
A Systematic Analysis of Basin Effects on Surface Ground Motion

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Abstract

“Basin effects” refers to trapped and reverberating earthquake waves in soft sedimentary deposits overlying convex depressions of the basement bedrock, which significantly alter frequency content, amplitude, and duration of seismic waves. This has played an important role shaking duration and intensity in past earthquakes such as the M_w 8.0 1985 Michoacán, Mexico, M_w 6.9 1995 Kobe, Japan, and M_w 7.8 2015 Gorkha, Nepal. Although the phenomenon has been understood and addressed in the literature, it has not been fully incorporated in seismic hazard analysis, and Ground Motion Prediction Equations (GMPE). In this study, we perform a finite element analysis to conduct an extensive parametric study on the characteristics of surface ground motion associated with basin effects. We use an elastic medium subjected to vertically propagating SV plane waves and utilize idealized basin shapes to examine the effects of geometric and material properties. We specifically study the effects of four dimensionless parameters, the width-to-depth (aspect) ratio, the rock-to-soil material contrast, the dimensionless frequency quantifying the depth of the basin relative to the dominant incident wavelength, and dimensionless distance quantifying the separation of the basin edges relative to the dominant wavelength. Our results show that basin effects can be reasonably characterized using at least three separate parameters, each of which can significantly alter the resultant ground motion. To demonstrate the application of dimensional analysis applied here, we investigate the response of the Kathmandu Valley during the 2015 M_w 7.8 Gorkha, Nepal earthquake using an idealized basin geometry and soil properties. Our results show that a simplified model can capture notable characteristics of the ground motion associated with basin effects which suggests that such

studies can provide useful insights, relevant to the parameterization of basin effects in GMPEs and design code provisions.

1. Introduction

The effects of material, layering, and geometry of Earth’s surficial layers on surface ground motion is referred to as “site effects”. One subcategory of site effects, “basin effects”, refers to the influence of bowl-shaped loose sedimentary deposit on duration and intensity of earthquake ground motion. Researchers have shown that basin effects would significantly change the amplitude, frequency and duration of seismic waves, which played an important role in many past events including the 1985 M_w 8.0 Michoacán, Mexico, the 1994 M_w 6.7 Northridge, USA, the 1995 M_w 6.9 Kobe, Japan, and the 2015 M_w 7.8 Gorkha, Nepal ([26], [35], [25], [4]).

The start of basin effects studies dates back to approximately half a century ago. Since then, theoretical approaches have been a major part of the literature, and they can be categorized into analytical/semi-analytical and numerical methods. Initially, the out-of-plane (SH wave) problem attracted more attention due to its scalar nature, and, therefore, its simplicity. Among others, seminal was the work by Aki & Larner (1970) [2], who devised a method (Aki-Larner method) based on Rayleigh ansatz to calculate the elastic wavefield in a layer over a half-space medium with a periodic irregular interface subjected to harmonic SH wave incidence. The resultant scattered wavefield is presented by a linear combination of plane waves with discrete horizontal wavenumber over a frequency range which is defined by shear wave velocity and depth of the basin. Despite its success in modeling laterally heterogeneous geological media, Rayleigh ansatz, small periodic length, and truncation of wavenumber components are the main drawbacks of the method. In the examples they solved, they observed lateral interference of waves which were absent in the solution of flat layer approximation (FLA, assuming horizontally stratified media). Parallel to Aki & Larner [2], Boore (1970) [9] studied an irregular layer over half-space with reference to ocean-continent boundary using finite difference method (FDM) for a transient input motion. They validated the method versus analytical solutions and showed the capabil-

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ity of the method within a certain frequency range. They observed a significant Love wave perturbation in the vicinity of the ocean-continent transition zone where both the amplitude and phase of the wavefield are affected. Later, Boore et al. (1971) [10] compared FDM (transient time-domain solution) and Aki-Larner (harmonic frequency-domain solution) for the case of layer over half-space and basin configurations. They transformed the FDM solution to the frequency domain and applied an exponential time-domain window to remove boundary reflected waves. They showed that the results are in good agreement for two different basin configurations while the wavefield could not be adequately captured (for strong reverberations and mostly late arrivals) by the FLA due to lateral interference caused by non-planar basin shape.

Shortly after, Trifunac (1971) [41], and Wong & Trifunac (1974) [45] used the wave expansion method to devise a semi-analytical solution for semi-cylindrical and semi-elliptical basins, respectively. In both cases, they considered out of plane harmonic wave incidence and concluded that while the FLA may work for few cases, it cannot reliably predict the 2D response of basins to seismic wave incidence due to complex 2D interference. Moreover, they found that increasing the frequency of incident wave would complicate the wave interference in the basins, a phenomenon that can also occur due to the change in incident angle.

The complexity due to mode conversion in SV-P (in-plane) problems made them more prevalent a decade after the first studies on SH case. Among others, Bard & Bouchon (1980) [6] studied the problem of in-plane basin response using a modified Aki-Larner method for cosine basins subjected to P and SV incident motions. They considered two cases of low and high-velocity contrasts, and two different basin geometries, narrow (to investigate entrapment of waves) and wide (to investigate surface wave generation). For wide basins with high-velocity contrast, they observed a clear generation of Rayleigh waves and showed that higher Rayleigh mode would be better excited by SV incident wave because of the lower value of shear wave velocity. Moreover, they concluded that the general wavefield pattern is similar in both P and SV incidence cases, while the maximum amplification happens mostly because of the direct wave arrival in the case of P wave, and Rayleigh wave generation in the other one.

Later, Dravinski (1982) [17] examined the scattering of elastic waves by an alluvial valley of elliptical shape subjected to harmonic in-plane (P, SV, and Rayleigh) and out-of-plane (SH) incident motions using boundary integral (BI) method. Boundary methods are attractive due to the lower dimensionality of the problem, compared to FDM, but they are only efficient for configurations with smooth material transitions (no sharp contrasts). They observed the inter-

dependent effects of incident motion frequency and basin's depth, and concluded that at the low-frequency regime, the SH incident is less sensitive to basin depth compared to P and SV waves. In addition, in the case of the Rayleigh wave incident, they showed a comparable surface displacement amplification to the case of P and SV waves incidence. Dravinski & Mossessian (1987) [18] later studied single and multiple semi-elliptical dipping layers structure with weakly anelastic material using the indirect boundary integral equation (IBIE) for harmonic P, SV, and Rayleigh incident waves. They observed a significant change of surface displacement with a change of incident angle and location of observation point for a single layer basin. Adding the second layer strongly affected the surface amplification pattern and magnitude. However, adding the third layer didn't change the surface amplification significantly due to lower relative impedance to bedrock. They concluded that shear wave velocity contrast plays an important role in surface amplification in a basin. They also showed that semi-circular and semi-elliptical basins differ in wave propagation patterns and concluded that geometry of the basin is an influential factor in surface ground motion.

While researchers had been developing theoretical tools to better understand and quantify basin effects in 2D, the M_w 8.1 1985 Michoacán, Mexico earthquake occurred and it was inarguably a turning point in recognizing the significance of basin effects. Despite the large distance (≥ 350 km) from the epicenter, Mexico City experienced a disproportionately large amplitude and long duration of shaking. A large number of studies were undertaken, and were mostly focused on idealized 2D models of the basin ([7], [12], [26]). The ensemble of studies attributed the observed amplification to basin-edge effects and reverberation of earthquake waves in the sedimentary deposits. The consensus was not as strong for the observed ground motion duration, and some studies attributed it to 3D effects [13], and only recently it was shown that it might be due to the effect of frequencies higher than the fundamental frequency of the basin [14].

After the 1985 earthquake in Mexico City, idealized and realistic 3D models gained attention and were used to study basin effects in a more realistic setting by adding the out-of-plane component ([38], [33]). Examples include Hiroke et al (1990) [24], who used an extended Aki-Larner method to study 3D irregularly layered subsurface structures like basins. They observed three dominant 3D effects, namely localization, rapid growth and strong spatial variability of surface waves. Comparison to 2D simulations confirmed that the true amplitude and duration of surface motion cannot be fully reproduced by idealized 2D models. Pitarka et al (1998) [36] included finite fault (source factor) in the studies by performing a 3D FDM near-fault ground motion simulations using kinematic source modeling of the 1995 M_w 6.9 Hyogo-ken Nanbu (Kobe) earthquake. They showed that

the constructive interference between source and basin was the main reason for the catastrophic consequences of the event.

Up until twenty years ago, boundary methods (for example [26]) and FDM (for example [43]) had been the most common theoretical approaches for regional-scale simulation of basin effects. But recently, Spectral and pseudo-spectral methods have increasingly become more attractive for large-scale computer simulations in seismology since they combine the high accuracy with computational efficiency ([27], [16], [23]). Notably among others, Komatitsch and Vilotte [28] and Faccioli et al. [20] were the first to adopt the spectral element method (SEM) from the fluid dynamics community [34]. The adopted formulation of SEM uses the Gauss-Lobatto-Legendre quadrature with Lagrange interpolation instead of lower order interpolation functions used in the FEM, which leads to a significant reduction in computational time and an increased accuracy. Among others, Stupazzini et al (2009) [39] used the 3D SEM to study basin effects in the Grenoble valley. In addition to basin amplification, they also considered source factor and sediment pseudo-nonlinear response. They found that the hypocenter location and directivity effects play an influential role in surface ground motion. Moreover, the radiation mechanism and the relative location of the Grenoble valley to the fault strike were of important contribution. However, they concluded that the nonlinearity effect is not as important as the above-mentioned factors in this case study.

