Seismic wave amplification studies for shallow basins considering basin edge effects

Vijaya R & Boominathan A
Indian Institute of Technology Madras, Chennai, Tamilnadu, India
Prantik Mandal
National Geophysical Research Institute-CSIR, Hyderabad, Telangana, India

ABSTRACT
The variation observed in ground motion of most earthquakes is due to various site effects like local soil condition, basin effect and effect of surface topography. Influence of two dimensional sedimentary basin structures on ground motions, including wave reflections and surface wave generation at basin edges; known as basin effect, are found to have significant effect on seismic ground response. In the first part of present study, a basin medium 2km wide and 100 m deep reported in Khanbabazadeh (2014) subjected to 1999 Koceali earthquake is analysed using the finite difference programme FLAC 2D. The effect of basin edge and the variation of soil types on the amplification of seismic waves is investigated and the results are found to be comparable with the results published in Khanbabazadeh (2014). In the second part of the study, the basin response studies are carried out for typical shallow basins of Bhuj region of India, 1km wide and 50m deep. The bedrock inclination is varied from 10° to 30°. The soil profile is modelled using the measured shear wave velocity of Bhuj area which ranges from 200 to 500 m/s. The basin response analysis is carried out for four different type of input motions: Bhuj (2006), Kobe (1995), Imperial (1979) and Koceali (1999). From the computed time history of acceleration at the surface, the variation of peak ground acceleration along the surface of the basin is established. The effect of the input motion on the response of basins is analysed. It is found that the shallow basins of all bedrock inclinations amplify significantly for the Kobe input motion. Whereas for Bhuj input motion, significant amplification occurs for shallow basin with 10° inclination.

1 INTRODUCTION

The damage pattern observed in most of the earthquakes is not uniform and the variation is attributed due to various site effects like local soil condition, basin effect and effect of surface topography. Influence of two or three dimensional sedimentary basin structures on ground motions, known as basin effect, are found to have significant effect on seismic ground response. During the last few decades, numerous numerical and experimental studies have been conducted to investigate the effect of basin. The one-dimensional (1D) analyses have gained popularity as reasonable estimations are obtained at lower cost. Later it was found that such simple models would not adequately reproduce the observations and two-dimensional (2D) models began to be introduced. Graves (1995) and Davis et al. (2000) analysed long-period(1-10 sec) velocity recordings of the 1994 Northridge earthquake which indicates the presence of significant 2D basin induced effects in the observed patterns of strong ground motion. Linear equivalent 1D analyses carried out to study the site effects of Mexico city concluded that model results are far from the observed values and the difficulty is overcome by the use of 2D model (Kawase et al. 1989). The simulation based on 2D finite difference code show that both SV and SH wave amplification patterns are influenced significantly by the 2D effect of basin structure in Kobe city (Pitarka et al. 1997). Finite Element based site effect studies carried out by Kawase (1996) and Furumura et al. (1998) for Kobe Earthquake indicates amplification for the stations located near the basin edge. An idealized lens like focusing model that is formed by a curved basement/sediment interface at a depth of 3 to 4 km beneath Santa Monica, proposed by Gao et al. (1996) are capable of focusing waves and producing amplified motions. Alex et al. (1998) numerically simulated and analysed a series of schematic structures based on the deep-basin lens model. Though the model predicts the ground motion amplification due to basin effect, the proposed models are highly schematic and are inconsistent with the known surface and subsurface geologic structure. Ground response studies performed in Bhuj region by Kamal et al. (2015) reveal that 1D approach for a 3D basin is inadequate as the amplification factors predicted are 50% larger than recorded. Semblat et al (2009) considered a second order Ricker wavelet as the incident wave field and computed the surface motion at several points along the 2D basin surface. The amplification is found to be large near the basin edge, however duration is found to be large near the basin center. These site effects can be addressed quantitatively and ground motion response can be determined by developing validated 2D and 3D basin models (Graves et al. 1998). Choi et al. (2005) developed an empirical model to predict amplification factors for 5% damped response spectral acceleration that incorporates basin response effects, considering basin depth and source location. However, there are no detailed studies done on the 2D numerical modelling of basin effects for Indian site conditions to predict the ground motion.

