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Influence of basin parameters on seismic site response analysis

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ABSTRACT: The damage variation observed during the past earthquakes has demonstrated the strong influence of the characteristics of basins on the performance of buildings during seismic events. The estimation of seismic hazard considering basin effect becomes very important as most of the cities and civilization have developed along the basins. In the present study 2D modelling of non-linear seismic response of the basin was carried out using finite difference code FLAC. The basin model is divided into a finite difference mesh composed of quadrilateral elements or zones. The soil medium is considered a heterogeneous plastic medium using the Mohr-Coulomb plasticity model. At first, 2D nonlinear site response analysis was carried out for the Kutch basin (India) and compared with the recorded ground motion data. The developed model is further extended to carry out parametric studies on various factors influencing the seismic site response of basins. The effect of basin factors such as basin shape, basin type, bedrock slope are considered. A large number of basins of different geometry modelled and non-linear 2D site responses analysis was carried out for different earthquake motions recorded at various basins across the world. Further, the empirical correlations are proposed for estimation of basin amplification factors considering basin slope, bedrock slope, depth to width ratio, and horizontal distance from the rock outcrop. The proposed basin amplification factors are useful in seismic zonation of basin sites.

KEYWORDS: Seismic site response, basin effect, Kutch basin, FLAC, basin amplification factor.

1 INTRODUCTION

Damage of buildings observed from various earthquakes show that site conditions are playing a significant role in modifying ground motion characteristics. The site effects are mainly due to local soil conditions, basin effects and topography effects. To obtain surface ground motion corresponding to the particular site considered, seismic ground response analysis has to be carried out. Commonly 1D ground response analysis is carried out, which considers only upward propagation of shear waves. Although 1D ground response analysis can predict reasonably well the seismic response for certain cases, they are unable to simulate the amplification caused by multidimensional effects. 2D site response analyses are to be carried out to study the multidimensional basin effects on the seismic response. Through analytical studies, wave propagation patterns in 2D basins are studied widely; however, the effect of the basin on amplification of ground motion and structural response is not quantified. The ground motion models which included the basin factor in the attenuation relations also failed to match with the simulated results. With increasing computational efficiency, 2D numerical studies are carried out to study actual basins.

Ground motion prediction equations are developed to estimate the expected levels of shaking. Most of the empirical relations for determining the PGA are developed for rock site condition. However, there are few co-relations that take into account the soil type through shear wave velocity and there are very limited studies that consider basin effect. Those limited studies too consider basin effect in terms of sediment depth in the basin (Stewart et al. 2002; Abrahamson et al. 2014; Boore et al. 2014; Chiou &Youngs 2014; Campbell & Bozorgnia 2014). The 2D effects of basin, that is the lateral heterogeneity of the geologic medium in the site, is not included in any of the empirical correlations established so far.

In the present study, 2D modelling of non-linear seismic response of the basin was carried out using finite difference code FLAC. At first, a 2D basin model was developed to carry out nonlinear site response analysis for the Kutch basin (India) and compared with the recorded ground motion data. The various factors influencing seismic response of basin are investigated using the developed basin model. Further, the empirical correlations are proposed for estimation of basin amplification factors

2 DEVELOPMENT OF KUTCH BASN MODEL

2.1 *Kutch basin*

The Kutch basin in the western part of India falls under one of the most seismically active intra-plate regions of the world and has experienced 2 major earthquakes of Mw > 7.7 within a span of 182 years and several moderate-sized earthquakes. The 2001 Bhuj earthquake that occurred in the Kutch region caused severe damage in the regions 350 km away from the epicentre. After the 2001 Bhuj earthquake, a dense network of broadband seismographs and strong motion accelerographs were installed in the Kutch region by the Government of India. Based on the aftershock data of the 2001 Bhuj earthquake recorded by these strong motion networks deployed in the region, the studies on quantification of seismic site response of the Kutch basin is initiated. The site response (SR) estimated by Mandal et al. (2008) in the Kutch basin by the inversion of strong-motion data revealed significant spatial variation and high site response values (1.0–1.7) were observed at the regions south of Kutch mainland fault. The damage pattern obtained during the 2001 Bhuj earthquake also demonstrated the influence of basin effect (Narayan et al. 2002; Narayan & Sharma 2004).

