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IMPACT OF FREQUENCY CONTENT OF INPUT MOTION UPON LOCAL SITE EFFECT

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ABSTRACT

Occurrence of frequent earthquakes and the damages related to those are very difficult to control. Earthquakes can neither be prevented nor can be predicted. However, if the probable damages can be quantified in advance, suitable measures can be taken in the design parameters and appropriate considerations can be implemented in city planning. For a structure the stability of the foundation is equally important as that of superstructure's components. For a foundation to be stable, the designer should assess the actual level of ground shaking during the future earthquake. The level of ground shaking is measured at different recording stations in terms of the time history of the motion. Ground motion recorded during an earthquake covers a wide range of frequency content, amplitude and duration. Depending upon the characteristics of the superstructure, some of the frequencies may lead to resonance. The impact of ground motion on a structure can be determined once the Fourier spectra and response spectra at the site are known. While the Fourier spectra describe the motion in frequency domain, response spectra on the other hand take into account the natural frequency of the system itself. Past reported damages during many of the moderate to great earthquakes had clearly highlighted that the earthquake induced damages are not only confined to the epicentral region but moderate to considerable damages at large distant regions were also evidenced. Examples include 1897 Shillong earthquake (EQ), 1950 Assam EQ, 1999 Chamoli EQ, 2001 Bhuj EQ, 2011 Sikkim EQ and 2011 Sendai EQ are some of the classical examples where massive damages were recorded even at large distance as a result of local site effect. Once a motion in the form of wave travels upward from the bedrock to the ground level, it gets altered. For a safe earthquake design, the designer should consider these altered ground motions at the surface in the design. A typical site response analysis should be conducted to understand the change in various ground motion characteristics between the bedrock and the surface. Depending upon the subsoil properties, separate responses can be obtained for different subsoil deposits. The level of ground motion at the bedrock determined from a detailed seismic hazard analyses, should be taken into account while selecting the input motion for the site response analysis. In the absence of regional ground motion records, uses of recorded ground motion from other parts of the world are practiced for understanding the response of a site. The outcome of a typical site response analysis will provide information about the spectral acceleration at the surface, amplification factor range for the subsoil type and information about the predominant frequency of the motion as well. Based on several site response analysis studies, the limitation of Indian standard code in evaluating the local site effect was highlighted. In the present work, a new MATLAB code has been developed to perform site response analysis using linear approach in the frequency domain. Further using the developed coding site response of a typical borelog is attempted in this work. Due to very limited to no recorded ground motion available at bedrock for the site under consideration, 30 input motions from different parts of the world are considered. All the selected input

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motions were recorded at bedrock during different earthquakes. In the absence of recorded ground motions at the site, selected input motions show a wide range of ground motion characteristics. These input motions are applied at the base of a typical soil column and the responses in terms of change in predominant frequencies between the bedrock and the surface are observed. All the analyses are performed considering elastic halfspace below the soil column. Based on the present analysis, minimal to large shifts in the predominant frequencies of motions are observed between the bedrock and the surface for each input motion. Input motions with multiple peaks in the Fourier spectra, distributed over a wide range of frequencies show a considerable shift in the predominant frequency in various layers between the bedrock and the surface. On the other hand for input motions with single peak in Fourier spectra, the predominant frequency at the surface is found closer to the natural frequency of the soil column. Further for input motions having predominant frequencies close to the natural frequency of the soil column, no shift in the predominant frequencies between the bedrock and the surface are observed. These observations show that the predominant frequency of the surface motion is highly influenced by the frequency content of the input motion. Thus the maximum response at the surface can be observed even at frequencies other than the natural frequency of the soil column. Above observations are made based on linear ground response approach. Similar works based on equivalent linear and non linear ground response approaches can be attempted in the future.

Keywords: ground motion characteristics, site effects, site response, frequency shift, predominant frequency, natural frequency

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ABSTRACT: Near surface geology plays important role in modifying ground motion parameters. Site response analysis can be carried out to know the altered properties of the ground motion in advance. In this work a MATLAB program which can perform site response analysis in linear frequency domain method is developed. Further thirty input motions covering a wide range of ground motion characteristics are considered for site response of a soil column in order to understand the change in frequency content between the bedrock and the surface. Based on analyses, a large to negligible shift in the predominant frequency is observed.