Most of the studies in the past few years have been mostly focused on either case studies ([44], [19]) or idealized basin analysis ([33], [22], [21]). Although it has been shown that the realistic basin geometry, an accurate fault model, and 3D effects would impact the surface ground motion associated with basin effects, the lack of detailed stratigraphy information and material properties have directed the community toward idealized models and in most cases, 1D analysis. In this paper, we use dimensional analysis to conduct a comprehensive numerical parametric study of 2D idealized basin geometries and material properties. Our goal is to identify and prioritize parameters that govern basin effects, which could in turn help to parameterize basin effects in ground motion models (GMM) and engineering design provisions. After verification of our numerical toolbox, we examine the behavior of semi-elliptical and half-cosine basins by varying the material properties, geometrical configuration, and input motion characteristics. To make the results applicable for general basin configurations, we present them in the dimensionless form. Finally, to examine our proposed parameterization, we simulate the behavior of Kathmandu Valley, Nepal during the 2015 Gorkha earthquake. Our simplified results compare favorably to observations, a fact that suggests that simple basin geometries could be used to investigate and parameterize key ground motion characteristics.

2. Underlying Physics of Basin Effects

The underlying physics of basin effects is a combination of (a) trapping of seismic waves due to material contrast and consecutive reverberations of seismic energy, and (b) focusing effects at the edges of a basin, frequently referred to as *basin-edge effects*. Similar to one-dimensional site response, rock-to-soil material contrast plays an important role in the amount of trapped seismic energy in a basin, and thus in the amplification and elongation of seismic motion. One can readily quantify the role of material contrast by solving the wave equation for incidence on a two-material interface (Figure 1):

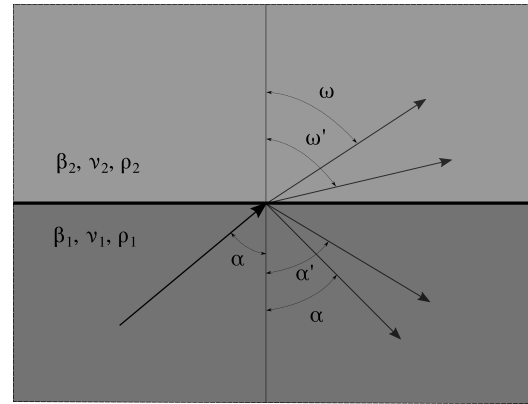


Figure 1. Schematic representation of reflection and transmission of a plane SV wave incident with angle α on a plane boundary of two materials

By satisfying traction equilibrium and displacement compatibility conditions at the material interface, displacement reflection and transmission coefficients can be computed as outlined in detail by Aki and Richards [3]. To show the variation of the reflection and transmission coefficients as a function of rock-to-soil shear wave velocity contrast, Figure 2 plots the displacement amplification coefficients for the idealized interface problem in Figure 1 subjected to a shear in-plane wave (SV). As can be seen, by increasing the material contrast while keeping all other parameters constant, the amplitude of the reflected S-wave increases and the amplitude of transmitted S-wave decreases. Besides, P-waves are generated at the interface due to mode conversion. This illustrates the entrapment and mode conversion that may happen in a basin during an earthquake.

Basin-edge effects, on the other hand, result from energy focusing and interference of seismic waves in the wedge-shaped edges of a basin. The constructive interference between direct waves and edge-induced surface waves is schematically depicted in Figure 3: when a vertically propagating plane SV wave incites on a sloped subsurface interface between bedrock and sediment, it generates a set of reflected and refracted P and S waves. Focusing on the latter,

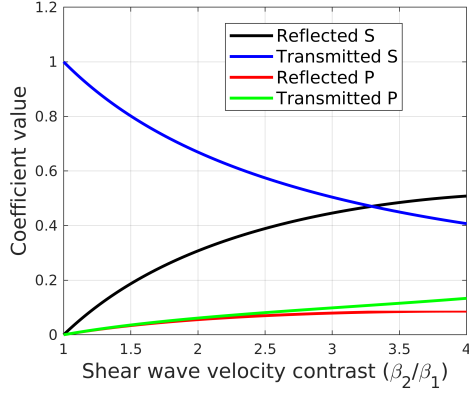


Figure 2. Variation of displacement reflection and transmission coefficients by changing material contrast. This figure shows the case of incident angle = 5° . Different patterns may be observed for higher angles. With reference to Figure 1, medium 1 is softer material.

Figure 3 illustrates the interference of SV direct arrivals, the reflections of SV waves from the bedrock-sediment interface, and the transversely propagating surface waves. This shows a complex interaction of wave components that frequently exacerbates the intensity of the wavefield in a basin.

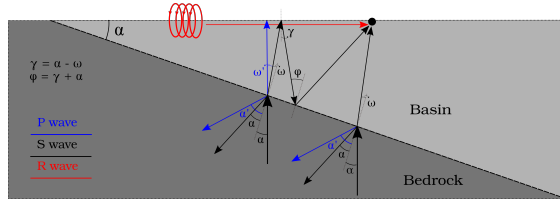


Figure 3. Schematic view of the coupled effect of material contrast and basin edge. P, S and R waves stand for Compressional, Shear and Rayleigh waves. β_1 and α_1 are S and P wave velocities in the dipping layer, and β_2 and α_2 are the ones for bedrock. In this figure, $\omega = \arcsin \frac{\beta_1}{\beta_2} \sin \alpha$, $\omega' = \arcsin \frac{\alpha_1}{\beta_2} \sin \alpha$ and $\alpha' = \arcsin \frac{\alpha_2}{\beta_2} \sin \alpha$. Other parameters and angles are shown in the figure.

The simulated particle motion on the ground surface of a 20° dipping layer subjected to a vertically propagating SV wave of Ricker type is shown in Figure 4. Points 1 to 5 lie on the rock outcrop, while points 6 to 16 lie on the surface of the sedimentary dipping layer. Point 6 is located exactly at the tip of the 20° wedge. As can be seen, the basin edge introduces very complex particle motion compared to the frequently assumed horizontally stratified medium which does not generate any vertical component. While its effects are evident on the rock outcrop motion in the vicinity of the wedge tip, it predominantly impacts the particle motion inside the dipping layer. We should also note that while the incident motion was purely horizontally polarized, the ground

motion has a significant vertical component arising from mode conversion, as well as very pronounced spatial variability, both of which are likely to affect distributed systems and long components of infrastructure such as pipelines.

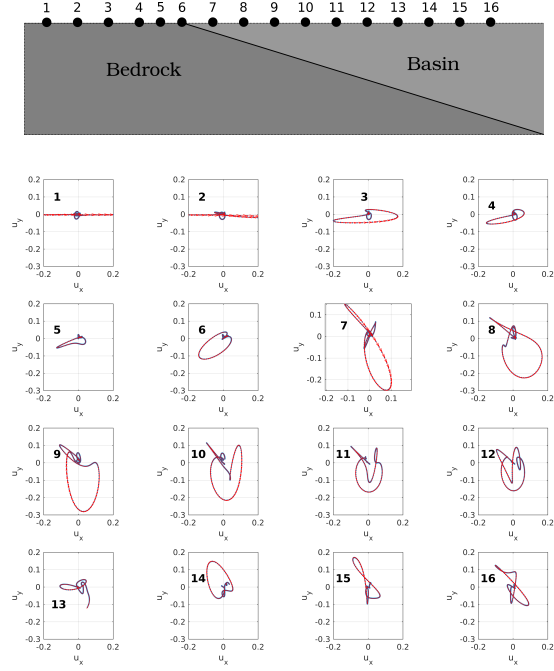


Figure 4. Particle motion diagram for a set of stations around the basin edge of 20° . Example is shown for material velocity contrast 2, and unit amplitude plane Ricker SV wave with a dominant frequency of 1 Hz.

3. Description of Numerical Model

The idealized numerical model we used in this study is a 2D basin consisting of two elastic, isotropic, and homogeneous materials for bedrock and basin. We performed analysis of wave propagation in a basin over halfspace using OpenSees, a FEM code that can solve the wave equation in a heterogeneous medium subjected to initial and boundary conditions using an implicit scheme [30]. We discretized the numerical model by requiring 12 quad elements per shortest propagating wavelength to resolve the frequency range of interest based on the dominant frequency of an incoming wave (Figure 5).

Free-field boundary conditions were placed along the side boundaries, at a distance greater than two times the dominant incident wavelength (λ_2 , see Figure 8) from basin edges. Free-field (FF) boundary condition comprises S- and P-wave absorbing elements (also known as “Lysmer dashpots” [29]), and free-field equivalent forces corresponding to 1D wave propagation conditions as shown in Figure 7 [15].

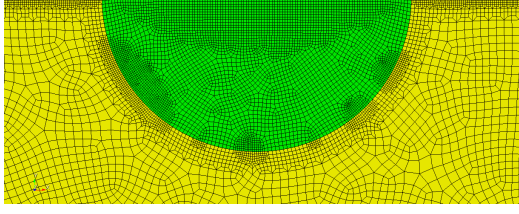


Figure 5. An example of discretized FE domain. The green area shows the basin and the yellow represents the bedrock. The domain is discretized using quad elements.

C_s and C_p are the dashpot coefficients for tangential and perpendicular directions relative to the domain, respectively, and are estimated as follows:

$$C_s = \rho v_s \quad (1)$$

$$C_p = \rho v_p \quad (2)$$

where ρ is the density of the halfspace, v_s and v_p are the shear and compressional wave velocities of the halfspace, respectively. The FF effective forces that represent the stress-field for 1D wave propagation conditions were computed as follows:

$$F_x = -(\rho C_p (V_x^m - v_x^{ff}) - \sigma_{xx}^{ff}) \Delta A_y \quad (3)$$

$$F_y = -(\rho C_s (V_y^m - v_y^{ff}) - \sigma_{xy}^{ff}) \Delta A_y \quad (4)$$

where F_x and F_y are perpendicular and tangential loads, respectively. V_x^m and V_y^m are model velocities in x and y directions that are computed at each time step during the FE analysis, v_x^{ff} and v_y^{ff} are FF velocities in x and y directions, and σ_{xx}^{ff} and σ_{xy}^{ff} are the FF stresses in x and y directions, respectively. The last four quantities can be calculated using D'Alembert's method for 1D wave analysis. ΔA_y is the element size in the vertical direction.

