Study on Cyclic Response of Dry Uniform Soil Deposit using Shake Table Tests and DEEPSOIL Program

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Abstract. Ground response analysis describes the free-field response of soil deposit to an input ground motion which is used to analyze the instability of soil deposit and surface mounted structures. This paper presents a study of such response of dry uniform soil deposit on bed rock subjected to sinusoidal motion of significant frequency range comparable with typical seismic recordings. For this a series of single-axis shake table tests were carried out on uniform dry clay, sand and gravel model subjecting sinusoidal motion of suitable frequency ranges. The length to height ratio of the laboratory soil model was kept about 1.71 for shake table tests. The models were prepared by dry pluviation technique. The height and rate of pluviation were adjusted accordingly to achieve the target relative density of the soil model. An assessment of the one dimensional ground response analysis has been carried out for similar characteristics soil column model subjected to identical ground motion using DEEPSOIL v7.0.

The result obtained from the shake table tests shows the influence of frequency on response of soil model and the variation of strength and displacement parameters at different depth. These results have been compared with the DEEPSOIL assessment to show the relative difference of the parameters to express the cyclic response of dry uniform soil deposit.

Keywords: Ground Response Analysis, Shake Table Tests, DEEPSOIL.

1 Introduction

The stress wave generated from the earthquake due to sudden release of elastic energy from underlying hard stratum affects the stability of soil deposit and overlying structures. Ground response analysis is primarily based on non-linear three dimensional wave propagation theory which deals with the excitation of a soil deposit by a wave field comprising seismic waves.

This paper presents an attempt to study the free-field response of three type dry uniform soil model against some significant sinusoidal input motion using shake table model test at geotechnical engineering laboratory, NIT Agartala. An assessment on laboratory reduced scale soil model was carried out at DEEPSOIL v7.0 program with appropriate scaling of identical input parameters.

2 Literature Review

There is several theoretical and numerical background of ground response analysis depending on dynamic response of soil deposit. There are also experimental investigations for ground response with the primary object of liquefaction study by simulating seismic condition on the soil model.

The equivalent linear method is inappropriate incase of thick soil column and a high level of input motion. The nonlinear methods are most preferable in this regard. Although the above two methods are adequate to estimate the longer period components of surface motion [1].

The peak amplification factor varies inversely with natural frequency which depends on the geometry and material properties of the soil deposit [6]. The cyclic stress ratio (CSR) is affected by the geometry of the soil model. More specifically the CSR increases with decrease the length to height ratio of the soil specimen [8].

3 Experimental Approach

This is a unique approach to evaluate the response of soil deposit against an input motion at the base of the model. For this a series of single horizontal axis shake table tests were performed on reduced scale soil models to analysis the soil behavior during a seismic condition under gravitational field of earth. For the entire model tests it is assumed that the shake table only has the inertial properties and soil model above it is characterized as Kelvin-Voigt solid.

3.1 Specification of Shake Table (Uni-axial)

The present experimental study was performed using a uni-axial shake table where the platform mounted on bearing and the soil model vibrated by single horizontal actuator connected with motor. The soil models were designed based on the performance of shake table under vibrating load with considering the following parameters.

Table 1. Specification of shake table at NIT Agartala

Parameters	Configurations
Table dimension	1m x 1m x 0.01m
Mass of the platform	140 kg
Maximum specimen mass	175 kg
Maximum specimen to platform mass ratio	1.25
Maximum actuator displacement	± 100mm
Maximum table acceleration	0.1g
Maximum operating frequency	0.1 – 24.17 Hz (6 – 1450 rpm)
Required excitation power	3 phase, AC motor, 7 HP, 415V, 10.6 amp

3.2 Laboratory Soil Materials

Uniformly graded sand, gravel and high plasticity clay have been selected for the present study. Sand and Gravel were washed with water and dried at 105^{o}C before use for soil model. The physical properties of the above soil materials are listed below.

