Sensitivity Analyses for Submarine Slopes under Seismic Loading

R. Rodríguez Ochoa
University of Oslo / International Centre for Geohazards

F. Nadim
Norwegian Geotechnical Institute / International Centre for Geohazards

A. M. Kaynia
Norwegian Geotechnical Institute

SUMMARY:
In a typical soil profile for offshore deep water, the clay layers extend beneath the seafloor for hundreds of meters beyond the geotechnical explorations, making it difficult to accurately establish their mechanical properties and locate the depth of the bedrock. To quantify the response of the soil mass accounting for the thickness of the soil mass, the stiffness at the base and the magnitude of submarine slope angles, a sensitivity analysis for a site in the Gulf of Mexico was carried out. The earthquake-induced shear strain within the soil deposit is a key parameter in the slope stability assessment, therefore the analyses focused on the maximum shear strain as the main outcome.
Based on these simulations one may conclude that the predicted response for the 100m soil profile is more sensitive to the stiffness of the bottom and the slope angles than that of the 200m soil profile.

Keywords: dynamic response analysis, offshore geohazards, submarine slopes, earthquake-induced shear strain, shear wave velocity

1. INTRODUCTION

The oil and gas industry remains the main source of energy all over the world despite the increasing attention to develop other sources of energy. Therefore vast effort is still focused on the quest for hydrocarbons, but many of the reservoirs are found in offshore sites with increasing water depths. Offshore structures are necessary for the development of oil and gas fields, many of them need to be placed in areas with potential submarine slide activity, for this reason it is important to take into account the stability of submarine slopes during the selection process of the sites.
In the south part of the Gulf of Mexico, in a region called Lakach, during the exploration activities the National Oil Company of Mexico (PEMEX) discovered a natural gas reservoir for development. The gas reservoir is located about 55 km from land with water depth about 1200m.
The geophysical survey was performed by Fugro GeoServices, Inc., from March 13th to April 24th in 2008, the geotechnical field investigation was carryout by Fugro Chance de Mexico, S.A. de C.V. from August 9th to November 23th in 2008 in a vessel called M/V Fugro Explorer, Fugro (2009, 2009a, 2009b).
Given the seismicity of the region, where the site is influenced by the subduction zone in the pacific coast, there is concern about submarine landslides trigger by earthquakes that could impact the marine environment and the natural gas production. Therefore it is important to estimate the dynamic behavior of the clay sediments at the site by means of numerical simulations to assess the stability of the submarine slopes under seismic activity.
To perform the ground response analysis, it is important to establish at what depth the control motion should be located to initiate the propagation of the shear waves throughout the soil. During the simulations the half-space is meant to be the boundary between the bedrock and the soil, but the geology of the offshore sites in deep waters normally makes it difficult to find the rock horizon clearly. In many offshore sites it is common to find layers of fine soil for hundreds of meters beneath seafloor, making it difficult to define reference bedrock on the basis of geotechnical and geophysical

explorations. An additional difficulty is to specify which shear wave velocity for the bedrock, there are different criteria depending on personal experience.
Taking into account the above issue, this paper explores the effect of the depth and stiffness of the bedrock in the response of the clay sediments, as well as the influence that the slope angle has on the dynamic response of the clay sediments. To achieve this, 1-D site response analysis for level ground was used as starting point to gain information about the response of the soil under earthquake loading conditions followed by simulations with sloping ground.
The sensitivity analyses were performed by means of using 2 computational programs for the simulations SHAKE(N) (Selnes, 1987) and AMPLE (Nadim, 1985), 2 soil profile thickness with different shear wave velocities at the half-space and 4 different slope angles. The initial shear wave velocities used for the half-space were based on the estimated geotechnical soil properties and the increasing velocities were assigned for sensitivity analyses.
The simulations illustrate in a quantitative manner the importance of the depth and stiffness of the half-space as well as the slope angle in the dynamic response of the soils. With SHAKE(N) the 100m soil profile shows more sensitivity to the increase in the shear wave velocity compared to the 200m soil profile, although the 200m soil profile produces larger shear strain values. Based on the simulations with AMPLE2, in general the sensitivity of both soil profiles is similar with respect to the shear wave velocity. Regarding the slope angle as changing variable, it can be seen the high impact that the slope angle has on the soil response, for example, when the slope angle increases from 0 degrees to 15 degrees the maximum shear strain increases about 20 times.

