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Ground nonlinear dynamic response by considering multi-dimensional seismic site effects

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ABSTRACT

A comprehensive study is performed to assess the ground dynamic responses by considering the nonlinear behavior of geomaterials. For this purpose, an in-house numerical code, called HYBRID, is developed to model the nonlinear behavior of geomaterials by using the Hardin-Drnevich constitutive model subject to vertically propagating sinusoidal waves. HYBRID code combines the finite elements method in the near field and the boundary elements method in the far field (FEM/BEM). Also, in order to consider the impacts of local topographical and geological conditions simultaneously, both 1D and 2D configurations are modeled. Responses are obtained for different geometrical points at the ground surface in terms of time history of displacement. Furthermore, the amplification/de-amplification patterns are underlined at different geometrical points for each configuration. Finally, some recommendations based on the presented results are proposed in order to quantify nonlinear 1D and 2D site effects.

RÉSUMÉ

Cet article présente une étude approfondie évaluant les réponses dynamiques du sol en considérant le comportement non linéaire des géomatériaux. À cet effet, un code numérique est développé pour modéliser le comportement non linéaire des géomatériaux. Ce code appelé HYBRID utilise le modèle de comportement de Hardin-Drnevich soumis à des ondes sinusoïdales se propageant verticalement. Le code HYBRID combine la méthode des éléments finis dans le champ proche et la méthode aux éléments des frontières dans le champ lointain (FEM / BEM). De plus, afin de prendre en compte simultanément les impacts des conditions topographiques et géologiques locales, les configurations 1D et 2D sont modélisées. Les réponses sont obtenues pour différents points géométriques à la surface du sol en termes d'historique du déplacement. De plus, les motifs d'amplification et de désamplification sont soulignés à différents points dòbservation pour chaque configuration. Enfin, quelques recommandations basées sur les résultats présentés sont proposées afin de quantifier les effets non linéaires des sites 1D et 2D.

1 INTRODUCTION

It has often been reported, after destructive earthquakes in mountainous areas, that buildings located at the top of cliffs or hills suffer much more intensive damage than those located at the bottom. the geomechanical properties of soils can also play an important role in seismic site response amplification. Therefore, the impacts of geometrical and geotechnical characteristics of a site can significantly affect the nature of strong ground motion during an earthquake. Many studies have been performed to consider such effects in various seismic codes. However, it is worth mentioning that the majority of seismic codes rest on seismic site effects by considering one-dimensional (1D) analysis, which allows measuring only the effect of nature and thickness of the sedimentary layer on the vertical propagation of body waves regardless of lateral heterogeneities. The evaluation of site responses in two-dimensional (2D) configurations are more complicated in comparison to those of (1D) models. In addition, the non-linear behavior of geomaterials is another vital factor to more accurately assess the site effects.

In order to consider the impacts of local topography and geological conditions simultaneously, both 1D and 2D configurations are modeled by means of HYBRID numerical code, combining finite elements in the near field and boundary elements in the far field (FEM/BEM) (Gatmiri, B. and Kamalian, M. 2002, Gatmiri, B. and Dehghan, K. 2005).

Several parametric studies have been carried out using HYBRID to extensively evaluate the effects of topographic characteristics of 2D irregularities on the seismic amplification/attenuation patterns (Gatmiri, B. et al. 2008/2009). Recently, some extensive assessments have been performed by Gatmiri, B. and Foroutan, T. 2012 and also Gatmiri, B. and Amini, D. 2014 on seismic site effect in curved/non-curved basins, taking account of topographical and geological impacts. A new set of geometric criteria was proposed to establish a simple method to include 2D combined site effects in building codes. The previous studies underlined the site effects considering linear behavior of materials. However, the extensive numerical assessment of 2D nonlinear seismic site effects besides other factors of site could be an essential matter in geo-seismic studies.