2.2 *Study area*

In the present study, the area lying between longitude range 70.10° E and 70.40° E at Latitude 23.4° N is selected and 2D seismic site response analysis is carried out to investigate the effect of subsurface geology on the basin response. The study area is selected such that the stations equipped with three-component digital accelerograph with varying sediment thicknesses are covered in that particular cross-section of the basin. The site amplification factor estimated at three stations BAN (Bandri), NER (Ner) and MGP (Meghpar) in the Kutch region, by Mandal et al. (2008) is used for comparing the numerical results of the present study.

Based on the geological and geophysical data of the Kutch basin, the depth and width of the numerical model is selected as 50m and 1km respectively, such that the d/b ratio corresponds to that of Kutch basin. The region beyond the study area is considered as a rock outcrop in the numerical model. The Kutch basin is assumed as a scalene triangular model based on the geological profile and sediment thickness of the region. Due to the ambiguity on subsurface basin profile, bedrock slope of 10^0 is assumed to simulate the behavior of shallow Kutch basin. The measured shear wave velocity (Vs) profile in the Kutch region reported by Sairam (2012) is used in the present study. The Vs value increases from 215 m/s to 505 m/s from the surface to 50 m depth. The basin is modelled as a double-layered system with 30m thick medium dense silty sand as the top layer (Layer I) and 20m thick dense silty sand as the bottom layer (Layer II).

2.3 *Numerical Modelling*

The 2D seismic site response analysis of Kutch basin is carried out by the finite difference method using FLAC program. The basin model is divided into a finite-difference mesh composed of quadrilateral elements or zones. Quadrilateral element is further sub-divided into two constant strain triangles.

The geologic media is required to be modelled as an unbounded media ideally to represent the infinite medium and to avoid spurious wave reflections. The use of a larger model can minimize this problem since the material damping will absorb most of the energy from the reflected waves. However, this solution leads to a large computational burden. Therefore, the best alternative is to provide absorbing boundaries. A technique of enforcing free-field motion with non-reflecting properties developed by Cundall et al. (1980) is used.

Mohr-Coulomb plasticity model is adopted to model the soil medium. The properties of soil used in the analysis for Mohr-Coulomb material modelling are summarized in Table 1. The energy losses that occur in the natural medium when subjected to dynamic loading should be reproduced by damping during a dynamic analysis. The hysteretic damping that has strain dependent modulus and damping functions is used in the analysis, as it does not require any reduction in time-step like Rayleigh damping. In the present study, the degradation curves for sand (average) based on Seed and Idriss (1970) are used. The more details on the numerical modelling of the basin can be found in Vijaya (2022) and Vijaya and Boominathan (2022).

Table 1. Properties of soils and rock

Parameter	Symbol	Value	Unit
Layer I			
Unit weight	ϒ	18	kPa
Friction angle	ϕ	30	deg
Cohesion	c	15	kPa
Shear wave velocity	Vs	308	m/s
Layer II			
Unit weight	ϒ	20	kPa
Friction angle	ϕ	35	deg
Cohesion	c	25	kPa
Shear wave Velocity	Vs	480	m/s
Rock			
Shear wave velocity	Vs	750	m/s

2.4 *Input motion*

Acceleration recorded at Sivlaka station (SIV) in the Kutch region by NGRI is used as the input motion (Mandal P, personal communication, Aug 13, 2015) for site response analysis of Kutch basin. The recorded time history of acceleration (aftershock) at SIV station in the Kutch region has PGA of 0.17g and the corresponding predominant frequency of 7 Hz (Figure 1).