INTRODUCTION

Near surface geology takes important role in modifying both amplitude as well as the frequency content of a surface motion. Thus, estimation of site response or local soil effects becomes absolute necessity. Classification systems considering average strength properties of local soil are available as per various standards [1; 2; 3]. Such quantitative classifications of local soil based on strength properties are very limited in different codal provisions. This shortcoming of standard codes has been highlighted by various researchers for India in the past. However the effect of local soil can be determined by performing regional site response studies. The response of a soil column to an earthquake loading can be found out mainly in two ways; The Time Domain analysis and the Frequency Domain analysis [4]. The time domain method is suitable for linear and non-linear analysis [5]. The soil is a highly inelastic material. Overcoming the challenges in accounting for the actual hysteresis loop of soil behaviour in modelling, equivalent linear approximations of nonlinear properties of soil (shear modulus, damping) are done in frequency domain which is known as equivalent linear approach for site response analysis [6]. The linear analysis can be performed both in time domain as well as in the frequency domain. In the time domain analysis, the governing equation of motion for linear approach $\{\ddot{x} + 2\beta\omega\dot{x} + \omega^2 x = a(t)\}$is repeatedly solved to get exact solution for the complete acceleration time history [7].In frequency domain analysis for linear approach, the acceleration time history of bedrock motion is first converted into frequency domain by discrete Fourier transformation. Then it is multiplied with transfer function obtained based on the solution of the wave equation between bedrock and the soil layer above it. This will give Fourier spectra at the top of soil layer. The acceleration time history at top of soil layer will be obtained by inverse fast Fourier transformation of above Fourier spectrum [6]. In this paper, site response based on linear approach in frequency domain is adopted. The objective of the present analysis is to understand the response of a typical soil column in terms of frequency content of motions at the bedrock and the surface. A MATLAB program for finding out response of multi-layered soil profile has been developed using linear approach in frequency domain.

RESPONSE OF MULTIPLE LAYERS RESTING ON ELASTIC HALFSPACE

Consider an elastic soil layer of uniform thickness H resting on elastic half space as shown in Fig 1. The displacement of a soil particle in a layer due to external loading is a function of time as well as position of the particle in the soil layer. This displacement can be determined as [6];

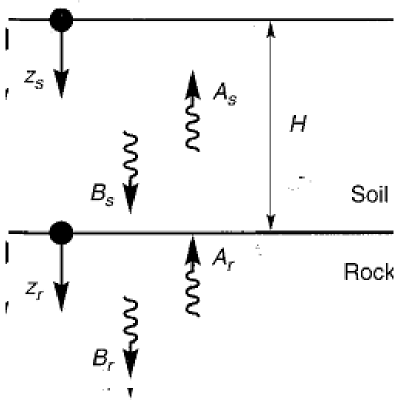

Figure 1, Elastic layer resting on elastic half space [6]

$$u_s(z,t) = A_s e^{i(\omega t + k_s^* z_s)} + B_s e^{i(\omega t + k_s^* z_s)} \quad (1)$$

where u_s is the displacement of the particle, A_s and B_s are the amplitudes of waves travelling in the negative and positive z_s direction respectively (Fig. 1), ω is the circular frequency of external loading, t represents the time and k_s^* is a complex wave number, which can be obtained as [6];

$$k_s^* = \frac{\omega}{V_s^*} = \frac{\omega}{V_s(1+i\beta)} \quad (2)$$

Where, V_s is the shear wave velocity of soil layer, β is the material damping in percent and ω is the circular frequency of external loading.
Similarly, the displacements in the elastic half space below the soil can be determined as [6];

$$u_r(z,t) = A_r e^{i(\omega t + k_r^* z_r)} + B_r e^{i(\omega t + k_r^* z_r)} \quad (3)$$

Considering the free surface condition, stress and displacement compatibility at the interface, the following relationships can be obtained [6];

$$A_r = \frac{1}{2} A_s[(1+\alpha_s^*)e^{ik_s^* H} + (1-\alpha_s^*)e^{-ik_s^* H}] \quad (4a)$$

$$B_r = \frac{1}{2} A_s[(1-\alpha_s^*)e^{ik_s^* H} + (1+\alpha_s^*)e^{-ik_s^* H}] \quad (4b)$$