This paper aims at quantifying the dynamic response of sedimentary basins filled with nonlinear alluvia, which are subjected to vertical sinusoidal wave incidents. For this purpose, first, the Hardin-Drnevich constitutive model is implemented into HYBRID. The Newton-Raphson method, which is a powerful technique for solving equations numerically, is utilized to integrate the responses over the time. Responses are obtained for different specific geometrical points at the surface of the irregularities in terms of the time history of displacement to cover the ascending/descending trends of ground responses by taking into account the nonlinearity of materials. Finally, some recommendations based on the presented results are proposed in order to quantify nonlinear 1D and 2D site effects.

2 NUMERICAL METHOD

Site response analysis of topographical structures could be carried out using various empirical (Nakamura, Y. 1989), analytical (Trifunac, MD. 1973 and Sanchez-Sesma, FJ. 1985) and numerical approaches. In order to study site effects in case of more complicated configurations, the different numerical methods has been recently developed such as domain type methods (e.g. Finite Element Method); boundary type methods (e.g. Boundary Element Method); and hybrid type methods which combine the effective characteristics of two or more methods such as the hybrid BE/FE method. The finite element method (FEM) has proven to be very effective in solving problems with bounded domains, particularly when inhomogeneity and nonlinear effects should be treated. The boundary element method (BEM) has shown to be a very powerful numerical technique for linear and homogeneous materials in case of both bounded and unbounded domains as it doesn't require domain discretization which can be an advantage in many practical applications.

Combination of FEM and BEM techniques seems to be an ideal solution in order to benefit from their advantages. This method has the advantage over frequency domain techniques in that it provides a direct way of obtaining the time history of the response which forms the basis for extension of nonlinear behavior. The basic theoretical development and numerical implementation and optimization of HYBRID code is extensively given in Gatmiri, B. and Kamalian, M. 2002.

3 PROBLEM PARAMETERS

3.1 Geometrical Parameters

In order to perform a comprehensive study on nonlinear dynamic response, 1D (a half-space) and 2D (an elliptical valley) configurations, are stimulated (Figure 1).

The irregularities are characterized by their depth, H and their half width at the surface, L. The value of L for all 2D valleys is kept equal to 100mwhile in 1D models it accounted for an infinite quantity. Both empty and fully-filled valleys are considered in 2D analysis. Simulations are carried out by considering a constant depth ratio, H/L, equal to 0.4. In 1D models, H is assumed to be 40 m. The sediment and bedrock areas are modeled by FEM and BEM, respectively. The selected height (H) and depth ratio (H/L) values in models have been chosen arbitrarily, so that they can take larger/smaller values. It is also worth noting that with the help of BEM, the bedrock is simulated as an infinite half-space.

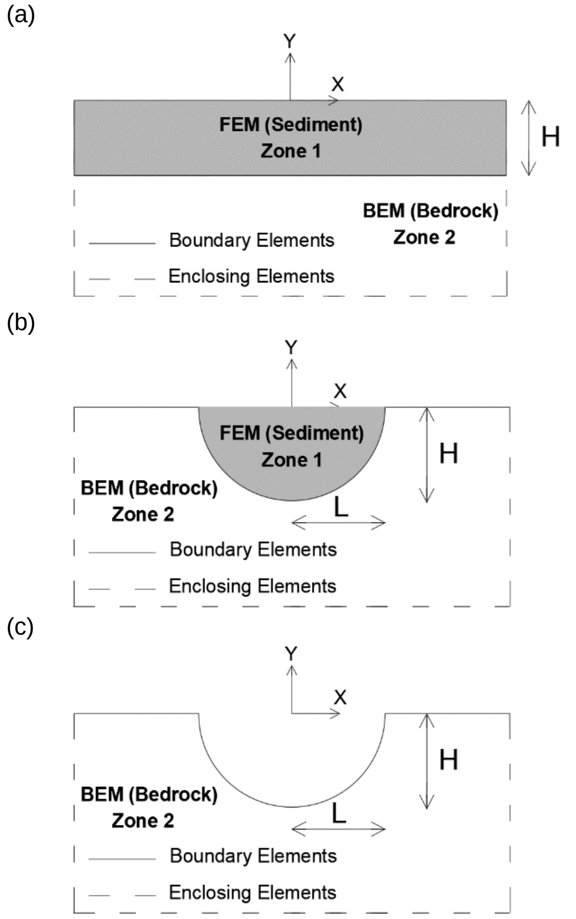


Figure 1. Configuration of models (a) 1D, (b) 2D fully-filled valley and (c) 2D empty valley