Fig.1. Typical soil materials

Table 2. Physical properties of laboratory soil sample (IS 2720).

Physical Properties	Clay	Sand	Gravel
USCS classification	CH	SP	GP
Specific Gravity (G_s)	2.75	2.67	2.78
Maximum void ratio (e_{max})	-	0.78	0.49
Minimum void ratio (e_{min})	-	0.36	0.30
Liquid Limit, LL (%)	52.71	-	-
Plastic Limit, PL (%)	27.77	-	-
Plasticity Index, I_P (%)	24.94	NP	NP

3.3 Design of Soil Model

All the soil models for the present experimental investigations were designed primarily based on configuration and operating condition of shake table. The dimensions of soil bin must be satisfied following two criteria.

- The mass of the model with soil bin should not exceed the allowable mass of the specimen within the shake table.
- The developed shear stress within the soil model against any vibrating frequency should be less than the maximum shear stress that can be achieved by shake table operated at limiting condition.

The power required to operate shake table was 7 HP (5.22 kW), which develop a maximum operating frequency of 24.17 Hz (i.e. 1450 rpm). Now from the work done capacity of the system per second, it was determined that the shake table can be achieved a maximum shear stress of about 23.07x10^{3} kN/m^{2}. So based on this criterion the resultant dimension of model container was 600 mm x 400 mm in plan and 400 mm in height. The mass of the soil model container was kept about 25 kg.

Fig. 2. Soil model container monolithically attached with shake table

The soil models were prepared by dry pluviation technique using hopper from a calibrated height to maintain the uniform density throughout the model. The rate of pluviation was adjusted to achieve the target relative density.

Table 3. Specification of the laboratory soil model

Soil Model	Symbol	Dimension* (L x B x H)	Void ratio	Density (gm/cc)	Sample Mass (kg)	Relative Density (%)
Uniform Clay Soil	UCSM	60 x 40 x 35	0.796	1.531	128.58	NA
Uniform Sand Soil	USSM	60 x 40 x 35	0.655	1.613	135.50	29.71
Uniform Gravel Soil	UGSM	60 x 40 x 16	0.433	1.940	74.50	30.04

*Dimension of the soil models are in cm.

3.4 Instrumentation and Measurement

- Traditional Accelerometer: Four Piezoelectric, DeltaTron®4507001 accelerometers were used in this study to measure the acceleration time history at the respective position of the soil model and platform with the application of NVGate® V6.00. The accelerometers were placed along primary diagonal of soil models at different depths from base of the model.

Table 4. Position of Traditional Accelerometers to the soil model from the base of model

Soil Model	Accelerometer 1	Accelerometer 2	Accelerometer 3	Accelerometer 4
UCSM	10 mm	150 mm	250mm	Platform
USSM	10 mm	100 mm	200 mm	Platform
UGSM	20 mm	50 mm	70 mm	Platform

- VARIAC (Single coil Transformer): This is a significant component of control panel to control the frequency of shaking. It is a variable autotransformer which controls the frequency of motion in terms of percentage output voltage which was calibrated using Tachometer. The maximum percentage output voltage was 100 which develop a shaking motion of 1450 rpm.

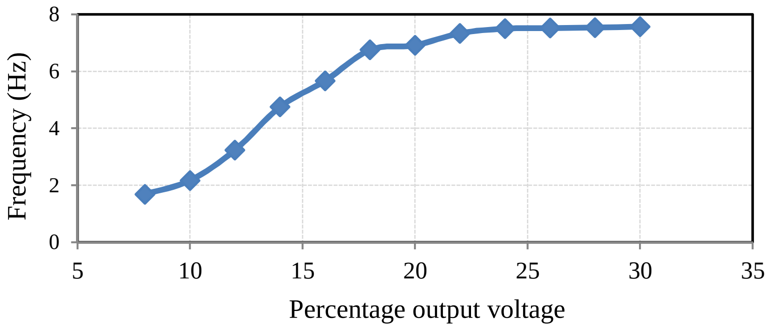

Fig. 3. Calibration of VARIAC against frequency using Tachometer

- OROS 3-Series Analyzer: This is the main component of control system which was connected with computer and four accelerometers at respective input panels to record and analyzed the signal. NVGate® V6.00, the OROS 3-Series analyzer multi-analysis software platform was applied to develop the spectral distribution of the analyzed signals like FFTs.