2. SITE CHARACTERIZATION

In order to characterize the site under investigation for stability analyses, it is necessary to divide the activities in two main stages, regional and site specific evaluations.
The objective of the regional survey is to get an overview of the relevant area and to give input for the site specific evaluations. The main sources of regional information are the geophysical surveys, including bathymetric mapping of the region and mapping of soil sediments. Location and estimation of slope angles, previous slide activities and possible unstable layers can be identified based on geophysical surveys.
The objective of the site specific evaluation is to determine the slope stability for critical slopes in the survey area and possible submarine slides that can damage the integrity of an offshore structure. Special laboratory testing has to be carried out to determine the soil response to a triggering mechanism such as earthquake loading.

2.1. Slope Geometry

In the Lakach area there were identified 9 potential unstable slopes ranging from 0.1 to 9.2 degrees during the high resolution shallow, 200m below seafloor, geophysical survey carried out by Fugro GeoServices, Inc., in the Lakach zone, Fugro (2009, 2009a).

2.2. Soil Geotechnical Properties

In situ and laboratory tests were carried out by Fugro (2009a, 2009b) to obtain the geotechnical parameters to establish the soil strength and soil deformation properties. In the area, 5 boreholes were completed until approximately 100m depth from the seafloor. In all boreholes, PCPT tests were carried out from the seafloor to 100m depth, also soil sampling at different intervals depending on the depth range. For advanced static and dynamic laboratory tests, 24 soil samples at different depths were obtained for each borehole by means of nickel Shelby type tubes.
Generally the sediments are cohesive materials classified as high plasticity clays (CH), calcareous soils with carbonate content between 11 to 23 %. The predominant clay mineral is montmorillonite followed by illite, according to the X-ray diffraction tests.
The undrained shear strength of the clay was estimated based on PCPT in situ tests, Triaxial UU, vane miniature (VM), torque-meter vane (TV) and pocket penetrometer (PP) tests.

Laboratory soil sensitivity varies from 3 to 5 until 20m depth and from 1.5 to 3 beneath 20m.
The stress history information was obtained by means of consolidation tests at constant rate (CRS); the pre-consolidation effective stresses $\sigma'_{v,m}$ were estimated using Casagrande and Becker methods as well as PCPT in situ tests using empirical correlations. The estimated OCR's indicate that the cohesive soils in general fluctuate from normally consolidated to slightly over consolidated.
The geotechnical properties of the sediments for this sensitivity study were obtained from the closest borehole, identified as AP-16, to the slope with the largest slope angle of 9.2 degrees, Fugro (2009, 2009a).
The undrained shear strength (s_u) soil profile for borehole AP-16 was obtained using the SHANSEP approach by Ladd and Foott (1974), see Fig. 2.1.

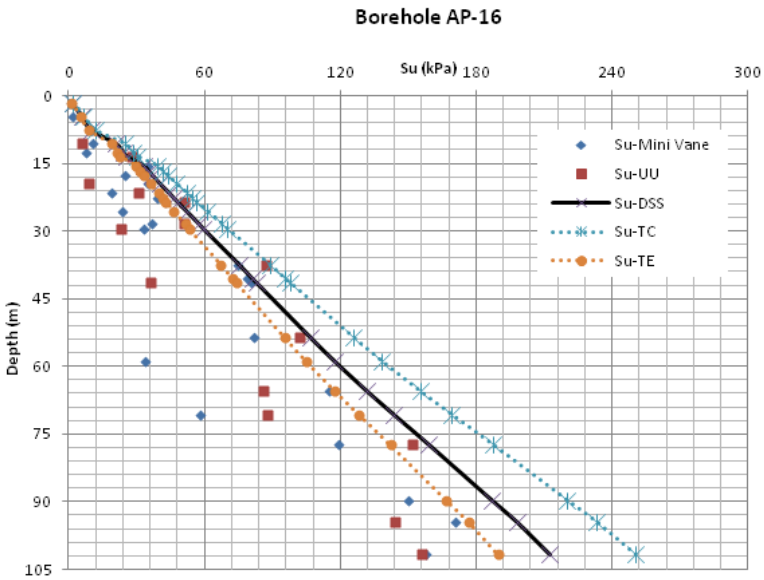

Figure 2.1. Undrained shear strength soil profile

3. SOIL DYNAMIC RESPONSE

In order to estimate the stability of a slope subjected to cyclic loading, like earthquake phenomena, it is important to understand the dynamic response of the sediments, to achieve this, ground response analyses were carried out using 2 computational programs SHAKE(N) (Selnes, 1987) and AMPLE (Nadim, 1985). Both computer programs use the simplified one-dimensional wave propagation through the soil medium. The former is based on the quasi-linear approach by means of transfer functions for horizontal soil layers and the latter is based on the non-linear approach which solves the one dimensional shear wave propagation problem in horizontal or sloping layered soil profile.

