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Study of 2D Basins and Site-City Interaction Effects on Ground Motion Characteristics

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ABSTRACT
The rapid increase of population in Indian metro cities like Delhi has pressurized the builders to construct residential buildings and houses even at vulnerable sites like near the river beds, ponds etc. Many lakes and reclaimed lands are dumped with soil to create land for the construction purposes. In India, presently earthquake engineers are using 1D fundamental frequency (F_{01D}) of sediment deposit in the designing of earthquake resistant structures. However, the closed basin may be 2D or 3D in nature and its fundamental frequency may not match the frequency predicted using 1D approach. In this paper, the numerically computed SH-wave fundamental frequency (F_{02D}) of various considered 2D rectangular and elliptical basins is presented. Another, aim of our study is to present the effects of site-city-interaction (SCI) particulars on the building response when both the city and the basin are under double resonance condition. The analysis of simulated results revealed that F_{02D} of basin increases with the increase of shape-ratio (ratio of the depth of basin to its half width). It is observed that the F_{02D} of the basin is more than the F_{01D} of that basin when shape-ratio is more than 0.25. The obtained F_{02D} of the elliptical basin is larger than that of the rectangular basin for the same shape-ratio and other parameters. Furthermore, the value of the ratio of spectral amplifications at the F_{02D} and F_{01D} fundamental resonance frequencies is around 2.24 for the considered smallest basin and respective parameters. A new empirical relationship has been developed to predict the F_{02D} of the elliptical basin. The results of SCI effects on the building response revealed an unexpected reduction of building response when both the city and basin are under double resonance condition.

Key words: 2D Basins response, Site-City Interaction, Viscoelastic FD algorithm, Double resonance**.**

INTRODUCTION

It is well known that the characteristics of ground motion at a site very much depends on the three factors namely source, propagation path and local site condition. Basin effects on the characteristics of ground motion have been recognized and studied by several researchers in last few decades. Aki and Larner (1970) has reported the response of two-dimensional basin by using a plane incident wave-front and proposed a theoretical semi-numerical technique, which is reliable to deep valleys with relative steep basement interface. Wong and Trifunac (1974) studied the surface motion of semi-elliptical valley using incident plane SH-wave front. Many researchers have used finite element method to study the effect of irregular underground interface and wave propagation in non-planar structures (Alterman and Karal, 1968; Smith, 1975; Hong et al., 1978). Seismologists have reported the variation of free field ground motion in basins because of phenomena such as resonance (Dobry and Vucetic 1987; Narayan et al., 2002), basement focusing effects (Kumar and Narayan, 2013) and surface waves generated in basin (Bard and Bouchon, 1980; Narayan, 2005; Kawase,1996; Graves et al., 1998). Theoretical results are verified by large-scale field tests carried out in last few decades at some of the best-known sites like Ohba valley in Japan and the parkway valley in New Zealand (Chavez –Garcia et al., 1998). The population in developing countries is increasing at a very rapid rate, especially in the metro cities like Delhi, Mumbai etc. due to the high birth rate, improved medical facilities, better job opportunities and other factors, which pressurize the builders to construct residential and government structures even at vulnerable sites like near the river bed and reclaimed lands. Many lakes and ponds are filled with loose soil to create land for the construction purposes. The current practice for computing the resonance frequency of the basin to avoid the double resonance is the use of simple relationship F_{01D}=Vs/4H (where F_{01D} is the 1D resonance frequency of basin, Vs is the shear wave velocity above the bedrock and H is the thickness of sediment above the bedrock), which is applicable for only 1D basin (1D basin means, a basin with its lateral extension is far away from the site of interest, with horizontal bedrock). However, in case of lakes or ponds filled with sediment have a finite lateral extension and their base may not be horizontal. Such types of sediment filled basins may be 2D (elongated filled lake or depressions) and 3D (circular pond) in nature. The 1D approach for predicting the resonance frequency of basin is not applicable in the case of 2D and 3D basins. But, earthquake engineers are using simply shear wave velocity and thickness of sediment above the bedrock at the site of interest in the basin, even in a basin that is 2D or 3D in

