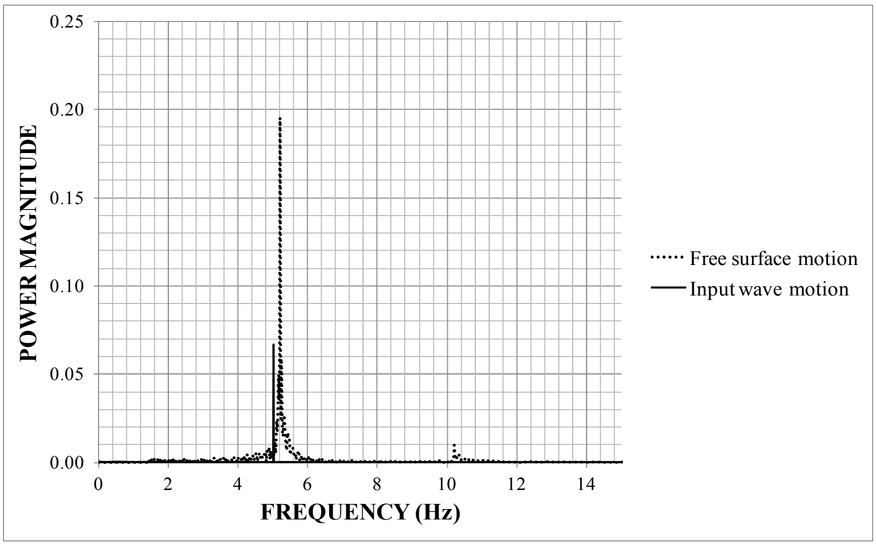


Figure 9. The power spectra plot for the input wave and the free surface motion for an excitation acceleration of 0.54g

The Fig. 10-12 compares the wave motion amplification factor as derived in Eq. (2), which characterizes the wave motion amplification through different layers of the Ganga sand, experimentally and analytically. It compares the amplification of the input peak acceleration of the acceleration time histories at each depth (accelerometer readings A1 to A5) to those predicted using SHAKE2000 analytical results. The peak acceleration of the input time histories is approximately 0.2g, 0.36g and 0.54g. Results shows that, for an excitation acceleration of 0.2g, the experimental result provides a peak ground acceleration 0.238g, whereas the calculated peak ground acceleration is about 0.267g. As for an excitation acceleration of 0.36g, the experimental result provides a peak ground acceleration 0.51g, whereas the calculated peak ground acceleration provides 0.54g. Similarly, for an excitation acceleration of 0.54g, the experimental result provides a peak ground acceleration 0.9g, whereas the calculated peak ground acceleration is about 0.83g. The Fig. 10 -12 shows a good agreement between the experimental and numerical ground motion amplification factors. The percentage difference of calculated ground amplification factors with the measured ground amplification factors are 15%, 5% and -8% for the excitation acceleration of 0.2g, 0.36g and 0.54g respectively.

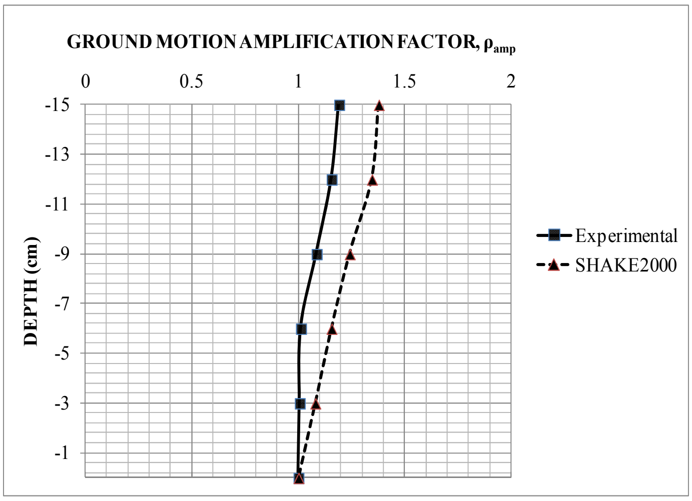


Figure 10. Comparison plot of variation of ground motion amplification factor of Ganga sand with experimental and SHAKE2000 analysis for an excitation acceleration of 0.2g

