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Site Specific Ground Response Analysis for Quantifying Site Amplification at A Regolith Site

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Abstract - A numerical model has demonstrated that it can simulate reasonably well earthquake motions at the ground level during a seismic event. The most widely used model is an equivalent linear approach. The equivalent linear model was used to compute the free-field response of Adelaide regolith during the 1997 Burra earthquake. The aim of this study is to quantify the amplification at the investigated site. The model computed the ground response of horizontally layered soil deposits subjected to transient and vertically propagating shear waves through a one-dimensional-soil column. Each soil layer was assumed to be homogeneous, visco-elastic, and infinite in the horizontal extent. The results of this study were compared to other studies and forward computation of the geotechnical dynamic parameters of the investigated site. The amplification triggered by the 1997 Burra seismic event was deduced. This study reveals the amplification factor up to 3.6 at the studied site.

Keywords: site response analysis, regolith, site amplification, Adelaide

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Introduction

A site specific ground response analysis has to be taken into consideration for seismic hazard assessment. It has been well established that rock-based earthquake motions can be amplified on soft soil sites and cause severe structural damages, such as in the 1985 Mexico earthquake, the 1988 Armenian earthquake, and the 1989 Loma Prieta earthquake in California (Somerville and Graves, 1996). Amplification of rock site also occurred during the 1997 Burra earthquake in Adelaide.

A numerical model for a site specific ground response analysis demonstrated that it was able to simulate reasonably well the soil behaviour due to dynamic loading. The widely used approach is the equivalent linear approximation of nonlinear response techniques which is implemented in the EERA computer programmes (Bardet *et al.*, 2000). The EERA (Equivalent-linear Earthquake Response Analysis) programme was developed from the basic principles of the SHAKE programme (Schnabel *et al.*, 1972) which has been one of the most commonly used computer programmes in geotechnical earthquake engineering since it became available in 1972 (Idriss, 1990 and 1991; Dickenson *et al.*, 1991; Rollins *et al.*, 1992; Yokel, 1992). EERA was selected for this study because the programme took full advantage of the latest development of FORTRAN 90 and the Windows platform. EERA is not a stand-alone programme. It is an add-on programme embedded in Microsoft Excel.

The 1997 Burra earthquake has proven that amplification phenomenon is a real threat for Adelaide City, South Australia. Earthquake ground acceleration recording in Adelaide regolith is very much stronger than on rock just outside the city during the 1997 Burra earthquake (DMITRE Minerals, 2013). Therefore, recognizing the soil response to seismic ground motions is necessary in order to understand how the actual seismic waves will affect the founded structures on Adelaide regolith. Regolith is composed of unique geological materials which generally have variable impedance properties compared to that of bedrock (Setiawan *et al.*, 2016). Regolith is formed or altered by land surface processes, whereas bedrock is formed or altered by deep-seated crustal processes. Wilford and Thomas (2013) suggested that the characterization of regolith and bedrock was based on their formation processes, instead of their material type. Different formation processes result in distinctive characteristics of regolith units when compared to bedrock. In general, the density, strength, and cohesion of regolith masses are typically lower than bedrock masses (NCST, 2009).

The aim of this paper is to quantify the site amplification using the site specific ground response analysis of the 1997 Burra earthquake. Results of this site specific ground response analysis are presented.

Site Characteristics

The locality of the studied site is shown in Figure 1. The sub-surface characteristics of the