Where $\alpha_s = \frac{\rho_s V_{ss}^*}{\rho_r V_{sr}^*}$, knows as specific impedance , V_{ss}^* is the complex shear wave velocity in soil layer and V_{sr}^* is the complex shear wave velocity in elastic half space which is considered as rock in this case.
For the case having number of elastic layers one upon the other, the values of amplitudes A and B for each layer starting from the free surface layer (1, 2, 3, …) can be written as [6];

$$A_1 = B_1 \quad (5)$$

$$A_2 = \frac{1}{2}[A_1 (1+\alpha_1^*)e^{ik_1^* H_1} + B_1(1-\alpha_1^*)e^{-ik_1^* H_1}] \quad (6)$$

$$B_2 = \frac{1}{2}[A_1 (1-\alpha_1^*)e^{ik_1^* H_1} + B_1 (1+\alpha_1^*)e^{-ik_1^* H_1}] \quad (7)$$

Similarly,

$$A_3 = \frac{1}{2}[A_2(1+\alpha_2^*)e^{ik_2^* H_2} + B_2 (1-\alpha_2^*)e^{-ik_2^* H_2}] \quad (8)$$

$$B_3 = \frac{1}{2}[A_2 (1-\alpha_2^*)e^{ik_2^* H_2} + B_2 (1+\alpha_2^*)e^{-ik_2^* H_2}] \quad (9)$$

Where the subscripts in the above equations denote soil layer number starting from the free surface. Using the above equations, the amplitudes of displacements in any two layers p & q will be related as [6];

$$\frac{u_p}{u_q} = \frac{A_p + B_p}{A_q + B_q} \quad (10)$$

Similarly, the acceleration amplitudes of p^{th} and q^{th} layers ($\ddot{u}_p$ and $\ddot{u}_q$ respectively) can be also determined using the correlation $\frac{\ddot{u}_p}{\ddot{u}_q} = \frac{\omega^2 u_p}{\omega^2 u_q}$. In case, the acceleration history of one layer is known, the acceleration time history for another layer can be determined using the above equation. In the present work, a MATLAB coding is s developed to estimate the ratio $\frac{u_p}{u_q}$ as per the above discussion for specific values of p and q to be decided by the user. The code will follow an iterative procedure to calculate $\frac{u_p}{u_q}$ starting from free surface towards deeper layers in accordance with eq. 10. If q is considered as the bedrock layer number where the input motion is applied, output at any layer can be calculated from the developed code.

INPUT DATA CONSIDERED

For the present work, a typical borehole shown in Table 1 is selected to perform the site response analysis [8]. Borehole properties such as layer thickness, density, and shear wave velocity (SWV) can be put as input parameters in the code for a multilayer system. Field measured N-SPT values were converted to SWV using the correlation $V_s = 68.96\ (N)^{0.51}$[9]for all soil type. This correlation was developed based on measured N-SPT and SWV till 30 m depth for the city of Lucknow. Damping ratio of 5% is considered for all the soil layers. For the bottom most layer which is considered to be elastic half space having SWV greater than 700 m/s, a damping value of 2% [10] is used in the modeling. In absence of recorded ground motion for this site, 30 globally recorded input motions have been selected from SHAKE2000 [11] database as listed in Table 2. All the selected ground motions show a large variation in the ground motion characteristics. Peak Ground Acceleration (PGA) and frequency content of these motions are varying from 0.008g to 1.03g and 0.26 Hz to 16.5 Hz respectively as can be observed form Table 2.

Table 1.Borehole considered in the analysis [8]

GWT at 0.9m below Ground level (GL)							
Depth below GL	Soil description	Thickness of layer (m)	Soil classification	Sample	SPT N values	V_s	Unit weight (KN/m^3)
1	Fill	1			2	98.2	17
2	Silty sand	1	SM	UDS	4	139.84	17.33
3	low compressibility clay	1	CL	SPT			
4	Silty sand	6	SM	SPT	8	274.7	18.5
5				SPT	14		
6				SPT	18		
7				UDS			
8				SPT	22		
9				UDS			
10	Medium compressibility	2	CL	SPT	24	374	19.21
11				SPT	26		
12	Silty sand	8	SM	UDS	33	524	20.41
13				SPT			
14				SPT	37		
15				UDS	45		
16				SPT			
17				SPT	55		
18				UDS	62		
19				SPT			
20	Medium compressibility clay	4	CL	SPT	71	607.36	21.08
21				UDS	66		
22				SPT			
23				SPT	69		
24	Silty sand	3	SM	UDS	79	682	21.67
25				SPT			
26				SPT	84		
27	Medium compressibility clay	3	CL	UDS	95	714.61	22
28				SPT	96		
29				SPT	101		