In the present study the seismic response of shallow basins for typical soil condition of Bhuj region, India subjected to different earthquake motion is carried out using the finite difference programme FLAC2D. Initially a validation study is carried out in FLAC2D for basin model published by Khanbabazadeh (2014) and obtained comparable results. Similar approach is then used to study the response of typical basins of Bhuj region, India.

2 BASIN EFFECT

The fact that many of the modern civilization and cities were developed in river basins points towards the importance of evaluation of site amplification due to basin effects. The velocity contrast between the soft alluvial soils within the basin and the hard bedrock forming the edge of the basin serves to trap body waves and causes some incident waves to travel through the basin soil as surface waves. Such trapping of body waves (Figure 1) and the creation of slowly attenuating surface waves results in stronger shaking and longer durations than would be experienced under typical one-dimensional conditions (Kramer 1996). Depending on the curvature of the terrain, focusing and defocusing of the seismic waves will occur. Waves are scattered or trapped depending on whether the topography is concave or convex (Lay et al. 1995).

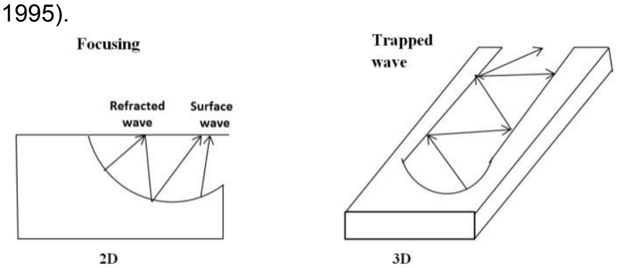


Figure 1: Two and three dimensional basin effect

3 VALIDATION OF NUMERICAL MODEL USED FOR THE STUDY

FLAC (Fast Lagrangian Analysis of Continua), an explicit, finite difference program, one of the powerful numerical software's in geotechnical engineering is used for modelling the basin. The solution method consists of discrete model approach in which the continuous medium is discretised into small elements and the forces are concentrated at the nodes of a two-dimensional mesh. The nonlinearity in the stress-strain law is followed directly by each element as the solution marches on in time.

In the initial part of the present study, seismic response of clayey basin with different bedrock inclinations subjected to Koceali earthquake as reported in Khanbabazadeh (2014) is analysed using a finite difference based programme FLAC2D.

3.1 Basin Geometry

The 2km wide and 100m thick basin reported in Khanbabazadeh et al. (2014) is considered. The bedrock inclination is varied from10° to 40° at the basin sides. The model is divided into a finite difference mesh composed of quadrilateral elements or zones. Half width of the modelled basin with bedrock inclination 10° is shown in Figure 2 (not to scale). For accurate representation of wave transmission through model, the element size is kept smaller than one-tenth of the wavelength associated with the highest frequency component of the input wave (Kuhlemeyer et al. 1973). Figure 3 shows the grid generated for stiff clayeybasin model with 40° bedrock inclination.The maximum zone size used for medium and stiff soil is 4 and 6m respectively.

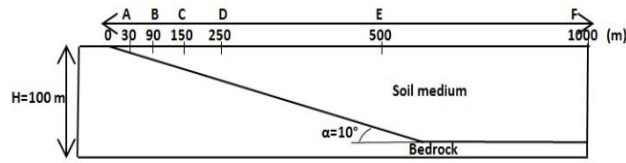


Figure 2.Half width of modelled basin's geometry

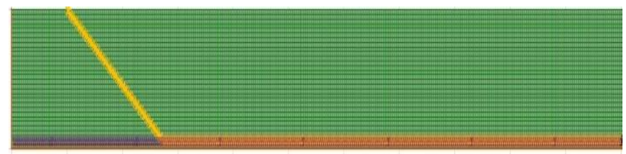


Figure 3.Meshing of 2D basin model for half width

3.2 Boundary Conditions

The base of the model is considered as rigid, due to the presence of high impedance rock at bottom. At the lateral boundaries, in addition to the static boundary conditions, free-field boundaries (Cundall, 2011), which has non-reflecting properties, are provided. The waves propagating upward suffer no distortion at the boundary as the free field grid supplies conditions that are identical to those in an infinite model. Figure 4 shows a schematic representation in which the lateral boundaries of the main grid are coupled to the free-field grid by viscous dashpots to simulate a quiet boundary and the unbalanced forces from the free-field grid are applied to the main-grid boundary.