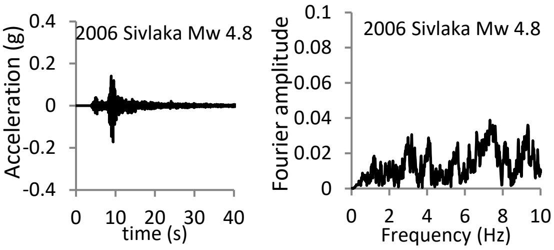


Figure 1. (a) Acceleration time history and (b) Fourier spectra of the input motion

2.5 *Numerical analysis*

Before running a dynamic analysis, gravity is allowed to develop and the model is stepped to equilibrium. The maximum unbalanced force and displacement are monitored at the ground surface to detect equilibrium. Then the non-linear ground response analysis is carried out for the basin models. From the 2D ground response analysis, the acceleration time histories (horizontal and vertical component) are obtained at the surface at 20 locations of regular intervals. The Fourier amplitude spectra is then computed for the acceleration time histories obtained at rock outcrop and basin surface. The site amplification factor, i.e. the ratio of Fourier amplitude on the surface of the basin to that of the rock outcrop is then calculated and plotted against the normalized distance x/L; where x is the distance from the rock outcrop from the left edge and L is half of the width of basin. Thus, the x/L value of 0 and 2 correspond to the left and right ends of basin width. It should be noted that, the region of basin surface that is directly above the bedrock slope is defined as basin edge; the region that is completely devoid of bedrock slope is defined as basin centre and basin surface between these two is defined as the region between centre and edge.

2.6 *Validation*

The seismic site response analysis of the numerical basin model with 10^0 bedrock slope was carried out for the Sivlaka motion. The horizontal component of acceleration time history obtained from the 2D site response analysis of shallow triangular basins subjected to the recorded motion (SIV) in the Kutch region. The Fourier amplitude spectra are computed from the horizontal component of acceleration time histories obtained from the 2D numerical simulations for rock outcrop and basin surface. The site amplification i.e. amplification factor is then calculated as the ratio of Fourier amplitude obtained at the basin surface to that at the rock outcrop. The site amplification thus calculated is compared with that obtained from recorded ground motion data reported by Mandal et al (2008).

The site amplification estimated at 3 stations BAN, NER and MGH is used for comparison with results of the present numerical study. It should be noted that the locations x/L = 0.6 i.e. basin centre, x/L = 0.8 i.e. region between centre and edge and x/L = 1.2 i.e. basin edge, in the numerical model correspond to the stations BAN, NER and MGH in the site respectively. The comparison of site amplification values obtained from the numerical model with the recorded ground motion showed that the numerical model has peaks of site amplification at similar frequencies as that obtained from the recorded motions at the locations x/L = 0.6 (basin centre), 0.8 (region between centre and edge) and 1.2 (basin edge). The triple peak of site amplification obtained at station BAN is captured at the corresponding location x/L = 0.6 by the numerical model at frequencies 2Hz, 5Hz and 8Hz. However, the numerical model did not predict the first peak at around 0.1 Hz that is obtained from the recorded ground motion data. The absence of amplification at lower frequencies could be due to the assumed stiff soil profile. Therefore, it can be inferred that the site amplification pattern across the basin surface is captured well by the numerical basin. More details on the validation of the basin model can be found in Vijaya and Boominathan (2022).

3 FACTORS INFLUENCING BASIN RESPONSE

The 2D non-linear explicit finite difference basin model developed and validated in the previous section is used to analyze the various basin factors influencing surface response. The various factors namely basin shape, basin type and bedrock slope influencing the ground motion parameters are investigated. A schematic layout of the shallow trapezoidal basin considered in the study is shown in Figure 2. All the basin models considered are subjected to four different bedrock motions recorded in various basins across the world. The acceleration time histories obtained from the analysis at 20 different locations of regular intervals along the basin surface are presented in this section.