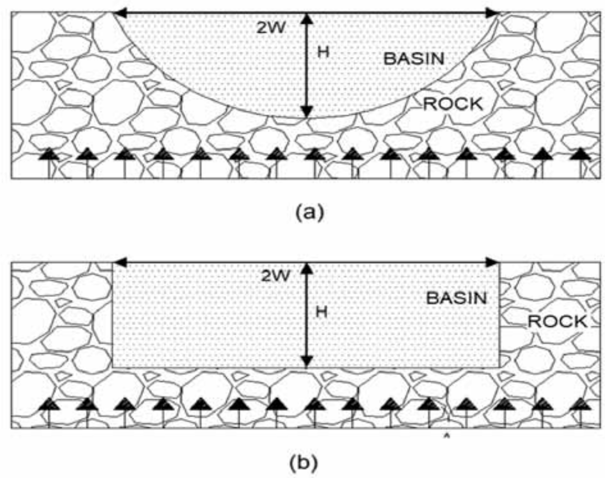

Figure 1. Sketches of the (a) Rectangular basin model and (b) Elliptical basin model considered for simulation.

nature. In order to predict the resonance frequency (F_{02D}) of 2D basins as well as to study the effects of shape and shape-ratio of basin on the F_{02D}, the SH-wave responses of the rectangular and elliptical basin models with different shape-ratio (shape-ratio of basin is defined as ratio of depth of basin to its half width) have been computed and analyzed.

The government of India is planning to develop around 100 smart cities and most of them are falling in different basins. It appears that the interaction of basin with the city may play a major role in altering the response of building of the city as well as free field motion during an earthquake. Site-city-interaction (SCI) comprises the combined effects of kinematic soil-structure-interaction and inertial structure-soil-interaction with the underlying basin on a global scale (Bard et al., 2005). Guéguen et al., (2002) proposed the term SCI for the first time. If ~ 30 m soil at a site is so much important for the seismic hazard assessment, an essential input to build seismic resistant buildings, then why not to give due importance for the 30 m height of buildings of any city? It is pertinent to state that for ensuring safe buildings, all the factors like proper link between sediment and underlying rock strata, proper anchorage between sediment and foundation and proper link between foundation and main frame of the building are all equally important for ensuring safety to the building during a large magnitude earthquake. To start with, for ensuring apt design of a building and its lateral influence on surrounding buildings in a city, it is essential to take in to cognizance the results from study of SCI. Varied design characteristics and their relative importance are important in selecting a proper area specific building design starting from foundation and extending upwards covering the entire building frame. In this paper, the effects of SCI on the building response under double resonance condition are also studied.

Salient Features of the used SH-Wave FD Program

Most of the seismologists are using fourth-order staggered-grid finite-difference (FD) method to simulate the ground motion characteristics (Narayan and Kumar 2008). Narayan and Kumar (2013) developed a fourth-order accurate computer program to apply frequency-dependent damping in the time-domain simulation of the basin. The staggered-grid finite-difference approximation of the viscoelastic SH-wave equation for the heterogeneous anelastic medium is used for the simulation of responses of the various considered basin and site-city models. The frequency-dependent damping in the time-domain FD simulations is applied based on the GMB-EK rheological model (Emmerich and Korn, 1987) and a material independent anelastic function developed by Kristek and Moczo (2003). The input parameters like unrelaxed moduli and anelastic coefficients are computed using S-wave velocity and quality factor at a particular reference frequency F_r (F_r=1.0 Hz) using Futtermann's relation (1962). To avoid the edge reflections, the sponge boundary condition is implemented on the model edges (Israeli and Orszag, 1981).

Basin Model Parameters and Source Implementation

Bard and Bouchon (1985) simulated responses of various two dimensional sinusoidal and rectangular basins to study the effects of the basin and formulated an equation to determine the fundamental frequencies of basin against the H/W ratio ('2W' is the width of basin and 'H' is the maximum depth of basin). It can be observed that for H/W<0.25, the fundamental frequency of a 2D basin (F_{02D}) varies only slightly and can be approximated by one-dimensional (1D) theory. For, two-dimensional basins, they have given an empirical relation to predict the F_{02D} in terms of F_{01D} and the W and H of the basin.

Table 1. The considered rheological parameters for the building block model, basin and rock.