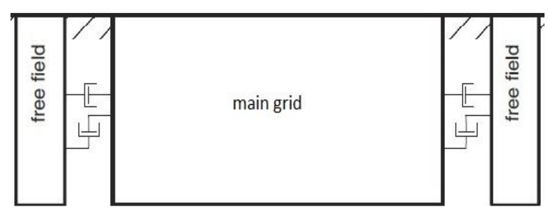


Figure 4. Schematic representation of free field boundary (Cundall, 2011)

The unbalanced forces that are applied to main grid from free-field grid is calculated based on the formula given in Equation 1.

$$F_x = -\left[\rho C_p\left(v_x^m - v_x^{ff}\right) - \sigma_{xx}^{ff}\right]\Delta S_y$$
$$F_y = -\left[\rho C_s\left(v_y^m - v_y^{ff}\right) - \sigma_{xy}^{ff}\right]\Delta S_y \quad [1]$$

Where
ρ= density of material along vertical model boundary
C_p= p-wave speed
C_s = s-wave speed
ΔS_y = mean vertical zone size at boundary grid point
v_x^m = x-velocity of grid point in main grid

v_y^m = y-velocity of grid point in main grid
v_x^{ff} = x-velocity of grid point in free field
v_y^{ff} = y-velocity of grid point in free field
σ_{xx}^{ff} = mean horizontal free field stress at grid point
σ_{xy}^{ff} = mean free field stress at grid point

3.3 Material modelling

To study the effect of soil type on the seismic ground response, two type of soil material, stiff and medium clay as reported in Khanbabazadeh (2014) are considered. The soil medium is modelled using Mohr-coulomb plasticity. The failure envelope for this model corresponds to a Mohr-Coulomb criterion (shear yield function) with tension cut off (tensile yield function).

3.4 Damping

The hysteretic damping in conjunction with non-linear constitutive model as provided in FLAC is used. The hysteretic damping is implemented by modifying the strain-rate calculation so that the mean strain-rate tensor, averaged over all subzones, is calculated before any calls are made to constitutive model functions. At this stage, the hysteretic logic is invoked, returning a modulus multiplier that is passed to the constitutive model. The model then uses the multiplier to adjust the apparent value of tangent shear modulus of the full zone being processed. Since the multiplier calculated is a numerical derivative, coarse spacing of points in the modulus-reduction curve leads to unacceptable errors. Therefore the hysteretic model uses only continuous functions to represent the modulus-reduction curve, so that analytical derivatives may be calculated. In this study, the degradation curves for clay materials based on Ishibashi and Zhang (1993) are fitted to the Hardin/Drenvich model in FLAC2D (Figure 5). The Hardin/Drenvich model is used to provide energy dissipation in the elastic range and natural damping is applied in the plastic range.

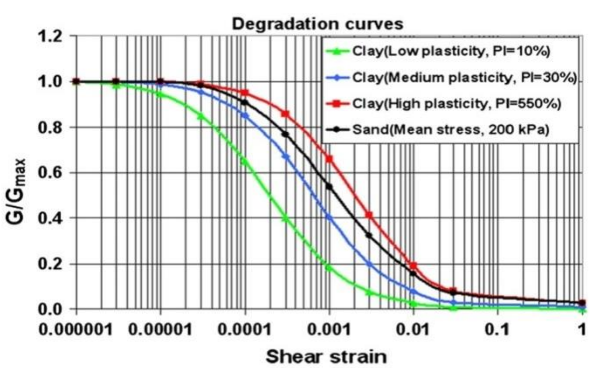


Figure 5. Modulus Reduction curves by Ishibashi and Zhang, 1993 (from Khanbabazadeh et al. 2014)

3.5 Input motion

The basin model is subjected to Koceali earthquake (Figure 6) with peak ground acceleration (PGA) level of 0.4gand a predominant frequency of 0.3 Hz. Before running a dynamic analysis, the gravity is allowed to develop and the model is stepped to equilibrium. The maximum unbalanced force and displacement is monitored at the ground surface to detect equilibrium.

