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Quantifying the edge-induced seismic aggravation in shallow basins relative to the 1D SH modelling

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ABSTRACT

Basin effects have long been proven to be of significance to seismic ground motions. However, 1D site response analysis, especially based on the equivalent nonlinear method, dominates engineering practice. In this paper, we aim to quantify the edge-induced aggravation in shallow sedimentary basins in addition to the 1D site effects. We chose a fixed shape for all shallow basins. Vertical heterogeneities are configured based on 31 KiK-net site profiles, complemented by another 19 hypothetic soil profiles. We then simulate both the 1D and 2D ground motions of each basin subjected to nine earthquake records modelled as vertically propagating *SH* waves. We use the aggravation factor, the ratio of 2D to 1D response spectra, to characterize the additional amplification induced by the lateral heterogeneity. Our results indicate that, for shallow basins, it is the region close to the basin edge that experiences the most significant aggravation, increasing 1D amplification by a factor between 1.2 and 1.5 mainly within the period band from 0.1 s to T_h, where T_h is the 1D fundamental resonance period at the basin centre.

1. Introduction

For a long time now, researchers have recognized basin effects as the changes in strong ground motions induced by the lateral finiteness of surficial and sub-surficial soil layers. Basin effects have received much attention for two reasons: firstly, basin effects may amplify ground motion by a large factor; secondly, many urban areas subjected to large seismic risk are situated atop sedimentary basins (e.g., Los Angeles, Tokyo and Taipei).

The amplification of ground motion due to sedimentary basins has been widely investigated using analytical and numerical approaches (e.g., [1-4]). In addition, field measurements have also been utilized to investigate how the geometrical and dynamic properties of a basin affect ground shaking (e.g., [5-10]).

Both approaches are conducive to understanding the physical mechanisms underpinning the ground motion amplification in alluvial basins. These mechanisms have been identified as (a) Basin resonance (e.g., [11-13]; [14,15]); (b) Local generation of surface waves by the lateral irregularities (e.g., [5,6,10,16-21]); and (c) Other wave phenomena due to the multi-dimensional geometry, such as focusing effect (e.g., [22-24]).

Even if the mechanisms pertaining to basin effects are well known, the routine engineering practice to account for site effects is still based on the 1D approach using either code-based design spectra or, more often, site-specific equivalent linear or nonlinear computations. Both approaches overlook the effects of lateral variation in wave velocity, and this lateral inhomogeneity has been shown to have a significant impact on ground shakings (e.g., [8,25-27]). Thus multidimensional site effects need to be accounted for. However, a multidimensional modelling is not feasible for many basins due to budget and time constraints to construct a multidimensional model both geotechnically and geometrically. Thus 1D site response analysis will still be dominant for many years to come. Therefore, calibrating the current 1D-based result by a certain factor to indirectly account for basin effects seems to be a tenable alternative at this stage.

The purpose of this research is to explore a technically robust and practically applicable approach to bridge the gap between 1D and 2D seismic analysis. To this end, we adopted the "aggravation factor" proposed by Chávez-García and Faccioli [28] as a measure of the additional 2D amplification or de-amplification relative to the 1D computation. To obtain a comprehensive aggravation factor which is robust and practical, we first configured a fairly large sample of relatively shallow basins filled with layered sediments. The layered structures were designed mainly based on real soil profiles at KiK-net sites. To account for the variation in excitations and obtain a robust median aggravation factor, a set of representative earthquake records was

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selected as input motions. Ground motions in these basins were numerically computed using both 2D and local 1D models. Then the ground motion aggravation factor (2D/1D) of each basin was calculated and characterized as a function of spectral period and receiver location relative to the basin edge. The period- and location-dependent aggravation factor was then integrated to a constant aggravation factor. Finally, the scatter of aggravation factor was explicated.

2. Method

One of the major difficulties in bridging 1D to 2D analysis has to do with the selection of a proxy to specify the difference between them. Chávez-García and Faccioli [28] introduced an “aggravation factor” (*AG*). Aggravation at a site is defined as the ratio of the ground response spectra at the site computed using a 2D model to that at the same site computed using its equivalent local 1D model. The *AG* serves to quantify the additional amplification or de-amplification caused by the lateral heterogeneities of a sedimentary structure relative to the 1D approach (e.g., [2,10,29-33,63]). The *AG* bridges the gap between 1D and 2D directly.

