EXAMINING THE ASSUMPTION OF HOMOGENEOUS HORIZONTAL LAYERS WITHIN SEISMIC SITE RESPONSE ANALYSIS

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ABSTRACT

One-dimensional analyses can be conducted to estimate the impact of superficial soil layers on earthquake ground motions. Such analyses are based on the assumption that all boundaries are horizontal and that the response of a soil deposit is predominantly caused by horizontal shear waves propagating vertically from the underlying bedrock. This assumption is made even for sites with a relative large surface area, e.g. the footprint of large infrastructure such as power plants.

An important step then is to create a model of the near subsurface that is representative of the overall area under analysis. This means it is essential to evaluate geomechanical characteristics of the soil at certain locations and extend these measurements over the whole site. As a consequence of this, it is assumed that the soil characteristics, which include stratigraphy, geometry and geotechnical properties, are homogeneous. Recent observations, however, have clearly demonstrated that even over a small area (~1km^2) ground conditions can vary greatly.

The purpose of this study is to examine the impact of relaxing the assumption of infinite horizontal layers by undertaking a parametric study of the variability in amplification across areas with gently dipping subsurface layers. Starting from a 1D approach the influence of dipping layers is evaluated through simplified but geometrically representative models. Randomization of shear-wave velocity profiles using the Toro (1995) method, as implemented in STRATA, is used to compute the variability in site amplification that would be captured by a standard 1D technique. This provides a baseline for comparison with the variability introduced by the dipping layers. Subsequently, two-dimensional simulations are conducted for the same sites with dipping layers to estimate the error made through the assumption of 1D response. The goal of this study is to understand when the 1D assumption can be used in the presence of dipping layers.

1 INTRODUCTION

Seismic site response analyses are one of the most important aspects of seismic hazard assessment. This step is generally required for critical structures (such as power plants) and for buildings not located on hard rock.
A critical aspect of this kind of study is the capability to assess all the possible site uncertainties, which can arise both from geo-mechanical and geometrical points of view. Geological conditions can vary rapidly within a small area (e.g. within the roughly 1 km^2 footprint of some critical infrastructures). Generally *ad hoc* procedures are used to account for this variability (if it is known to exist), which can be difficult to justify, time-consuming and associated with an unknown level of conservatism.
Engineering judgement plays a key role in the final selection of the parameters for the analyses. A selection of the most relevant geological conditions are analyzed and then extended to the whole model. Furthermore, simplifying assumptions can be made, such as 1D response can reproduce the real situation quite well, but again this needs to be judged on a site-by-site basis.
This approach has been the predominant approach for many years, because it leads to easy-to-understand and generally reliable results but the assessment of its associated uncertainties is still challenging.

Several authors have compared the response of 1D and 2D models, in particular for sedimentary valleys (e.g. Bard and Bouchon 1985). Some of the studies have focused on real cases, taking into account complex geometries and non-linear effects (e.g. Kapuskar et al. 1989), whereas others (e.g. Sanchez-Sesma and Velazquez 1987; Paolucci and Morstabilini 2006) have studied canonical forms, such as the response of a single dipping layer, and find closed-form solutions for them.
This study starts from these previous studies and aims to assess the error we commit by making the 1D assumption instead of more complex solutions, which consider variability in terms of soil mechanical properties and variability in terms of geometrical characteristics of the site (e.g. gently-dipping layers). In contrast to previous studies, which were related to real locations, this one is more generic, since it is seeking to provide general guidance.

1.1 Review of the available methods

According to basic theory (e.g. Kramer, 1996), whenever the site presents a not very complex geometry (e.g. valleys) and the analysis that we want to conduct is a preliminary one (e.g. soil nonlinearity is not taken into consideration), a 1D linear viscous-elastic analysis can be used (Figure 1-A). The basis of this approach is to model the site as a series of parallel flat layers that extend infinitely in the horizontal direction excited by a horizontal input motion (SH waves), which can be a significant simplification.

Rathje and Kottke (2011) have added the possibility to make this simple model more realistic from the point of view of its geo-mechanical uncertainties. In their software STRATA, they have introduced the possibility of randomizing the shear-wave velocities profiles, using Toro (1995) technique (Figure 2).

This should overcome, at least partially, the problem of lack of reliable site information (e.g. thickness of layers, stiffness of layers, depth of bedrock) over an entire building footprint, which is often the case for real projects.