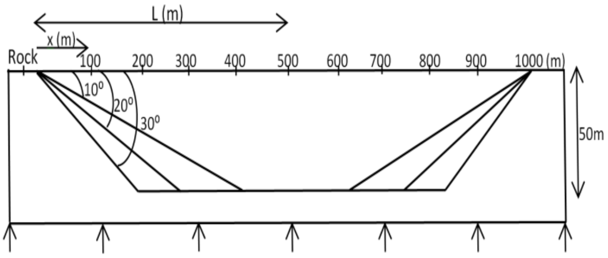


Figure 2. Schematic layout of the shallow Trapezoidal basins used in the study (not to scale)

3.1 Typical seismic response of basins

The typical horizontal acceleration time history is obtained along the basin surface at three typical locations (basin edge, basin centre and region between centre and edge) of the shallow trapezoidal basin of slope 10° subjected to Sivlaka earthquake and are presented in Figure 3. It can be seen from the figure that the PGA of horizontal acceleration time histories are found to vary substantially across the basin surface.

It is observed from Figure 3 that the horizontal PGA value is maximum at the basin edge (0.75 g) and reduces towards the basin centre (0.5 g). The PGA is higher at the basin edge as significant wave scattering by the inclined bedrock slopes happen at the edge region, leading to the generation of surface waves. As we move towards the basin centre the amplitude of acceleration reduces eventually due to the dampening of waves with distance.

3.2 Effect of basin shape

To study the effects of basin shape on the seismic response of basin, five different basin shapes – trapezoidal, triangular, rift, rectangular and semi-circular are considered. In the analysis shallow (d/b ratio of 0.05) basin with 10º bedrock slope is only considered. The spatial variation of PGA amplification factor obtained from the basin models subjected to Sivalaka motion is presented in Figure 4. It is seen from Figure 4 that the PGA amplification factor ranges from 1.4 to 2.2, 1.0 to 2.05, 1.05 to 1.75, 1.75 to 3.0, 1.5 to 3.5 for trapezoidal, triangular, rift, rectangular and semi-circular shape basins respectively.

Table 2 presents the peak values of PGA amplification and their locations. It is observed from the table that the maximum amplification occurs at basin edge region for trapezoidal, rift and rectangular basins; whereas for triangular and semi-circular basins, it occurs at the region between centre and edge and basin centre. It can be noticed from Table 2 that the maximum amplification occurs for a semi-circular basin. It is due to the fact that the shape of the circular basin, significant wave focusing and trapping occurs in the entire basin medium.