- AC induction motor: Three phase AC induction motor was used to vibrating the platform at a required frequency. The capacity of the motor was 7 HP.

3.5 Laboratory Input Motion

The uniform soil models were subjected to sinusoidal base motion of significant frequency range from 1.75 Hz to 6.00 Hz.

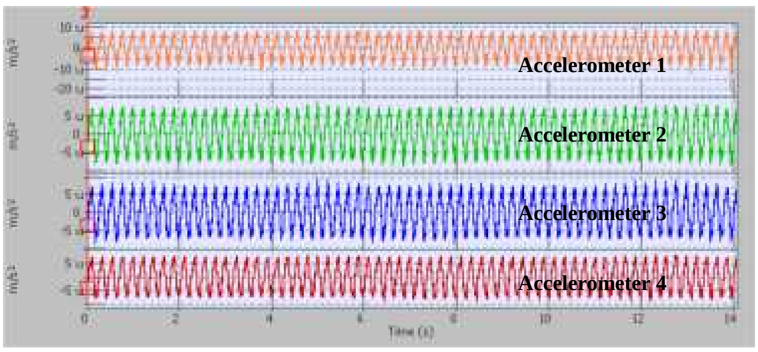

Fig. 4. Typical acceleration time history of UGSM at 4.50 Hz

3.6 Test Program

There are total 16 tests on three uniform soil model of about 30% relative density which were performed at 1.75Hz, 2.25Hz, 2.75Hz, 3.25Hz, 3.50Hz, 4.50Hz. To show the significant variation of the amplification factors against frequencies, some tests were also assigned to higher frequencies, such as, 5.00Hz, 5.25Hz, 5.50Hz, 6.00Hz on the soil model.

Based on the performance of shake table at different payload, the frequencies were achieved for the three different soil models.

4 An Assessment of 1D Ground Response Analysis

This section describes the one dimensional site response analysis program of scaled uniform experimental soil model under a strong ground motion on DEEPSOIL v7.0.

4.1 Soil Column Models

The one dimensional uniform layered soil column models were designed based on scaled identical parameters of shake table soil model. As the base of the shake table models were treated as rigid and the accelerometers were placed at different depth position, the soil columns are also designed as layered damped soil on rigid bed rock. The entire programs were analyzed by nonlinear time domain approach.

Table 5. Properties of scaled soil column models

Soil Model	Scale*	Layer	Height (m)	Density (gm/cc)	Shear wave velocity (m/s)
UCSM	100	4	35	1.531	180
USSM	100	4	35	1.613	300
UGSM	100	4	16	1.940	360

* Scale represents the soil column height with respect to laboratory soil model.

4.2 Selection of Input Ground Motion

For the present study single component of ground motion were selected based on corresponding maximum response of laboratory soil model for analysis of designed soil columns using DEEPSOIL v7.0 [10].

Table 6. Selection of Input Ground Motion

Soil Model	a_{max} (g)	Sensor	Depth	Frequency	Input Motion	a_{max}	Scale*
UCSM	$4.45x10^{-7}$	3	25cm	5.5 Hz	Mammoth Lake	0.38g	$8.5x10^{5}$
USSM	$8.57x10^{-7}$	3	20 cm	6.0 Hz	Kobe	0.58g	$6.8x10^{5}$
UGSM	$5.97x10^{-7}$	3	7 cm	5.5 Hz	Kobe	0.58g	$9.7x10^{6}$

* Scale represents the acceleration of input motion to the laboratory soil model.