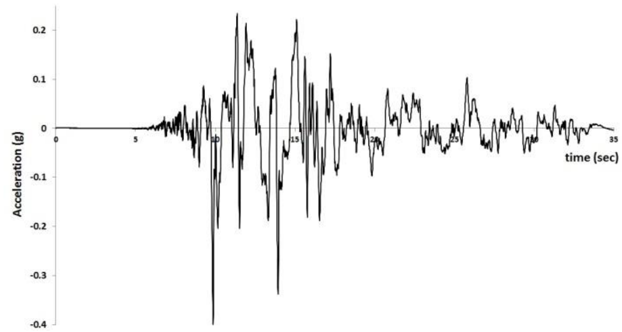


Figure 6. Time history of acceleration at bedrock

The dynamic time step (Δt_d) used by the FLAC programme for analyses of medium and stiff clayey basin is 0.00046 and 0.00097 seconds respectively. The dynamic time step for the grid constituting rectangular zones (Cundall, 2011) is calculated using the Equation 2.

$$\Delta t_d = 0.5 \min \frac{A_z}{L_d C_p} \quad [2]$$

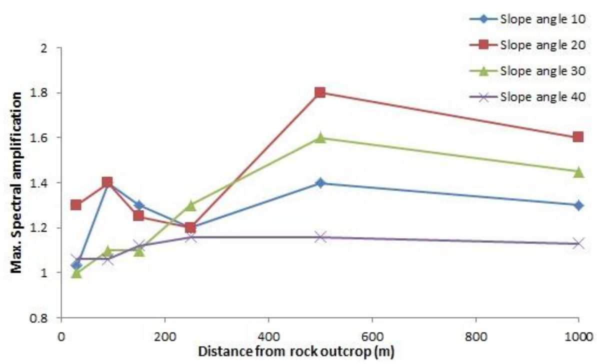
Where
A_z = Area of rectangular zone
L_d = Length of the diagonal
C_p = p-wave speed

3.4 Validation of results

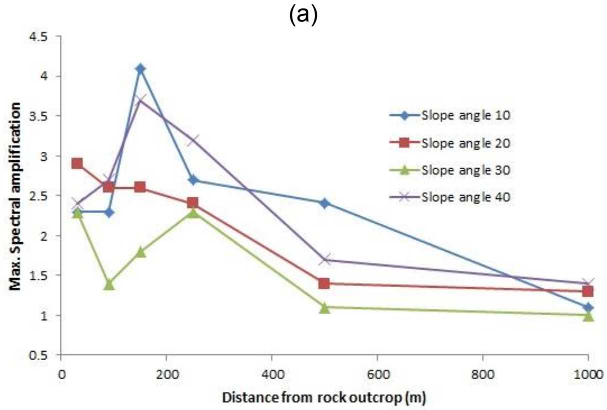
The typical time history is recorded along the basin surface at various points from A to F as shown in figure 2 and the spectral acceleration at the frequency domain are also calculated for the corresponding points. The results of point B and F located near the basin edge and centre of the basin is used for the comparison of time history and Fourier spectra.

It is observed that the PGA value at the centre and edge of the basin is significantly higher than the PGA of the input motion at bedrock due to the effect of basin. Further, PGA near the edge is found to be 30% higher than that observed at the basin centre, owing to the basin edge effect.