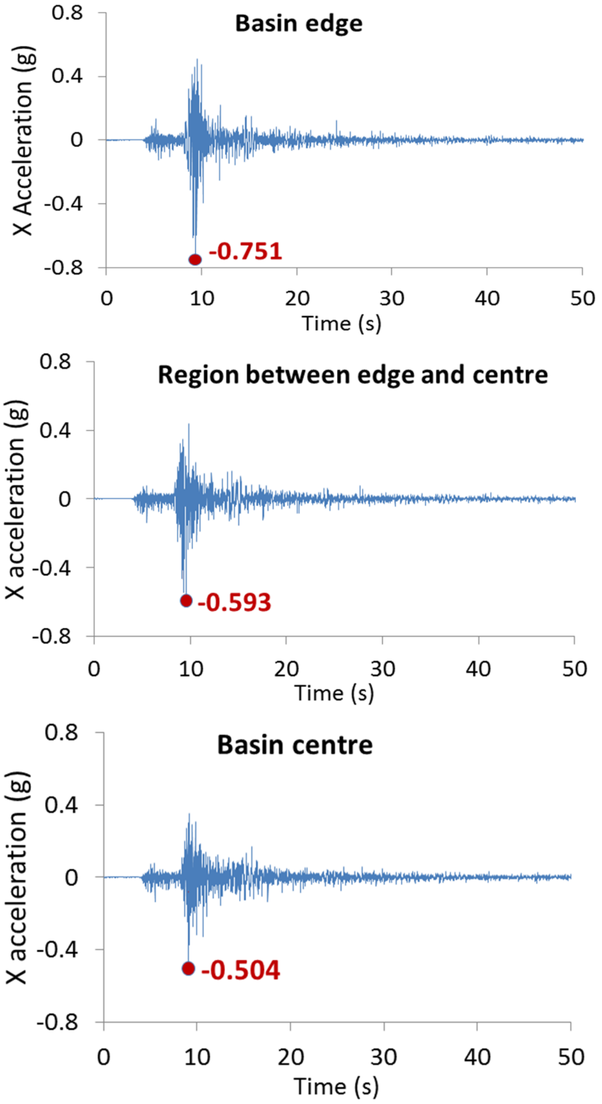


Figure 3. Horizontal component of acceleration time history obtained at (a) edge (x/L = 0.3), (b) between basin center and edge, and (c) basin centre (x/L=1.0).

The variation in predominant frequency of the surface motion for various basin shapes is also presented in Table 2. The surface motion's predominant frequency increases than input motion's predominant frequency at basin edge region for triangular, trapezoidal and rift basin. For all basin shapes, except triangular, the predominant frequency of surface motion decreases than that of input motion at basin centre and the region between centre and edge. The significant duration of acceleration time history is computed for basin surface motion and rock outcrop motion and the change in duration presented in Table 2. It is noted from the table that 20 to 40 % increase in duration occurs at the basin centre for trapezoidal, rift and rectangular basins due to the constructive interference or superposition of surface waves happening towards the centre of the basin owing to the basin geometry.

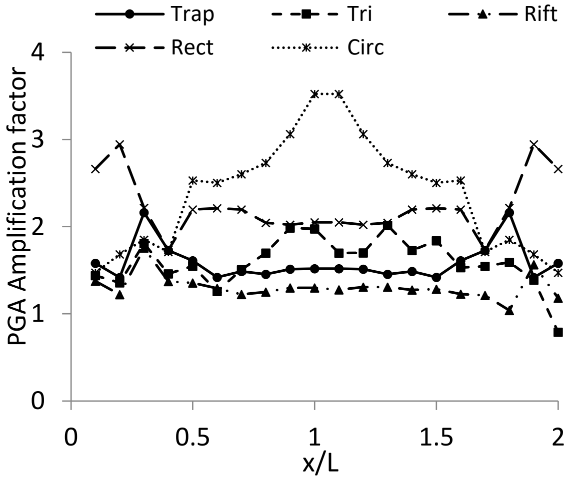


Figure 4. Effect of basin shape on PGA amplification factor (d/b = 0.05, θ=10°, Sivlaka earthquake)

Table 2 Effect of basin shapes

Basin shape	Ground motion parameters		
	PGA Amplification	Predominant Frequency	Increase in Significant Duration
Trapezoidal	2.2 (edge)	Increases to 10 Hz at Edge and decreases to 2Hz at centre	40 % increase at centre
Triangular	2.05 (centre & region between centre and edge)	Frequency varies between 2 and 10 Hz across the surface	40 % increase at centre
Rift	1.75 (edge)	Increases to 10 Hz at Edge and decreases to 2Hz at centre	40 % increase at centre
Rectangular	3 (edge)	2 Hz across the basin surface	40 % increase at centre
Semi-circular	2.5 to 3.5 (region between centre and edge to centre))	3 Hz across the basin surface	Not modified

3. 3 Effect of bedrock slope

To study the effects of basin slope on the seismic response of basin, five different bedrock slopes – 10°, 20°, 30°, 40° and 50° are considered. Table 3 presents the peak values of PGA amplification and their locations, for various bedrock slopes. It can be noticed from the table that the peak amplification occurs at edge region for all the slopes.

Table 3 also presents the variation in predominant frequency of the surface motion for various bedrock slopes. It is noted from the table that for all bed rock slopes the predominant frequency of the surface motion at the basin centre decreases to 2 to 3 Hz from 7 Hz of the input motion frequency while at the edge region the predominant frequency is found to vary from 6Hz to 10Hz.