ANALYSIS

Using the developed MATLAB code in accordance with the methodology discussed earlier, linear site response analyses are performed. The developed code facilitates the assignment of selected acceleration time history to one layer and its response in another layer can be determined. Both the layers can be chosen by the user in the code. In the present work, in order to understand the response of the borehole considered above to the selected ground motions, the input is assigned at the bottom most layer and response in all other layers are estimated.

RESULTS AND DISCUSSION

For all the thirty input motions, outputs in the form of Fourier spectra at all the layers are found. Based on the obtained Fourier spectra, predominant frequency at each layer are determined. Table 3 presents the variation in predominant frequency versus layer corresponding for all the input motion. Values tabulated under lay8 (Layer 8) are the predominant frequencies of input motions. It can be seen from the Table 3 that for some motions, the shift in predominant frequency is large between bedrock and surface however for others, this shift is negligible. In case of input motions 10 and 27, the shift in the predominant frequency is less whereas for rest of the input motions, a large shift in the predominant frequency is observed as shown

Table 2.Details of input motions selected

Sr. No.	Ground Motion Details as per SHAKE2000	PGA (g)	Duration (s)	Predominant Frequency (Hz)
1	ADAK, ALASKA 1971-M 6.8;R-67KM, N81E	0.098	24.58	3.32
2	ANCHORAGE, ALASKA 1875, M-6, R81-GOULE HALL STATION	0.036	18.59	5.42
3	ANCHORAGE ALASKA 1975, M 6, R 79, WESTWARD HOTEL STATION (BASEMENT)	0.049	38.96	1.00
4	ANZA 02/25/80, BORREGO AIR BRANCH 225	0.046	10.25	2.39
5	ANZA 02/25/80 1047, TERWILLIGER VALLEY 135	0.080	10.01	6.54
6	BISHOP-ROUND VALLEY 11/23/84 1914, MCGEE CREEK SURFACE 270	0.075	6.80	3.9
7	BORREGO MOUNTAIN 04/09/68 0230, EL CENTRO ARRAY 9, 270	0.056	39.95	0.46
8	BORREGO MOUNTAIN 04/09/68 0230, PASADENA-ATHENAEUM, 270	0.009	60.23	0.61
9	BORREGO MOUNTAIN 04/09/68 0230, TERMINAL ISLAND, 339	0.008	51.80	2.50
10	CAPE MENDOCINO EARTHQUAKE RECORD 04/25/92, MW-7.0, 90 DEG COMPONENT	1.03	59.98	4.44
11	CHALFANT 07/20/86 1429, BISHOP PARADISE LODGE,070	0.046	39.95	16.5
12	CHILE EARTHQUAKE, VALPARAISO RECORD, 3/3/85	0.120	79.39	2.1
13	COALINGA 05/02/83 2342 PARKFIELD, FAULT ZONE 6/ 090	0.055	39.95	0.43
14	COALINGA 05/09/83 PALMER AVE ANTICLINE RIDGE, 090	0.215	40.00	2.29
15	GEORGIA, USSR 06/15/91 0059, BAZ X	0.033	34.07	1.22
16	IMPERIAL VALLEY 10/15/79 2319, BONDS CORNER 230	0.100	19.88	1.41
17	KERN COUNTY 7/21/52 11:53, SANTA BARBARA COURTHOUSE 042	0.086	75.35	1.84
18	KOBE 01/16/95 2046, ABENO 000	0.22	139.98	0.26
19	KOBE 01/16/95 2046, KAKOGAWA 000	0.250	40.91	0.91
20	KOBE 01/16/95, KOBE PORT ISLAND 090	0.530	42	0.79
21	LIVERMORE 01/27/80 0233, HAYWARD CSUH STADIUM 236	0.027	15.98	3.61
22	LIVERMORE 01/27/80 0233 LIVERMORE MORGAN TERR PARK 265	0.197	24	5.61
23	LOMA PRIETA TA 10/18/89 00:05, ANDERSON DAN DOWNSTREAM 270	0.240	39.59	2.14
24	LOMA PRIETA TA 10/18/89 00:05, HOLLISTER DIFF ARRAY 255	0.270	40	1.48
25	MICHIOACAN EARTHQUAKE 19/9/85, CALETA DE CAMPOS, N-COMPONENT	0.140	81.06	1.39
26	NORTHERN CALIFORNIA 09/22/52 1141, FERNDALE 134	0.070	40	1.31
27	NORTHRIDGE EQ 1/17/94 1231, ANACAPA ISLAND	0.013	40	4.46
28	NORTHRIDGE EQ 1/17/94 1231, ARLETA 360	0.310	39.94	1.46
29	PARKFIELD 06/28/66 04:26, CHROME # 8	0.116	26.09	0.85
30	TRINIDAD 11/08/08, 10:27, RIO DEL OVERPASS E	0.130	22.0	3.14

