Malaysian Journal of Geosciences (MJG)

DOI: http://doi.org/10.26480/mjg.01.2021.35.40

ISSN: 2521-0920 (Print)
ISSN: 2521-0602 (Online)
CODEN: MJGAAN

REVIEW ARTICLE

2-DIMENSIONAL GROUND RESPONSE ANALYSIS: A REVIEW

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ARTICLE DETAILS

Article History:

Received 07 April 2021
Accepted 11 May 2021
Available online 03 June 2021

ABSTRACT

Earthquake is one of the natural disasters that is caused by ground shaking in soil. Ground response analysis is conducted to obtain the ground motion acceleration on soil surface. Conventional 1-D ground response analysis often suggests that soils are horizontally layered, with little consideration for heterogeneous distribution of soil properties. In this study, literature on 2-D ground response analysis studies has been study as it covers vertically and horizontally waves. Therefore, researcher works were presented in numerical modelling as substantial parameters for studies in near-surface structure. Besides, aspects for future research in the area 2-Dimensional Ground Response Analysis are included. The paper contributes to the understanding of 2-Dimensional Ground Response Analysis for the application of seismic risk mitigation.

KEYWORDS

Ground Response Analysis, microzonation, numerical method.

1. INTRODUCTION

Ground response analysis is used to emphasize the microzonation maps in a particular region. Different regions will have different microzonation maps as different subsurface data is required. Subsurface data which include local geology and the geotechnical condition, cause wave propagation. This is important for assessing the performance of the algorithm liquefication hazard, and determination of the earthquake-induced forces. Moreover, the analysis led to instability of earth and earth-retaining structures. It will also be important to determine the fault rupture model from the source of an earthquake, the propagation of stress waves to top of bedrock beneath the specific site, and to determine the ground surface motion below ideal conditions. The shaking of the ground at a specific location is attributed to the impact of the earthquake occurrence occurring at that location, according to ground response research (Kramer, 1996). The intensity and magnitude of an earthquake are determined by the site's position and ground characteristics. It is necessary to evaluate the ground shaking for that specific location to assess the seismic hazards. Any site's ground motion speed can be measured in terms of peak ground acceleration (PGA) and the geological characteristics of the ground position and the input ground motion data will determine the PGA values (Shukla D., and Solanki C.H., 2021).

It is crucial to examine the mechanism involved in the propagation of stress waves from point of an earthquake which the delivering across the earth on particular site. Then, these are considered in determining whether the soils above the bedrock influence ground surface motion.

Following the ground response study, it is essential to take the following steps. (1) collection of data, (2) develop numerical model (3) perform numerical analysis and (4) result interpretation. Shear wave velocity, damping, soil depth and type of soil are input data that are needed to perform the analysis. The input data were divided into four groups (Yoshida, 2018), geological or topological configuration such as soil profiles and cross-sectional shape, mechanical properties such as elastic modulus and Poisson's ratio, input earthquake motion and parameters to control the flow of the computer program or the method of the analysis.

The basic approach to begin the study is with input data, geological or topological configuration in category 1. Category 2 mentioned above, as well as the soil's mechanical properties including elastic modulus and Poisson's ratio are inserted. Moreover, to proceed with the analysis, input earthquake motion must also be obtained. Last category is parameters input to control the method of analysis such as linear, equivalent linear or non-linear analysis. Figure 1 shows the steps required for the ground response (see to: (Yoshida, 2018) for guidance).

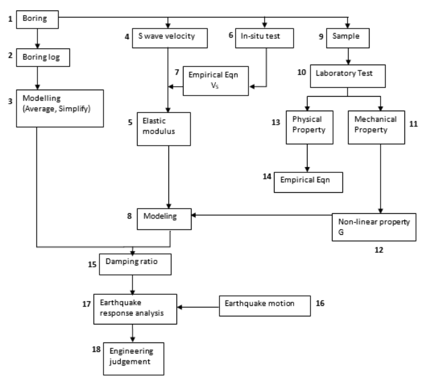

Figure 1: Steps for seismic ground response analysis (Yoshida, 2018)

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Cite the Article: Norazah Arjuna, Azlan Adnan, Nabilah Abu Bakar, Nabila Huda Aizon, Noor Sheena Herayani Harith (2021). 2-Dimensional Ground Response Analysis: A Review. *Malaysian Journal of Geosciences, 5(1): 35-40.*