For incident motion, we used a unit amplitude vertically propagating plane SV wave of Ricker type [37] (Figure 6, Eq. 5). This is applied as a shear force at the base of the numerical domain where absorbing boundary conditions (Lysmer dashpot) is prescribed. The force is calculated based on Eq. 6 where F_{input} and ΔA_x are input force and element size at the bottom, respectively.

$$V(t) = (1 - 2\pi^2 f_0^2 t^2) e^{-\pi^2 f_0^2 t^2} \quad (5)$$

$$F_{input} = \rho C_s V(t) \Delta A_x \quad (6)$$

Synthesizing the above, the vertical side boundaries would ideally respond as 1D columns subjected to vertically propagating shear waves, had there not been a scattered wavefield (albeit weak in this case) that is leaking from the basin sediments at each reverberation. A schematic view of the

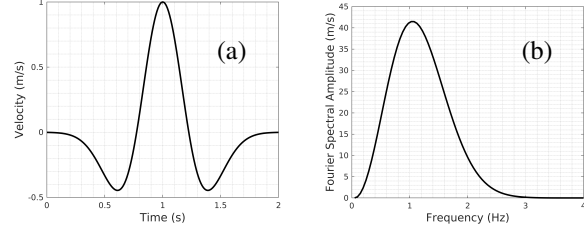


Figure 6. Ricker wavelet in a) time-domain and b) frequency domain

numerical domain together with prescribed boundary conditions is depicted in Figure 7.

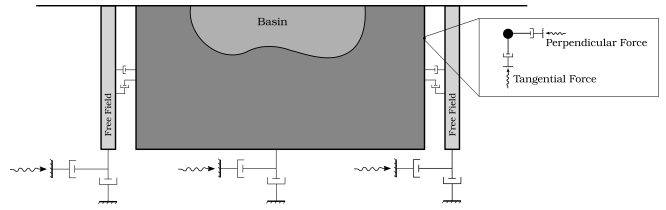


Figure 7. Schematic view of the FEM domain and boundary conditions. The prescription of Lysmer dashpot and free field forces on each boundary node is magnified on the right.

4. Parametric Analysis

In this section, we investigate the variation of surface ground motion with basin geometry, material properties, and input motion characteristics by performing a parametric study on two idealized configurations, Semi-Elliptical (SE) and Half-Cosine (HC). The SE basin is used as a frequently employed idealization that can easily be parameterized. It is suitable to study the physics of wave propagation inside a basin by investigating the effect of dimensionless parameters that will be presented later. The HC basin is used as a more realistic representation of the basin shape while remaining easy to parameterize for geometric and material properties. Eq. 7 gives the mathematical expression of the bedrock-sediment interface depth for an HC basin. Parameters b , D , and a are shown in Figure 8.

$$\begin{cases} b & |x| \leq D/2 \\ \frac{b}{2} [1 + \cos(\frac{\pi(x-D/2)}{a})] & D/2 \leq |x| \leq D/2 + a \\ 0 & |x| \geq D/2 + a \end{cases} \quad (7)$$

The dimensionless parameter space for the problem in hand can be derived using Buckingham's π theorem [11]. For a dynamic problem in elastodynamics, three parameters are needed to define a material. Here, we use β (shear wave

velocity), ν (Poisson's ratio) and ρ (density) as representative parameters for each material, totalling six parameters, namely β_1 , ν_1 , ρ_1 , β_2 , ν_2 and ρ_2 . In addition, a , b and $D + 2a$ are used to define geometry of a basin. Finally, f_0 , the dominant frequency (the frequency at which the maximum Fourier spectral amplitude happens) of input motion, is used to represent the excitation. Given that we have 10 parameters, and using three characteristic parameters to represent length ($[L] = b$), mass ($[M] = \rho_2 b^3$) and time ($[T] = b/\beta_1$), we end up with 7 (π_1 , π_2 , π_3 , π_4 , π_5 , π_6 , and π_7) dimensionless parameters as follows:

$$\begin{aligned} \pi_1 &= \nu_1, \pi_2 = \nu_2, \pi_3 = \frac{a}{b}, \pi_4 = \frac{\beta_2}{\beta_1}, \pi_5 = \frac{f_0 b}{\beta_1}, \\ \pi_6 &= \frac{\rho_1}{\rho_2}, \pi_7' = \frac{D + 2a}{\lambda_1} = \frac{(D + 2a)f_0}{\beta_1} \end{aligned} \quad (8)$$

Note that π_7' is derived by multiplying $\pi_7 = (D + 2a)/b$ and π_5 . The dominant dimensionless parameters in our problem are π_3 , π_4 , π_5 and π_7' . To reduce the computational cost, we perform the parametric study only for these four parameters, and later show that the effects of π_1 , π_2 and π_6 are negligible for the problem in hand. The default values of $\pi_1 = 0.33$, $\pi_2 = 0.33$ and $\pi_6 = 1$ are assumed for most part of this article, similar to [26].

Table 1 shows the dimensionless parameters together with their corresponding values that will be used in the following sections. Besides, Figure 8 shows a schematic visualization of two idealized basin geometries mentioned above.

Table 1. Parameter space considered in this study

π_3	π_4	π_5	π_7'
0.5, 1, 2, 4	1.5, 2, 3.5, 5	0.125, 0.25, 0.5, 1, 2, 4	0.25, 0.5, 1, 1.5, 2, 2.6, 3.2, 3.8, 4.4, 5, 8, 12

Aspect Ratio (AR) is defined as a over b (see Figure 8). Shear wave velocities β_1 and β_2 correspond to the velocities of the sediments and the bedrock, respectively. f_0 is the dominant frequency of the incident wavefield, ζ is the dimensionless width of the basin defined as $(D + 2a)/\lambda_1$, where λ_1 is the dominant wavelength in the sediments defined as β_1/f_0 . To compare the various realizations of the parametric space, we normalize the peak velocity amplitude on the ground surface by the peak amplitude on rock outcrop referred to as amplification factor (AF). In addition, we utilize seismogram synthetics (SS) on the ground surface and vector field snapshots to represent the spatiotemporal variation of the wavefield.

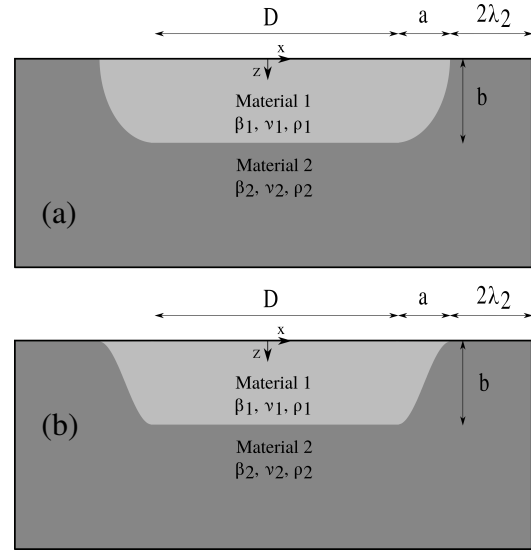


Figure 8. Schematic view of a) SE and b) HC basins. λ_2 is defined as β_2/f_0 .

4.1. Numerical Model Verification

We present two verification examples of our numerical models: (a) a semi-circular basin from Mossessian & Dravinski (1987) [32], and (b) a trapezoidal basin from Kawase & Aki (1989) [26]. Models are presented using dimensionless parameters explained earlier.

4.1.1. SEMI-CIRCULAR BASIN: MOSSESIAN & DRAVINSKI (1987)

The first verification example is a semi-circular basin, with geometry characteristics and material properties described in Mossessian & Dravinski [32] and listed in Table 2. Mossessian & Dravinski used the indirect boundary integral method to compute the steady-state basin response and reported the Amplification Factor (AF) along the surface as the peak ground surface spectral amplitude normalized by the peak incident spectral amplitude (U_x/U_x^{inc}). Figure 9 shows the comparison of their results to those of our numerical model. To compare our synthetic time-domain results with the steady-state basin response of Mossessian and Dravinski (1987) [32], we extracted the steady-state part of the ground surface displacement, applied the Fast Fourier Transform (FFT), and normalized them by the peak spectral amplitude of the incident motion. The comparison shows a very satisfactory agreement between the two studies.

Table 2. Material, geometry and incident motion parameters for semi-circular basin study [32]

π_1	π_2	π_3	π_4	π_5	π_6	π_7'
0.333	0.333	1	2	0.5	0.66	1

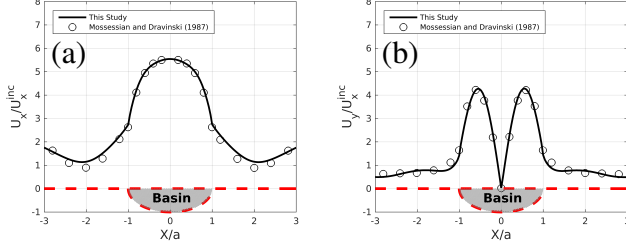


Figure 9. Surface AF in a) horizontal and b) vertical directions for semi-circular basin of Mossessian and Dravinski [32]

4.1.2. TRAPEZOIDAL BASIN: KAWASE & AKI (1989)

The second verification example is the trapezoidal basin response published by Kawase and Aki (1989) [26]. Table 3 shows the parameters we used to simulate this example. Figure 10 shows an excellent agreement of the two studies in the spatiotemporal domain.

Table 3. Material, geometry and incident motion parameters for trapezoidal basin study [26]

π_1	π_2	π_3	π_4	π_5	π_6	π_7
0.333	0.333	2	2.5	0.25	1	2.5

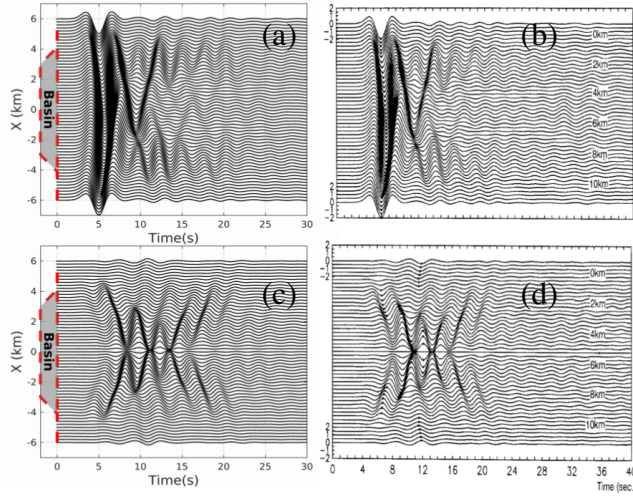


Figure 10. Comparison of ground surface seismogram synthetics in a, b) horizontal and c, d) vertical directions between this study (left) and Kawase & Aki [26]. The figures on the right are extracted from Kawase & Aki [26].