The significant duration of horizontal component of acceleration obtained at basin surface is computed and it is found that 15 to 35 % increase in significant duration occurs at the region between edge and centre and at the basin centre for all bedrock slopes due to the superposition of surface waves happening towards the centre of the basin owing to the basin geometry.

Table 3 Effect of basin slopes

Basin slope	PGA Amplification	Predominant Frequency
10	2.15 (edge)	Increases to 10 Hz at edge and decreases to 2 Hz at centre
20	2.2 (edge)	Increases to 10 Hz at edge and decreases to 2 Hz at centre
30	1.75 (edge)	Increases to 10 Hz at edge and decreases to 2 Hz at centre
40	2.15 (edge)	Increases to 10 Hz at edge and region between edge and centre and decreases to 3 Hz at centre
50	2.9 (edge) 2.1 (centre)	Increases to 10 Hz at edge and region between edge and centre &decreases to 3 Hz at centre

3.4 Effect of type of basin

To study the effects of basin type on the seismic response of basin, two d/b ratios – 0.05 and 0.25 corresponding to shallow and deep basin, respectively are considered. The trapezoidal basin shape with 30° bedrock slope and Sivlaka input motion is used. Table 4 presents the peak values of PGA amplification factor and their locations for shallow and deep basins. It can be seen from the table that, for shallow basins i.e. d/b=0.05 the maximum amplification of 1.2 is observed at the basin centre. It can be noted from Table 4 that the predominant frequency of the surface motion obtained at the basin centre from the 2D analysis is around 2 Hz for shallow basin and 3 Hz for deep basin, which is the same as that of fundamental frequency of the site (f0) obtained from the 1D linear wave propagation analysis (f0 = Vs/4H). While at the edge region the predominant frequency is increased to 10Hz. It should be remembered that the predominant frequency of the input Sivlaka motion used in the present parametric analysis is 7Hz. Hence it can be said that the predominant frequency of the surface motion is altered significantly from that of input motion across the entire basin surface. However, there is absolutely no spatial variation of predominant frequency at the basin centre for both shallow and deep basin.

It is also found that the basins with higher d/b ratio show substantial increase in the duration of surface motion at the region between centre and edge and at the basin centre, revealing a significant 2D effect of the basin across the basin surface. Whereas for basins with lower d/b ratio, the increase in duration is significant at the region between centre and edge, indicating that for shallow basins significant 2D effect of basin is observed only till the region between centre and edge.

3.5 Effect of input motion

For studying the effects of input motion characteristics on the seismic response of the basin, trapezoidal basin shape with 10° bedrock slope and d/b ratio 0.05 are considered. To analyse the effect of input motion, recorded ground motion data from various basin sites are selected. Thus the basin is subjected to four different earthquakes: 2006 Sivlaka Mw 4.8, 1995 Kobe Mw 6.9, 1979 Imperial Mw 6.5and 1999 Kocaeli Mw 7.4 (Source: PEER strong motion database). The peak ground acceleration (PGA) of the input motions varies from 0.17g to 0.35g and predominant frequency varies from 0.3 Hz to 7 Hz.

Table 4. Effect of basin type

Type of basin (d/b ratio)	PGA Amplification factor	Frequency content
Shallow basin (0.05)	2.15 (edge)	Increase to 10 Hz at edge and decrease to 2 Hz at centre.
Deep basin (0.25)	2.2 (edge & centre)	Increase to 10 Hz at region between edge and centre and decrease to 3 Hz at centre.

Table 5 presents the peak values of PGA amplification factor and their locations for different input motions. The maximum PGA amplification factor is found to occur at the basin edge region for all input motions. It can be seen that the predominant frequency of surface motion is around 3.5 Hz at the edges and 2 Hz at the region between centre and edge and at the basin centre for all input motions. However when the basin is subjected to Sivlaka motion there is a significant increase in the predominant frequency which is observed between x/L = 0.3 and 0.5. It should be noted that the predominant frequency of the input motion used in the present parametric analysis varies from 0.3 Hz to 7 Hz whereas the predominant frequency of basin surface motion obtained from the analysis lies in the range of 2 Hz to 3.5 Hz.