S. No.	Material	Density (kg/m3)	Vs (m/s)	Qs	Poison's Ratio	μ_u (GPa)
1	Building	350	120	10	0.25	0.0064
2	Basin	1800	350	35	0.40	0.2620
3	Rock	2500	1800	180	0.25	8.2100

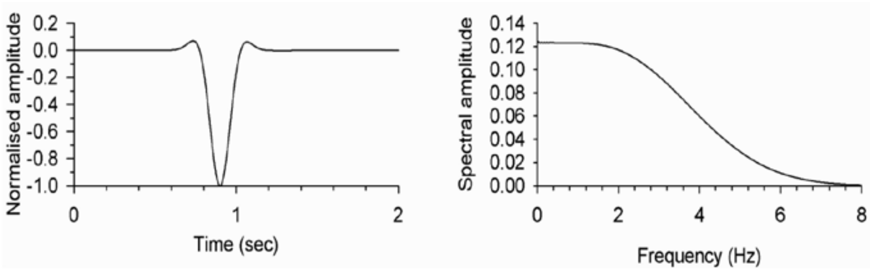

Figure 2. Gabor wavelet in time domain and its spectral.

$$F_{02D} = F_{01D}\sqrt{1 + \left(\frac{H}{W}\right)^2} \quad (1)$$

They have also mentioned that this formula predicts very accurately the fundamental SH-wave resonance frequencies of the sine-shaped valley provided the equivalent width 2w is chosen equal to the valley half-width 'l'. This relation can be extended to any valley shape, taking as equivalent width 2w, the length over which the local sediment thickness is greater than half the maximum thickness (Bard and Bouchon, 1985).

Zhu at el., (2016) also predicted the fundamental frequency of trapezoidal basin considering the Bard and Bouchon (1985) proposed equation by taking the equivalent area of trapezoidal basin to that of the rectangular basin. Considering the fact that the elliptical basin is more common in nature, our focus is on to determine the fundamental resonance frequency of closed basin of large depth to the half-width ratio (h/w>0.25). To infer the role of the shape and shape-ratio of the basin on the resonant fundamental frequency, the SH-wave responses of rectangular and elliptical basins are computed. Eight models of the elliptical basin, namely, BE1, BE2, BE3, BE4, BE5, BE6, BE7 and BE8 models having same depth (H) of 51 m and width (2W) as 123 m, 153 m, 177 m, 201 m, 225 m, 249 m, 273 m and 303 m, respectively are considered. Similarly, for the rectangular basin BR1, BR2, BR3, BR4, BR5, BR6, BR7 and BR8 models of depth 51 m and width of 123 m, 153 m, 177 m, 201 m, 225 m, 249 m, 273 m and 303 m, respectively are taken. The parameters of sediment in the basin and bedrock are kept same for all the basin models. The basin sediment and bedrock are homogenous and viscoelastic in nature. The S-wave velocity and quality factor at reference frequency 1.0 Hz, density and unrelaxed rigidity are given in table 1.

The center of the basin model is considered as a reference point for all the distance measurements. In the model, the thickness of air above the free surface is 120 m. The numerical model is discretized with a grid size of 3.0 m in the horizontal direction, while in the vertical direction the grid size is kept 3.0 m up to 300 m and then increased to 10.0 m thereafter. The time step is kept 0.0003 s to make the computation stable. A receiver is kept at the center of the basin at the free surface. Absorbing boundaries are applied at the bottom and side edges up to 200 grids to avoid the edge reflections.

A plane horizontal SH-wave front is generated at a depth of 270 m using various point source along a line. A particular point source was generated using shear stress σ_{ZY} in the form of Gabor wavelet. The mathematical form of the Gabor wavelet is given below

$$S(t) = \mathrm{Exp}(-\alpha)\cos[\omega p(t - ts) + \phi] \quad (2)$$

Where

$\alpha = \alpha = [\frac{\omega p(t-ts)}{\Upsilon}]^2$

wp = predominant frequency

Υ = controls the oscillatory character

ts= the duration (2 ts)

φ = phase shift

Figure 2 shows the generated Gabor wavelet for fp= 2, Υ= 0.5, ts= 1.5 and φ=0 and its spectra. The frequency content in the Gabor wavelet is 0- 8.0 Hz.