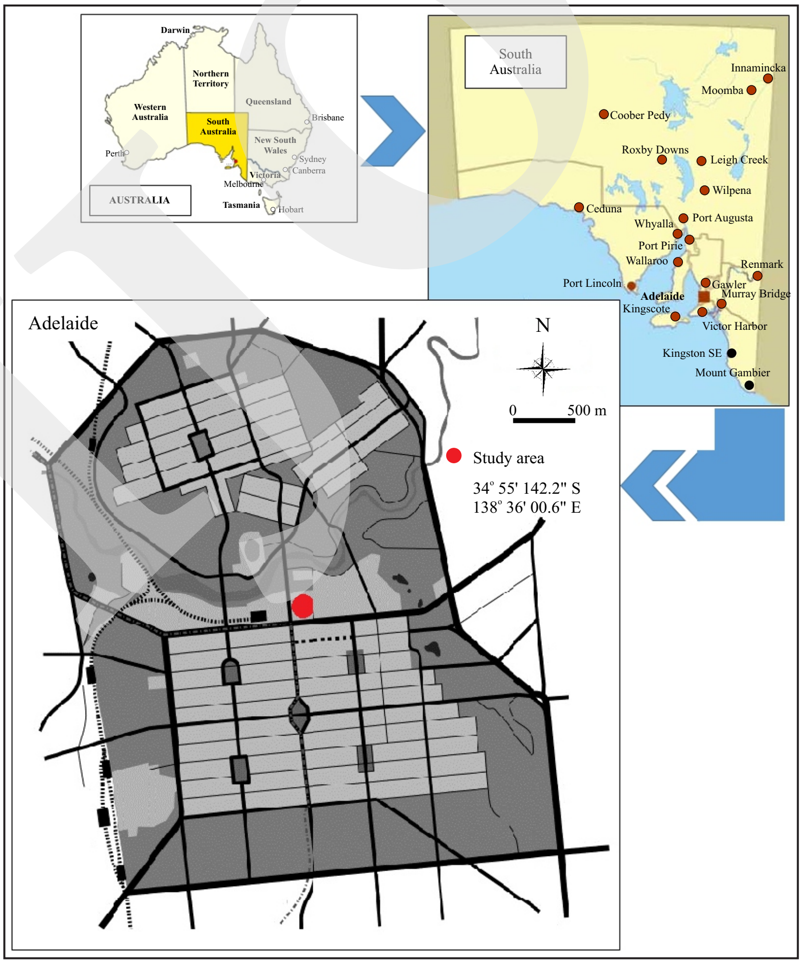

Figure 1. Locality map of the study site.

studied site were developed based on the results of the site investigations conducted by Selby and Lindsay (1982), Selby (1984), Sheard and Bowman (1996), and Collins *et al*. (2006). Selby and Lindsay (1982) has developed the subsurface profile which is applicable for the regolith site [*i.e*. government house site (GHS)] as indicated in Figure 2 (the sequence of steps for site specific ground response analysis). Collins *et al*. (2006) measured the shear wave velocity of the regolith (GHS) site, measurement at GHS was used to represent the shear wave profile at the investigated site.

The studied site (Adelaide, South Australia) is located in the eastern part of the St. Vincent Basin (Selby and Lindsay, 1982). The upper surface of the ground in the studied area, below the fill and surficial layer, mostly consists of Holocene stratigraphic units (Callabonna Clay and Pooraka Formation). The thickness of the Holocene units is up to 21 m thick (Selby and Lindsay, 1982; Sheard and Bowman, 1996). Then, it is succeeded by Keswick Clay at limited locations and Hindmarsh Clay at some areas of the city. Below the Hindmarsh Clay is either unit of Carisbrooke Sand or Burnham Limestone or Hallet Cove Sandstone. It is followed by either Gull Rock Member of Blanche Point Formations or Sand unit of Port Willunga Formation or Tandanya Sand Member of Chinaman Gully Formation. Subsequently, there are South Maslin Sand and Clinton Formation prior to the Precambrian bedrock at most areas. Finally, the Precambrian bedrock is encountered about 64 m or less at the north of the city and can be up to 118 m or more at the south of the city (Selby and Lindsay, 1982). In the present study, all materials and formations above the Precambrian bedrock is classified as regolith (Eggleton, 2001).

METHODOLOGY

A flow chart in this study is elaborated in this section. Then it is followed by input parameters for the site response analysis.