in Table 3. It is observed that for majority of the input motions, shift in the predominant frequency has occurred only once and then remains constant at layers compared to input motion. However, there are input motions such as motion 2 and 6 where shift in predominant frequency is observed recurrently between the layers from bedrock to the surface as shown in Table 3. Another important observation which can be made from Table 3 is that for all the input motions, predominant frequencies obtained at the surface are in the range 4.37 Hz to 4.84 Hz except for input motion 2 and 6. A detailed discussion explaining the possible reasons of such shifts has been attempted further. Fourier amplification ratio (F.A.R.) which is defined as the ratio of Fourier spectrum of response to Fourier spectrum of input motion [10]. The plots of F.A.R. versus frequency in accordance with eq. 10 for input motion 10 are presented for all the layers as shown in Fig 2. It has to be highlighted here that plots shown in Fig. 2 will be identical for all the input motions. It is because the linear method of site response analysis uses constant values of layer properties (shear modulus and damping ratio) independent on strain levels or acceleration time history. Thus, for all the motions, the plots shown in Fig. 2 will remain same. From Fig 2 it can be seen that peaks of F.A.R. is occurring nearly at the same frequencies for all the layers and these frequencies are found out to be 4.66 Hz and 9.91 Hz. The natural frequencies of soil column for different modes can be predicted with these results [10]. In this case the fundamental natural frequency of soil column is 4.66 Hz and in 2nd mode, the natural frequency is 9.91 Hz. The values of F.A.R. at these two natural frequencies will have a direct impact on the predominant frequencies of motion at different layers. In order to further elaborate this statement, consider an input motion having predominant frequency 'f_p'. This motion will experience a shift in the predominant frequency from f_p to a new frequency f_{p1} only when;

$$\mathrm{Amp}_{p1} * \mathrm{F.A.R.}_{p1} > \mathrm{Amp}_{p} * F.A.R._{p} \qquad (11)$$

Where, Amp_p, Amp_{p1} represent Fourier amplitudes at frequency f_p and f_{p1} respectively. $\mathrm{F.A.R.}_p$ and $\mathrm{F.A.R.}_{p1}$ represent the values of F.A.R. at frequency f_p and f_{p1} respectively. Since Amp_p is the Fourier amplitude at predominant frequency f_p, its amplitude will be higher than the amplitude Amp_{p1} at any other frequency f_{p1}. Thus, shift in the predominant frequency of motion at any layer, will entirely depends on the value $\mathrm{F.A.R.}_{p1}$ in accordance with eq. (11). Further, the value of $\mathrm{F.A.R.}_{p1}$ will be maximum at frequency close to natural frequency of soil column (4.66 Hz in Fig 2). Hence, an input motion has high chances of shift, to a predominant frequency close to 4.66 Hz.