Table 5. Effect of input motion

Input motion	Ground motion parameter	
	PGA Amplification	Increase in significant duration
Sivalaka motion (low amplitude, high frequency)	2.2 (edge)	35 % increase at centre
Kobe motion (med amplitude, low frequency)	1.7 (centre)	15 % increase at centre
Imperial motion (high amplitude , med frequency)	2.1 (edge)	60 % increase at centre
Koceali motion (med amplitude, low frequency)	1.6 (edge)	15 % increase at centre

Table 5 also presents the maximum increase in duration and their locations when subjected to different input motions. It is revealed from the table that the basin subjected to Imperial earthquake has the maximum increase in SD of 60% and the basin subjected to Sivlaka earthquake has 35% increase in duration. While a marginal increase of 15% is observed when subjected to Kobe and Kocaeli earthquake. It can be noted that a substantial increase in duration is obtained for medium frequency Imperial and high frequency Sivlaka earthquakes; while for low frequency Kobe and Kocaeli earthquake only a marginal increase in duration is obtained. As the significant duration considers only 5 to 95 % of the energy of motion, there is a decrease in the significant duration of basin surface motion with respect to the rock motion found at the basin edges

4. BASIN AMPLIFICATION FACTOR

The 2D effects of basin, that is the lateral heterogeneity of the geologic medium in the site is not included in any of the empirical correlations established so far. Based on the parametric analyses carried out in the present study, the empirical correlation for PGA basin amplification factor considering basin factors such as basin shape, bedrock slope (θ), basin type (depth to width ratio - d/b) is proposed at various normalized horizontal distance from the rock outcrop (x/L). Figure 5 shows the 2D basin factors that are considered.

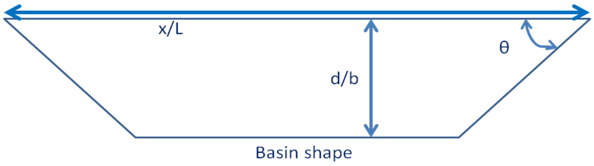


Figure 5. Schematic representation of basin showing the basin factors

The PGA amplification factor is computed at regular intervals of x/L = 0.5 across the basin surface for each basin model. The PGA amplification factor (AF_{PGA}) is defined as the ratio of PGA obtained at the basin surface to that of rock outcrop. Finally, empirical co-relations are developed for basin amplification factors by multiple variable non-linear regression analysis. The basin factor thus obtained can be multiplied with PGA of rock site to obtain the ground motion amplitude at the basin surface.

The empirical relation for amplification factor developed from the 2D basin factors such as θ, d/b and x/L, for each basin shape, by multiple variable non-linear regression analysis are given below:

Trapezoidal basin

$$AF_{PGA} = 0.011\,(\theta) + 6.8\left(\frac{d}{b}\right) - 1.31\left(\frac{x}{L}\right)^4 + 5.5\left(\frac{x}{L}\right)^3 - 7.72\left(\frac{x}{L}\right)^2 + 4.15\left(\frac{x}{L}\right) + 0.65$$

Triangular basin

$$AF_{PGA} = 0.0121\,(\theta) - 0.00383\left(\theta * \frac{x}{L}\right) + 5.4\left(\frac{d}{b}\right) - 0.83\left(\frac{x}{L}\right)^4 + 3.54\left(\frac{x}{L}\right)^3 - 5.43\left(\frac{x}{L}\right)^2 + 3.38\left(\frac{x}{L}\right) + 0.72$$