Method of Statement

A sequence of steps (Figure 2) is used to interpret the earthquake motions in the stable

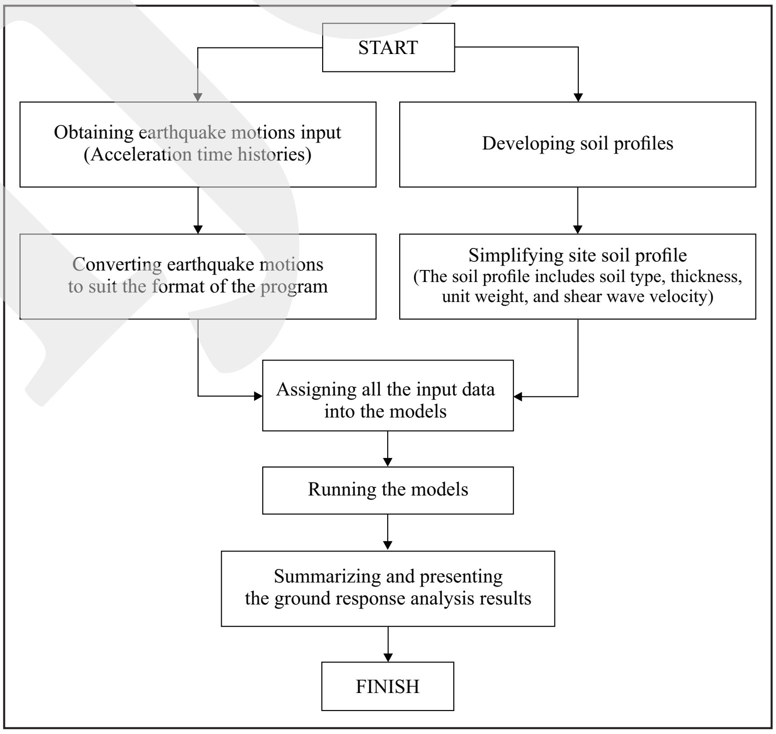

Figure 2. Sequence of steps for site-specific ground response analysis.

ground surface or bedrock to account for their effects on the soil profile at any specific site. Initially, site characterization and earthquake input motions manipulation were carried out. A simplified soil profile was developed and compatible earthquake motions were formatted. Both the simplified profile and acceleration input motions are used as the input of the models. Subsequently, the programme was run in accordance with the model requirements. Finally, the results were summarized and presented.

Input Parameters

The EERA programme basic input parameters are: (i) earthquake acceleration time histories; (ii) soil profile; and (iii) dynamic soil characteristics, *i.e.* strain dependent modulus reduction and damping behaviour. The acceleration input motions recorded within the regolith (*i.e.* GHS station) was used in this study. In this study, the input motions were scaled into desired maximum acceleration of 0.1 gravity (g) which represent the expected disastrous scenario of a future seismic event at the investigated site. The GHS station recorded three components of the 1997 Burra earthquake which were E-W, N-S, and U-D components. A sample of the input motions is shown in Figure 3.

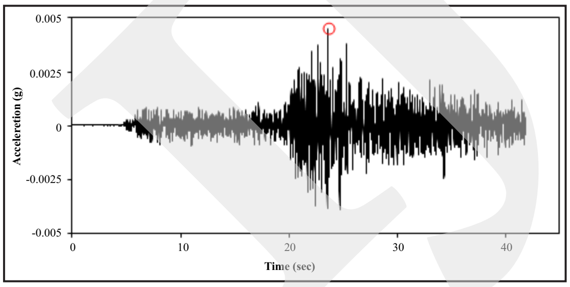

Figure 3. Sample of ground acceleration input for the site response analysis.