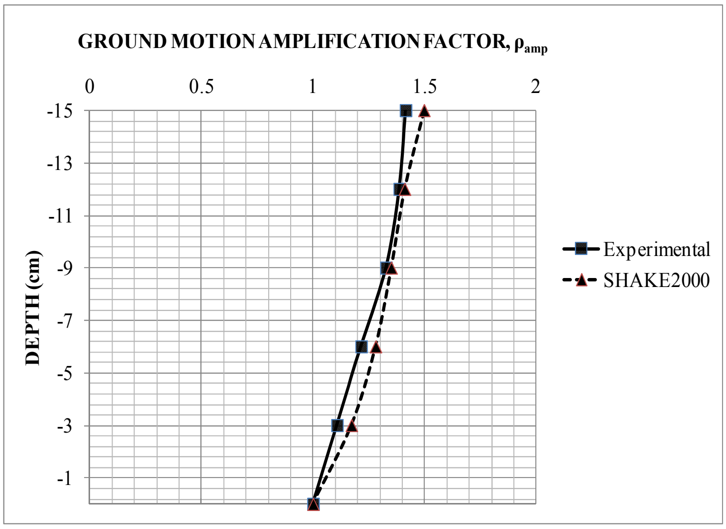


Figure 11. Comparison plot of variation of ground motion amplification factor of Ganga sand with experimental and SHAKE2000 analysis for an excitation acceleration of 0.36g

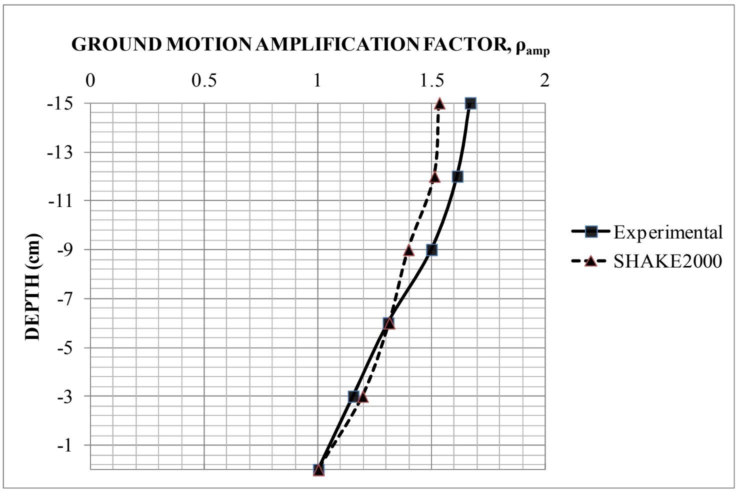


Figure 12. Comparison plot of variation of ground motion amplification factor of Ganga sand with experimental and SHAKE2000 analysis for an excitation acceleration of 0.54g

CONCLUSIONS

The present study involves ground response analysis of local Ganga sand using both experimental and analytical methodology. The experimental investigation includes shake table experiments using a flexible laminar container, whereas the analytical component involves equivalent linear approach using SHAKE 2000. The major observations obtained from the study are as follows:

1) The shake table experiments with the flexible laminar box revels that, surface wave motion shows an amplification of about 20%, 40% and 65% for the respective input excitation of 0.2g, 0.36g and 0.54g as the wave reaches the top surface of the Ganga sand.

2) Increasing in the shaking intensity increases the amplification factors of Ganga sand. As compared to soils in previous studies, the Ganga sand shows comparatively larger amplification at higher frequency.

3) From the shear stress time history, it is inferred that Ganga sand offers a higher hysteretic damping at higher excitation frequency and lower hysteretic damping at lower excitation frequency.

4) The comparison of the power spectrum of the input and surface waves shows that Ganga sand provides amplification in the power magnitude of the dominant frequency of the surface wave by about 240% and 190% for input excitation of 0.36g and 0.54g, respectively.

5) The analytical simulation of ground response is done using equivalent linear model through SHAKE 2000. The experimental observations are in good agreement with analytical results, with only 15%, 5% and 8% deviation in measured and simulated ground amplification factors for the excitation acceleration of 0.2g, 0.36g and 0.54g, respectively.

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