Results from the two verification tests presented here, where we tested the code against two different geometries and material properties, serve as evidence of the capabilities and accuracy of the numerical model.

4.2. Results

In this section, we present the results of a parametric analysis for each basin geometry, separately. For the SE basin, we try to elaborate on the underlying physics of basin effects by first investigating AR . We then examine the effects of dimensionless frequency. Furthermore, the role of material contrast and dimensionless width will be discussed. Finally, we study the dimensionless parameters that were claimed to have a lesser impact on surface ground motion. For the HC basin, we will not discuss every parameter in detail due to similarities in the wavefield with SE. However, we focus on the differences and try to show why HC is a more reliable idealized geometry to study basin effects. At the end of the HC section, we also present the effect of damping on surface amplification. We further try to show the suitability of HC basin by doing a case study of Kathmandu Valley, Nepal during the 2015 Gorkha earthquake in the final section of the article.

We consider a parameter space that covers a broad range of geometric, material, and excitation parameters. The AR , which is an index for the average slope of basin corners, ranges from 0.5 (deep basin) to 4 (shallow basin). Dimensionless frequency (η), which represents the relative size of the basin to a dominant incoming wavelength, ranges from 0.125 to 4. Material velocity contrast (β_2/β_1) ranges from 5 (soft basin) to 1.5 (stiff basin). Dimensionless width (ζ), which quantifies the separation of two basin edges, ranges from 0.25 (narrow basin) to 12 (wide basin).

4.2.1. SEMI-ELLIPTICAL BASINS

Figure 11 shows the maximum AF of the horizontal component of ground surface motion from the ensemble of SE basin analyses corresponding to $D = 0$, as a case with complex 2D wavefield due to the short distance of two basin edges. The effect of ζ will be discussed later in the article.

Results show that for a given AR , the amplification factor generally increases with increasing material contrast β_2/β_1 . This is not particularly surprising since high β_2/β_1 implies a higher percentage of energy entrapment in sediments, and lower energy leakage. There are, however, a few notable results: in the case of $AR = 0.5$, $\eta = 4$ and $\beta_2/\beta_1 = 1.5$ (dashed red circle in Figure 11), that is a deep basin with relatively stiff sediments subjected to high-frequency ground shaking. We observe a very high amplification ($AF = 2.95$) which is close to the maximum AF that we observed from the ensemble of simulations. As shown in Figure 12, this happens due to the synchronous arrival of direct waves and edge-induced surface waves at the center of the basin where they constructively interfere. Based on this figure, wavefield evolution can be explained in four stages as enumerated below:

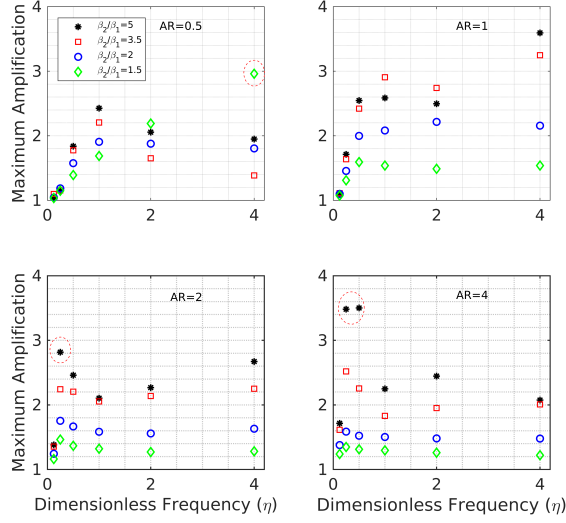


Figure 11. Maximum horizontal AF for all SE analyses. Red circles show unexpected results due to constructive wave interference.

- The incident wave hits the deepest part of the basin. One can identify the onset of wavefield distortion in the basin. The sediment-rock material contrast plays an important role since it determines the amplitude of the seismic pulse that enters the basin, and regulates the amount of time it takes to reach the basin surface.
- Vertically incident waves from the base, and laterally propagating surface waves generated at the basin edges travel toward the basin center.
- Waves interact while waves propagate toward the basin center.
- Maximum amplification occurs when they contact at the center.

On the opposite end, for a very shallow basin with very soft sediments, the case of $AR = 4$, $\beta_2/\beta_1 = 5$, and $\eta = 0.25$ to $\eta = 0.5$, a similar phenomenon of constructive interference in the middle of the basin occurs, as shown in Figure 13. This shows that the maximum happens in the middle of the basin at time 5. In addition to high AF, due to material velocity contrast, we clearly recognize the reverberations of trapped energy in the sediments, which beyond the large AF leads to a prolonged motion duration.

4.2.1.1. Effect of Aspect Ratio (AR): AR defines the average slope of basin edges, which have shown to be of important contribution during seismic events [25]. In this subsection, we present the result of surface amplification for various AR values. The spatial variation of horizontal

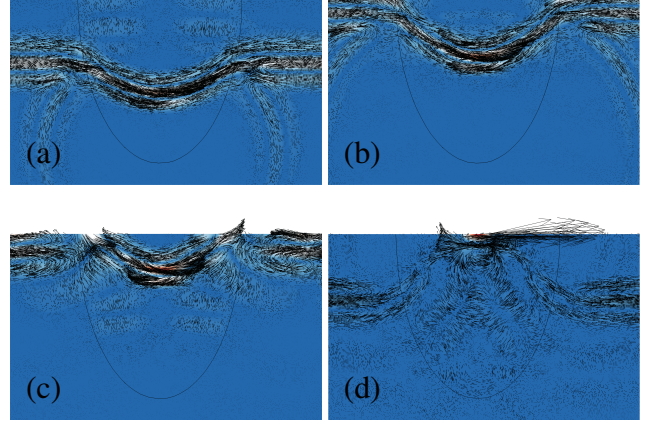


Figure 12. Snapshots of the wavefield for an SE basin with $AR = 0.5$ and $\beta_2/\beta_1 = 1.5$, subjected to vertically propagating shear waves of $\eta = 4$: a) incident wave enters the basin; b,c) body and surface waves travel towards the basin center; d) body and surface waves generate the maximum AF at the basin center.

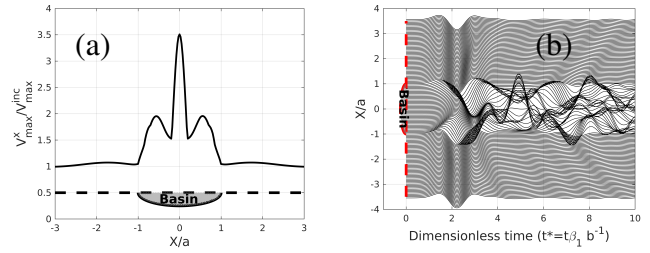


Figure 13. a) AF and b) SS in horizontal direction for $AR = 4$, $\eta = 0.5$ and $\beta_2/\beta_1 = 5$.

and vertical amplifications are portrayed in Figures 15 (low frequency) and 16 (high frequency) for a set of aspect ratios, velocity contrasts, and dimensionless frequencies. Figure 14 illustrates the SS for the top panel of Figure 15, and helps to explain the observed surface amplification.

From these figures, one can observe a large variation of the AF in both horizontal and vertical directions. By focusing on Figure 15, it is clear that for this particular setting, $AR = 1$ has the largest amplification in the horizontal direction for both material contrasts due to constructive interference of direct arrival of incident wave and laterally propagating edge-induced surface waves as can be seen in Figure 15-a and c. For shallower and deeper basins, the wave interference does not happen similar to the semi-circle and results in the maximum amplification closer to the basin edges. The AF of the vertical component which arises purely from mode conversion (recall that our input motion was a vertically propagating horizontally polarized SV wave) is generated primarily from edge-induced (Figure 14-d,f,h)

surface waves except for $AR = 0.5$ (Figure 14-b). For the deepest basin, the basin edges are not playing as important role as their shallower counterparts.

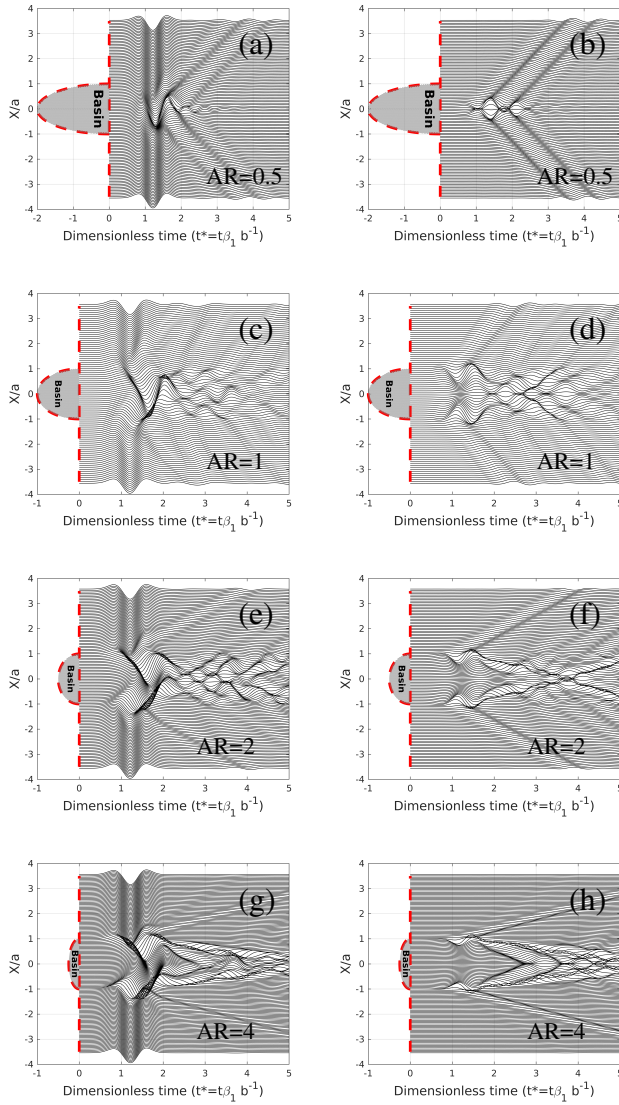


Figure 14. SS for $AR = 0.5$ (top panel), $AR = 1$ (second from top panel), $AR = 2$ (second from bottom panel) and $AR = 4$ (bottom panel) in a, c, e, g) horizontal and b, d, f, h) vertical directions. $\eta = 1$ and $\beta_2/\beta_1 = 2$ are assumed.