The process starts with a soil boring investigation (1), followed by the translation of data from the compiled soil boring log (2) into soil profile modelling (3). Soil profile modelling separates the soil into four categories: sand, silt, clay, and bedrock. Obtaining an appropriate amount of soil mechanical properties can be a challenging job. There are insufficient results to establish if the mechanical and in situ properties data are correct, necessitating a laboratory test. There are two methods for evaluating the elastic modulus (5): on-site estimation using the to measure on site using the wave velocity (4) and using empirical equations based on other field measurements (6). The wave velocity can be obtained from the SPT N-value (7).

In addition, nonlinear soil parameters (12), is one of the mechanical properties (11) that can be obtained directly from laboratory test (10) by using undisturbed samples taken from site (9). This was based on previous experience within the research team which had found focused on empirical equations or prior knowledge (14). Other parameters such as physical property (13) based on plasticity index may be important. Conversion from test data is required to represent the material property (12) by the empirical equations proposed. The next step is to obtain the values of the computer program's parameters in (8). Stress-strain relationship are conveyed by means of a mathematical formula in many computer programs with determination of coefficients value. Damping characteristic (15) and earthquake motion (16) is compulsory for the earthquake response analysis (17). The results must be evaluated after the analysis is complete (18).

As shown in Figure 2, obtaining the modulus reduction curve, shear wave velocity, and damping-strain curve are necessary to determine the dynamic site characterization. Dynamic site characterization is also included in mechanical properties category data mentioned before (Yoshida, 2018). From the dynamic site data, selection of rock motion is required to proceed in ground response analysis. The result of this analysis is summarised in site-specific design spectra.

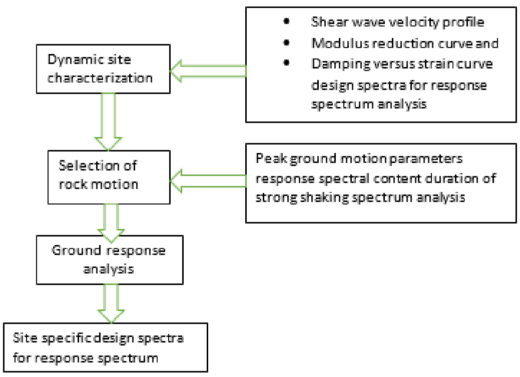

Figure 2: Site specific ground response analysis (Govindaraju L. et al. 2004)

The dimensionality of the model where incoming shear waves propagate from the underlying bedrock can be divided into three categories: one-dimensional (1-D), two-dimensional (2-D), and three-dimensional (3-D) shear wave propagation methods.

For flat or gently sloping sites with parallel material boundaries, the 1-D approach in ground response analysis is useful. Consequently, such situations are normal used in geotechnical earthquake practice. Furthermore, the 1-D method is recommended as many commercial programs with different soil models are applicable in personal computers, and it is proven this methodology survived by real earthquakes using the 1-D design in structures (Govindaraju L. et al. 2004). In addition, (Phillips C. and Hashash Y., 2009), 1-D ground response analysis methods are commonly used to measure the effect of soil deposits on propagated ground motion. Besides (Shukla D. and Solanki C. H., 2021) and (Mazlina M. et al., 2021) also using site's soil profile with the 1-D ground response analysis to hazards contribution.

Assumption for 1-D ground response analysis (Govindaraju L. et al. 2004) which are all boundaries are horizontal, soil and bedrock are assumed to extend infinitely in the horizontal direction (half-sphere) and because of the decrease in velocities of surface deposits, inclined incoming seismic rays are reflected in a near-vertical direction. As a result, shear waves propagating vertically from the underlying bedrock are unlikely to have caused the observed shift in the soil deposit's response.

In general, the use of 1-D equivalent linear wave propagation models may be unadvisable when the lateral soil spatial variation is not homogeneous and the underlying bedrock interface is obviously variable (Chen G. et al 2015). Available evidence shows that the dynamic response of the soil is classified as a linear action under low levels of strain to determine the amplification of seismic waves. However, for higher stress-strain levels, laboratory testing of soil samples reveals a nonlinear relationship that reflects the nonlinear nature of the soil response. (M. Hosseini et al 2010).