3.1. Shake(N)

Simulations were carried out using an improved version of the original program SHAKE (Schnabel, et. al., 1972) called SHAKE(N) (Selnes, 1987). This computer program for analysis of earthquake response in horizontally layered sites was used to estimate the dynamic response of the clay layers in the site. The program contains a wide range of options to facilitate site response studies such as computations of time-histories of acceleration, velocity, displacement, transfer functions, Fourier spectra, duration, Husid plot, response spectra and spectral ratios.

3.1.1. Input control motion
The control motion to perform the ground response analysis was the Denali earthquake, in Alaska USA. Magnitude 7.9 recorded at the UA station K2-06 in November 3rd, 2002, having a focal distance of 270 km. This motion was recommended by Geomatrix (2006) to perform the ground response

analysis in the region. The peak ground acceleration (PGA) was scaled to 0.098 g corresponding an earthquake with return period of 500 years, according to the Probability Seismic Hazard Analysis (PSHA) for the area done by Geomatrix (2006). For the simulations the recorded component 360 with duration of about 120 sec determined by means of 5-95 % total energy on Husid plot was used. The response spectrum for this motion is shown in Fig. 3.1.

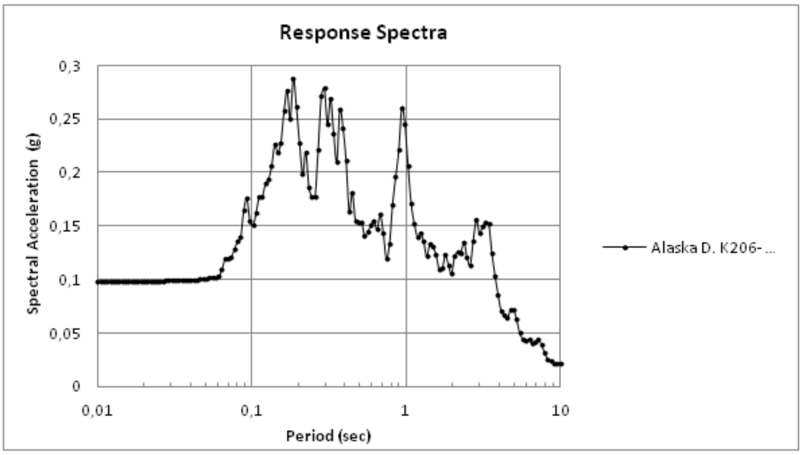

Figure 3.1. Response spectrum for Denali motion (damping ratio ξ = 5%)

3.1.2. Soil profile models

To perform the sensitivity analyses, 2 soil models were established, the 100m soil profile thickness composed by 13 clay layers and the 200m soil profile thickness with 17 clay layers. The change in soil stiffness G and damping ratio ξ with respect to shear strain were obtained by means of resonant column tests until 10^{-1} γ (%), beyond this, cyclic DSS tests were run to estimate the G/G_{max}-γ (%) and ξ-γ (%) curves (Fugro, 2009b).

3.1.3. Stiffness at the base: Shear wave velocity (Vs) of half-space

To estimate the effect of stiffness at the base of the clay sediments, which is related with the propagation of shear waves in elastic media, 6 shear wave velocities (Vs) were used at the half-space for simulations using the 100m soil profile thickness: 300, 433, 500, 600, 750 and 1000m/s; and 5 shear wave velocities were used for the simulations with the 200m soil profile thickness: 433, 500, 600, 750 and 1000m/s. The base case initial shear wave velocities of respectively 300m/s and 433 m/s for the 100m and 200m deep profiles are based on the estimated geotechnical soil profile.

3.1.4. Dynamic response

In this study, the maximum shear strain was considered to be the main output because of its significance for the stability of slopes. The maximum shear strain is calculated at the middle of each layer. These simulations show an increase in the soil response as the shear wave velocity at the half-space increases having the largest response at the middle of layer 2 in all simulations, in addition the soil profile of 200m shows larger response than the 100m, see Fig. 3.2.

3.2 Ample

Non-linear dynamic response simulations were done using a modified version of AMPLE (AMPLE2), a computer program for nonlinear one-dimensional site response analysis (Nadim, 1985). AMPLE2 solves the one dimensional shear wave propagation in horizontally or sloping layered soil profile using infinite slope model. The soil profile is modeled as a nonlinear shear beam and the resulting nonlinear wave propagation problem is solved in the time domain by the explicit central difference method. AMPLE2 provides several choices for the constitutive law for soils, ranging from the linear elastic to the simple strain softening model. In this analysis the hyperbolic, failure-seeking model was used.