What happens if the site is not anymore representable as a series of parallel flat layers? We are excluding from our discussion obviously 2D or 3D sites like alluvial basins or narrow valleys and focusing on geometries with gentle dipping layers, e.g. at edges of wide shallow valleys.

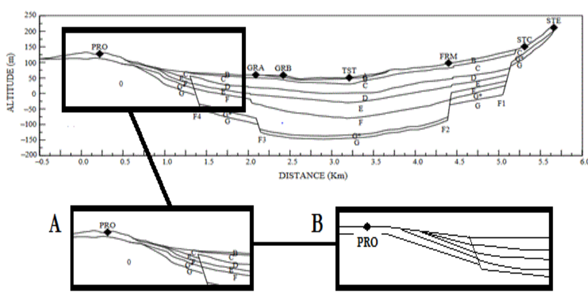


Figure 1. Example of the edge of a valley. A) lateral edge zoom; B) lateral edge possible simplification. Example taken from (Makra and Raptakis 2007)

Could a situation like that be accurately studied with 1D model, with its advantages of speed and simplicity, or is it necessary to move to 2D analyses, which are generally much slower and more complex to set up (e.g. the need for many input parameters) and analyze?

In this work, the 1D approach both in the standard way and by using randomization are studied. The first version will result in a series of transfer functions computed by changing the thickness of the layers, per the geometrical situation (Figure 2-A). The second set, in addition to this variability, will account for the randomization of the shear-wave velocity profiles, trying to account for both geometrical and geo-mechanical issues (Figure 2-B). These second results will be compared to the 2D results, which are the most correct way to model response of such a site. A possible future step would also involve comparison of 1D and 2D simulations with actual observations.

The goal of the work is to try to estimate the standard deviation that when included in the randomized model leads to 1D results that are comparable to those from the 2D analyses. This would mean that 2D analyses could be avoided for these cases, thereby saving time and effort in modeling and interpretation of results.

Future steps will include randomization within the 2D model and understanding the implications of this on possible site response for this type of site.

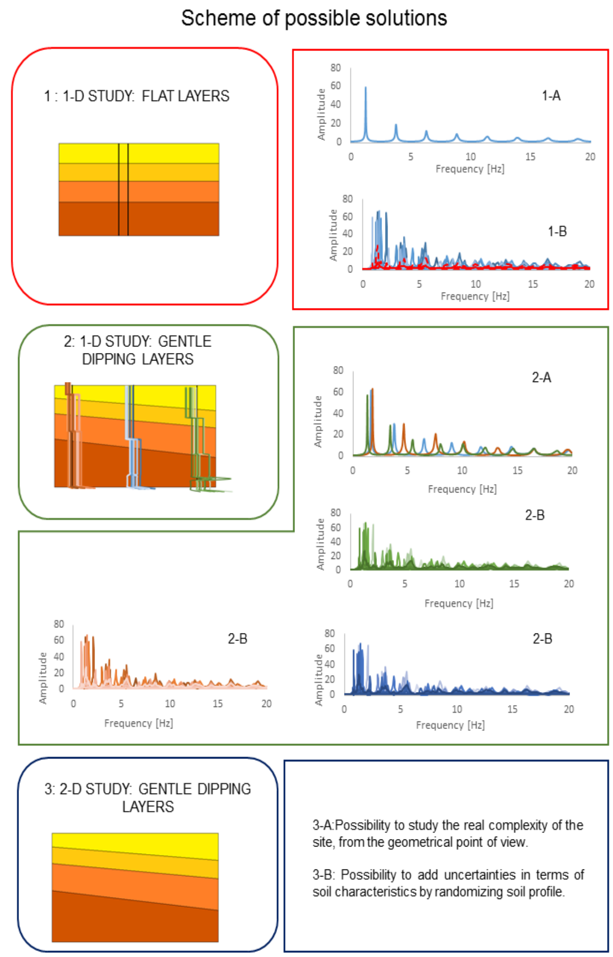


Figure 2. Above left: 1-D analysis with flat layers. Above right: comparison of transfer functions from classical analysis (1-A) and randomized one (1-B)

Centre: 1-D analysis for dipping layers. Comparison between classical analysis (2-A) and randomized one (2-B).