The developed soil profile data *i.e.* soil type, layer thickness, unit weight, shear wave velocity were added as shown in Table 1. To validate the appropriateness of the used shear wave velocity of this study, an in-situ ambient noise single station was deployed at the GHS. Due to unforeseen factors, the single station microtremor measurement was carried out at a distance of about 200 m from the location of Collins *et al*. (2006). A forward computation using the geotechnical dynamic parameters of the investigated site was carried out. A forward computation proposed by Garcia-Jerez *et al*. (2016) was employed to obtain a computed spectral ratios between the horizontal and vertical components (HVSR). The computed HVSR was compared to the observed HVSR of the measured microtremor as presented in Figure 4. Generally, the comparison between the observed and calculated HVSR curves suggests a comparable result. The lateral and vertical variability of the subsurface characteristics could be the main reason for the discrepancies in the results due to the 200 m separation distance as mentioned earlier. The modulus reduction and damping curves of each soil type were specified. Since there was no laboratory testing to determine these curves, the default curves were used, as shown in Figures 5 to 7.

Results of The Site Response Analysis

The site specific ground response analysis yielded the following data: peak ground acceleration, stress and strain at each layer, amplification at the ground surface or the surface of each layer, Fourier amplitude, and the response spectrum. A summary of the site response analysis outputs using the EERA is presented in Table 2. Amplification ratio for all input motions is presented in Figure 8, whilst outputs of the absolute spectral acceleration are shown in Figure 9.

Discussion

The results of the site specific ground response analysis are as follows. The expected absolute maximum ground surface acceleration at the investigated site was estimated between 0.18 g and 0.21 g. The fundamental frequency of the investigated site is about 1.8 Hz. Response spectrum analysis with a critical damping ratio of 5% estimated a range of maximum spectrum

Table 1. Simplified Soil Profile Input for Site Response Analysis

Note	Layer Number	Soil Material Type	Thickness of layer (m)	Total unit weight (kN/m^3)	Shear wave velocity (m/sec)	References
	1	Sand	3	21.31	170	
	2	Clay	3	23.99	160	
	3	Sand	3	23.87	180	Selby & Lindsay (1982) and Collins *et al.* (2006)
	4	Clay	26	23.44	330	
	5	Sand	6	23.48	400	
	6	Sand	11	23.46	500	
	7	Sand	13	23.26	710	
Bedrock	8			22.80	800	

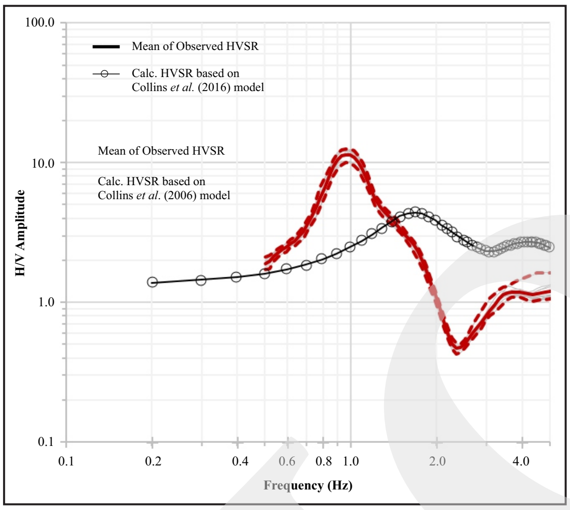

Figure 4. A comparison between mean of observed HVSR and calculated HVSR of the investigated site.

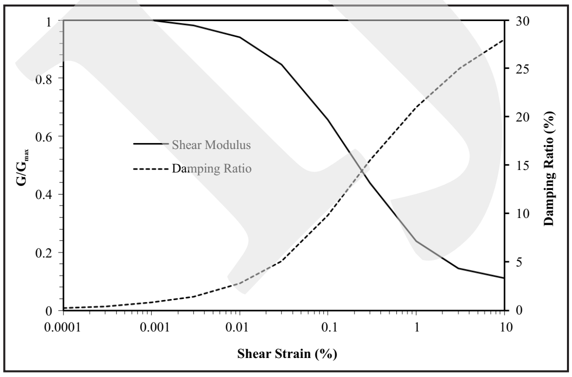

Figure 5. Modulus for clay by Seed and Sun (1989) upper range and damping for clay by Idriss (1990) cited in Bardet *et al*. (2000).