Nevertheless, 2-D method of analysis is dependent on bedrock depth. Microtremor array measurements are used to estimate if the boreholes are not deep enough to hit bedrock, the seismic bedrock depth. The data from microtremor array studies was combined with topographical properties and geological section to obtain 2-D shear wave velocity, according to studies by (M. E. Hasal and R. Iyisan, 2014). Furthermore, (Pehlivan M et al., 2012) found the effect of horizontal soil property variability on the ground response can be evaluated using 2-D site response analysis with properties that differ both vertically and horizontally. In the frequency or time domains, it can be solved using dynamic finite-element analysis. Two- or three-dimensional mapping may be used for sloping or irregular ground surfaces, as well as embedded structures. Dynamic finite element analysis (R. B. Jishnu et al 2013) is widely used to solve such problems. However, this is a fundamentally difficult problem for 1-D analysis as PGA values obtained can be less conservative depending on the site and earthquake ground motion data, necessitating 2-D analysis.

In addition, the presence of a soft soil valley and/or a hill should contribute to the acceptance of 2-D or 3-D numerical schematizations, likely due to the focalization of seismic waves at the valley's ground surface and at the crest, respectively (A. Amorosi et al 2018). Moreover, (Reddy M. V. R. K. et al., 2021) current study investigate the ground reaction of pond ash obtained from Odisha in one-dimensional (1-D), two-dimensional (2-D), and three-dimensional (3-D) dimensions under various earthquake motions.

2. 2-Dimensional Ground Response Studies

Many researchers use ground response analysis to upgrade the knowledge for seismological and structural behaviour. 2-D ground response analysis is preferred for problems, in which 1-D is significantly larger than others such as earth dams, tunnels, cantilever retaining wall etc., (P. Nautiyal et al 2019). Besides, 2-D analysis requires certain conditions such as sloping or irregular ground surface, the presence of heavy structures or stiff, embedded structures, or walls and tunnel (S. L. Kramer 1996).

The effect of local geology in the change of seismic wavefield at a recording site is called site effects which local geology contains of surface topography and surface sedimentary site. Parameters used to describe the behaviour of site effects are the geometry of soil stratigraphy (thickness and lateral discontinuities), the shape of topographic relief and the dynamic, physical and mechanical properties of soil and rock materials (A. Ansal 2004).

In this paper, 5 categories of studies can be summarized in 2-D ground response analysis studies such as the study of site effects, development of seismic microzonation, seismic wave propagation in soil, seismic response, and the study of edge effect.

2.1 Study site effects

The effects on ground motion as seismic waves interact with the complex geological system in the first 100 metres or so of the earth's crust are referred to as the site effect. Studies from (A. Cipta et al. 2018) use 2-D ground response analysis to analyse the effect of site amplification and basin resonance. Ground motion is amplified by basin structure and depth at different locations, depending on the depth of the basin, distance from the source, distance from the basin edge, and the magnitude of the earthquake. Moreover (M. Tapia et al. 2006) who critically discussed that 1-D numerical analysis result for basin effects can underestimate the site amplification effects thus 2-D or 3-D ground analysis is required to obtain more accurate results. In addition, (P. P. Capilleri et al. 2018) presented the 2-D ground response analysis can consider both stratigraphic and topographic effects for the amplification on the ground. Dams, bridges, industrial facilities, residential areas, and source locations need seismic wave amplification. Seismic waves disperse and reflect at the surface, at the layer interface, and around topographic anomalies, amplifying the effects of earthquakes (M. Bararpour et al. 2016). Furthermore, (H. Reda et al. 2016) investigated 2-D ground response analysis to verify the presence of local site effects by comparing simulated versus transfer function. (R. Iyisan and H. Khanbabazadeh 2013) studied analytical methods for examining 2-D and 3-D dynamic behaviour is the general method among researchers to reduce the receivers used in alluvial valley in order to assess site effects during earthquakes. The parameters most often used for description of site effect analysis are site and soil characterization.

2.2 Develop seismic microzonation

Several researchers (C. Lacave et al. 2008), (M. Tapia et al. 2006) have studied 2-D ground response analysis to obtain seismic microzonation study for a particular area. In addition, (A. Cipta et al. 2018) used data from earthquake that occurred on January 11th, 1963 as the maximum plot to obtain the surface peak ground acceleration and spectral acceleration values of Catania (Italy). Both PGA value and spectral acceleration can be obtained from the seismic microzonation data.