The maximum spectral amplification i.e. ratio of maximum spectral acceleration on the surface of the basin to the reference rock site (rock outcrop) is computed along the basin surface. Figure 7 shows the variation of maximum spectral acceleration along the stiff and medium clayey basins surface with respect to the rock outcrop. In case of stiff clayey basin, for bedrock inclination of 10° and 20°, peak points of spectral amplification are observed near the basin edge, indicating the wave reflection and refraction near the edges. The amplification near the edge decreases with the increase in bedrock inclination. For the stiff clayey basin with bedrock inclination of 40°, no significant two-dimensional behaviour is observed. In the case of medium clayey basin, the amplification near the basin edge is found prominent for bedrock inclination of 10° and 40°. There is no effect of basin edge observed after 500m from the basin edge in both stiff and medium clayey basin. Towards the centre of the basin, the spectral amplification curve is almost flat, indicating 1D amplification of basin centre. A remarkable increase in maximum spectral amplification is found in medium clayey basin compared to stiff clayey basin. In the stiff clayey basin, the maximum amplification occurred at 500 m from the basin edge for all the bedrock inclinations. In the medium clayey basin, the peak occurred at 150 m to 250 m from the basin edge.



(a)



(b)

Figure 7.Variation of maximum spectral amplification with distance from rock outcrop for (a) stiff clayey basin and (b) medium clayey basin

The conclusions obtained from the analysis are comparable with the results reported in Khanbabazadeh (2014). Thus, the further study of the response of typical shallow basins of Bhuj region India, subjected to various ground motions is carried out by similar approach.

4 TYPICAL SHALLOW BASINS OF BHUJ REGION, INDIA

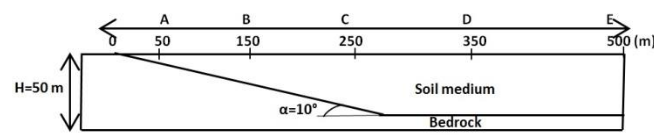
4.1 Basin modelling

In the second part of the study, response of typical basins of Bhuj region (India) is analysed. The contour of sediment thickness of Bhuj area reported in Chopra (2009) indicates the presence of shallow basin in the Bhuj area. Hence, a typical shallow basin of 1km width and 50m depth is considered in the present study. The analysis is carried out for three different bedrock inclinations 10°, 20° and 30° for double layered shallow basin. The measured shear wave velocity (Vs) of Bhuj region obtained from National Geophysical Research Institute (NGRI), India is used to characterize the soil condition. The Vs value for 50m depth is found to vary from 215 m/s to 505 m/s.

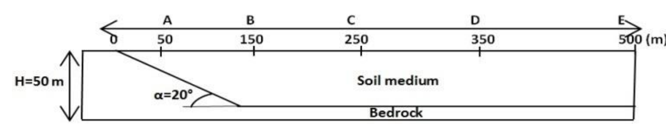
The basin modelling is carried out using FLAC2D by similar approach discussed in section 3. The basin is modelled as double layered system. The top layer has 30m thick medium dense sand with average shear wave velocity 308 m/s and the second layer 20m thick dense sand with average shear wave velocity of 480 m/s. The soil properties used in the analysis are summarised in Table 1. Half width of the modelled basin is shown in Figure 8.

Table 1: Geotechnical properties of the materials

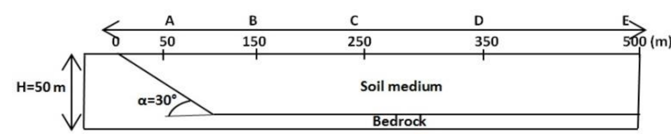
Material	Density (kN/m^3)	Vs (m/s)	Cohesion (kPa)	Friction Angle
Rock	23	750	-	-
Dense Sand	20	480	25	35°
Medium dense sand	18	308	15	30°



(a)



(b)



(c)

Figure 8.Half width of modelled basins with bedrock inclination (a) 10° (b) 20° and (c) 30°

The soil medium discretisation, boundary conditions and damping are adopted as in the validated model. The model is divided into a finite difference mesh composed of quadrilateral elements. The basin is subjected to four different recorded ground motions: Bhuj (2006), Kobe (1995), Imperial (1979) and Koceali (1999) and their details are summarised in Table 2. The PGA of input motions considered varies from 0.17g to 0.35g and Predominant frequency varies from 0.3 Hz to 7 Hz.