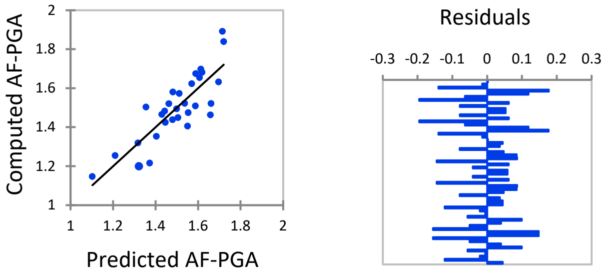
Rift basin

$$AF_{PGA} = 0.01\,(\theta) - 0.00037 * \left(\theta * \frac{x}{L}\right) + 4.6\left(\frac{d}{b}\right) - 0.98\left(\frac{x}{L}\right)^4 + 4.3\left(\frac{x}{L}\right)^3 - 6.2\left(\frac{x}{L}\right)^2 + 3.4\left(\frac{x}{L}\right) + 0.68$$

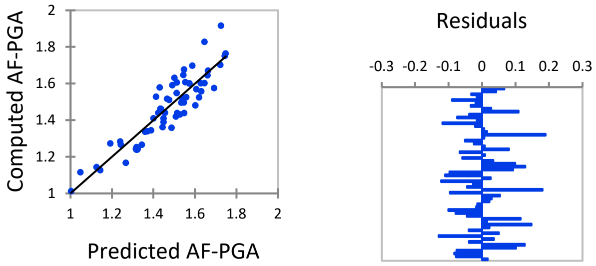
Rectangular basin

$$AF_{PGA} = 2.13\left(\frac{d}{b}\right) - 0.45\left(\frac{x}{L}\right)^4 + 1.88\left(\frac{x}{L}\right)^3 - 2.5\left(\frac{x}{L}\right)^2 + 1.1\left(\frac{x}{L}\right) + 1.42$$

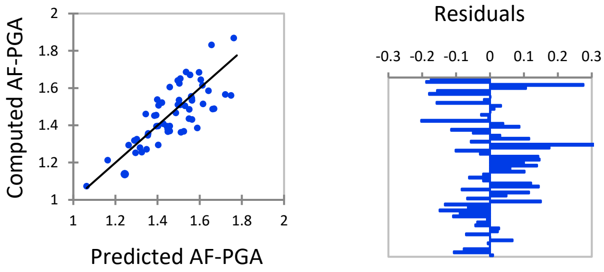
A scatterplot is plotted for the computed amplification factor from numerical analysis versus the amplification factor predicted from the proposed equations, as shown in Figure 6. The residuals plot for the computed and predicted amplification factor is also shown in Figure 6 along with the scatterplot. It can be seen from the scatterplot that the proposed relation for PGA amplification factor predicts reasonably well. However, the residuals for PGA amplification factor is found to be less than 20% for the majority of the cases.



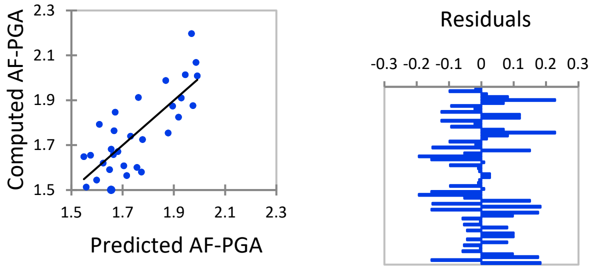
Trapezoidal basin



Triangular basin



Rift basin



Rectangular basin

Figure 6. Scatterplot of computed and predicted PGA amplification factor and their residuals

5 CONCLUTIONS

The site amplification is computed for Kutch 2D basin model and compared with recorded data. The numerical model is able to capture the site amplification at different spatial locations and different frequencies, however the amplification is over estimated due to the scale effect and assumptions in numerical modelling.

The triangular and circular basin shapes are found to be more critical than other shapes, since the basin edge effect is predominant over the entire basin medium. Similarly the steepest (50°) and gentlest (10°) bedrock slopes substantially influence the ground motion across the basin surface, due to wave trapping and the exposure of bedrock soil interface over a huge surface area, respectively. The deep basin causes significant amplification than the shallow basin due to the enhanced wave focusing and wave trapping.

Empirical co-relations are developed for PGA amplification factor considering basin factors and they can be used for basins with similar site condition considered in the present study

6 ACKOWLEDGEMENTS

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