3.2.1. Input control motion

The control motion to perform the ground response analysis with AMPLE is called Imperial Valley-06 in California USA, magnitude 6.5 recorded at the Chihuahua, Mexico station in October 15th, 1979. The PGA was scaled to 0.098 g corresponding to an earthquake with return period T equal to 500 years, according to the Probability Seismic Hazard Analysis (PSHA) for the region prepared by Geomatrix (2006). The recorded component named 282 had duration of about 20 sec determined by means of 5-95 % total energy on Husid plot. The response spectrum for this motion is shown in Fig. 3.3.

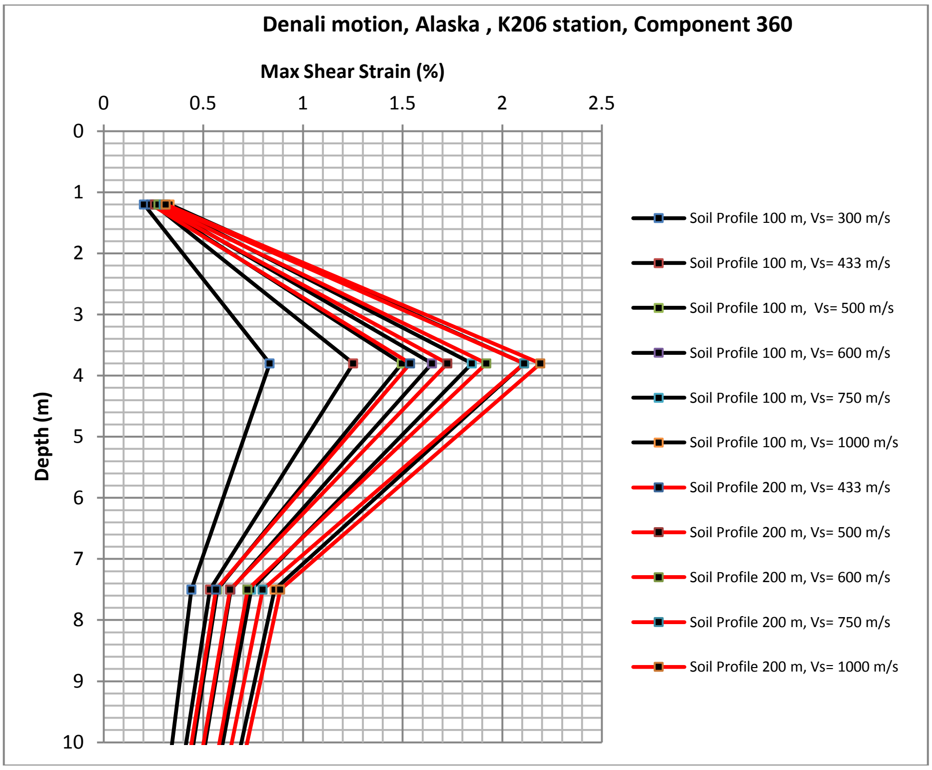

Figure 3.2. Maximum earthquake induced shear strains with SHAKE(N) simulations

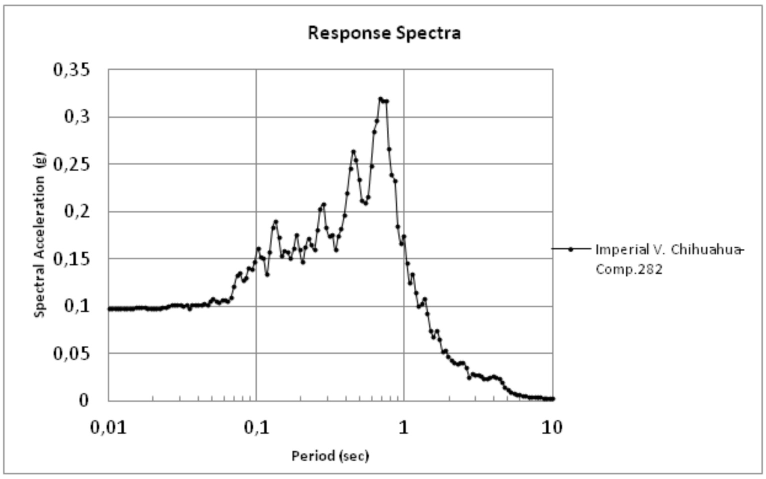

Figure 3.3. Response spectrum for Imperial Valley-06 motion (damping ratio ξ = 5%)

3.2.2. Soil profile models

The same soil profiles were used as with SHAKE(N) but with a reduction in the thickness of the top clay layers to improve the performance of the computer program, resulting 22 clay layers for the 100m soil profile and 26 clay layers for the 200m soil profile.