ANALYSIS OF SIMULATED RESULTS

Fundamental frequency of 2D basins

The SH-wave responses were computed at the center of basins. The response of model without basin was also computed to infer the spectral amplifications and resonance frequency. A comparison of the SH-wave response of the

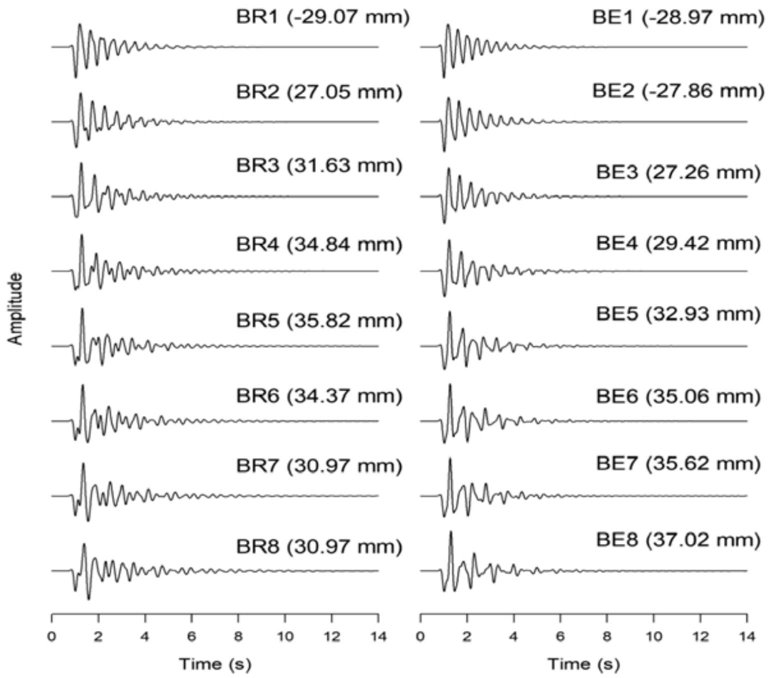

Figure 3. SH-wave responses of different rectangular basin models (left) and elliptical basin models (right) (Note: maximum amplitude in mm in each trace is given in brackets).

rectangular (left) and elliptical (right) basin models is shown in figure 3**.** The analysis of figure 3 depicts that there are tremendous effects of basin shape and shape-ratio on the free field ground motion. It is observed that as the width of basin increases in both cases (elliptical and rectangular), the duration of ground motion is increasing. This may be due to the back and forth propagation of the Love waves generated in the basins. More peaks are observed in case of the rectangular basin as compared to the elliptical basin. The maximum amplitude values are approximately matching with each other. The spectral amplifications at the center of all the basins are computed using the ratio of spectra of responses of model with and without basin. A comparison of SH-wave spectral amplifications at the center of the elliptical and rectangular basin is shown in figure 4.

The obtained F_{01D} of the basin is 1.71 Hz and respective spectral amplification value is 6.15 for the 1D basin cases. Now, the analysis of figure 4 depicts that the frequency corresponding to the first spectral ratio peak is varying with the basin type as well as the shape ratio (H/W) of the basin. It means that the frequency corresponding to the first spectral ratio peak is the 2D fundamental frequency (F_{02D}) of the basin. Corresponding to all the shape-ratio, the F_{02D} of the elliptical basin is larger than that of the rectangular basin. Further, the F_{02D} and the maximum spectral amplification values of both rectangular and elliptical basins are increasing with the increase of shape-ratio. The largest spectral amplification (13.78) is obtained in the BE1 basin at the fundamental frequency. In contrast to this, in some of the considered rectangular basin models, the largest spectral amplification was obtained at the first mode.