3.2 Mechanical properties of materials: Hardin-Drnevich Constitutive Model

The bedrock is assumed to be homogeneous linear elastic while the Hardin-Drnevich (1972) constitutive model (kondner 1963) is considered for alluvia:

$$\tau = \frac{\gamma}{\dfrac{1}{G_0} + \dfrac{\gamma}{\tau_f}} = \frac{G_0 \gamma}{1 + \dfrac{\gamma}{\gamma_r}} \qquad [1]$$

where G_0 and τ_f denote the elastic shear modulus and the shear strength, respectively. The strain value at the intersection between the initial modulus and the shear strength is called the reference strain, which is one of the good indices to grasp the nonlinear characteristics:

$$\gamma_r = \frac{\tau_f}{G_0} \qquad [2]$$

By Dividing equation (1) by $G_0\gamma$, we obtain

$$\frac{G}{G_0}=\frac{1}{1+\dfrac{\gamma}{\gamma_r}} \quad [3]$$

If $\gamma=\gamma_r$, Equations (1) and (2) result in

$$\tau=\frac{\tau_f}{2}, \quad \frac{G}{G_0}=0.5 \quad [4]$$

Therefore, the reference strain is sometimes denoted as $\gamma_{0.5}$.

In many cases, as the measured shear wave velocity is not available, the G_0 (or $G_{\max}$) can be assessed by correlating it with other soil properties such as the void ratio (e), over-consolidation ratio (OCR) and so on. So, various equations have been provided, in order to calculate or estimate $G_{\max}$. From the laboratory tests, it is suggested that the maximum shear modulus may be calculated as (Hardin and Richart 1963):

$$G_{\max}=625\times F(e)\times OCR^k\times p_a^{1-n}\times(\sigma'_m)^n \quad [5]$$

where $F(e)$ is a function of void ratio (e), and it may be taken as $1/(0.3+0.7e^2)$ (Hardin 1978). σ'_m is the mean principal effective stress; k is an over-consolidation ratio exponent related to the plasticity index (I_p); $p_a=100\ kPa$ is the atmospheric pressure with the same unit as σ'_m and $G_{\max}$; n is the stress component and is usually taken as 0.5, but can be computed for each soil at different effective confining pressures. So:

$$G_{\max}=625\times OCR^k.p_a^{1-n}.(\sigma'_m)^n/(0.3+0.7e^2) \quad [6]$$

In this paper, the above equation has been used to calculate $G_{\max}$. The material parameters for bedrock and alluvia for both linear and nonlinear (Hardin-Drnevich model) behaviors are presented in Table 1. As the purpose of this paper is to study the nonlinear dynamic behavior of sediments in comparison with the linear behavior regardless of material saturation, in adopted models the alluvial layers are assumed to be dry.

Table 1. Characteristics of materials.

Characteristics	Bedrock (Linear)	Alluvium (Linear)	Alluvium (Nonlinear)
Friction Angle (Degree)	---------	---------	30
Cohesion (KPa)	---------	---------	0
OCR	---------	---------	1.3
Elastic Modulus (MPa)	6720	861	---------
K	---------	---------	0
n	---------	---------	0.5
e	---------	---------	0.9
Bulk Modulus (MPa)	11200	718	---------
K_0	0.5	0.5	0.5
γ (Kg/m^3)	2.45×10^4	1.63×10^4	1.8×10^4

3.3 Sinusoidal Incident Wave characteristics

The main focus of this work is to study of the effect of geometrical and geotechnical characteristics of irregularities on their dynamic response. The seismic load is a vertical cyclic sinusoidal wave incident:

$$u(t)=A_0\sin(2\pi t/T) \quad [7]$$

where the amplitude, A_0, is a constant value of 0.2 m; and T = 0.5 sec. It is assumed that the incident signal lasts 3 sec and the amplitude is zero as soon as it reaches t = K.Δt which K represents the cycle number and Δt is a fixed value of 0.02 sec (Figure 3).