To study the effects of the stiffness at the base on the dynamic response, the same shear wave velocities as in SHAKE(N) were used for this sensitivity analysis.

3.2.3. Slope angles

Taking into account the relationship between earthquake-induced shear strains in the soil mass and the stability of soil slopes, it is possible to evaluate the performance of clay slopes under seismic loading. To evaluate the influence of the slope angle in the response of the submarine slopes, 4 slope angles were used in the simulations: 0, 5, 10 and 15 degrees.

3.2.4. Dynamic response

The computed maximum shear strain in each layer was targeted as the main outcome given the close relationship with slope stability. These simulations show an increase in the soil response as the shear wave velocity at the half-space increases, having the largest response at the middle of layer 3 in all simulations. In addition, contrary to SHAKE(N), the soil profile of 100m depth shows larger response than the 200m soil profile depth. Moreover it can be seen throughout these simulations the important role of the slope angle in the dynamic response of the soil profile, the larger the slope angle the larger the response, see Fig. 3.4.

It should be noted, however, that the shear strains computed with AMPLE2 for a sloping soil profile are predominantly accumulated shear strains in the downslope direction, whereas the shear strains computed with SHAKE(N) are cyclic shear strains.

The color code in the Fig.3.4 is as follows: black for slope angles equal to 0 degrees, green for 5 degrees, yellow 10 degrees and red 15 degrees. The continuous lines correspond to soil profiles of 200m thickness and the dot lines correspond to soil profiles of 100m thickness.

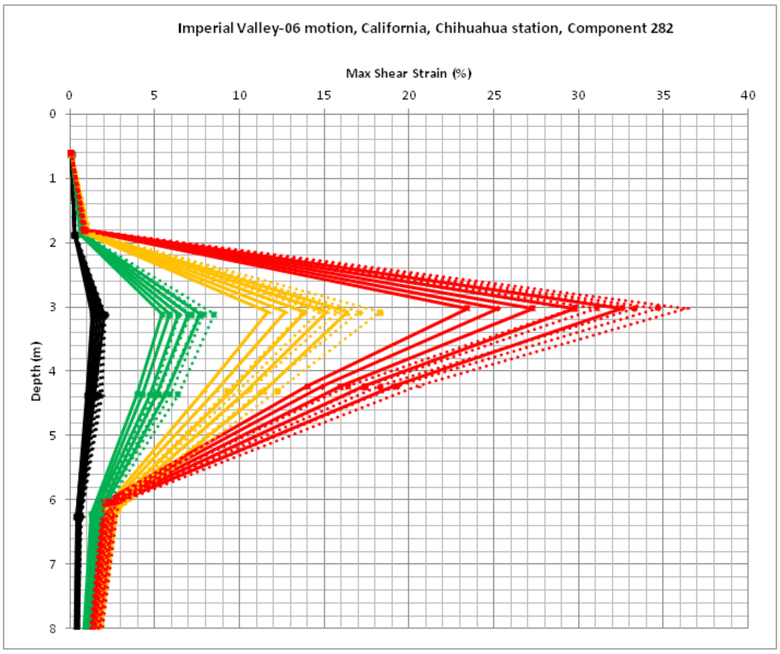

Figure 3.4. Maximum earthquake induced shear strains with AMPLE2 simulations

4. SENSITIVITY ANALYSES

The presentation of the results from the simulations using the computer program SHAKE(N) was set up in two main configuration. The first one was the soil profile thickness as changing variable with different shear wave velocities at the half-space; the second one was the shear wave velocity at half-space as changing variable for each soil profile. The maximum shear strain in the middle of layer number 2 at 3.75 m depth, which had the largest response in the simulations, was the main output.

The set up for the presentation of the results with AMPLE2 was basically the same as SHAKE(N), but with the slope angle as an additional changing variable. The main output was the maximum shear strain in the middle of layer 3 at 3.125 m for the horizontal layers.

4.1. Results of Sensitivity Analyses with Shake(N)

4.1.1. Changing variable: soil profile thickness

Based on the simulations, a larger response in the 200m soil profile than the 100m soil profile was observed. However as the value of the shear wave velocity increases the response in the 100m soil profile gets more intense than the 200m soil profile, see Fig. 4.1.