Figure 16 shows how higher frequency input motion would affect the resultant wavefield while other parameters are the same as Figure 15. Increasing the frequency, in general, would result in a more localized interaction of basin and incident motion. This is projected in Figure 16 where higher amplifications at basin corners happen over a shorter distance (see Figure 16-a and c). In addition, as a result of more localized interaction, the spatial variation of surface amplification is exacerbated (see Figure 15-b and d)

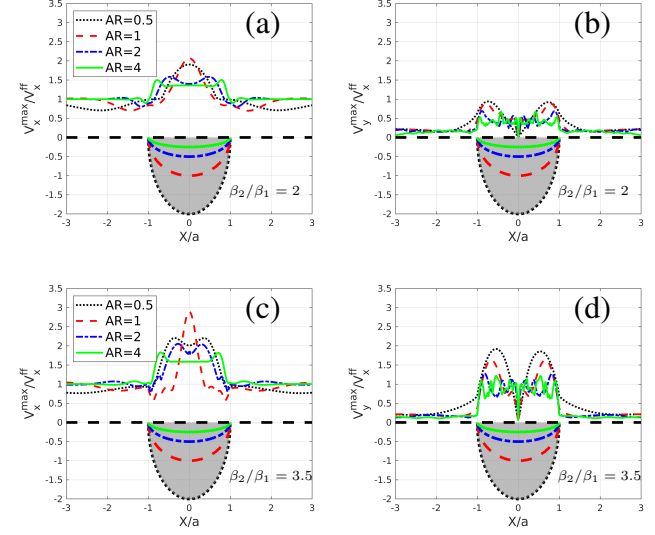


Figure 15. AF in a,c) horizontal and b,d) vertical directions for SE basin for a range of ARs, $\eta = 1$, $\beta_2/\beta_1 = 2$ (top panel) and $\beta_2/\beta_1 = 3.5$ (bottom panel).

which could cause serious damage to long components of infrastructure system due to torsional particle motion.

Based on the last three figures, the three parameters, namely the coupled behavior of basin geometry, material properties, and incident motion frequency content will affect the surface ground motion in a basin. For the rest of the article, we use $AR = 1$ as a point of comparison and try to investigate other parameters by assuming a constant $AR = 1$.

4.2.1.2. Effects of Dimensionless Frequency (η) and Material Contrast (β_2/β_1): In this subsection, we investigate the case of $AR = 1$ in detail. Figures 17 and 18 show the effects of dimensionless frequency (η) and material contrast (β_2/β_1) on the AF of the surface ground motion. Recall that parameter η measures the basin response sensitivity to an incoming wave by quantifying the relative size of the basin to the incoming dominant wavelength. Focusing on Figure 17, for $\eta \ll 0.5$ and $\eta \gg 4$, the basin is too small or too large compared to the incident wavelength, respectively. In the first case, the wave barely “sees” the basin (basin-bedrock medium behaves as a halfspace), and in the second case, the interaction happens similar to a 1D two-material column. Therefore, $\eta = 0.125$ (wavelength 8 times larger than basin depth) results in a negligible vertical component since the basin is too small for the seismic wave to experience substantial mode conversion. This figure also illustrates the aforementioned strong spatial variability of surface ground motion for higher frequencies. Moreover, due to the complexity of the wavefield in the basin, no specific η yields a maximum

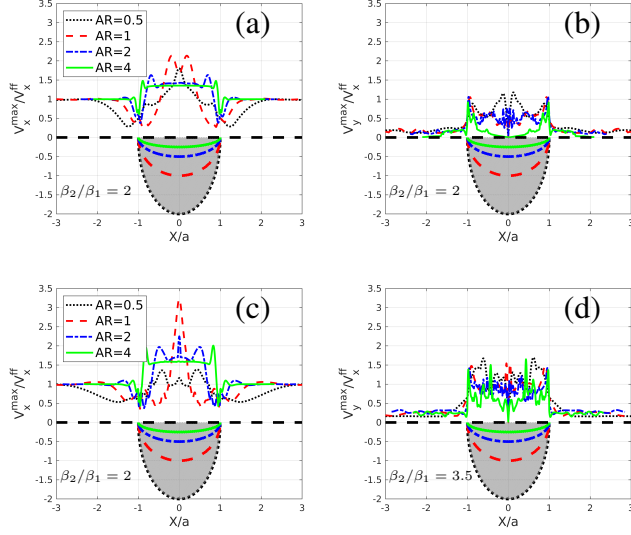


Figure 16. AF in a,c) horizontal and b,d) vertical directions for SE basin for a range of ARs, $\eta = 4$, $\beta_2/\beta_1 = 2$ (top panel) and $\beta_2/\beta_1 = 3.5$ (bottom panel).

AF across the basin which can be observed in both the horizontal and vertical components and is more pronounced near basin edges.

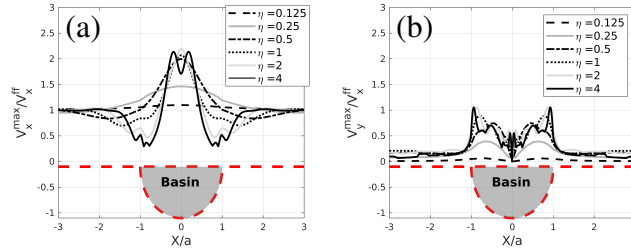


Figure 17. AF in a) horizontal and b) vertical directions for SE-shaped basin with AR=1 and $\beta_2/\beta_1 = 2$

Figure 18 further details the $AR = 1$ case by showing the effect of material contrast for different η . We considered three different values for η to better illustrate the coupled effect of parameters of interest. The AF of the vertical ground motion component shows surprisingly high value. While the incoming wave is a plane SV-wave, the AF vertical component near the edges is comparable to the horizontal one, and the spatial variability suggests that structures near the edges would experience not only strong transverse and vertical shaking but also rotational motion. In addition, higher frequency incident motions interact on a local scale with the geometry and material properties of the basin, which affect the ground motion characteristics over shorter distances. The opposite is true for longer wavelengths. For the case

of $\eta = 0.5$, both horizontal and vertical AFs reveal that the incident motion interacts with the basin as a whole, a fact evidenced in the smooth spatial variation of AF across the basin. By looking through this figure, the localization effect of frequency increment is obvious. For example, by comparing Figures 18-b and 18-d, one can see a similar trend that Figure 18-d has more wiggles due to higher frequency content.

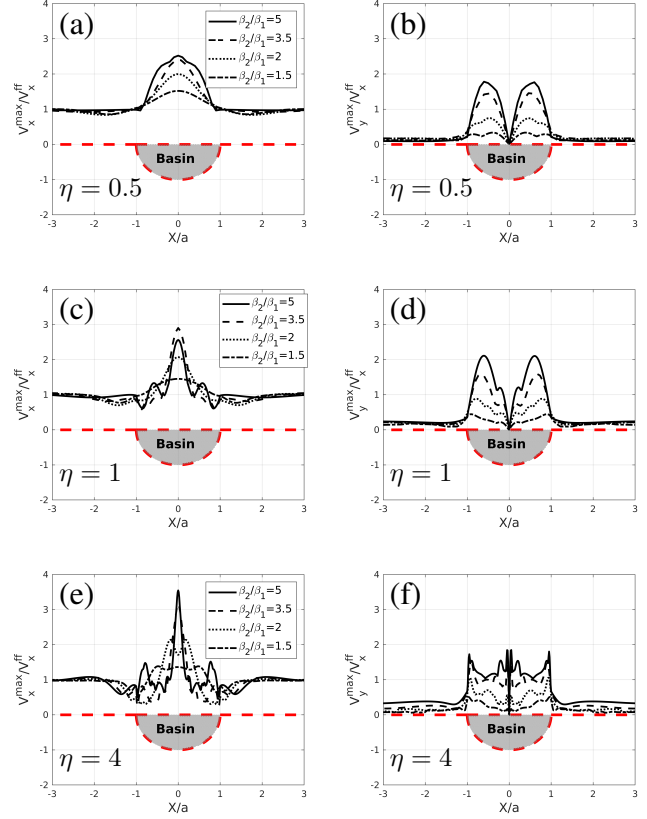


Figure 18. AF in horizontal (left panel) and vertical (right panel) directions for SE basin with AR=1 and a,b) $\eta = 0.5$, c,d) $\eta = 1$, e,f) $\eta = 4$. Three different η s are shown to also show the coupled effect of material contrast and dimensionless frequency.

4.2.1.3. Effect of Dimensionless Width (ζ): So far we have investigated three parameters with $D = 0$ to observe the wavefield in a basin. For this subsection, we focus on edge-induced Rayleigh waves by assuming a $D > 0$ value. Figure 19 shows the effect of the dimensionless width (ζ) on the spatial distribution of surface amplification on the surface of a SE basin. Note that the minimum value of ζ is equal to $\frac{2a}{\lambda_1} = 2\eta AR$. By increasing ζ , the amplification decreases and a separation between two corners appears. This results in a nearly 1D response in the middle of the basin (blue star) while the 2D effects dominate by moving toward the basin edges. This does not mean that the middle of the basin will experience purely horizontal motion

since the Rayleigh wave's traverse motion will still generate significant vertical movement. This phenomenon will be explained in more detail in a later section of this article.