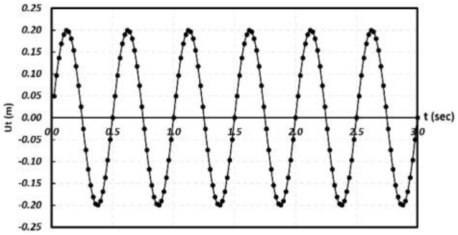


Figure 3. Sinusoidal incident wave signal over the time.

4 STUDY OF NONLINEAR SEISMIC SITE RESPONSE

3.1 Geometrical Station Points

In order to study the influence of material nonlinearity, some geometrical points are chosen as stations in each model. Then, the curves of the horizontal displacement response have been derived for each station point. Due to the symmetry of the configuration, only one side of the valley is studied (Figure 4).

The topographical effects in 2D models on ground motion can be neglected on the outcrop at distances further than (X=3L) (REF) (Gatmiri, B. and Arson, C. 2008; Gatmiri, B. et al. 2009; Gatmiri, B. and Amini, D. 2014/2015). Therefore, the result of station points located between X=0 and X=3L are provided in this study.

The responses for nonlinear / linear materials are calculated and presented in the following graphs (where applicable), in order to define the impacts of nonlinearity on the seismic responses in comparison to the linear case.

3.2 Spatial Evolution

3.2.1 1D Site Effects

There are lots of numerical research and field works which represent the seismic response of 1D soil layer considering the geological effects of the soil (Schnabel, P.B. et al. 1972, Bardet, J.P. et al. 2000, Bardet, J.P. and Tobita, T. 2001 and Hashash, Y.M.A. 2005). In addition, there are various numerical software/codes which are able to calculate the 1D linear and/or nonlinear soil layer responses with the depth of H. The main advantage of HYBRID code over these methods/codes is the application of the BE method to model the rocky bed (far field) to prevent from the radiation of seismic waves as well as scattering.

The nonlinear behavior of one element (as a sample) in terms of G/G_{max} curve, stress-strain graph and finally the time histories of σ_x and σ_y stresses are presented in Figures 5 to 7. It can be clearly seen from Figures 5 and 6 that the nonlinear behavior in 1D model, is correctly considered in accordance with the aforementioned Hardin – Drnevich constitutive model in section 2. From Figure 7 it is revealed that the relation between the σ_x and σ_y stresses depends on the K_0 parameter (is fixed at 0.5 in this study), completely which is a common phenomenon in 1D numerical site effects.

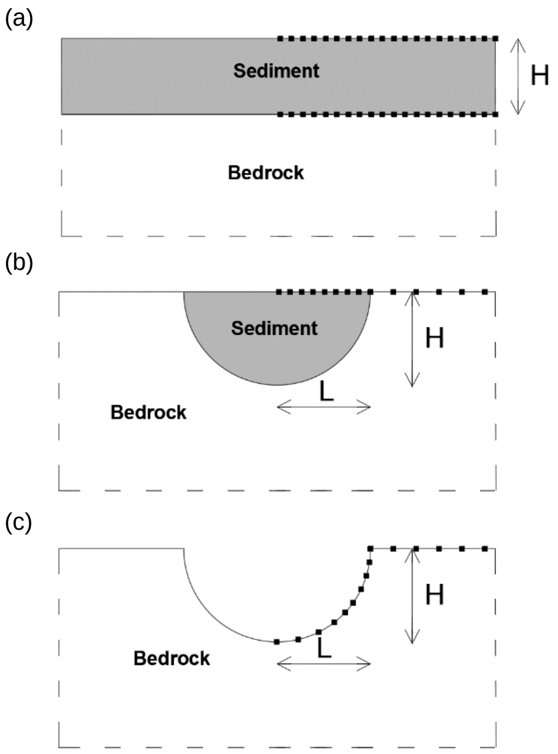


Figure 4. Observational geometrical points of models (a) 1D, (b) 2D full-filled valley and (c) 2D empty valley.