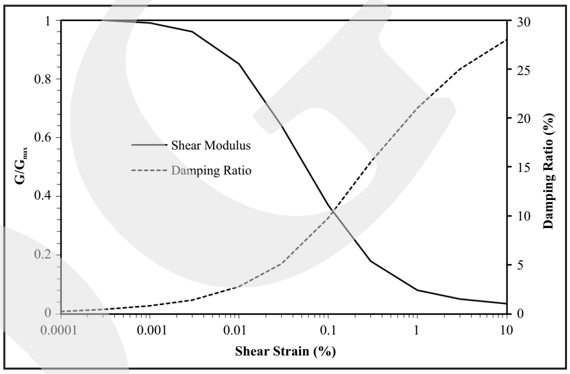

Figure 6. Modulus for sand by Seed and Idriss (1970) - Upper Range and damping for sand by Idriss (1990) cited in Bardet *et al*. (2000).

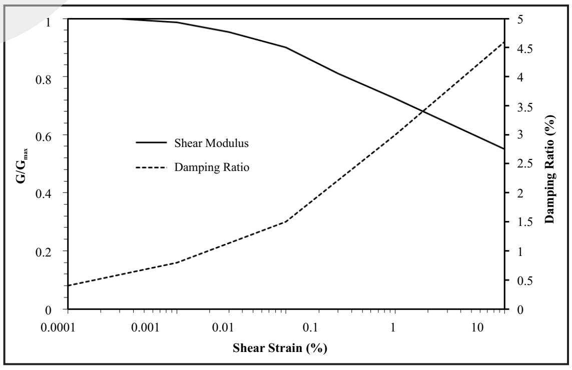

Figure 7. Attenuation of rock average and damping in rock by Schnabel (1973) cited in Bardet *et al.* (2000).

acceleration from 0.71 to 0.79 g, and a maximum spectrum at 0.2 sec varies from 0.43 to 0.57 g.

The ground response analysis outputs at the soil site were compared with the results from a study by Love (1996), Mitchell and Moore (2007), Mitchell (2009), and Poulos *et al*. (1996). The highest calculated peak ground acceleration (PGA) was 0.21 g in this study. This estimation is slightly lower than the average PGA predicted by Love (1996). Love (1996) expected an average PGA of 0.25 g. The averages of site specific ground acceleration in this study (0.18 g and 0.21

Table 2. Summary of the Main Results of Site-specific Ground Response Analysis

Output parameters	EERA Approach		
	GHS-EW	GHS-NS	GHS-UD
Absolute peak ground acceleration at soil level	0.19g	0.21g	0.18g
Max amplification ratio	35.01 at frequency of 4.4 Hz	29.35 at frequency of 4.4 Hz	38.54 at frequency of 4.4 Hz
Fundamental frequency (Hz)	1.8	1.8	1.8
Max response spectrum at ground level	0.73g at period of 0.1sec	0.79g at period of 0.1sec	0.71g at period of 0.09sec
Response spectrum at 0.2 sec	0.46g	0.57g	0.43g
Response spectrum at 1.0 sec	0.07g	0.04g	0.02g

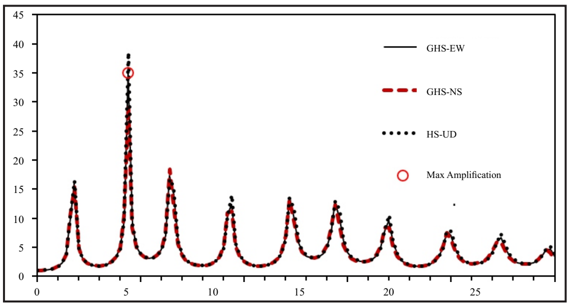

Figure 8. Plot of amplification ratio for all input motions.