5 Analysis of Laboratory Model Test Result

The laboratory model test programs were designed as uniform soil on rigid rock subjected to significant bedrock motion. The result shows the influence of frequency on the response of soil model at different depth by plug-in of NVGate ® in FFTs. Briefly it can say that FFT converts an acceleration time signal to the frequency domain by appropriate algorithms.

The natural frequencies are corresponding to the local maxima of acceleration response of the soil model [6]. The fundamental frequency is the lowest natural frequency having highest soil response and the corresponding period of vibration is known as characteristics site period [6].

5.1 Uniform Clay Soil Model (UCSM)

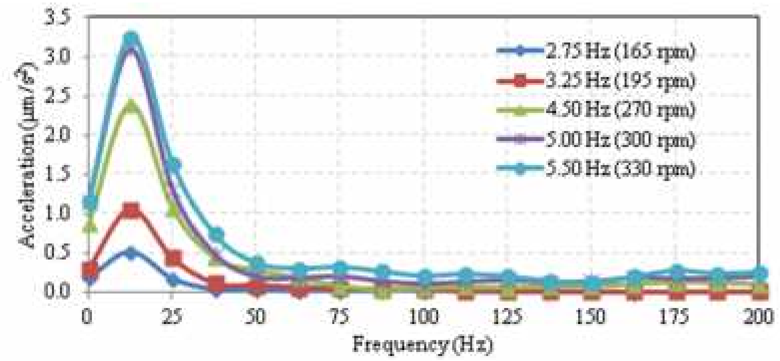

Fig. 5. Influence of frequency on response of UCSM layer at 10 mm from base

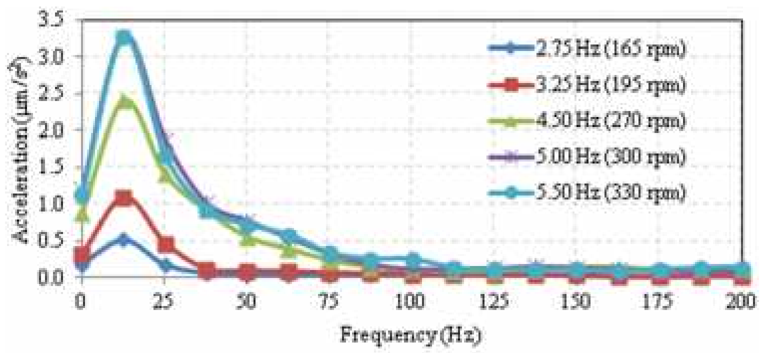

Fig. 6. Influence of frequency on response of UCSM layer at 150 mm from base

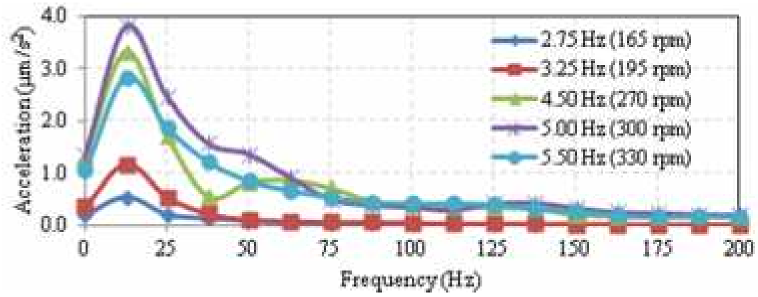

Fig. 7. Influence of frequency on response of UCSM layer at 250 mm from base

For the UCSM model vibrating under different frequency loading attain a same fundamental frequency 12.5Hz. Hence considering this as a constant parameter we can compare the variation of amplification factor in different depth at various exciting frequency. It shows that the amplification factor will be high near the model surface and it more significantly varies at lower frequency and at lower depth.