In order to evaluate the nonlinear seismic ground response in 1D model, the horizontal displacement (U_x) of the observational points are calculated by means of a HYBRID (FE/BE) method. The displacement of two points which are located in the center of the model on bedrock (beneath the soil) and top of the sediments are presented in Figure 8 (a) and (b), respectively.

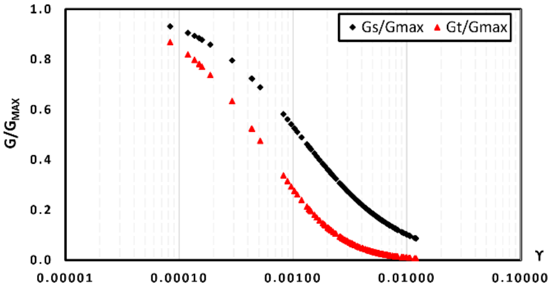


Figure 5. G/G_{max} (G_{sec}/G_{max} and $G_{tangent}/G_{max}$) versus experienced strains for one of the elements in 1D model.

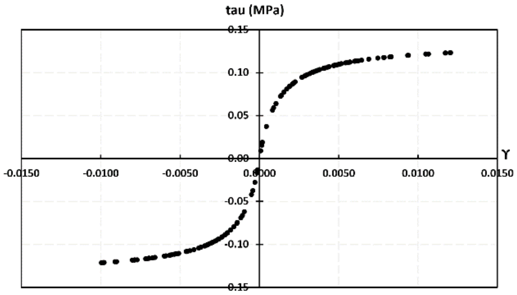


Figure 6. Shear stress-strain curve for one of the elements in 1D model.

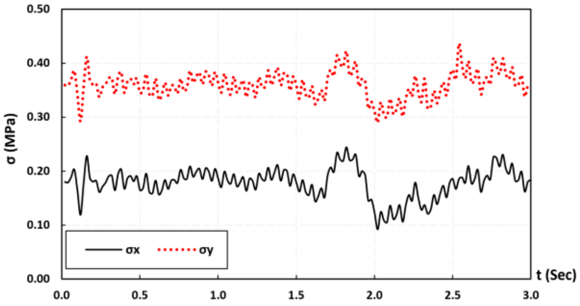


Figure 7. The variations of σ_x and σ_y stresses for one of the elements in 1D model.

To consider the changes in the responses due to the nonlinearity of the materials, the linear seismic responses are also provided for the same points. The presented results for the point on the top of the sediments reveal that the nonlinearity can significantly impact the soil layer seismic responses in a way that the range of nonlinear response variations is much more limited in comparison those of linear, which means the nonlinear ground responses will be smaller than linear ones; but as expected, the trends for the point on the bedrock are approximately the same for both linear and nonlinear alluvia which means that the presence of the sediments don't affect the bedrock responses, expectantly

In addition, by comparing responses in Figure 8, it can be said that the ground response amplifies on the top of the alluvium due to the presence of softer material on the stiffer rocky bed.

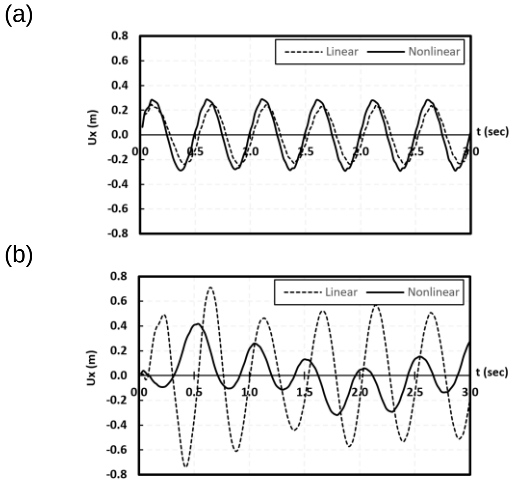


Figure 8. Time history of nonlinear / linear horizontal displacements in 1D model (a) on the bedrock and (b) on the top of the soil.