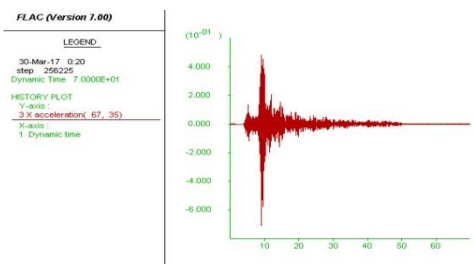
Filtering of seismic motion is carried out to remove the higher frequencies with low energy. The cut-off frequency selected based on the energy content are 4, 5, 8 and 20Hz for Koceali, Kobe, Imperial and Bhuj motion respectively. The soil layers are discretized to allow the wave of selected frequencies to propagate without distortion through the grid.

Table 2: Details of selected ground motions

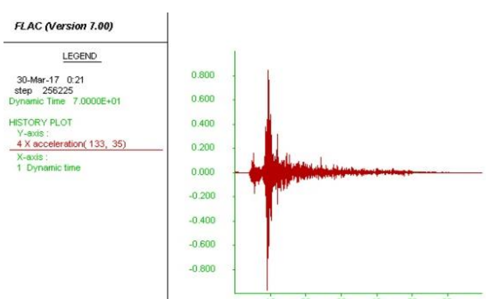
S No	Earthquake	Year	PGA	Predominant frequency
1	Bhuj	2006	0.17	7
2	Kobe	1995	0.26	0.6
3	Imperial	1979	0.35	1.3
4	Koceali	1999	0.29	0.3

4.2 Results and Discussions

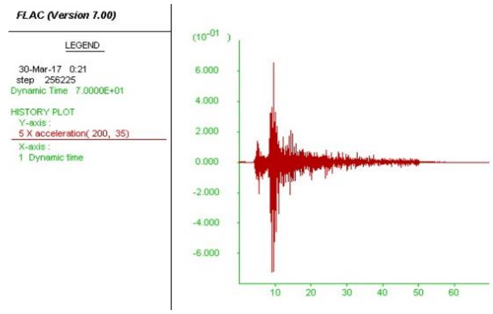
Typical time history of surface acceleration obtained from the analyses of shallow basin with 10° slope angle for Bhuj input motion at various points from A to E is presented in Figure 9. It can be noticed from Figure 9 (b) that the PGA value near the edge of the basin, i.e. at point B, is significantly higher than the PGA at other points, owing to the basin edge effect. It can also be observed from the schematic layout of basin shown in Figure 8 (a) that the basin near point B is more vulnerable to the generation of surface waves due to the interference of body waves and reflected waves from the basin slope.