In another observation, it can be seen from Table 3, input motions 10 and 27 having predominant frequencies (4.44 Hz and 4.46 Hz respectively) very close to the fundamental natural frequency of the soil column. For this reason, the Amp_p of input motions 10 and 27 near their respective predominant frequencies experience maximum $\mathrm{F.A.R.}_p$. The values of Amp_{p1} however cannot have $\mathrm{F.A.R.}_{p1} > \mathrm{F.A.R.}_p$ to show a shift in predominant frequency. In addition, other input motions (other than 10 and 27) having

Table 3, Frequency contents of all responses

Predominant frequencies of responses										
Input motion no	1	2	3	4	5	6	7	8	9	10
lay1	4.71	9.91	4.81	4.78	4.39	10.35	4.54	4.77	4.56	4.60
lay2	4.73	4.73	4.81	4.78	4.39	10.35	4.54	4.77	4.56	4.60

lay3	4.73	4.73	4.81	4.78	4.39	4.68	4.54	4.77	4.56	4.44
lay4	4.71	4.73	4.81	4.73	4.39	10.35	4.54	0.61	0.44	4.44
lay5	4.71	9.91	4.81	4.73	4.39	10.35	4.54	0.61	0.44	4.44
lay6	4.22	9.91	1.00	2.39	4.39	3.9	0.46	0.61	0.39	4.44
lay7	4.22	9.91	1.00	2.39	6.54	3.9	0.46	0.61	0.39	4.44
lay8	3.32	5.42	1.00	2.39	6.54	3.9	0.46	0.61	0.39	4.44
Predominant frequencies of responses										
Input motion no	11	12	13	14	15	16	17	18	19	20
lay1	4.44	4.66	4.39	4.71	4.73	4.44	4.77	4.52	4.84	4.62
lay2	4.44	4.66	4.39	4.71	4.73	4.44	4.77	4.52	4.84	4.62
lay3	4.44	4.66	4.39	4.71	4.73	4.44	4.77	4.52	4.84	4.62
lay4	4.44	4.66	4.39	4.71	4.73	4.44	1.84	4.52	4.84	4.62
lay5	4.44	4.66	4.39	4.71	4.71	4.44	1.84	4.52	4.84	0.79
lay6	4.44	4.66	0.44	2.29	4.54	1.41	1.84	0.26	2.72	0.79
lay7	16.5	3.89	0.44	2.29	4.49	1.41	1.84	0.26	2.72	0.79
lay8	16.5	2.10	0.44	2.29	1.22	1.41	1.84	0.26	0.91	0.79
Predominant frequencies of responses										
Input motion no	21	22	23	24	25	26	27	28	29	30
lay1	4.64	4.61	4.78	4.61	4.79	4.73	4.68	4.37	4.64	4.59
lay2	4.64	4.61	4.78	4.61	4.79	4.73	4.68	4.37	4.64	4.59
lay3	4.63	4.61	4.78	4.61	4.79	4.73	4.68	4.37	4.64	4.59
lay4	4.63	4.61	4.29	4.61	4.79	4.73	4.68	4.37	4.64	4.59
lay5	4.59	4.61	4.29	4.61	4.79	4.73	4.46	4.37	4.64	4.59
lay6	4.59	4.32	4.29	1.48	4.79	1.32	4.46	4.37	4.64	3.15
lay7	3.61	4.32	2.15	1.48	1.39	1.32	4.46	4.37	0.85	3.15
lay8	3.61	5.61	2.15	1.48	1.39	1.32	4.46	1.46	0.85	3.15

predominant frequencies different from the natural frequency of soil column (Table 3), a considerable shift in the predominant frequency is observed at various layers. In order to understand the shift of predominant frequencies, obtained Fourier amplitude spectra for thirty input motions have been categorized into two classes in this work as i) the Fourier amplitude spectrum consists of large number of peaks well distributed over a wide range of frequencies and ii) the Fourier amplitude spectrum consists of only one or a few peaks in narrow frequency range. Fourier amplitude spectra from category (i) and (ii) are shown in Fig 3 and 4 respectively. It can be seen from Fig 3 that Fourier spectrum of input motion 2 has multiple peaks well distributed over a wide range of frequencies. For input motion 2, in layer 7 predominant frequency shifts from 5.42Hz to 9.91 Hz as shown in Table 3, which is close to the natural frequency of soil column in 2nd mode (Table 3). Though F.A.R. value is very less in layer 7 (Fig 2), Amp of input at this frequency is high enough to cause a frequency shift. In other words, input motion 2 has multiple peaks, with significant values of Fourier amplitudes Amp_{p1} near 9.91 Hz (f_{p1}). A small value of $F.A.R._{p1}$ leads to a frequency shift. Again in layer 4, input motion 2 experiences another frequency shifting to 4.73 Hz (f_{p2}). This value of