2.3 Study seismic wave propagation in soil

The seismic wave propagation in a heterogeneous medium can be studied using a 2-D ground response analysis (C. Du and G. Wang 2015). In this research, the vertically incident plane wave is input through a displacement boundary, and the soil shear modulus is modelled as a spatially random field with correlation distances in both horizontal and vertical directions. The effect of amplification factors is then investigated. Meanwhile, to evaluate the response of a valley to SH waves, (N. Theodoulidis et al. 2018) use 2D ground response analysis.

2.4 Study basin effect

(D. Komatitsch and J-P. Vilotte 1998) conducted 2-D dynamic analysis on the basin to study the edge effect on the spatial variation of surface ground motion. The main aspects of the studies are the superposition of two weakly interacting effects: the shape of the surface topography and the shape of the sedimentary basin for this incident wavelength. However, the effects of the basin structure are constrained. (R. Iyisan and H. Khanbabazadeh 2013) too studied the impact of basin edge on the dynamic behaviour of the basin by using a variety of bedrock inclinations that are chosen, ranging from gentler 10 and 20 slopes to steeper 30 and 40 slopes at the valley. By focusing on the earthquake response examination of the basin that is laterally confined and in the form of filled sediment, (B. Ozaslan et. al., 2021) study presents the effects of heterogeneities in both vertical and lateral directions on the local seismic response. Moreover, (Peyman Ayoubi, et al., 2021) use an elastic medium exposed to vertically propagate SV plane waves. They also examine the results of basin geometry and material properties using idealized basin shapes.

2.5 Seismic response

(A. Cipta et al. 2018) and (A. Pagliaroli et al. 2018) use 2-D ground response analysis to study the basin effects that influence the seismic response.

A summary of 2-D ground response studies is given in Table 1 below. Many researchers use 2-D ground response studies to investigate the effects of soil amplification and seismic response. Most of the research in this 2-D ground response studies are aimed at peak ground acceleration, amplification, site effects and transfer function.

Table 1: Summary from Previous Studies

Author	Input				Output				
	SPT Data	Shear wave velocity	Basin	Stratigraphic and topographic	Peak ground acceleration (PGA)	Amplification	Seismic response	Site effects	Transfer Function
(C. Lacave et al. 2008)	✓				✓	✓			
(M. Tapia et al. 2006)	✓		✓		✓	✓	✓		
(A. Cipta et al. 2018)	✓		✓		✓	✓	✓		
(C. Du and G. Wang 2015)		✓					✓		
(N. Theodoulidis et al. 2018)		✓					✓		
(A. Pagliaroli et al. 2018)			✓				✓		
(P. P. Capilleri et al. 2018)				✓		✓			
(H. Reda et al. 2016)				✓	✓				✓
(D. Komatitsch and J-P. Vilotte 1998)			✓		✓				
(R. Iyisan and H. Khanbabazadeh 2013)		✓						✓	
(B. Ozaslan et. al., 2021)		✓					✓		
(Peyman Ayoubi, et al., 2021)		✓	✓					✓	

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Since placing enough receivers in an alluvial valley to determine site effects during earthquakes is costly, analytical methods for evaluating 2-D and 3-D dynamic activity of the sites have increased in popularity among the researchers (R. Iyisan and H. Khanbabazadeh 2013).

3. Numerical Method in 2-D Analysis

Ground response analysis is required to replace the physical observation on site. However, further investigation is necessary to explore the geotechnical investigations. Overall, this work offers a successful to the substantial parameters for numerical modelling studies in near-surface structure.

Based on literature review by (J. F. Semblat 2011) five methods can be identified, which are Finite Difference Method, Finite Element Method, The Spectral Element Method, The Boundary Element Method and Discrete Wavenumber Method.