5.2 Uniform Sand Soil Model (USSM)

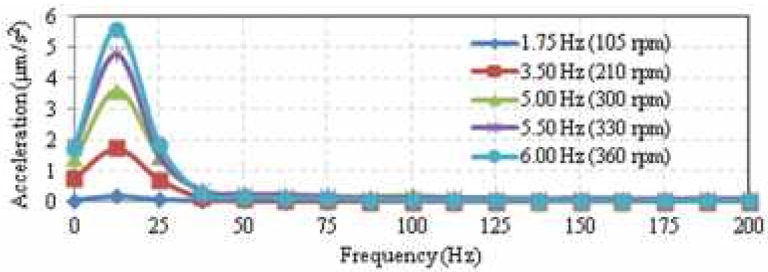

Fig. 8. Influence of frequency on response of USSM layer at 10 mm from base

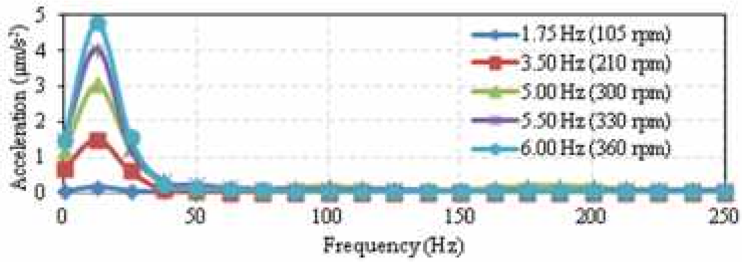

Fig. 9. Influence of frequency on response of USSM layer at 100 mm from base

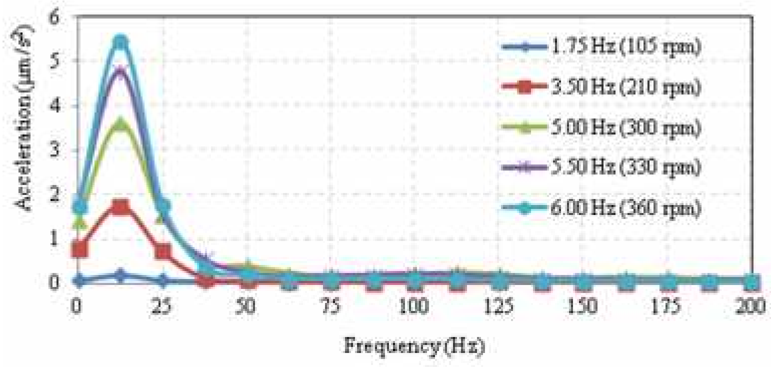

Fig. 10. Influence of frequency on response of USSM layer at 200 mm from base

The uniform sand soil models (USSM) also attain a same fundamental frequency of 12.5Hz as UCSM model at different vibrating frequency. In this model the amplification factor attains a maximum value just above the model base which increases proportionally with exciting frequency. Then the amplification factor attenuated up to depth of 100 mm towards the ground surface. It again starts to increase toward the model surface and attain a maximum value near soil surface. From the comparison of UCSM and USSM model it can say that unlikely the UCSM model, USSM model attains a significant variation of amplification factor throughout the depth at higher frequency.