f_{p2} is close to the fundamental natural frequency of the soil column. In layer 4, F.A.R.$_{p2}$ is much higher (2 times) compared to the F.A.R.$_{p1}$ (Fig 2). Thus, the condition $\mathrm{Amp_{p2} * F.A.R._{p2} > Amp_{p1} * F.A.R._{p1}}$ satisfies here. Further, in layer 1, though F.A.R.$_{p2}$ is higher (1.5 times) than F.A.R.$_{p1}$, condition $\mathrm{Amp_{p1} * F.A.R._{p1} > Amp_{p2} * F.A.R._{p2}}$ prevails as $\mathrm{Amp_{p1}}$ is much larger than $\mathrm{Amp_{p2}}$. Thus, it can be seen that input motion 2 consisting of a multiple peaks show predominant frequency shift at both fundamental natural frequency as well as 2nd natural frequency as shown in Table 3. For category (ii), input motion 8 has only one or two distinguished peaks in a narrow range of frequencies as shown in Fig 4. For this input motion the condition $\mathrm{Amp_{p1} * F.A.R._{p1} > Amp_{p} * F.A.R._{p}}$ as explained earlier is not satisfying below layer 3. As a result predominant frequencies of motions at various layers remain same as that of input motion (Table 3). In layer 3 however, the above condition is satisfied for f_{p1} = 4.77 Hz, resulting in shift in the predominant frequency with respect to input motion as shown in Table 3. For other layers above layer 3, the predominant frequency remains constant. For further shift in the predominant frequency to a new value above layer 3, the condition $\mathrm{Amp_{p2} * F.A.R._{p2} > Amp_{p1} * F.A.R._{p1}}$ should be satisfied. $\mathrm{Amp_{p2}}$ and F.A.R.$_{p2}$ are the Fourier amplitude and F.A.R. respectively at frequency 'f_{p2}'. Since f_{p1} is close to the fundamental natural frequency of soil column, the value of F.A.R.$_{p1}$ is greater than F.A.R.$_{p2}$. For

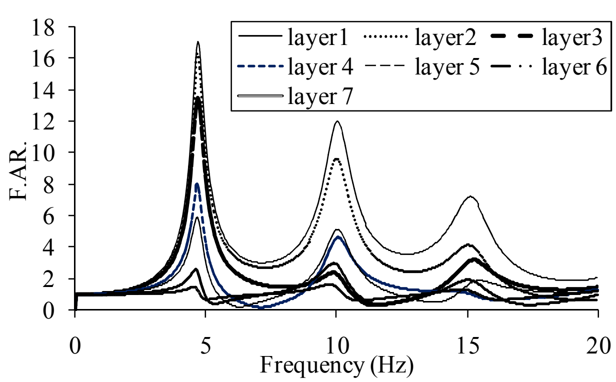

Figure 2, F.A.R. for different layers.

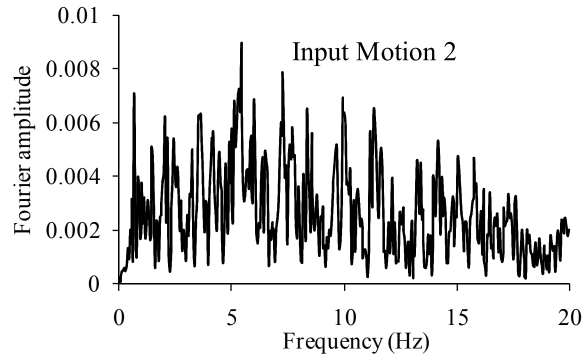

Figure 3, Fourier amplitude spectra for motion 2

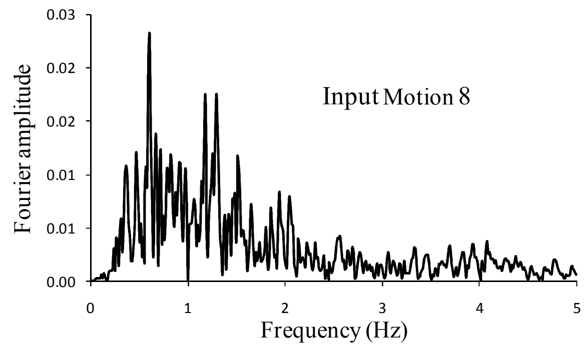

Figure 4, Fourier amplitude spectra for motion 8

further shift to occur, the value of $\mathrm{Amp_{p2}}$ needs to be much higher which is not possible for motion 8 as it consists of a few peaks in a narrow frequency range as shown in Fig 4.