Bottom left: 2-D analysis of dipping layers. Bottom right: evaluation of the possible 2-D analyses (3-A), (3-B)

2. COMPARISON BETWEEN 1D AND 2D RESULTS

As indicated in Figure 2, a series of steps will be taken to evaluate the difference between 1D and 2D results. Considered that the first model (1-A, 1-B) is well known, the second and the third ones will be studied here. First, a simple general geometry must be chosen that can be applied to many situations.

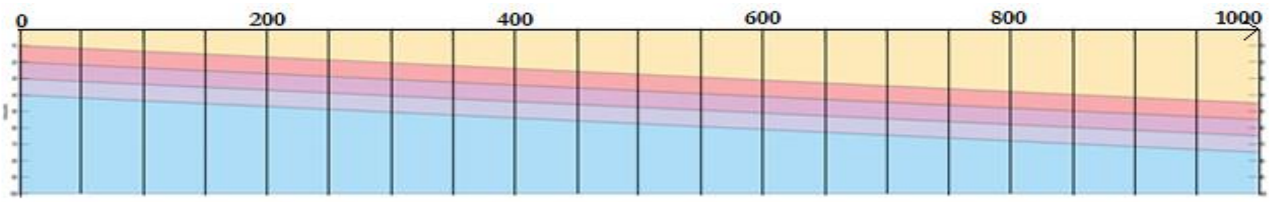


Figure 3. Scheme of the model used for the analysis

Figure 3 represents the model selected for this purpose. Each different color represents a different layer, in terms of geotechnical properties. Furthermore, each of these layers is inclined at the same angle, which is a reasonable assumption when the same geological processes are acting on all layers. This geometry has been used because of its simplicity and potential for leading to general guidelines.
Table 1 reports the shear-wave velocity of the model.

Table 1. Shear-wave velocity of each layer of the model

Layer Number	Vs [m/s]
1	300
2	350
3	400
4	500
Bedrock	1000

2.1 Randomized Profile

The idea behind the second approach (Figure 2) is that of linking both geo-mechanical issues and geometrical ones in a single 1D model. Indeed, several linear viscoelastic analyses will be computed along the x-axis (Figure 3, black lines) and in each of them the shear-wave velocity profiles will be randomized.
Before anything else, it is useful to examine the consequences of both the geometrical aspects and the shear-wave velocity randomization on the model. To do this, a comparison in terms of standard deviation of the shear-wave velocities at each depth is carried out. Focusing on Figure 3, 21 profiles have been selected (one every 50 m). The blue curve (Figure 4) has been computed in this way: a matrix of n-rows (each row represents a single meter thickness) and m-columns (equal to the number of profiles chosen) has been created. This matrix contains shear-wave velocity profiles (Eq.1):

$$\begin{bmatrix} V_{1,1} & \cdots & V_{1,m} \\ \vdots & \ddots & \vdots \\ V_{n,1} & \cdots & V_{n,m} \end{bmatrix} \qquad [1]$$

Then, logarithms of each element of this matrix are evaluated and finally, for each row of this matrix a standard deviation is computed. The result is represented by the blue curve in Figure 4.
The red curve in Figure 4 represents both the geometrical aspects of the model as well as the variability from the randomization. To compute this each of the 21 profiles has been randomized 100 times, using the Toro (1995) technique to randomize the V_s of each layer. This randomization has been evaluated using the coefficients from Toro (1995) for the appropriate $V_{s,30}$ for this site, i.e. for 180-360m/s as the models have $V_{s,30}$ between 200 and 400 m/s.
Table 2 reports coefficients used:

Table 2. Parameters of the Toro (1995) model for Vs=180-360 m/s, where ρ_0, ρ_{200}, Δ, d_0 are respectively the initial correlation, correlation coefficient at 200m, model fitting parameter, initial depth parameter.

σ_{lnVs}	ρ_0	ρ_{200}	Δ	d_0	b	Profiles
0.31	0.99	0.98	3.9	0	0.344	266

According to Table 2, coefficient σ_{lnVs} leads to the starting point of the red curve. The biggest gap between the two curves, which is represented by the green curve, is close to the surface and at maximum depth. The peak of the standard deviation (red and blue curves) is roughly at half of the maximum depth reached. This happens mainly for geometrical reasons and is understandable when looking at Figure 3.