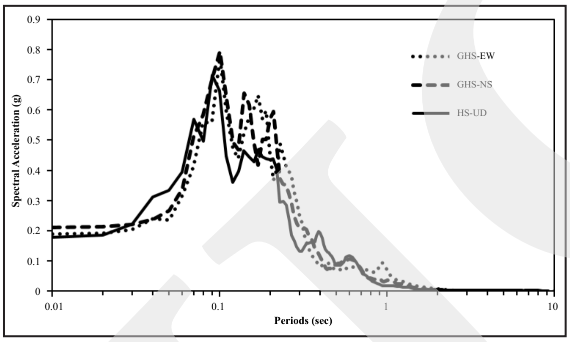

Figure 9. Response spectral acceleration outputs at soil site.

g) are higher than the value used by Mitchell and Moore (2007) and Mitchell (2009), which was only 0.15 g. On the other hand, the average PGA of this study is lower than the PGA (0.23 g) estimated by Poulos *et al*. (1996) for approximately similar soil profile in Adelaide City. The discrepancy varies from 0.051 to 0.076 g. This may due to differences in the method or the input data used in the analysis. In addition, the differences may reflect the complexity of the ground motion induced by earthquakes, which involves frequency, content, travel path, duration, and other characteristics.

A comparison of the spectral acceleration values with 5% damping ratio of this study to Love (1996) findings shows a reasonably good agreement. The average of the spectral accelerations of the present analysis is between 0.63 g and 0.69 g. Love (1996) estimated an average spectral acceleration of 0.76 g.

As aforementioned above, amplification is expected to occur at the investigated site. Evidence of site amplification is demonstrated in the recorded ground motions during the 1997 Burra earthquake. The earthquake ground acceleration in regolith site is very much stronger than that recorded on a rock just outside the city during the 1997 Burra seismic event (DMITRE, 2013). Therefore, a further investigation was undertaken to quantify this amplification at the studied site. The site amplification was estimated using a comparison between the maximum acceleration of the top surface layer and the maximum acceleration at the bedrock level as shown in Figure 10. These profiles were used to deduce the amplification factor at the investigated site. The results indicate an amplification factor at the surface level of 2.9 to 3.6. The site amplification factor was also estimated by the mean of the results as proposed by Herak (2008). The amplification as computed using Herak (2008) in the present study is representing a linear estimate of amplification. The result is presented in Figure 11. Generally, site amplification up to 3.1 of the studied area is suggested. However, these amplification factors do not consider the nonlinear behaviour of subsurface material. Therefore, a precaution should be addressed when applying this estimate into a common practice. A nonlinear site response analysis is suggested for further investigation.