3.2.2 2D Site Effects in Empty Topographies

An empty elliptical topography with the depth ratio (H/L) equals to 0.4 under vertical sinusoidal incident wave is modeled in order to compare the responses with those of in fully-filled topography (next subsection). As the valley is empty, there is no sediments in this model. The displacements of 5 important observational points (according to Figure 9) are selected and shown in Figure 10.

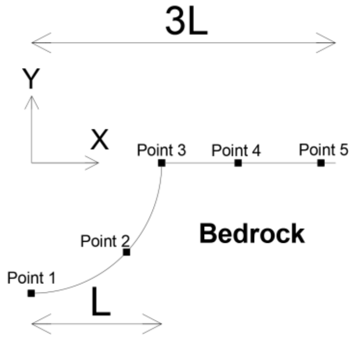
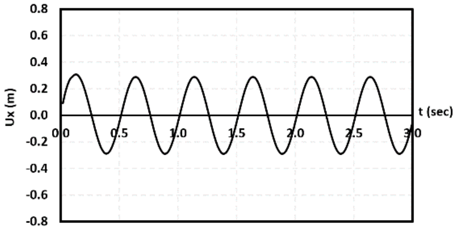


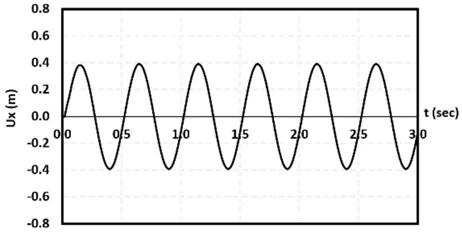
Figure 9. Selected points among the observational points to present their displacements in 2D - empty topographies.

It is obvious from Figure 10 the ground response is amplified cyclically by moving from the center of the valley to the edge of that. In other words, the existence of the 2D irregularities attenuate the seismic responses in the center of the valleys in comparison with the free field response.

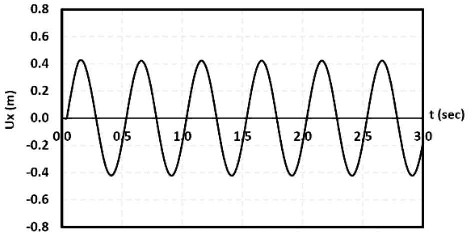
(a) Point 1



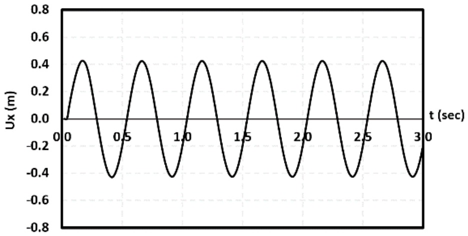
(b) Point 2



(c) Point 3



(d) Point 4



(e) Point 5

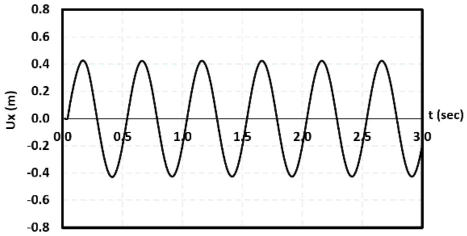


Figure 10. Time history of horizontal displacements of 5 points (in order) of bedrock (surface of empty irregularities) considering 2D topographies.

3.2.3 2D Site Effects in Fully-filled Topographies

The empty elliptical topography of the previous section (H/L= 0.4) is filled with a drained linear/nonlinear sediment in accordance with the provided geo-mechanical properties in Table 1. The G/G$_{max}$ curves versus shear strains for one of the elements at the bottom of the model are provided in Figure 11. In addition, the nonlinear shear modulus (G) of sediments varied according to the shear stress-strain curve in Figure 12. It can be seen from Figure 13 that the relation between σ_x and σ_y becomes more complex over the time in comparison to the 1D model because the two-dimensionality of the soil model can change the distribution of the vertical and horizontal stresses, unlike in 1D model.