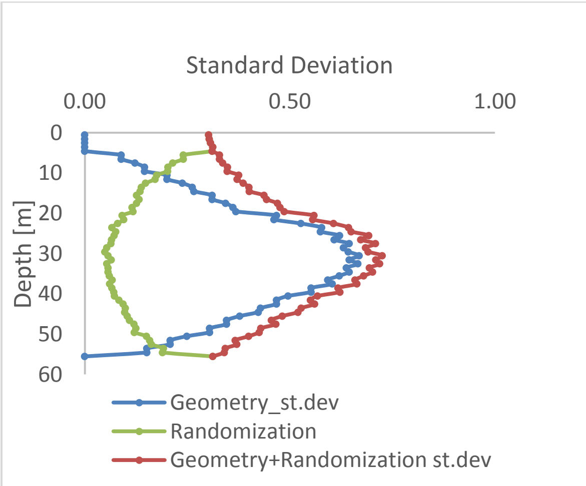


Figure 4. Comparison among standard deviation of the logarithms of the velocity profiles with only geometric effects (blue), with geometric and randomization effects (red) and the difference between the two (green).

2.2 2-D Analyses

The aim of this work is to assess the possibility of using 1D analyses instead of 2D analyses in some cases. To verify this possibility, a set of 2D analyses must be performed.

The general idea is to recreate the same model as shown in Figure 3 within a finite element software package. Currently we are using Abaqus (Simulia) for these simulations. When implementing the model several parameters, such as the dimension of the main model, the dimension of the single element, the correct boundary conditions, have to be carefully chosen.

2.2.1 Description of the model

The Abaqus model must be as similar as possible to the 1D analysis. This means that several rules have to be followed. First, a viscous linear elastic analysis is performed. Abaqus gives the possibility of defining the damping in terms of the Rayleigh formula, which is an

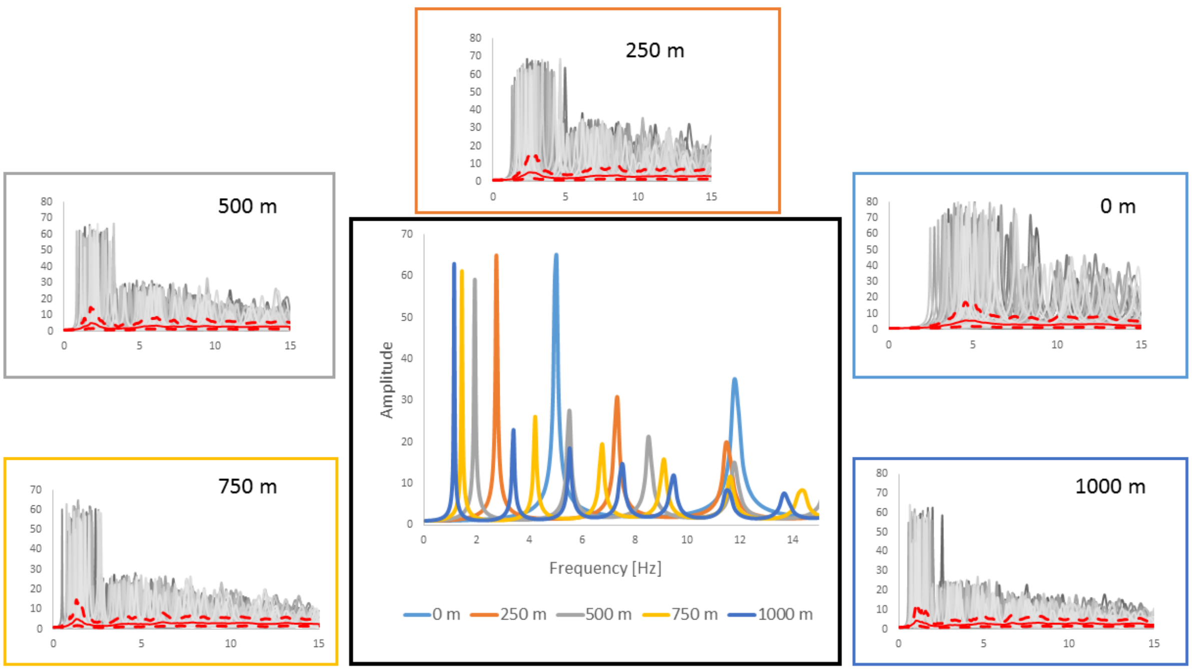


Figure 5. Comparison between standard analyses (center) and randomized ones (0m, 250m, 500m, 750m, 1000m). The red curve is the median amplification and dashed lines are the 16th and 84th percentiles.