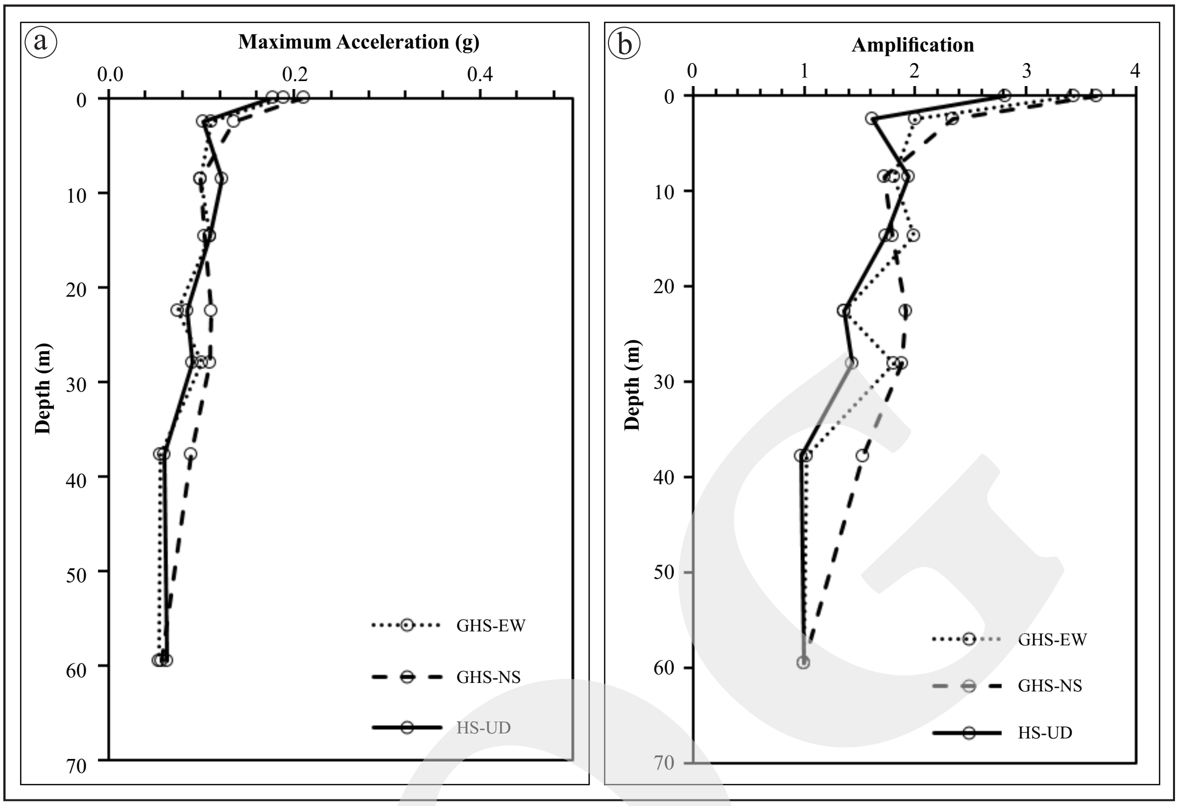

Figure 10. (a) Maximum acceleration profile and (b) amplification profile of the investigated site.

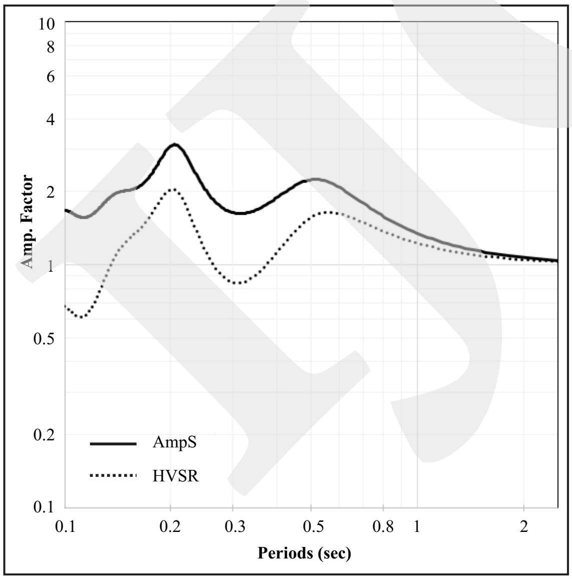

Figure 11. Amplification factors of the investigated site using Herak (2008) approach.

Quantifying site amplification at a highly seismicity region like Indonesia is compulsory as most of the provincial capital cities are founded on sediments with relatively exhibited moderate to high impedance contrast. This quantification will enable effective mitigating the risks of seismic hazard in Indonesia. The knowledge gained will be subsequently utilized by others, *i.e.* engineers, architects, planners, and regulators to guarantee the integrity of structures in the case of unexpected earthquakes.

Conclusions

A numerical model has demonstrated that it can simulate reasonably well the earthquake motions at the ground level during a seismic event. This study was using the most widely used model of an equivalent linear approach. The equivalent linear model was used to compute the free-field response of Adelaide regolith during the 1997 Burra earthquake. The model computed the ground response of horizontally layered soil deposits subjected to transient and vertically propagating shear waves through a one-dimensional-soil column. Each soil layer was assumed to be homogeneous, visco-elastic, and infinite in the horizontal extent. The results of these ground response analyses clearly indicate that the input parameters are modified at the studied site due to local site effects. Furthermore, the results of this study were compared to the other studies and forward computation of the geotechnical dynamic parameters of the investigated site. Hazard spectra and amplification triggered by the 1997 Burra seismic event were deduced. This study reveals the local site effects by amplification factor up to 3.6 at the studied site.

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