5.3 Uniform Gravel Soil Model (UGSM)

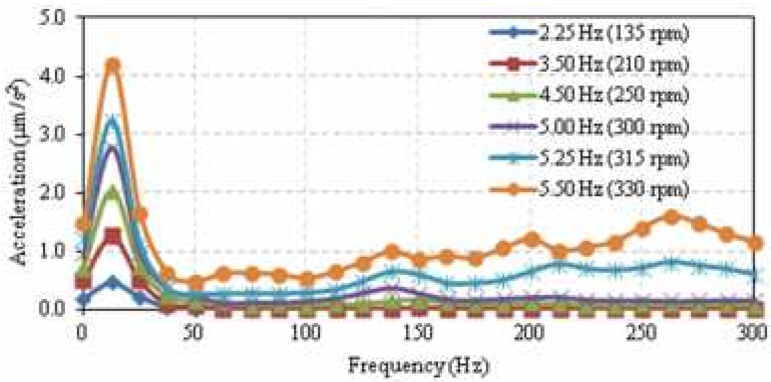

Fig. 11. Influence of frequency on response of UGSM layer at 20 mm from base

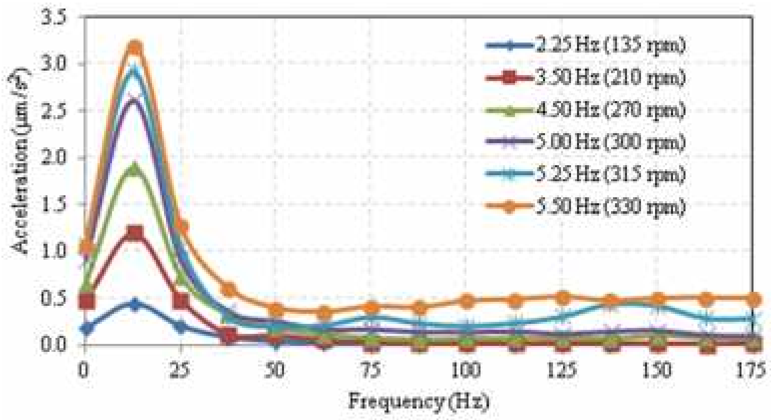

Fig. 12. Influence of frequency on response of UGSM layer at 50 mm from base

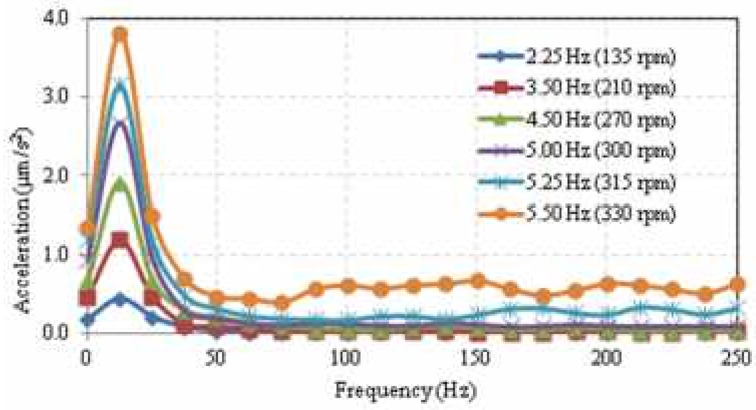

Fig. 13. Influence of frequency on response of UGSM layer at 70 mm from base

In case of uniform gravel soil model (UGSM), the amplification factor varies same way as USSM model though the base layer attains the higher value than surface layer.

6 1D Ground Response Assessment Results

As the surface layer of laboratory soil model attains a maximum value of spectral acceleration and amplification factor during vibration, it will be more significant to compare the one-dimensional ground response assessment result for surface layer.

