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On the effects of an unknown depth-to-bedrock in seismic site response analyses for deep-water sites

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ABSTRACT: Seismic Site Response Analysis (SSRA) plays a key role in defining design earthquake motions at the ground surface or at the structure foundation level. Standard practice consists in (1) performing a Probabilistic Seismic Hazard Analysis (PSHA) to define the ground motion at the seismic bedrock, and (2) quantifying the effects of shallow sediments on the ground motion by means of a SSRA. Although such an approach is well rooted in engineering practice, it requires the knowledge of the seismic bedrock characteristics as well as the sediment cover properties, which represent a challenge for deep-waters sites. Unlike onshore sites, where one can often rely on a detailed subsurface profile, offshore sites often face limitations due to depth-limited investigations, leading to difficulties in accurately modelling the seismic wave propagation. Whilst stochastic analyses can partially overcome these issues by introducing modelling uncertainties in the input parameters, the need of time-domain analyses to capture the soil non-linear behaviour for large shear strains (>1%) may prevent the use of such methods for offshore sites.
Motivated by the challenges experienced in industrial projects, the main aim of this paper is to contribute to the development of best practices to be applied when performing SSRA for offshore structures. By performing 1D total-stress non-linear SSRA for a real case-study, the paper seeks to understand the influence of bedrock modelling on SSRA results for deep-waters sites in earthquake-prone areas.

Keywords: Seismic Site Response Analysis (SSRA); bedrock; offshore; wellhead platform.

1 INTRODUCTION

The low energy depositional environment of offshore sites favours the formation of thick sediment deposits of varying degree of consistency. Softer sediments are usually found close to the seafloor while more competent materials lay tens or even hundreds of meters deeper. Seismic hazard assessments aimed at defining design actions at such sites should therefore account for: (1) the behaviour of soft soils, and (2) the modification of earthquake motion through these rather thick deposits.

Common practice consists in performing a Probabilistic Seismic Hazard Analysis (PSHA) to define the ground motion at the seismic reference conditions, ideally taken in correspondence of bedrock formations (i.e., site class A/B, V_S > 750 m/s, in compliance with ISO 19901-2), and quantifying the effects of shallow sediments on the ground motion by means of a non-linear Seismic Site Response Analysis (SSRA).

Compared to onshore sites, the application of the standard approach for deep-water sites imposes additional difficulties. Unlike onshore sites, where one can often rely on a detailed subsurface profile based on extensive drilling, geophysical surveys and publicly available information, offshore geotechnical surveys are usually characterized by poor-quality and depth-limited investigations. A poor characterization of the shallow sediments negatively affects the soundness of SSRAs, which is aggravated by the unfeasibility of performing additional seabed exploration campaigns. Moreover, and perhaps more critically, insufficient data regarding the properties and depth of the seismic bedrock significantly increases the uncertainty in the estimates of response spectra at the mudline.

The objective of this study is to examine the effects, in terms of mudline seismic design response spectra, of different valid assumptions regarding the reference soil conditions (i.e., seismic bedrock) for a deep-water site in offshore Myanmar. The site is a typical example of a deep sediment offshore deposit that is chosen for the construction of a wellhead platform. PSHAs were performed assuming three different reference soil conditions, represented by the time-averaged shear wave velocity of the upper 30 m ($Vs_{,30}$). Compatible earthquake time history records were then selected to be used as input for subsequent one-dimensional, non-linear, time-domain SSRAs. For each reference soil condition, different numerical models were tested by changing the overall height of the soil column (H), from 90 to 300 m.

2 CASE STUDY

2.1 Site conditions

The site under study is located in the gulf of Moattama in offshore Myanmar. The water depth at the site is 133 m approximately. Stratigraphy and soil properties were derived based on in-situ and laboratory testing data. The former dataset includes CPTu, and suspension PS logging measurements that were taken along a 150 m long borehole. Additional field data from vane shear testing (VST) was also available for the upper 15 m. The dataset of laboratory testing is rather broad, encompassing index test results, triaxial and simple shear testing, as well as resonant column and cyclic triaxial tests.