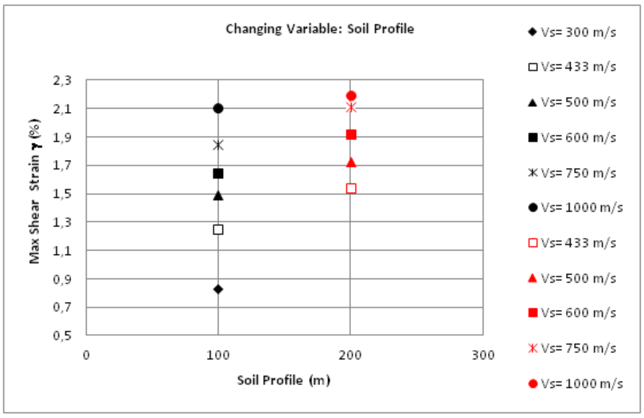

Figure 4.1. Sensitivity analysis based on soil profile thickness with SHAKE(N)

4.1.2. Changing variable: Vs at half-space

The simulations with SHAKE(N) show an increment of the normalized shear strain γ' with respect to the normalized shear wave velocity Vs', it shows that the response in the clay sediments with 100m thickness is more sensitive to the change in the shear wave velocities at the half-space than the 200m soil thickness. As an example, when the shear wave velocity increases 2 times the initial shear wave velocity the response in the 200m soil profile is 40% more than the initial one, and for the 100m soil profile there is an increment of 100%, see Fig. 4.2.

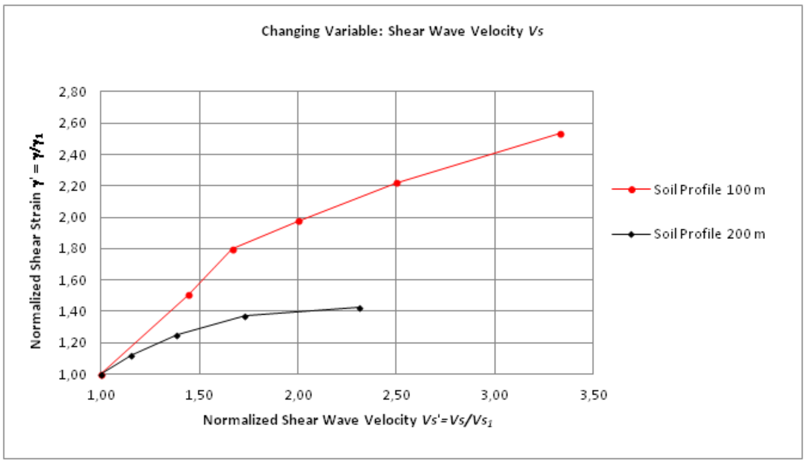

Figure 4.2. Sensitivity analysis based on shear wave velocity in half-space with SHAKE(N)

The normalized shear strain γ' comes from the ratio γ/γ_1 where γ_1 is the induced shear strain using the initial velocity Vs_1 at half-space in the simulations, therefore it is used as reference strain. The reference strain is γ_1= 0.83 (%) for the 100m soil profile and γ_1= 1.54 (%) for the 200m soil profile. Similarly the normalized shear wave velocity Vs' comes from the ratio Vs/Vs_1 where Vs_1 is the initial shear wave velocity used in the half-space for the simulations. The reference velocities are Vs_1 = 300m/s for the 100m soil profile and 433m/s for the 200m soil profile.

4.2. Results of Sensitivity Analyses with Ample2

4.2.1. Changing variable: soil profile thickness

Contrary to SHAKE(N) simulations, in general, a larger response for the 100m soil profile than for the 200m soil profile was predicted by AMPLE2. One of the reasons for this relates to the change in control motion since the soil profiles are the same in both simulations. The spread of points indicates the sensitivity of the soil response with respect to the stiffness at the base. However, it is not easy to judge which soil profile is more sensitive to the stiffness at the base because the spread of data points looks similar, see Fig. 4.3.