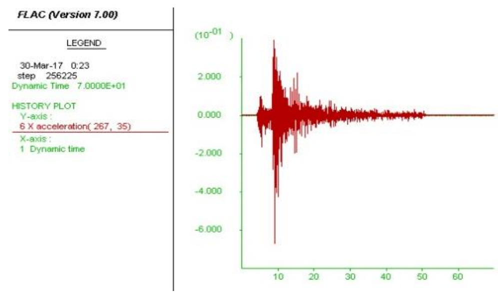
(a) Point A – 50m from the basin edge



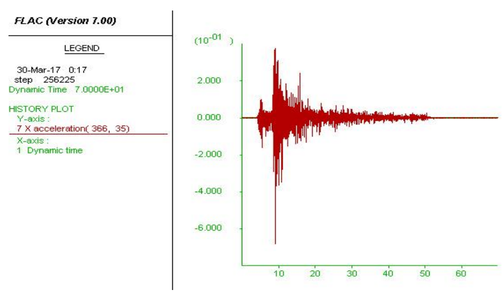
(b) Point B – 150m from the basin edge



(c) Point C – 250m from the basin edge



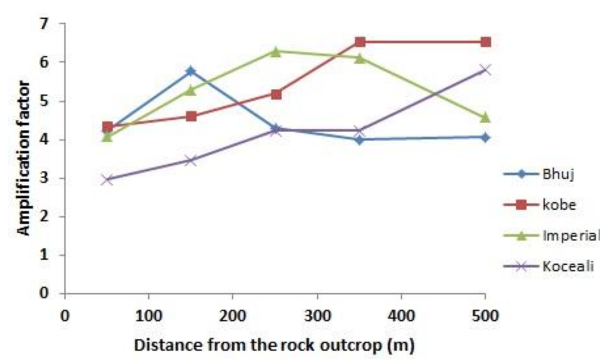
(d) Point D – 350m from the basin edge



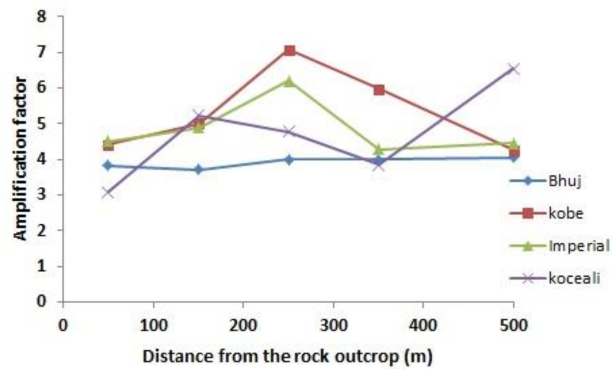
(e) Point E – 500m from the basin edge

Figure 9. Acceleration time history of shallow basin with 10° slope angle at various points along the surface

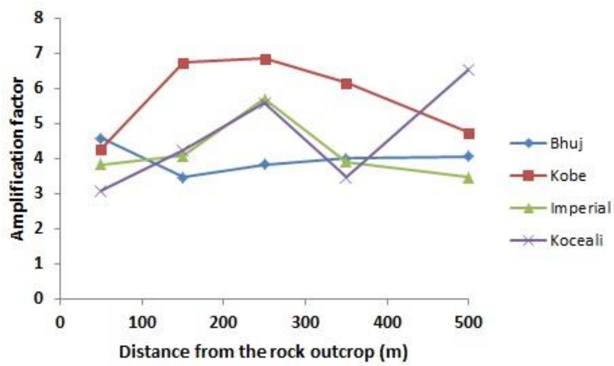
The amplification factor i.e. ratio of peak ground acceleration on the surface of the basin to the input motion is computed along the surface of the basin. The variation of the amplification factor along the surface from edge to the centre of the basin with different bedrock inclination and earthquake motion is shown in Figure 10.



(a)



(b)



(c)

Figure 10.Variation of amplification factor with distance from the basin edge for shallow basin with bedrock inclination of (a) 10° (b) 20° and (c) 30°

It is noticed from Figure 10 (a) that there is no definite pattern of amplification observed for shallow basin with 10° bedrock inclination. It is also observed from Figure 10 (a) that amplification occurs almost along the whole stretch of basin surface as the basin edge extends for a long distance of about 300m. For basin with 20° and 30°bedrock inclination as shown in Figures 10 (b) and (c), the maximum amplification is observed at 250 m from the basin edge for all input motions except Bhuj motion, for which the amplification curve is almost flat. Higher amplification is observed at the center of the basin for Koceali ground motion. It is found that in the case of shallow basin, maximum amplification ranges from 3 to 7 for all input motions and bedrock inclination.

Figure 10 also indicates the occurrence of maximum amplification for all three bedrock inclinations for Kobe input motion. The amplification of motion caused by the Bhuj motion is found to be the least.

5 CONCLUSION

Initially for validation purpose, a 2D site response analysis is carried out for a 2km wide and 100m deep basin subjected to 1999 Koceali earthquake as reported in Khanbabazadeh (2014), using the finite difference programme FLAC2D.The surface ground motion characteristics obtained from the analyses are comparable with the results reported in Khanbabazadeh (2014).

The further analysis is carried out for a typical shallow basin of Bhuj region of 1km wide and 50m deep with different inclinations. The measured shear wave velocity in the Bhuj region is used to characterize the soil conditions. The basin is subjected to four different type of ground motions. It is found from the numerical analysis that the response in shallow basin is found to be strongly dependent on the angle of bedrock inclination and input motion.The maximum amplification for the considered Bhuj basin occurs for the Kobe (1995) input motion. For the basin with steep inclination, the maximum amplification is found to occur at 250m from the edge of basins due to basin edge effect.