A comparison of transfer functions between 1D standard analyses and 1-D analyses with randomized profiles (both linear viscoelastic) is shown in Figure 5.

artifice to reproduce the real damping. In this formula, the damping matrix, C is assumed to be a linear function of the mass matrix, M and the stiffness matrix, K, through two coefficients, α_R and β_R, in this way:

$$C = \alpha_R M + \beta_R K \qquad [2]$$

Therefore, by imposing the damping value that should be reached, these two terms can be computed. The critical aspect of this method is that it is a frequency-

dependent method. Consequently, it should be used with prudence, especially if the analysis is not linear.
The second aspect of this analysis is the way in which the bedrock is specified (this is also true in the 1D case). There are two principal ways to include bedrock within site response analysis: the first, which is used here, is the infinite rigid bedrock, whereas the second, which is more realistic from a geo-mechanical point of view, is considering the bedrock as “another” layer, with stiffer characteristics than the others. We could say that the first one is the preliminary choice, when there is a lack of information about the site. The second possibility allows a more realistic model to be produced, but it requires an in-depth knowledge of the site. As stated above, in this set of analyses an infinite rigid bedrock will be assumed and no dashpots introduced.
The third important concept that must be controlled is the dimension of the single element of the model (Lysmer and Kuhlemeyer, 1973), which should follow this rule:

$$\Delta l_{max} \leq \frac{\lambda_{min}}{10} \leq \frac{V_{s,min}}{10 \cdot f_{max}} \qquad [3]$$

where:
- Δl_{max} is the maximum dimension of the element;
- λ_{min} is the minimum wavelength of the model;
- $V_{s,min}$ is the minimum shear wave velocity presented in the model;
- f_{max} is the maximum frequency for which we would like to obtain an accurate result;

Following this rule, the shallowest layer will be the one with the smallest elements.
The final important issue is the boundary conditions, which are fundamental in finite element analyses. There are several approaches in the literature to model the boundary conditions for this kind of problem. The main issue is the reproduction within a finite model of a semi-infinite phenomenon. It is understandable that the wave path is conditioned by this finite geometry and could alter the output.
To prevent this, a free-field (Wolf, 1988) boundary condition is created. Theoretically, it is a semi-infinite domain with horizontal layers of linear-elastic materials. In Abaqus, this has been implemented in a subroutine (Nielsen 2006, 2014), which allows the generation of free-field elements. This subroutine can be used either in 2D or 3D models, with complex morphologies, as long as a buffer zone, which has to link the main model (complex morphology) to the free field element, is provided.
Following this series of rules, the model has these characteristics:
- the main model length is 800m;
- the lateral buffer zones length is 600m;

Figure 6 shows an outline of the model.

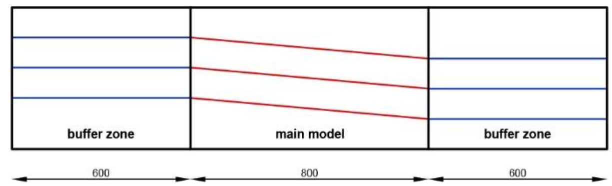


Figure 6. Outline of the model in Abaqus

Four different models have been generated, each of them presenting a different slope angle of the layers, from 1 degree to 4 degrees, which implies different thicknesses of the first layer (Table 3).

Table 3. Evaluation of Δh, the additional thickness of the first layer coming from the geometry.

Sloping angle [°]	Δh [m]	Thickness first layer [m]
1	13.6	23.6
2	28	38
3	41.6	51.6
4	56	66

The maximum value of the dipping angle has been set to 4 degrees because, as Table 3 shows, Δh starts to become too big, which means the geometry effect will dominate the site response analysis.
Finally, table 4 displays geo-mechanical characteristics of each layer, apart from the damping ratio, which is of the order of 1%. Table 4 does not show it, because it is represented through the Rayleigh method, which means different values of alpha and beta for each layer and for each model.

Table 4 Geo-mechanical characteristics of each layer

	Layer 1	Layer2	Layer 3	Layer 4
γ [KN/m^3]	1800	1800	2000	2000
V_p [m/s]	755.9	1530.5	982.0	1224.7
V_s [m/s]	308.6	362.5	400.9	500.0

2.2.2 ANALYSIS PROCEDURE AND RESULTS

From a theoretical point of view this analysis could be processed with any time-history because it is a linear viscoelastic model and here only the transfer functions are considered. A series of different input have been chosen to test the model, all of them taken from the Itaca database (Italian Accelerometric Archive). For each set of triaxial time-histories (N-S, E-W, U-D) belonging to a single earthquake, the maximum of the two horizontal and the vertical one have been chosen. Each of the geometries has been tested with the same set of time-histories. Previously it was checked that

Strata and Abaqus give comparable results for the 1D case.