3.1 Finite Difference Method

Using this approach, partial differential equations can be calculated directly under any scenario. It can approximate by linear combinations of function values at the grid points, which are replaced with a set of discrete equations, called finite-difference equations. The finite-difference method is typically represented on a regular grid; therefore, it is seldom used for irregular CAD geometries, but regular rectangular or block-shaped models. It is the most commonly used measure to model seismic wave propagation in an elastic media. Studies by (M. Tapia et al. 2006), the propagation of seismic waves in the 2-D cross-section of the valley can be modelled using the finite-difference method. However, the method is accurate in elastodynamics but apply to simple geometries (J. F. Semblat 2011). Beside, (M. E. Hasal and R. Iyisan 2014) reported that for modelling seismic wave propagation in an elastic medium, the finite difference approach usually employs a uniform mesh. It is simple and straightforward to use, but it falls short of simulating complex boundary conditions such as surface topography, subsurface geometry, and sloping bedrock.

Furthermore, Finite Difference Method could be carried out for topographical structure site response review (M. Kamalian et al 2006). It can solve nonlinear wave propagation problems in the time domain by completely formulating the numerical method.

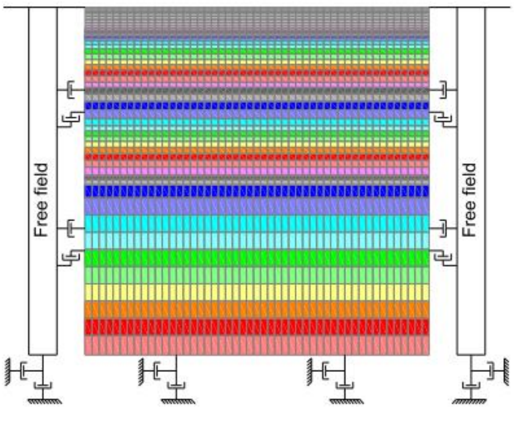

Figure 3: 2-D Finite Difference Method Model (F. A. F. Lopez et al 2015)

A finite-difference method model (FLAC) as shown in Figure 3 was used by (F. A. F. Lopez et al 2015). Absorbing boundaries were used at the sides of the model under consideration for the seismic waves. FLAC engage a special lateral boundary known as free field, in which these lateral boundaries are coupled to the free field mesh through viscous damping dashpots which simulate absorbing boundaries. However, studied by (Carolina Volpini et. al., 2019) due to geometric scattering of waves, a 2-D model with the same dimensions and material properties would normally overestimate the soil's dynamic stiffness and radiation damping.

In addition, (J. Miksat et al 2010) found that to model 3-D amplification effects inside the basin, a finite-difference approach was used. They discovered that shallow earthquakes produce more powerful surface waves than deep earthquakes, and that computational modelling can measure frequency-dependent site amplifications for the Taipei basin.

3.2 Finite Element Method

The finite-element method (FEM) is a computational method that divides a model into small, finite-sized geometrically simple components. Finite-element mesh is formed by combining all these basic shapes. Partial differential equations describe a system of field equations mathematically and these equations are formulated for each element. Each element approximates a simple function such as a linear or quadratic polynomial, with a finite number of degrees of freedom (DOFs). Sparse matrix solvers are the solution for combination of all elements.

The finite element method is capable to deal with complex geometries and numerous heterogeneities (even for inelastic constitutive models but has several difficulties such as numerical dispersion and numerical damping. It is very useful for modelling complex geometry and boundary conditions because it allows irregular mesh with elements of various sizes and geometries to be used. (J. F. Semblat 2011).

FEM has been shown to be effective in solving problems with bounded domains, particularly when inhomogeneities and nonlinear effects must be considered. For domains with infinite extensions, regular finite element discretization produces wave reflections at the edges of the FE mesh, which can only be partially prevented in some cases by using so-called transmit discretization. The disadvantage of FE being formulated in transformed spaces, cannot be used in nonlinear dynamic analysis (M. Kamalian et al 2006).

Several finite element softwares are capable of modelling geotechnical engineering problems where it can be used to analyse structures such as retaining walls, slopes, embankment dams, etc. In finite element method, the region to be analysed is divided into several elements connected at their command nodal points. A finite element mesh used in the seismic analysis. By means of finite element method, it can calculate each element in horizontal and vertical movements of each nodal point at each stage in the analysis.