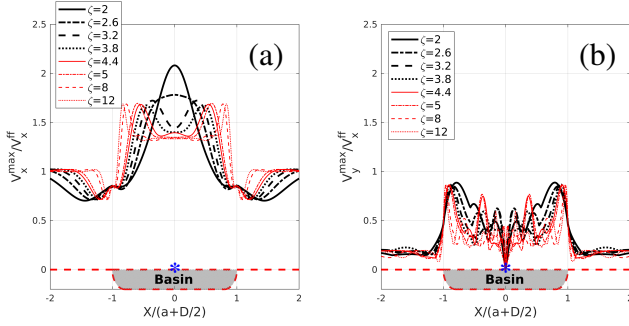


Figure 19. Effect of dimensionless width ($\zeta = (D + 2a)/\lambda_1$) for SE basin for a) horizontal and b) vertical components. $AR = 1$, $\eta = 1$ and $\beta_2/\beta_1 = 2$ are assumed

4.2.1.4. Effect of Other Dimensionless Parameters: In this subsection, we examine the effects of three dimensionless parameters we have not investigated yet (see Eq. 8), namely the Poisson's ratio of the sediments (ν_1) and the bedrock (ν_2), and the ratio of mass density of the sediments to the bedrock (ρ_1/ρ_2). The parameter space we consider is shown in Table 4. Figure 20 shows the effects of Poisson's ratio on the surface amplification for $\beta_2/\beta_1 = 2$ and $\beta_2/\beta_1 = 3.5$, $\eta = 1$ and $AR = 1$. The effects of Poisson's ratio is negligible compared to the four main dimensionless parameters we discussed earlier. We should also note here, however, that the effects of Poisson's ratio for nearly incompressible material behavior ($\nu \approx 0.5$ or undrained loading conditions) are likely to be more pronounced.

Table 4. Considered parameters for studying effects of π_1 , π_2 and π_6

	$\pi_1 (\nu_1)$	$\pi_1 (\nu_2)$	$\pi_6 (\frac{\rho_1}{\rho_2})$
Value	0.25, 0.35, 0.45	0.2	$\frac{2}{3}$, 0.8

Similarly, Figure 21 shows the effects of density contrast (ρ_2/ρ_1) on the spatial variability of peak amplification, for the case of an SE basin with $\eta = 1$ and $AR = 1$. Results are shown for two velocity contrasts $\beta_2/\beta_1 = 2$ and 3.5. As can be seen, the effects of density contrast are on the order of 5% in the vicinity of the peak horizontal and vertical amplification, which, despite being more impactful than the effects of Poisson's ratio shown above, are still considered as secondary importance when compared to the four parameters investigated earlier.

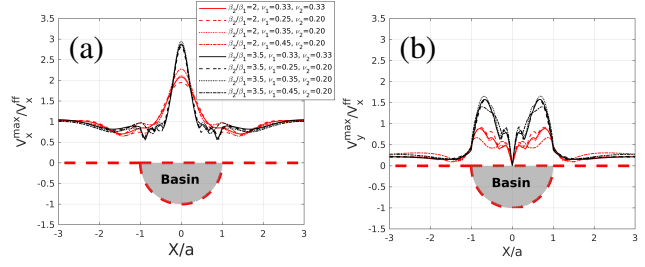


Figure 20. Effect of ν on surface ground motion for two different β_2/β_1 values, for SE basin with $\eta = 1$ and $AR = 1$ in a) horizontal and b) vertical directions

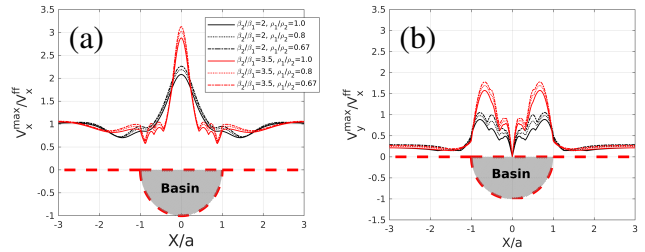


Figure 21. Effect of ρ_1/ρ_2 on surface ground motion for two different β_2/β_1 values, for the case of an SE basin with $\eta = 1$ and $AR = 1$ in a) horizontal and b) vertical directions

4.2.2. HALF-COSINE BASINS

Although SE have been widely used as idealized basin geometry ([41], [17]), its edges do not resemble realistic basin corners. In more realistic scenarios, one would expect landscape evolution processes, such as weathering, to lead to a smoother variation with depth near basin edges. Given the important role of focusing and diffraction close to the edges (see Figure 22), we here study a more realistic idealized basin shape, referred as Half-Cosine shaped (HC) (see Figure 8 for a schematic representation).

Figure 22 shows the comparison in the particle motion of the two basin geometries (SE and HC) near the edge. The bottom row schematically depicts the geometry of the basin edge and the location at which the comparison is taking place. As can be seen, the wavefield is strongly affected by the basin edge geometry (and convexity). Note that the edge geometry caused a horizontal shift in the wavefield, and it seems that each point on the SE basin corresponds to a further point in HC. For example, points 4 and 11 have similar particle motions.

For the rest of this section, we focus on the parameters that are directly affected by edge geometry, namely AR and ζ . Although η and β_2/β_1 would significantly change the wavefield in a basin, they are not detailed here for the sake of brevity, and results are shown for the case of $\eta = 1$ and

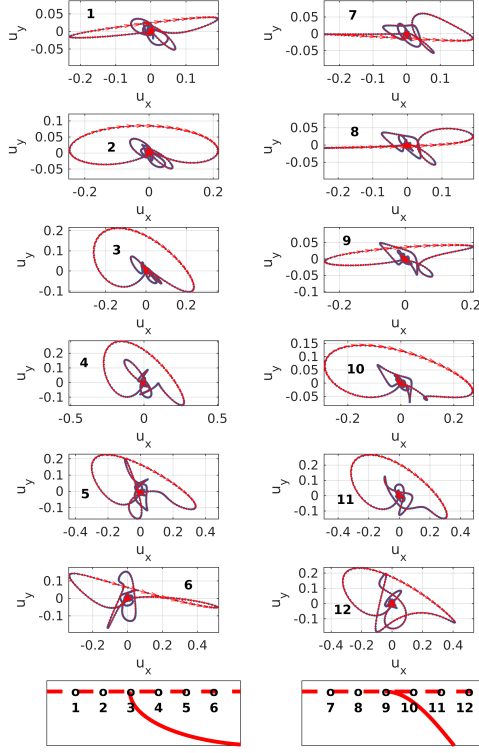


Figure 22. Particle motion comparison for SE and HC basins in the vicinity of basin edge. $AR = 1$, $\eta = 1$ and $\beta_2/\beta_1 = 2$ are assumed.

$\beta_2/\beta_1 = 2$, similar to SE geometry.

4.2.2.1. Effect of Aspect Ratio (AR): The effects of AR for HC are depicted in Figure 23. The edge convexity effects manifest in the spatial distribution of AF. As can be seen, by changing the basin geometry, the separation of edges does not happen as fast as it happened in the case of the SE basin (Figure 15) because of gradual variation of the basin-bedrock interface depth over distance. This shows how a more realistic basin geometry could affect the amplification variation in a basin, especially for shallower ($AR > 1$) configurations that are more prevalent in nature.

4.2.2.2. Effect of Dimensionless Width (ζ): Figure 24 shows the effect of ζ on the surface ground motion in the horizontal and vertical directions. The considered parameter space of ζ covers a wide range of basin widths, from narrow basins to wide ones. Results illustrate the fading effect of basin edges on the amplification factor close to the basin middle. This does not mean that the basin middle would behave as a purely 1D column due to Rayleigh waves traverse propagation within the basin which mostly contributes to the vertical component of surface amplification. As can be seen, for separation of $\zeta \geq 5$, two corner half-cosines have

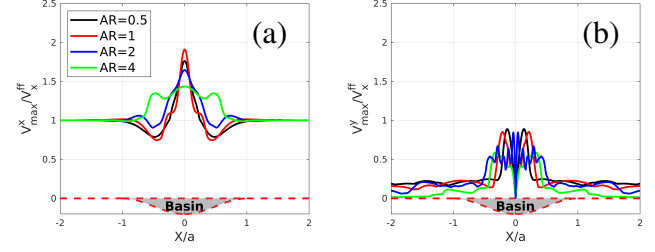


Figure 23. AF for different AR s of HC basins of $D = 0$, $\eta = 1$ and $\beta_2/\beta_1 = 2$ in the a) horizontal and b) vertical directions.

minimal influence in shaping the horizontal amplification curves, which is evidenced by a uniform spatial distribution of AF over a large distance.

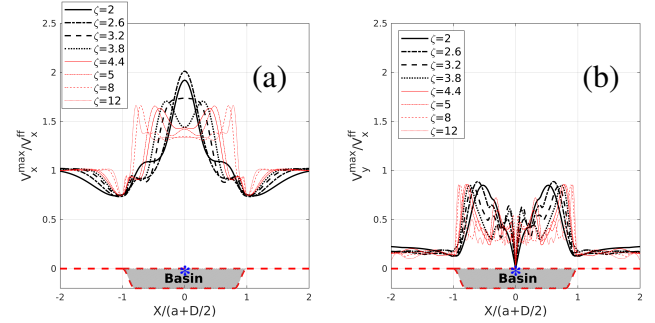


Figure 24. Effect of dimensionless width (ζ) on the surface amplification in a) horizontal and b) vertical directions. $AR = 1$, $\beta_2/\beta_1 = 2$ and $\eta = 1$ are assumed.