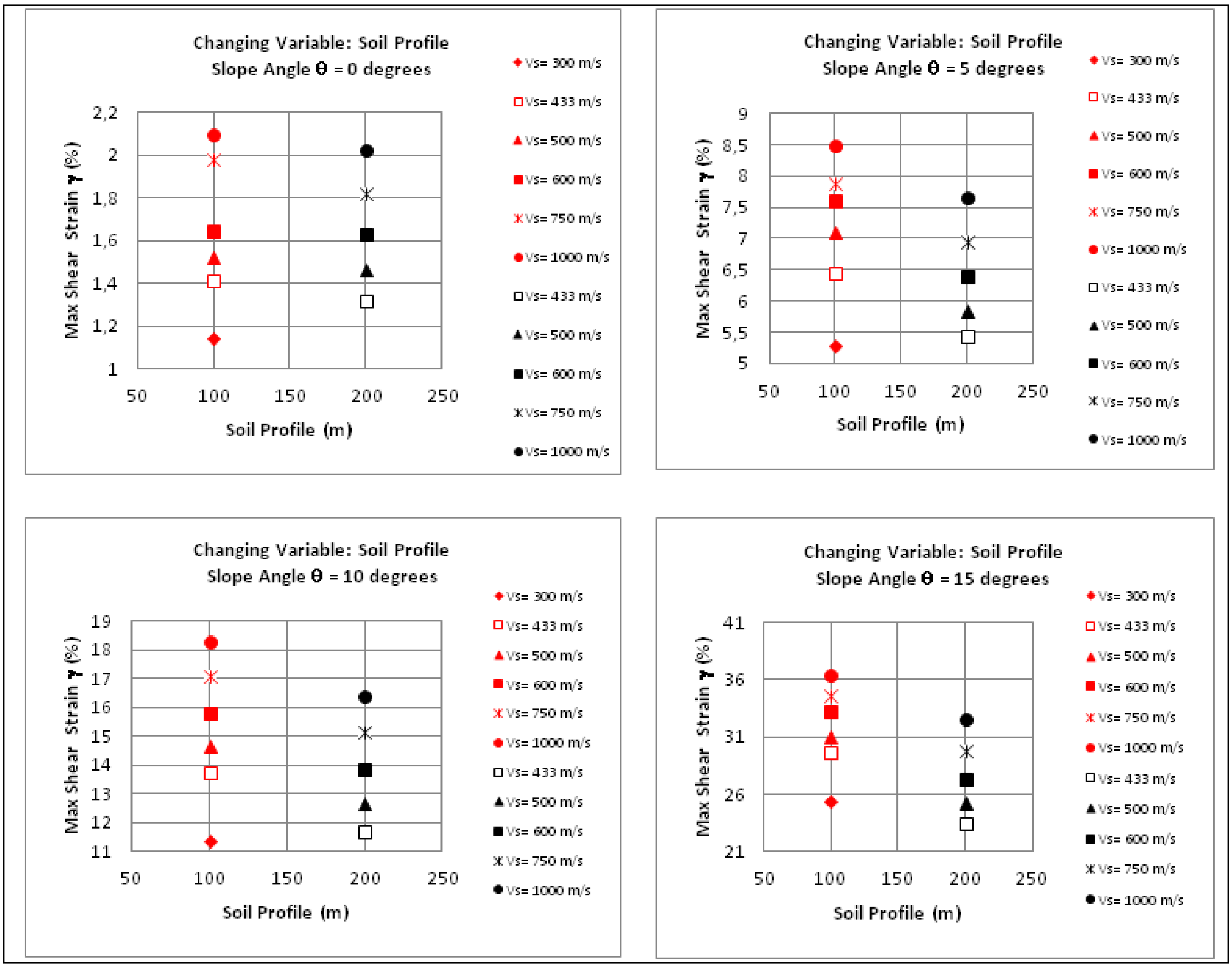

Figure 4.3. Sensitivity analysis based on soil profile thickness with AMPLE2

4.2.2. Changing variable: Vs at half-space

The simulations with AMPLE2 show also an increase in the normalized shear strain γ' with respect to the normalized shear wave velocity Vs'. However, the sensitivity of both soil profiles is very similar. In general the response of both soil profiles has an increment of 40 % when the shear wave velocity is 2 times the initial one.

It also can be seen that the lower the slope angle the larger the sensitivity in both cases. Even though the curves are similar for all the slope angles it can be seen that the sensitivity is slightly larger, for the 200m than the 100m with slope angles of 0 degrees and 15 degrees, and the opposite effect is observed for the slope angles of 5 and 10 degrees, see Fig. 4.4.

Again, it should be noted, that the shear strains computed with AMPLE2 for a sloping soil profile are predominantly accumulated shear strains in the downslope direction.