VALIDATION OF DEVELOED CODE

In order to check the authenticity of the developed code, site response analysis performed as per [10] has been repeated. Based on equivalent linear approach, site respone of typical sites in Mumbai were attempted by [10]. Based on the analysis, a natural frequency of 6.88Hz was found by [10]. Using the same borehole details shown in Table 4, linear site response analysis is performed using the developed code in this work. Typical plot of F.A.R. versus frequency for the borehole is shown in Fig 5. Based on the Fig 5, a natural frequency of 6.88 Hz is found for the selected borehole site (MBH 1). For the same borehole (MBH 1), [10] also found the natural freuency of 6.88Hz following equivalent linear approach in DEEPSOIL. Thus it can be said that the findings based on developed code is found matching well with the existing literature. This exercise enhance the confidence about the code outcomes and also about the observations made earlier.

Table 4, Borelog for MBH1 site [10]

Bore log MBH 1: Mangalwadi site, Mumbai					
Layer no	Soil type	Thickness (m)	Unit weight (Kn/m^3)	V_s (m/s)	Damping ratio
1	Backfill	1.5	16	203	0.05
2	Loose sand	1.5	17	218	0.05
3	Loose sand	1.5	17	226	0.05
4	Loose sand	1.5	18	245	0.05
5	Clay	2	18	268	0.05
6	Clay	1.8	18	293	0.05

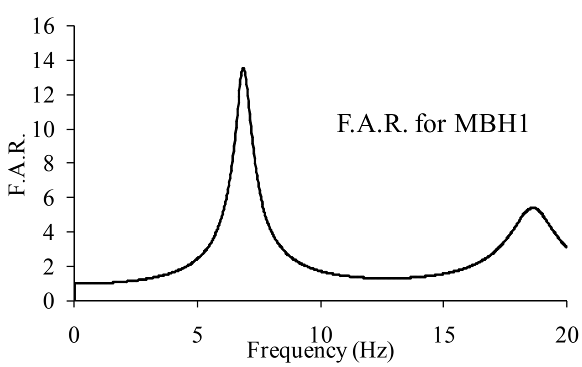

Figure 5, F.A.R. for MBH1 site

CONCLUSIONS

The importance of local soil in deciding the extent of damage during an earthquake has been evidenced during various earthquakes in the past. In absence of recorded ground motion at a site, typical site response based on recorded ground motions from the sites are followed in large number of ground response studies. In the present work, a MATLAB program has been developed to perform site response based on linear approach in frequency domain. A list of 30 ground motions recorded in different parts of the world are considered in order to understand the shift in frequency content of motion at various layers. All the selected input motions show a wide variation in the ground motion characteristics. Based on the comparison of predominant frequency for different layers with respect to the Fourier spectra of input motions, following three important conclusions are made;

- For input motions having one or two peaks, chances of shift in predominant frequency among various layers between bedrock and the surface is less.
- For input motions having multiple peaks well distributed over a wide range of frequency which is possible due to abrupt change in the subsurface geology, frequent shift in the predominant frequency is possible both at 1st and 2nd mode natural frequency.
- Input motions with predominant frequency close to the natural frequency of soil column, no considerable change the frequency content at various layers is observed.

Thus based on the above observations, it can be concluded that the predominant frequency of the motion at the surface layer need not be always equal to the natural frequency of the soil column itself but can have other values as well. However in case the input motion has predominant frequency close to the natural frequency of the soil column, the predominant frequency of motions versus depth will be almost constant.

These observations are made based on limited ground response analysis. In order to further enhance the above outcomes, large number of similar analysis can be performed in the future works. Also, the response of soil using equivalent linear and nonlinear approach upon the frequency content can be assessed in similar way in future.

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