Figure 7 displays an example of the time-histories selected for the bedrock. Figure 8 displays a comparison between an input motion and an output taken from 1 degree Abaqus analysis, at the central node of the surface.

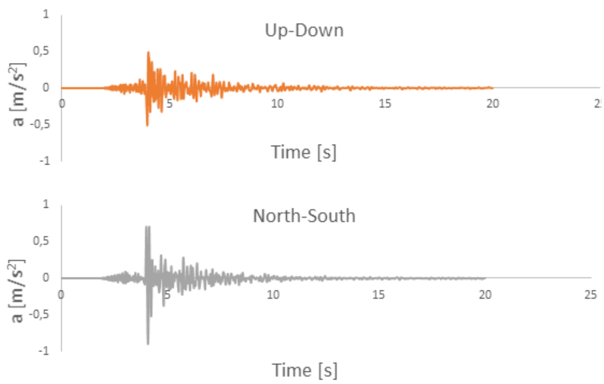


Figure 7. Example of the input time history, taken from ITACA

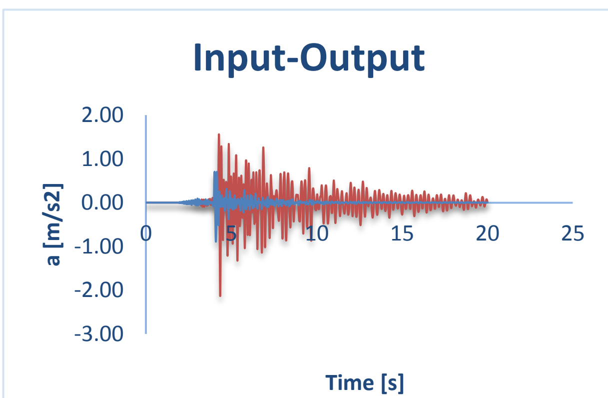


Figure 8. Input (blue) and Abaqus output (red) accelerograms, taken from the center of the model (400m).

To evaluate the effect of the sloping layers, transfer functions have been computed every 100m and they have been compared to those from STRATA. This procedure has been repeated for each of the geometries. For this purpose, the 1D profile at the center of the main model has been selected. Indeed, the goal of this work is to assess the reliability of 1D analysis for this kind of geometry. Therefore, it is interesting to make this comparison and to evaluate how far is the 1-D response from the 2D calculation that takes into account non-vertically incident waves. Figure 9 and Figure 10 display these results: Figure 9 corresponds to 1 and 2 degrees slopes, whereas Figure 10 shows the results for 3 and 4 degrees slopes. As expected the greater the slope the greater the mismatch, because geometrical complexity dominates.