The obtained F_{02D} of the BR1, BR2, BR3, BR4, BR5, BR6, BR7 and BR8 rectangular basin models are 2.16 Hz, 1.98 Hz, 1.90 Hz, 1.85 Hz, 1.80 Hz, 1.78 Hz, 1.75 Hz and 1.73 Hz, respectively very much corroborates with the same obtained using the relationship given by Bard and Bouchon (1985) for the rectangular basin (Table 2). Similarly, the F_{02D} of the BE1, BE2, BE3, BE4, BE5, BE6, BE7 and BE8 elliptical basin models are 2.46 Hz, 2.23 Hz, 2.18 Hz, 2.08 Hz,2.00 Hz, 1.95 Hz,1.93 Hz and 1.88 Hz, respectively. There is only minor deviation ($<5\%$) as compared with the same computed using the concept of equal area (Zhu and Thambiratnam, 2016) and using the Bard and Bouchon (1985) empirical relation for the rectangular basin. This may be due to use of different numerical method and discrete frequency in FFT. Zhu and Thambiratnam (2016) have used the relation by taking the equivalent area of trapezoidal basin to that of rectangular, keeping the depth same. Hence, the equivalent width of the basin decreases. Furthermore, the obtained spectral amplifications at F_{02D} are larger in the elliptical basin as compared to those in the case of the rectangular basin Figure 4. This may be due to larger amplitude of the Love wave generated and focusing effect at the bottom of the elliptical basin. An empirical relation has been developed between the shape ratio (H/W), F_{01D} and F_{02D} for the elliptical basin, as shown in figure 5, and corresponding equation is given below.

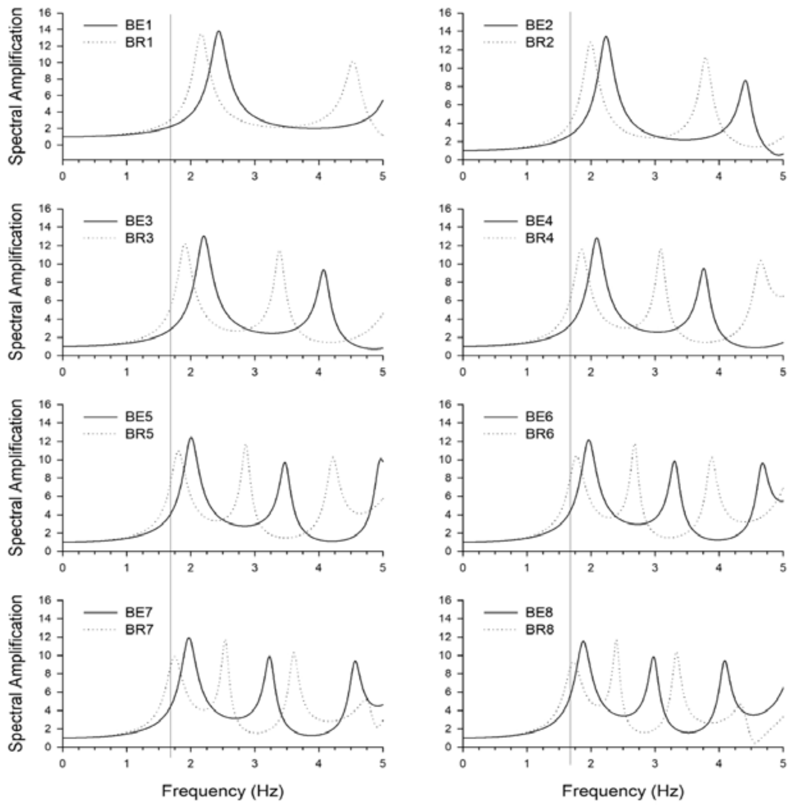

Figure 4. A comparison of spectral amplifications at the entre of considered various elliptical (continuous line) and rectangular (dotted line) basins models.

Table 2. The numerically predicted and computed F_{02D} of both the rectangular and elliptical basin models using Bard and Bouchon (1985), corresponding 1D resonance frequency (F_{01D}) computed analytically and spectral amplifications.

Basin size(m)		Basin shape ratio	Rectangular (BR) Basin				Elliptical (BE) Basin			
Depth	Width		Model	F_{02D} (BB)	F_{02D} Sim.	SAF	Model	F_{02D} Emp.	F_{02D} Sim.	SAF
51	123	0.82	BR1	2.22	2.16	13.50	BE1	2.52	2.46	13.78
51	153	0.67	BR2	2.06	1.98	12.76	BE2	2.27	2.23	13.46
51	177	0.57	BR3	1.98	1.90	12.19	BE3	2.14	2.18	13.0
51	201	0.51	BR4	1.92	1.85	11.54	BE4	2.05	2.08	12.80
51	225	0.45	BR5	1.88	1.80	10.96	BE5	1.99	2.00	1243
51	249	0.41	BR6	1.85	1.78	10.38	BE6	1.94	1.95	12.14
51	273	0.37	BR7	1.83	1.75	9.86	BE7	1.90	1.93	11.87
51	303	0.34	BR8	1.81	1.73	9.28	BE8	1.83	1.88	11.53