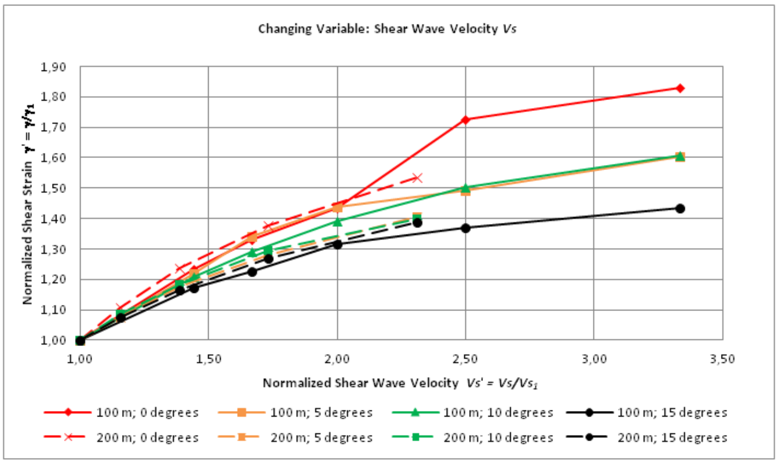

Figure 4.4. Sensitivity analysis based on shear wave velocity in half-space with AMPLE2

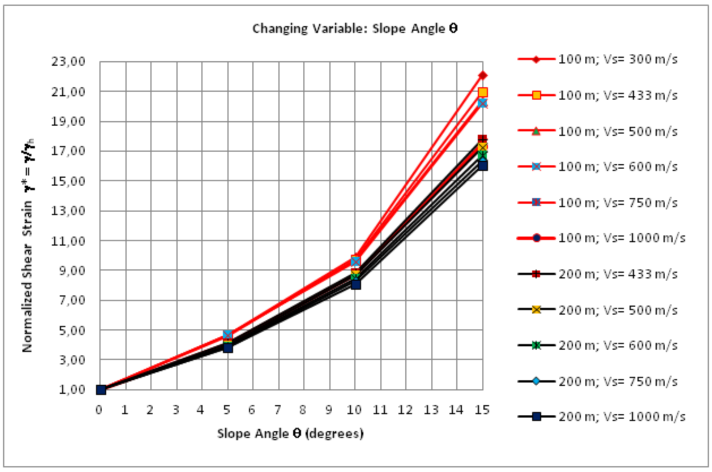

Figure 4.5. Sensitivity analysis based on slope angle with AMPLE2

The normalized shear strain γ^* in Fig. 4.5 comes from the ratio $\gamma^* = \gamma/\gamma_h$ where γ_h correspond to the induced shear strain with horizontal soil layers, slope angle $\theta = 0$ degrees.

5. CONCLUSIONS

This paper explores the influence in the dynamic response of clay sediments with respect to the thickness of soil media, the stiffness at the base of the sediments and the slope angle of submarine slopes. To quantify the effect of this variables in the response of the sediments, 2 computer programs were used SHAKE(N) and AMPLE2 with the following main observations for each software:
SHAKE(N): The 100m soil profile shows more sensitivity during the increase in stiffness at the base compare to the 200m soil profile, although the 200m soil profile exhibit larger shear strain values. As an example, when the shear wave velocity increases 100 % the initial velocity at the half-space, the shear strain increases 40 % for the 200m soil profile and 100 % for the 100m soil profile.
AMPLE2: Based on the simulations with AMPLE2 the sensitivity of both soil profiles with respect to the stiffness at the base show to be similar, although the 100m soil profile shows larger shear strains, both soil profiles exhibit and increment of 40% when the shear wave velocity at the half-space increases 100 %. It also can be seen that the lower the slope angle the larger the sensitivity in both soil profiles.

With respect to the slope angles as changing variable, in general, it can be seen the high impact that the slope angles have on the soil response, for example from 0 degrees to 5 degrees the maximum shear strain is about 4 times larger than the horizontal condition, with 10 degrees about 9 times, and with 15 degrees about 19 times larger than the horizontal condition. These results are not surprising because the shear strains computed with AMPLE2 for a sloping soil profile are predominantly accumulated shear strains in the downslope direction. The steeper slopes have a lower static safety factor and less resistance to inertial forces. Therefore they experience larger earthquake-induced shear strains through the mechanism described by Newmark (1965). Moreover these simulations show more sensitivity with 100m soil thickness with respect to the slope angle than the 200m soil thickness.
From these simulations one may conclude that the 100m soil profile is more sensitive to the stiffness of the bottom and steepness of the slope than the 200m soil profile. Therefore one may infer that the shorter the soil thickness the more sensitive the dynamic response of the soil mass relative to the stiffness at the base, and also relative to the slope angle and vice versa.

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