Chávez-García and Faccioli [28] recommended to primarily considering the *AG* as a constant factor for the whole basin width. Zhu and Thambiratnam [20] and [34] explored the variation in *AG* with regard to structural period and receiver location and defined a spectral aggravation factor (*SAG*):

$$SAG\left(T/T_h,\, x/L\right) = \frac{SA_{2D}(T/T_h,\, x/L)}{SA_{1D}(T/T_h,\, x/L)} \tag{1}$$

$$T_h = 4H/\overline{V_s} \tag{2}$$

$$\overline{V_S} = \left(\sum_{i=1}^{n} V_{Si} H_i\right)/H \tag{3}$$

where

SA_{2D} $(T/T_h, x/L)$ and SA_{1D} $(T/T_h, x/L)$ – 5% damped spectral acceleration (*SA*) at receiver x/L computed using a 2D model and its corresponding local 1D model respectively;
x- Distance of a surface point from the basin centre;
L- Basin half-width;
T- Spectral period;
T_h- Fundamental period of the equivalent plane layers of a basin using the weighted average method.
H, $\bar{V}_S$- Total Thickness and average *S*-wave velocity of soil layers at basin centre, $H = \sum_{i=1}^{n} H_i$;
H_i, V_{Si} – Thickness and *S*-wave velocity of the i^{th} soil layer;
SAG $(T/T_h, x/L)$ reflects explicitly the period-and location-dependence of the aggravation and thus is adopted in this investigation.

3. Numerical modelling

There are very few sedimentary basins of which both detailed information on the geometry and dynamic properties are available. If we request, in addition, that high-quality strong ground motions at many stations on the free surface are available, we find that there are not enough such basins to constitute a statistical study. For this reason, we use numerical modelling in this paper. We choose a specific form of alluvial basins and compute their seismic responses, which we use as the basis for our study of the *SAG*. The number of basin models used in this study is large enough to allow us to draw statistically robust conclusions.

3.1. Modelling method and verification

We simulate ground motions of each basin using an explicit finite difference code, 2DFD_DVS, developed by Moczo et al. [35,36], Kristek et al. [37] and Kristek and Moczo [38]. This FD method solves the equations of motion in 2D heterogeneous isotropic viscoelastic structures with a planar free surface. This scheme is 4th-order accurate in space and 2nd-order accurate in time. The computational region is a rectangle area where the bottom, left and right side boundaries are modelled as non-reflecting boundaries. The upper-frequency limit is chosen as 10 Hz, and then computation parameters are chosen to ensure accuracy up to this frequency. The spatial step is one-tenth of the minimum wavelength and the time step is set to satisfy the stability condition (Eq. (4)) for the 4th-order staggered grid FD scheme:

$$\Delta t \le \frac{6h}{7\sqrt{2}V_{P\,\max}} \tag{4}$$

where *h* and Δ*t* are the spatial and time step respectively; and $V_{P\,max}$ is the maximum *P*-wave velocity.

The rheology of the medium corresponds to the generalized Maxwell body, which allows the quality factor (*Q*) variable for different materials but constant within the frequency range of interest. The quality factor of soil layers for shear (Q_S) and compressional (Q_P) waves are defined as:

$$Q_s = V_s/10 \tag{5}$$

$$Q_P = 2Q_S \tag{6}$$

where Q_S and Q_P are the quality factors for shear and compressional waves respectively; and V_S is the shear-wave velocity.

The code also allows 1D simulation for local 1D models defined by the distribution of material parameters along each vertical grid line. Thus, 1D computations are also realized by the same code. This technique was thoroughly verified in detail by Makra et al. [31] and Riga [39]. However, two international blind tests on the reliability of numerical tools in Turkey Flat, California [40] and Ashigara Valley, Japan [41] concluded that the credibility of the numerical results depended not only on the numerical approach itself but also on the end users' understanding of the technique. Hence, a verification study was carried out at the initial stage of this project not to re-examine the performance of the 2DFD_DVS, but to consolidate a correct application of this FD tool.

Bard and Bouchon [17] presented results for a homogeneous basin (depth $H = 500$ m and half-width $L = 5000$ m). The densities, *S*-wave velocities and *P*-wave velocities of the deposit and bedrock are 2.0 and 3.3 kg/m^3, 700 and 3500 m/s, and 1400 and 6060 m/s respectively. Ground motion for this model was simulated when subjected to vertically propagating *P* waves in the form of a Ricker wavelet (predominant frequency $f_p = 0.86$ Hz). Their results have been widely verified and thus selected as a benchmark.

The time-domain results by Bard and Bouchon [17] and those from the present study are illustrated in Fig. 1(a) and (b) respectively. A comparison between Fig. 1(a) and (b) shows that our results are consistent with those by Bard and Bouchon [17]. Surface waves (Rayleigh waves in this case) are triggered at the basin edges, propagating along the basin surface and then being reflected after reaching the opposite edge. The consistency between both results justifies our implementation of this numerical tool. The vertical displacement at the basin centre ($x/L = 0$) is also displayed in Fig. 1(c).

3.2. Basin configurations

Previous studies [16,17,20] showed that seismic ground motion of shallow basins is dominated by the propagation of surface waves initiated at basin edges. These locally generated surface waves result in intense ground shaking in a close-to-edge area [19]. In contrast, for deep basins, 2D resonance will be the dominant phenomenon, inducing in-phase ground motion across the whole basin. Since shallow basins feature a different seismic ground motion pattern from deep basins,