$$F_{02D} = F_{01D}\sqrt{1 + 1.7\left(\frac{H}{W}\right)^2} \tag{3}$$

The developed empirical relation reveals that it is very simple to find out the F_{02D} of the elliptical basin and there is no need of computation of effective width of elliptical basin based on the concept of equal area to compute F_{02D} using the relation of Bard and Bouchon (1985) for rectangular basin.

SCI effect on building

SCI effects on building response

In order to study the SCI effects on the building response ten storey (B10) buildings situated in a basin was considered. The plan of B10 buildings is 63 m x 63 m and height of 30 m. The effective density of the building was obtained as 350 kg/m^3 considering the dead load and

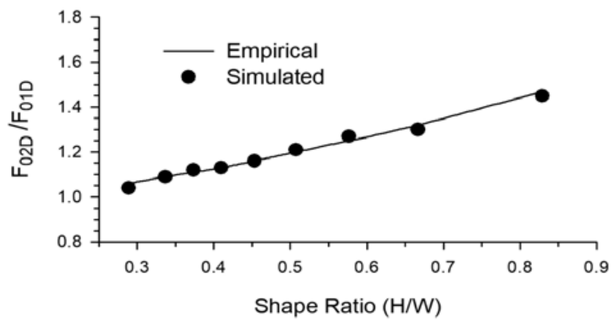

Figure 5. Variation of F_{02D}/F_{01D} frequency ratio with shape-ratio of elliptical basin models.

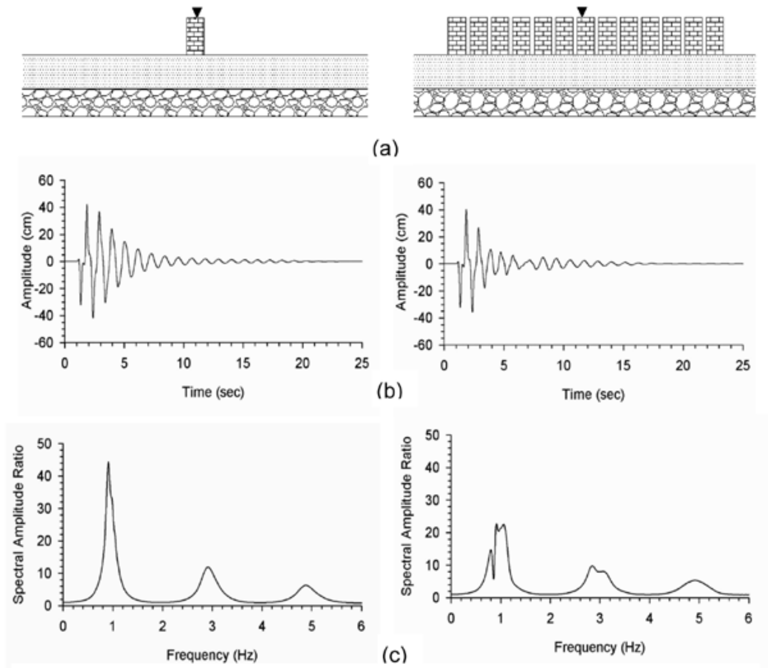

Figure 6(a). Single building in basin (left) and city in basin (right); **(b)** SH-wave response of single building in basin (left) and city in basin (right); (c) spectral amplifications at the top of single building in basin (left) and at the top of a building situated at the centre of city in basin (right).

live load acting on the building. The total dead load acting on the building is calculated using the length, height, thicknesses and densities of walls (20.0 KN/m^3), slabs and beams (25.0 KN/m^3). The value of live load acting on the floor of each storey of the building is assumed as 3.0 KN/m^2. The ratio of the total load to the total volume of the building gives the building density. The time period of the building is calculated using the following formula (IS: 1893, 2002) for the RCC framed system with building height H in m.

$$T = 0.075H^{0.75} = \frac{1}{F_{02D}} \tag{4}$$

The effective S-wave velocity for the building block-model is computed using the Eigen frequency of building (1/T) and effective density, which is to be incorporated in the numerical grid for homogenous building blocks. The period is used to find out the S-wave velocity in the building block model using equation $F_{02D} = \frac{V_S}{4H}$. A 1D sediment-filled basin is considered for the study of SCI effects. The depth of basin is taken as 87 m.