6 REFERENCES

Alex, C. M. and Olsen, K. B. 1998. Lens-effect in Santa Monica?,*Geophysical Research Letters*, 25(18): 3441-3444.

Choi, Y., Stewart, J. P. and Graves, R. W. 2005.Empirical Model for Basin Effects Accounts for Basin Depth and Source Location,*Bulletin of the Seismological Society of America*, 95(4): 1412–1427.

Chopra, S., Rao, K. M. and Rastogi, B. K. 2010.Estimation of Sedimentary Thickness in Kachchh Basin, Gujarat Using SP Converted Phase, *Pure and Applied Geophysics*, 167: 1247-1257.

Cundall, P. A. 2011. FLAC 2D Manual: A computer program for fast Lagrangian analysis of continua (Version 7.0), Minneapolis, Minnesota, USA.

Davis, P. M., Rubinstein, J. L., Liu, K. H., Gao, S. S. and Knopoff, L. 2000. Northridge Earthquake Damage Caused by Geologic Focusing of Seismic Waves, *Science Magazine*, 289(5485): 1746-1750.

Furumura, T. and Koketsu, K. 1998.Specific distribution of ground motion during the 1995Kobe earthquake and its generation mechanism, *Geophysical Research Letters*, 25(6): 785-788.

Gao, S. H., Liu, P. M., Davis, and Knopoff, L. 1996. Localized amplification of seismic waves and correlation with damage due to the Northridge earthquake: evidence for focusing in Santa Monica, *Bulletin of the Seismological Society of America,*86:209-230.

Graves, R. W. 1995. Preliminary analysis of long-period basin response in the Los Angeles region from the 1994 Northridge earthquake, *Geophysical Research Letters*, 22(2): 101-104.

Graves, R. W., Pitarka, A. and Somerville, P. G. 1998.Ground-Motion Amplification in the Santa Monica Area: Effects of Shallow Basin-Edge Structure, *Bulletin of the Seismological Society of America,* 88(5): 1224-1242.

Kamal and Narayan, J. P. 2015.3D basin-shape ratio effects on frequency content and spectral amplitudes of basin-generated surface waves and associated spatial ground motion amplification and differential ground motion, *Journal of Seismology,* 19(2): 293-316.

Kawase, H. 1996. Site effects observed during the Hyogo-Ken Nanbu earthquake of 1995 and strong motion simulation including the basin edge effect, *Proceedings of the 11th world conference on Earthquake Engineering,* Japan.

Kawase, H. and Aki, K. 1989. A study on the response of a soft soil basin for incident S, P, and Rayleigh waves with special reference to the long duration observed in Mexico City, *Bulletin of the Seismological Society of America*, 79: 1361-82.

Khanbabazadeh, H. and Iyisan, R. 2014. A numerical study on the 2D behavior of the single and layered clayey basins, Bulletin *of Earthquake Engineering*, 12: 1515–1536.

Kramer, S. L. 2013. *Geotechnical Earthquake Engineering*, Prentice Hall, New Delhi, India.

Kuhlemeyer, R. L. and Lysmer, J. 1973. Finite element method accuracy for wave propagation problems, *Journal of Soil Mech Foundation Division,* ASCE, SM99: 421–427.

Lay, T. and Wallace, T. C. 1995. *Modern Global Seismology*, Academic Press, San Diego, California, USA.

Narayan, J. P. and Sharma, M. L. 2004. Effects of local geology on damage severity during Bhuj earthquake of Jan. 26, 2001, India, *Proc. of the 13th World Conference on Earthquake Engineering,* Vancouver, B.C., Canada, 2042.

Pitarka, A., Irikura, K. and Iwata, T. 1997. Modelling of ground motion in the Higashinada (Kobe) area for an aftershock of the 1995 January 17 Yogo-Ken Nanbu, Japan earthquake, *Geophysical Journal International,* 131: 231-239.

Semblat, J. F. and Pecker, A. 2009. *Waves and vibrations in soils: Earthquakes, Traffic, Shocks, Construction works*, IUSS Press, Pavia, Italy.