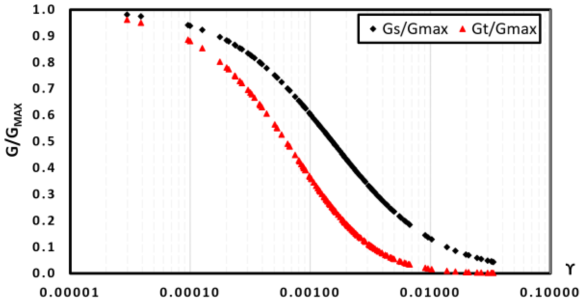


Figure 11. G/G$_{max}$ (G$_{sec}$/G$_{max}$ and G$_{tangent}$/G$_{max}$) versus experienced strains for one of the elements in 2D fulyl-filled model.

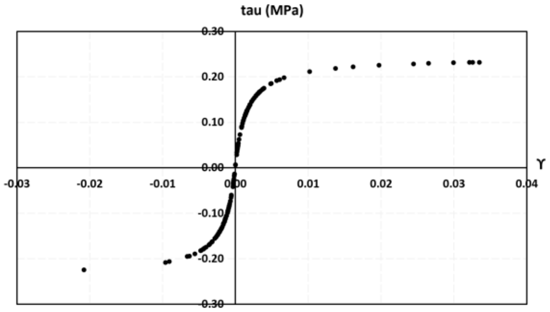


Figure 12. Shear stress-strain curve for one of the elements in 2D fully-filled model.

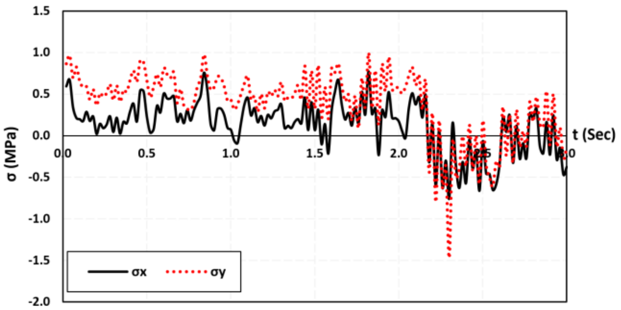


Figure 13. The variations of σ_x and σ_y stresses for one of the elements in 2D fully-filled model.

Similar to the empty valleys, different observational points are also considered in the fully-filled valleysto present the results (Figure 14). The nonlinear displacement time histories related to these points are presented in Figure 15 (in the same order of numbering). In fact, the ground surface nonlinear responses are provided in various locations particularly at the center, edge and out of the basin.

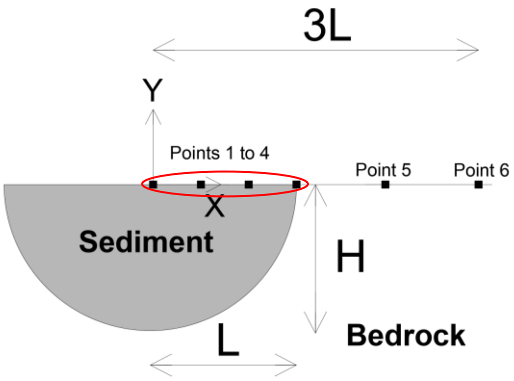


Figure 14. Selected points among the observational points to present their displacements in 2D – full-filled topographies.

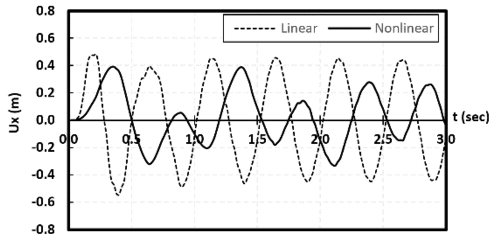
By looking at the presented graphs in Figure 15 the following items can be drawn:

- There are clear differences (in terms of maximum amplitude of displacements and the time in which the responses can reach these maximum displacements) between nonlinear and linear responses in the points located inside of the topography particularly in the center of the valleys. Moreover, the amplitude of the nonlinear responses is more limited because of the nonlinearity of the sediments.
- Moving from the center to the edge of the valley the nonlinear and linear responses are closely matched.
- In addition, the responses are amplified at the center and edge of the valley due to the more geological effects and topographical effects, respectively.