The site-city model is discretized with a grid size of 3.0 m in both the horizontal and vertical directions. Figure 6a shows the sketch for the single building situated in the basin (left) and the city situated in the basin (right). The total length of the city is 963 m and numbers of B10 buildings in the city is 13. The distance between two buildings is 12 m. So, the effective city-density is 0.85 (Sahar et al., 2015). The obtained F_{02D} of the building block is 0.97 Hz and the F_{01D} of the 1D basin is 1.0 Hz. It means that both the building and the 1D basin are under resonance condition. Figure 6b shows the SH-wave responses at the top of a single B10 building (left) and at the top of a building situated in the center of the city (right). An analysis figure 6b depicts that the SCI effects have caused a considerable decrease in both the amplitude and duration of ground motion at the top of building situated at the center of the city as compared to that at the top of a single building situated in the basin.

Similarly, figure 6c shows the spectral amplification of SH-wave at the top of a single B10 building (left) and at the top of a building situated at the center of the city (right). An analysis of figure 6c depicts that the spectral amplification at the top of the single B10 building has reduced to 22.5 from 45.0 when the same building is at the center of the city. It means that SCI has caused a reduction of spectral amplification of the order of 50% at the top of the building situated at the center of the city corresponding to the double resonance frequency.

DISCUSSION AND CONCLUSIONS

There is an excellent correlation between the computed F_{02D} of the rectangular basin using the FD response and the same computed using empirical relationship given by Bard and Bouchon (1985) for the rectangular basin. However, the empirical relationship given by Bard and Bouchon (1985) is not so effective for predicting the F_{02D} of the elliptical basin. The numerically computed F_{02D} of the elliptical basins very much matches with the same computed using the concept of the equal area proposed by Zhu and Thambiratnam (2016). Finally, the simulated results have been used to develop a new empirical relationship based on the regression analysis to predict the F_{02D} of the elliptical basin.

Simulated results revealed an increase of F_{02D} of both the rectangular and elliptical basins with an increase of shape-ratio (H/W) of the basin. But, this increase is more in case of the elliptical basin. Further, the spectral amplification at F_{02D} is also more in case of the elliptical basin as compared to the rectangular basin. It is alarming to know that the spectral amplification at F_{02D} of the basin is more than twice to that of F_{01D} of the same basin computed assuming it as 1D basin. The computed SCI effects on the building response revealed a reduction of building response upto 50% under double resonance condition. This finding calls for the study of SCI effects in a 2D and 3D basins where both the buildings and the basin are in 2D and 3D resonance condition.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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Quotations on Shapes, Patterns and Building design & Structure:

* "Good buildings come from good people, and all problems are solved by good design".

- Stephen Gardiner (1483-1555) was an English bishop and politician

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* "Colors answer feeling in man; shapes answer thought; and motion answers will".

-John Sterling (1806–1844) was a British author.

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* "We shape our buildings; thereafter they shape us".

-Winston Churchill (1874 –1965) was a British statesman, army officer, and writer.

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* "I found I could say things with color and shapes that I couldn't say any other way - things I had no words for".

- Georgia O'Keeffe (1887 -1986) was an American artist.

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* "There is a powerful need for symbolism, and that means the architecture must have something that appeals to the human heart".

-Kenzo Tange (1913-2005) was a Japanese architect.

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* "I don't think that architecture is only about shelter, is only about a very simple enclosure. It should be able to excite you, to calm you, to make you think".

-Zaha Hadid (1950 –2016) was an Iraqi-British architect.

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* "It is not the beauty of a building you should look at; its the construction of the foundation that will stand the test of time".

-David Allan Coe (1939--) is an American songwriter, outlaw country music singer, and guitarist

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* "My big thesis is that although the world looks messy and chaotic, if you translate it into the world of numbers and shapes, patterns emerge and you start to understand why things are the way they are".

-Marcus du Sautoy (1965--) is a Professor of Mathematics at the University of Oxford.