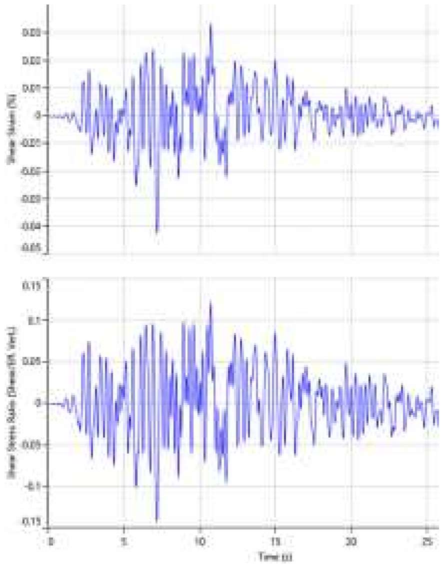

Fig. 14. Shear strain and shear stress ratio at surface layer of USCM

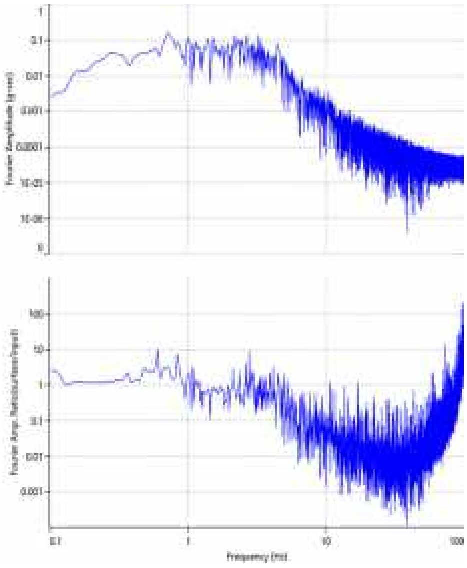

Fig. 15. Fourier amplitude spectrum of surface layer of USCM

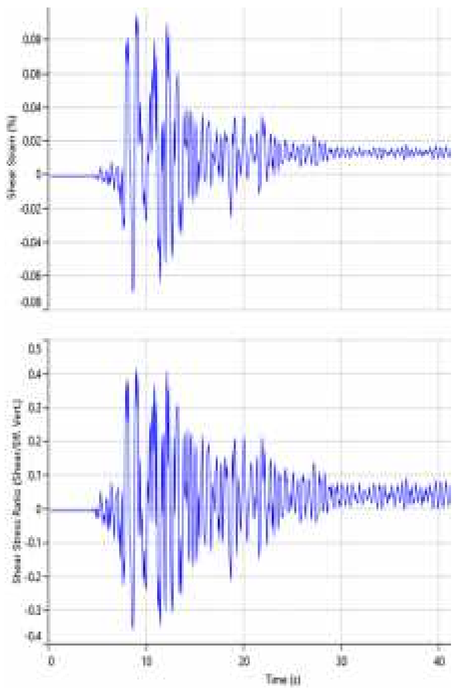

Fig. 16. Shear strain and shear stress ratio at surface layer of USSM

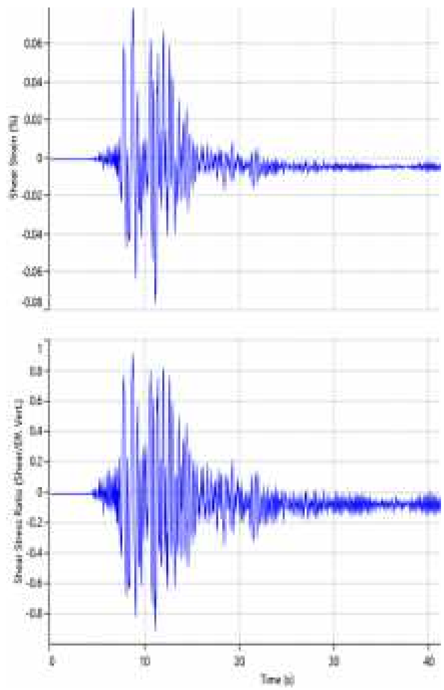

Fig. 17. Fourier amplitude spectrum of surface layer of UGSM

7 Conclusion

From the present experimental study and an assessment of identical soil column model on DEEPSOIL v7.0, the following conclusions can be drawn.

- For clay, amplification factor and spectral acceleration are significantly increases towards the soil surface specifically at low frequency vibration.
- For sand and gravel, amplification factor and spectral acceleration are highest near the base (i.e., bed rock) and gets attenuated upto a certain depth and again attain a highest value near the soil surface. In these cases the variation along the depth will be significant at higher frequency (probably greater than 5 Hz).
- Sand surface level reached highest amplitude of shear strain and shear stress ratio. Though for clay surface these parameters are more prominent at lower intensity of vibration.

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