Results of the HC basin response for representative ζ are compared to the analytical solution of a 1D two-layered linear elastic soil column [42] subjected to a vertically propagating SV Ricker wave. Figure 25 compares the velocity time series at the basin midpoint calculated from 2D wave propagation simulations for $\zeta = 3, 5, 9$, and 12 to the corresponding horizontally stratified 1D layered model. As can be seen by increasing ζ , the basin center (shown by a blue star in Figure 24) increasingly approaches the response of a 1D column. However, even for the case of $\zeta = 12$, edge-induced surface waves traveling horizontally are evident in the midpoint signal which confirms the incapability of common approach (1D analysis) in the engineering community to study basin effects.

4.2.2.3. Effect of Damping: In reality, during large earthquakes, the soft sedimentary deposit would undergo considerable deformation that causes wavefield attenuation. In this article, we are mostly concerned with the geometrical aspect of basin effects, and try to understand the underlying mechanism of wave propagation in a basin, the reason we

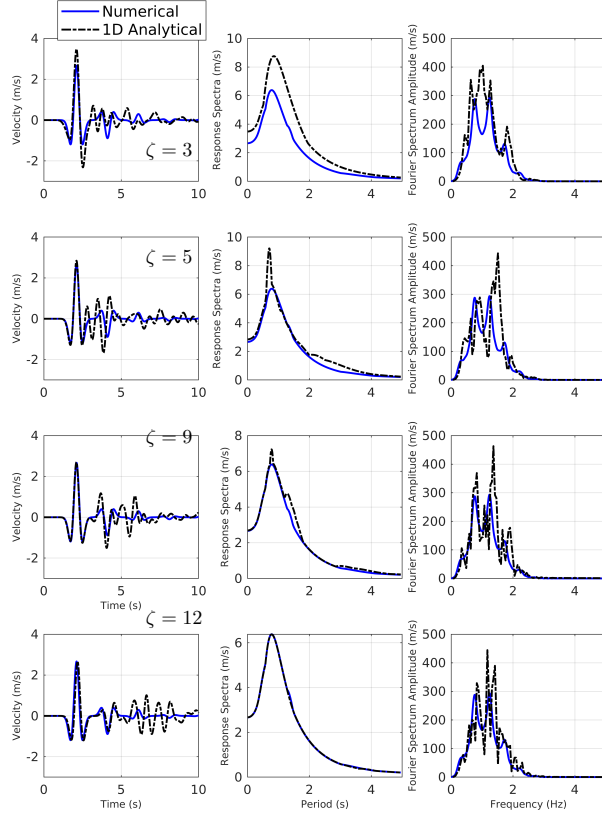


Figure 25. Comparison of the 1D analytical solution with the numerical results at the basin center. The ζ value is shown on the figure. $AR = 1$, $\eta = 1$ and $\beta_2/\beta_1 = 2$ are assumed.

have not included the damping parameter in the parametric study.

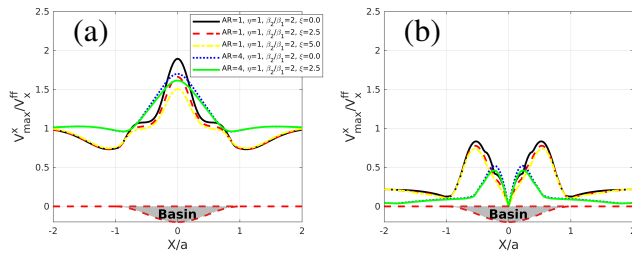


Figure 26. Effect of damping of surface AF in a) horizontal and b) vertical directions. We assumed two different damping parameters ($\xi = 2.5$ and 5.0), $\eta = 1$, and $AR = 1$ and 4 .

Figure 26 shows a comparison between different configurations and damping values (Rayleigh damping is used). As can be seen, the damping effect does not change the wave interference mechanism in a basin and we observe a similar amplification pattern as an un-damped case. Besides, for the examples presented here, the change in horizontal AF is

$< 20\%$ while it's negligible in the vertical direction. Moreover, It can be recognized that the amount of attenuation is less for the shallower basin due to the shorter propagation distance in this case, and, therefore, less attenuation.

Finally, wavefield snapshots of HC basin with $AR = 1$, $\beta_2/\beta_1 = 2$ and $\zeta = 3$ (to include more realistic geometries) are shown in Figure 27. The middle rectangle-like part of the basin behaves similar to a 1D column, while corner half-cosines generate surface waves and amplify the wavefield via focusing. Although the surface wave characteristics differ from the case of the SE-basin (due to differences in edge geometry), the general four-stage wavefield evolution can be observed: (a) body wave arrival, followed by (b-c) surface wave generation at the edges, followed by (d) interaction of body and surface waves in the middle, followed by (e-f) horizontal and vertical wave reverberations in the basin and energy leakage towards the halfspace.

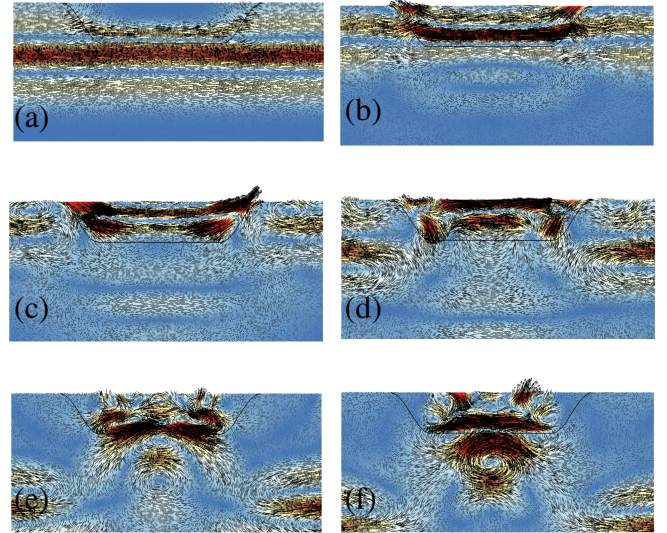


Figure 27. Snapshots of total wavefield for HC basin with $AR=1$, $\zeta = 5$, $\eta = 1$, and $\beta_2/\beta_1 = 2$. The trapezoidal black line shows the basin boundary.

The characteristic rotational wave pattern at the base of the basin shown in Figure 27-f is referred to as the “breathing zone” [31], a region where energy transfer occurs between the scattered P- and S-wavefields. HC basins with large ζ are an appropriate representation of wide shallow basin geometries, similar to the trapezoidal geometry used by Kawase et al (1989) [26] to study Mexico City. In the following section, we use such a procedure to study basin effects in Kathmandu, Nepal, during the 2015 M_w 7.8 Gorkha earthquake.

5. Basin Effects in Kathmandu, Nepal: A simplified model approximation

During the 2015 M_w 7.8 Gorkha earthquake [4], macroseismic observations and recorded evidence strongly showed that basin effects had played an important role in the characteristics of strong motion recordings, and the distribution of damage (or rather, the lack thereof). To test the extent to which simplified models can capture complexities of basin effects, we here approximate the Kathmandu basin with a HC idealized model. The model was selected to approximate the geometry of the top 0.5 km of basin sediments and is shown in Figure 29 (see among others, see Ayoubi et al [5] for more detail). The cross-section of the basin corresponds to the red line shown in Figure 28. The strong ground motion stations depicted in the same figure were installed by Hokkaido University and Tribhuvan University, and they reported the recorded accelerations during the mainshock [40]. These records will be used to evaluate the accuracy of the idealized model presented in this study.

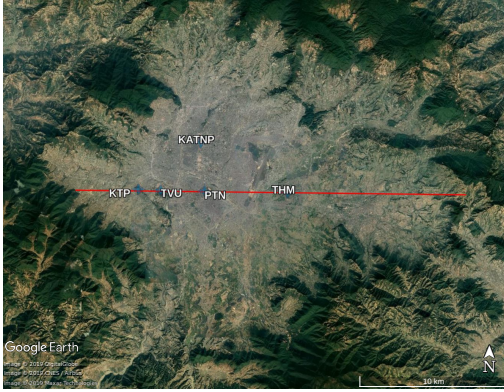


Figure 28. A plan view of Kathmandu basin. The location of strong ground motion stations is shown by their name. The red line shows the cross section that was used by Ayoubi et al (2018) [5] and is used in this study.

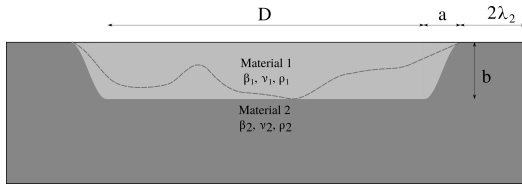


Figure 29. HC basin used in this study. Dashed line shows the realistic geometry of the basin which was used to find the corresponding simplified version in the current study.

To estimate the basin response of the idealized model, we use a train of two plane SV Ricker wavelets as shown in Figure 30, to excite a range of resonant modes of the basin. The cyan line of Figure 30-b shows the incident excitation

derived using de-convolution at depth of b (see Figure 29) from the East-West horizontal component of recorded motion at reference station KTP (see Figure 28 and Ayoubi et al (2018) [5], who used this motion as incident plane wave to simulate the basin response during the Gorkha mainshock). In Figure 30-b, we show the low frequency (blue line) and high frequency (red line) components of input motion which we sum to produce the idealized incident plane wave (Sum Incident Motion in the Figure 30). The time series of each wavelet and the combined input shaking are shown in Figure 30-a. We also assume that the basin is made of an elastic isotropic material with properties listed in Table 5. The bedrock properties were adopted from Wei et al (2018) [44], and the basin shear wave velocity was calculated using 1D velocity profiles published by Bijuckchehn et al (2017) [8] beneath the strong motion stations shown in Figure 28. The profiles are shown in Figure 31, along with the average profile that we used to estimate a 1D approximation of the sedimentary structure inside the basin. The latter was used to calculate the weighted average shear wave velocity for the simplified basin model listed in Table 5.

Table 5. Basin and halfspace parameters with reference to dimensional analysis of section 4.