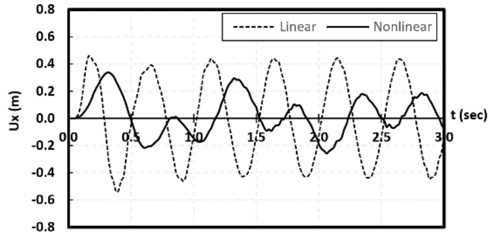
5 CONCLUSION

In this paper, the seismic responses of filled 1D and 2D topographies by linear/nonlinear drained alluvium are underlined. The Hardin-Drnevich constitutive model is implemented into a numerical code, called HYBRID which combines the finite element (FE) and boundary element (BE) methods in the near and far field, respectively. In fact, the site effects are evaluated on the seismic responses in terms of topographical and geological aspects. The sites are subjected to the vertical incident cyclic sinusoidal seismic wave. The main results are as follows:

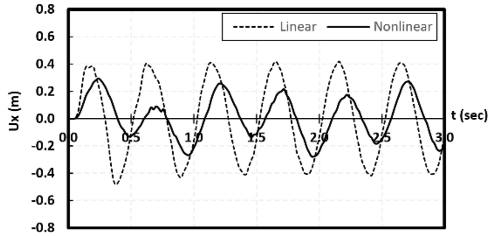
a) Point 1



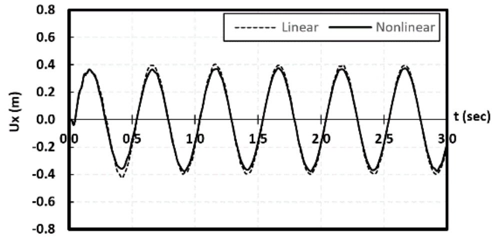
(b) Point 2



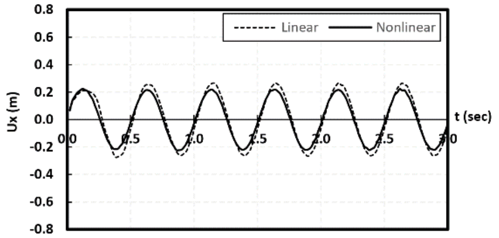
(c) Point 3



(d) Point 4



(e) Point 5



(f) Point 6

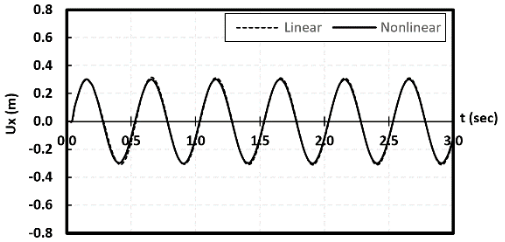


Figure 15. Time history of horizontal displacements of 6 selected points (in order) on the ground surface considering 2D topographies.

- The nonlinear behavior of the element is correctly implemented in all models, according to the Hardin-Drnevich constitutive model in terms of G/G_{max} curves, stress-strain graph.
- In 1D model, considering the geological characteristics, the ground response amplifies on the top of the alluvium due to the presence of softer material on a stiff bedrock, generally. In addition, the nonlinearity of the materials can effectively attenuate the seismic responses at the top of the soil layer in comparison with the linear responses.
- In 2D empty valleys, the ground responses are amplified by moving from the center of the valleys to the edge of that due to the steeper topography in comparison to the free field.
- In 2D fully-filled basins, the nonlinear ground surface displacements are smaller than and equal to the linear responses for points inside of the topography and points in the free field, respectively. Furthermore, by moving from the center to the edge of the valley, the geological effects are attenuated while the topographical effects dominate.

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