QUAD4M software spread P and/or SV waves with vertical incidence. (A. Pagliaroli et al. 2018) and (S. Amoroso et al. 2018) performed QUAD4M finite element to model the vertical incident (SV) in plane shear waves. They concluded that by adding viscous dampers at the bottom of the mesh where the input is applied in terms of shear stress history, QUAD4M can model an elastic foundation. Side boundaries, on the other hand, are perfectly reflecting; therefore, to minimize the effect of artificially reflected waves, side boundaries were extended around 500m in both directions from the basin's edges.

Meanwhile QUAKE/W has a finite element approach in which the governing motion equation for dynamic response of a system can be expressed as: $[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F\}$ Where; [M] is mass matrix, [C] is damping matrix, [K] is stiffness matrix, {F} is vector of loads, $\{\ddot{u}\}$ is nodal acceleration vector, $\{\dot{u}\}$ is nodal velocity vector, {u} is nodal displacement vector. (M. E. Hasal and R. Iyisan 2014) and (M. Bararpour et al 2016) used QUAKE/W 2-D analysis, to obtain the maximum absolute horizontal acceleration values at the surface. (M. Bararpour et al 2016) performed PLAXIS to their model based on the method defined by Lysmer and Kuhlmeyer 1969, viscous adsorbent boundaries have been implemented. They concluded that the amplification factors given by the analysis are greater than the amplification factors given by Italian code.

3.3 The Spectral Element Method

The spectral element method has been increasingly studied to analyze 2-D and 3-D wave propagation in linear media with a good accuracy due to its spectral convergence properties (J. F. Semblat 2011). (J. Miksat et al 2010) too used same approach to build a representation of the Taipei basin's ground motions. Another study by (A. Cipta et al. 2018) applied to investigate seismic wave interaction with 3-D structure of the Georgia Basin, British Columbia, Canada. (C. Du and G. Wang 2015) used SPECFEM2D to resemble a viscoelastic medium.

3.4 The Boundary Element Method

For dynamic analysis of linear elastic bounded and unbounded media, the Boundary Element Method (BEM) is capable of producing realistic numerical method. As the discretization is done, only on the boundary, resulting in smaller mesh systems of equations for wave propagation matter. For scattered waves in topographical systems, the outgoing waves across infinite domains are useful. As a consequence, when using this approach to solve problems with semi-infinite domains, there is no need to model the far field.

Similar work has also been pursued by (M. Kamalian et al 2006) who studied the seismic response of canyons and alluvial basins using a time-domain 2D Boundary Element System. Their formulation, however, was limited to anti-plane (SH) wave scattering. This approach has also been used to examine the site response of homogeneous and non-homogeneous topographic structures subjected to in-plane compression (P) and shear (SV) waves (A. Amorosi et al 2018), and (Yoshida, 2018).

3.5 Discrete Wavenumber Method

The discrete wavenumber method proposed by (C. Lacave et al. 2008) is used to measure the 2-D response of alluvial basins. The use of a double Fourier transforms to transform the direct problem from the space and time domain to the horizontal wavenumber and frequency domain is the framework of this approach. To solve the problem numerically, a discretization in both space and time, and thus in wavenumber and frequency, is used. Meanwhile, (J. Riepl et al 2000) investigated the method accounts for one irregular interface that separates the underlying hard rock from the sedimentary basin fill. Table 2 below summarizes the numerical method used in 2-D ground response analysis.

Table 2: Summary from Prior Studied

Method	Software	Reference
Finite Element Method	QUAD4M	(A. Pagliaroli et al. 2018)
		(S. Amoroso et al. 2018)
	Quake/W	(M. E. Hasal and R. Iyisan 2014)
		(M. Bararpour et al 2016)
	Plaxis	(P. P. Capilleri et al. 2018)
Spectral Element Method	SPECFEM2D	(C. Du and G. Wang 2015)
		(A. Cipta et al. 2018)
Discrete Wavenumber Method	Aki-Larner Method	(C. Lacave et al. 2008)
		(J. Riepl et al 2000)

4. Conclusion

The review on the literature on the 2-D ground response studies shows that most studies focus on site effects in ground response analysis. Moreover, to perform the numerical 2-D ground response studies, finite difference and finite element method were the popular approaches among researchers. Studies on the following areas are still inadequate and deserve attention of future research for more understanding of the 2-D ground response studies:

- Development seismic microzonation
- Seismic wave propagation in soil
- Study on edge effects
- Study on seismic response.

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