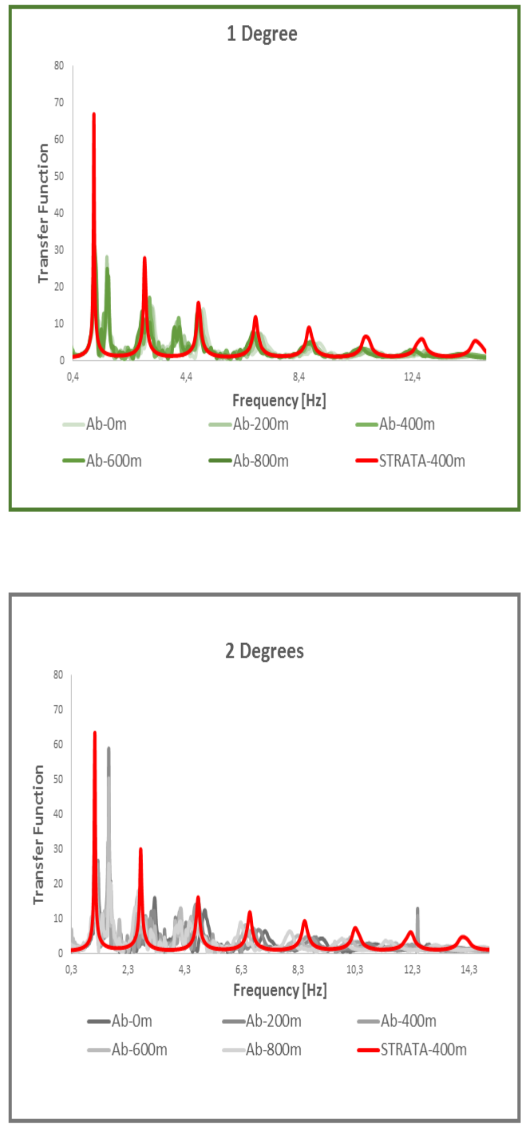
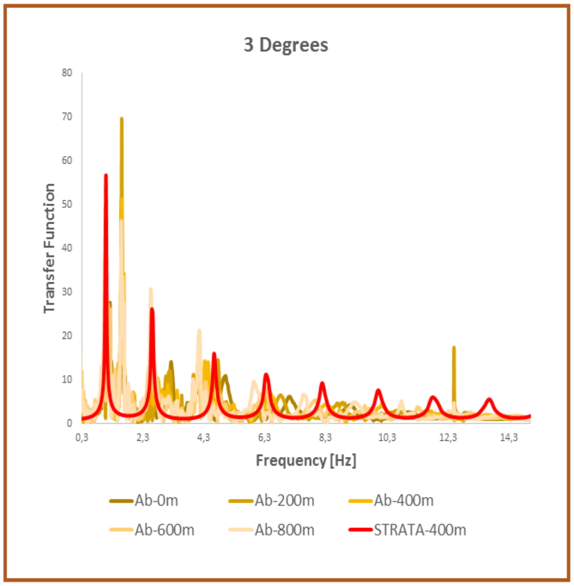


Figure 9. Above: 1-degree comparison between Abaqus transfer functions (0m, 200m, 400m, 600m, 800m) and STRATA transfer function (400m);
Below: 2-degree comparison between Abaqus transfer functions (0m, 200m, 400m, 600m, 800m) and STRATA transfer function (400m).



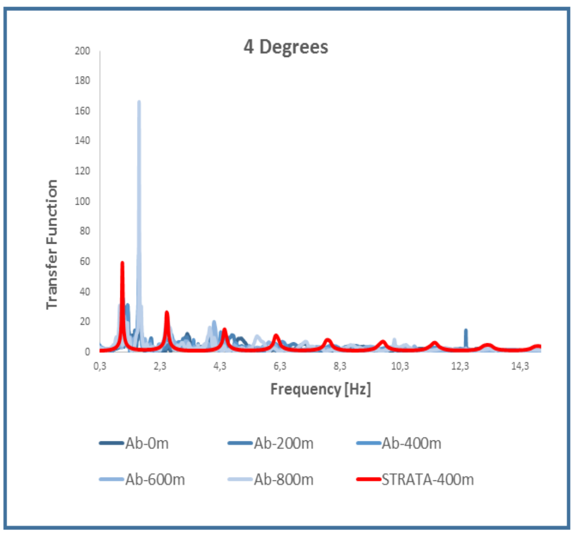


Figure 10. Above: 3-degree comparison between Abaqus transfer functions (0m, 200m, 400m, 600m, 800m) and STRATA transfer function (400m);
Below: 4-degree comparison between Abaqus transfer functions (0m, 200m, 400m, 600m, 800m) and STRATA transfer function (400m).

3. CONCLUSION

This work presents some preliminary evaluations of the capabilities of 1D analysis to compute the seismic response of gentle dipping layers. This is a kind of morphology that is quite common at the edge of large shallow valleys. The literature has clearly demonstrated that complex geometries, like narrow deep valleys, cannot be studied with 1D analyses. This work focuses on those geometries in a transition zone from flat layers to valleys. To do that, a logical scheme has been followed. Starting from 1D analyses with flat layers, which is the classical configuration and the most used one, this work studied configurations with a more complex geometry, i.e. gently-dipping layers (Figure 3) and they have been studied both with the classical method (1D) and in a more realistic way, using 2D models. Results from the two approaches have been compared in terms of transfer functions, to understand the error, we commit using simple 1D models.
This is a preliminary study, which is currently being expanded. New comparisons will be made in terms of elastic response spectra. Bigger models and higher complexities will be considered as well as more variations in the geo-mechnical properties, e.g. non-linear effects and different bedrock stiffness.

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