π_1	π_2	π_3	π_4	π_5	π_6	π_7'
0.333	0.2441	3.6	6.4	0.312	0.79	11.15

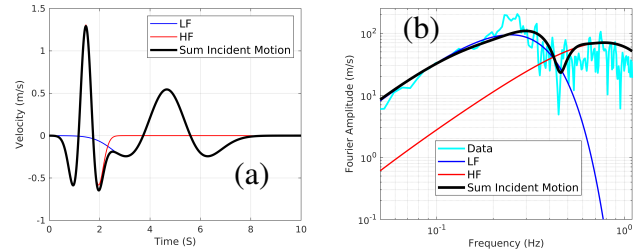


Figure 30. Time series and Fourier spectrum of incident motion from Ayoubi et al (2018) [5] and the current study. The low frequency (LF, blue line) and high frequency (HF, red line) show two Ricker wavelets that are summed to derive the input of the numerical simulation (Sum Incident Motion, black line)

Figures 32 and 33 show the results of the simplified basin analysis where Figure 32-a and 32-b show the AF of the horizontal, and vertical components at the surface of the basin. Basin edge effects can be readily observed in the form of localized ground motion amplification and strong spatial variability. The complex spatiotemporal variation of the basin wavefield is depicted by seismogram synthetics in Figures 32-c and 32-d. In this example, the incident motion includes two Ricker wavelets, each of which triggers the basin response at a different length scale. The constructive interference of the two is leading to the complex AF spatial variation of Figures 32-a and 32-b. It should be mentioned

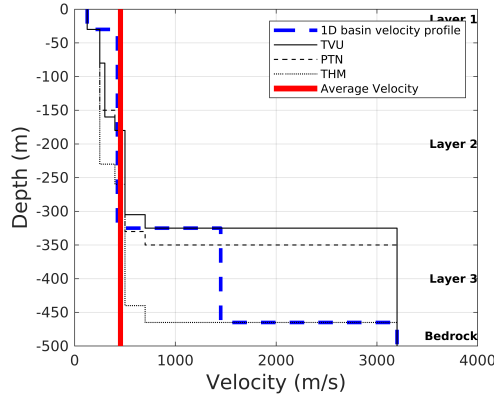


Figure 31. Black lines show the 1D velocity profiles by Bi-juckchehn et al (2017) [8]. Blue line shows the averaged and smoothed velocity. We temporally averaged the “1D basin velocity profile” (blue line) to obtain a single value for the shear wave velocity of the basin (red line).

that the response is expected to be more complicated when the basin is subjected to realistic broadband seismic shaking. However, the main features of the amplification curve and the strong presence of vertical motion inside the basin are expected to be present.

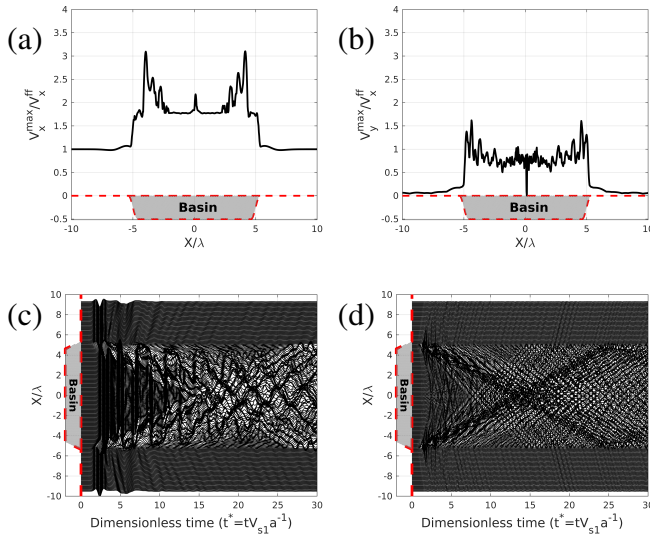


Figure 32. a) Horizontal AF, b) vertical AF, c) Horizontal SS and d) Vertical SS at the surface of the basin

Figure 33 shows a comparison between the amplification factor in the frequency domain for the simplified basin of this study, the numerical predictions by Ayoubi et al (2018) [5], and the ground motion records from a strong motion array in Kathmandu that recorded the M_w 7.8 Gorkha mainshock [40]. As can be seen, the simplified HC basin

model captures some characteristics (low frequency) of the complex ground motion records with very good accuracy. As expected, the simplified model does not capture higher frequencies (more than 1 Hz in this case) since it lacks detailed stratigraphy information that would manifest in high-frequency effects. It should be noted that the role of basin-edge effects in Figure 33-a, where the result for TVU station (closest to the basin edge) is shown, is not as good as other stations.

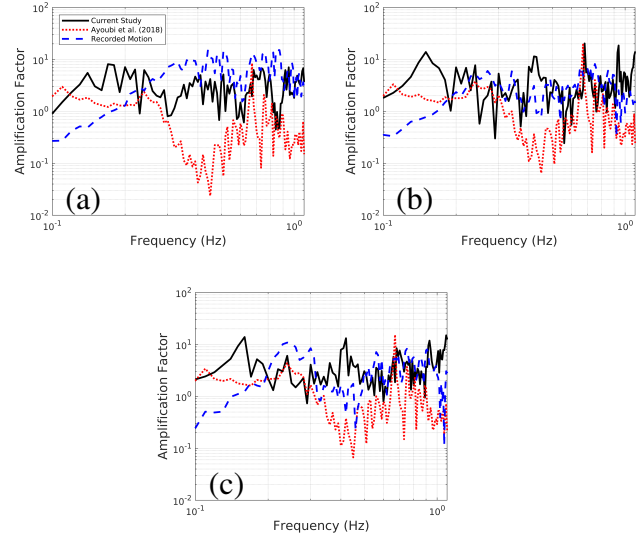


Figure 33. Comparison of simple HC basin (“Current Study”), realistic layered basin from Ayoubi et al (2018) [5], and recorded motion during the mainshock from Takai et al (2016) [40] for a) TVU station b) PTN station and c) THM station

6. Conclusions

In this article, we performed an extensive parametric study to examine the effects of material properties and interface geometry on the basin surface response. We first investigated a simple dipping layer. The calculated surface motion shows that the coupled effect of material contrast and basin-edge slope can drastically change the wavefield in a basin and produce a substantial vertical motion. We then defined two idealized geometries (Semi-Elliptical and Half-Cosine) and studied basin effects for elastic media subjected to vertically propagating SV wave of Ricker type using four dimensionless parameters; namely aspect ratio (AR), dimensionless frequency (η), material contrast (β_2/β_1), and dimensionless width (ζ).

AR is a key parameter in describing the geometry of basin edges. We observed that the location and magnitude of maximum horizontal amplification are affected by the AR parameter. Besides, SE and HC geometries would result in different amplification patterns depending on the AR . η

measures the relative size of a basin to the dominant wavelength. For lower values of η , an incoming wave treats the basin as a whole (very low values treats the medium as half-space) while for higher values, it interacts with basin locally. By increasing η , the spatial variation of amplification factor (both horizontal and vertical) enhances and the AF changes over shorter distances. Our results show that $\eta = 0.125$ had the least impact on the amplification factor and almost half-space condition was dominated. Material contrast was another parameter we considered in this study that controls the energy entering the basin and regulates the wave speed in each medium. Increasing material contrast generally resulted in a higher amplification factor due to the entrapment of earthquake waves within the basin. Last but not the least, the dimensionless width parameter was examined. It can change the pattern of wave interference by separating the whole basin into two 2D problems (corner half-cosine). We observed that for $\zeta \geq 5$, the basin tends to behave as two separate dipping layers with minimal interactions. Finally, we have shown that geometry plays a significant role in surface motion and the wavefield inside a basin. Therefore, we suggest using a cosine-shaped basin for idealized basin simulations.

Based on the results of the parametric study, dimensionless frequency, material velocity contrast, and aspect ratio seem to be the most influential parameters among the seven dimensionless parameters we investigated in this study. Regarding the dimensionless width (ζ), we have observed that its impact is not as influential as the above-mentioned three parameters in changing amplification factor in a basin. Moreover, while other dimensionless parameters may be able to play a significant role, their contribution is less of importance in studying the surface ground motion due to basin effects. This conclusion can be particularly important in developing the ground motion prediction equations (GMPE). Our findings show that the basin effects can be better incorporated by including a measure of η , β_2/β_1 and AR parameters. Currently, the most up-to-date GMPEs incorporate basin effects by specifying V_{s30} (average shear wave velocity in top 30 meters) and Z_1 (depth at which shear wave velocity is 1000 m/s) parameters while it has been observed in the literature that these two parameters are correlated [1].

In the last section of the article, a simple model of Kathmandu basin, Nepal during the 2015 M_w 7.8 Gorkha earthquake was studied. We used an elastic material subjected to vertically propagating the SV plane wave of Ricker type. We presented the amplification factor on the four strong ground motion stations in the basin and showed that even a simplified model can reproduce key features of the recorded ground motion. We assert that a more complex model is required to study the physics of the phenomena in more detail by incorporating source effects and 3D basin geometry.

Regarding simulation results, it seems that at least three parameters are required to represent the wavefield in the basin with reasonable accuracy, and calculate the amplification factor. For instance, assume in a simplified basin geometry, the shear wave velocity in the basin is 200 m/s ($V_{s30} = 200\text{m/s}$), the bedrock shear wave velocity is 1000 m/s, the depth of the deepest part of the basin is 500 m ($Z_1 = 500\text{m}$) and input motion has a dominant frequency of 1 Hz. AR is not known in this case and it was shown it could result in a significant change in wave interference pattern in a basin. This shows a one-to-many mapping since different values of AR can be obtained using the given parameters. Hence, we suggest to back up empirical data with synthetic ground motion simulations to boost the accuracy of GMPEs and to incorporate basin effects more accurately. Furthermore, the necessity of using a fixed value for the reference site in GMPEs can be removed by incorporating dimensional analysis, similar to the one we used in this study.

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