The uppermost 50 m are comprised by 20 m of soft to stiff dark clays underlaid by 30 m of coarse-grained materials with varying degree of density and fine contents. The coarse-grained soils between 20 m and 40 m are loose sands, while those found from 40 m to 50 m are denser and coarser. At greater depths, medium dense sand / silty sand layers and soft to stiff clay layers alternate until 80 m depth, where a thick firm to stiff clay is found. At 104 m depth, a 3 m thick medium to dense sand layer briefly interrupts the latter clayey material, which extends down to a depth of 150 m. Field data is not available below this level, which means that the depth and properties of the seismic bedrock (i.e., V_S > 750 m/s) are unknown.

2.2 Seismic hazard

2.2.1 Probabilistic Seismic Hazard Analysis

The study area is in a high seismicity region, associated with the interaction of the main Eurasian, Indian and Sunda Plates, with the Burma Microplate trapped between them. One particularly important issue in that area is the Sagaing Fault, a major active fault, which forms the eastern border of the Burma Microplate.

In accordance with the seismic design requirements provided by ISO 19901-2, considering both the seismicity of the area and the exposure level of the facility to be realized at the site, seismic hazard was assessed using a conventional probabilistic analysis (Cornell, 1968). Hazard calculations were performed using the OpenQuake Engine software (Pagani et al., 2014), which is an open-source seismic hazard and risk modelling tool. Results of the analysis were outlined in terms of 5% damped horizontal Uniform Hazard Spectra (UHS) for the Abnormal Level Earthquake (ALE) and Extreme Level Earthquake (ELE) scenarios. Following the detailed seismic action procedure by ISO 19901-2 the ALE and ELE return periods were respectively determined as 500 and 150 years, considering an exposure level L3 and a seismic reserve capacity factor Cr=2.0, as defined for the structure.

Given the high uncertainty in the characterization of the reference soil condition at the site, PSHA was performed for three values of $Vs_{,30}$, namely 350, 550 and 750 m/s, accounted in the site amplification coefficients of the GMPEs (Ground Motion Prediction Equations) adopted for the analysis (i.e., Chiou and Youngs, 2014, Abrahamson et al., 2014, Campbell and Bozorgnia, 2014, for shallow crustal regime). The first and second values (i.e., 350 and 550 m/s) are considered consistent with the subsoil conditions that are potentially found at the bottom of the 150 m soil column, while the latter value (i.e., 750 m/s) is taken as an upper limit value that considers the presence of very dense hard soil / rocky conditions. Figure 1, shows the UHS computed for the three different soil conditions. As lower values of $Vs_{,30}$ are considered, an amplification of the spectral acceleration can be observed. Focusing on the UHS computed for $Vs_{,30}$ equal to 350 m/s, the effects of soil non-linearity appear evident (e.g., shift of the spectral peaks towards longer periods). This can be explained considering the fact that the GMPEs selected for the analyses include a non-linear component of site amplification.

2.2.2 Earthquake time history records

Based on the outcomes of the PSHA, compatible earthquake time history records were selected to be used as input for subsequent SSRA.

Suitable sets of seven earthquake strong motion time histories were identified to represent each return period and $V_{S.base}$ scenario in terms of spectral compatibility, site classification, magnitude and distance ranges identified through seismic hazard disaggregation. Selected records were spectrally matched to the target UHS. All the selected records belong to a subset of the NGA-West2 database (Ancheta et al., 2013). Both the selection and matching procedures were performed using the software Select&Match, developed at Politecnico di Milano (Manfredi et al., 2022).

The selected sets of records show acceptable spectral compatibility. In the range of the structure's dominant period T_{dom} (i.e., 0.7 – 3.0 s) the average of the seven matched earthquake records does not exceed ±10 % of the target spectrum. Spectral matching was limited to have less modified accelerations, by considering records with original spectra as far as possible close to the target one and by defining acceptable upper and lower tolerances for the spectral variability of each matched signal. Moreover, records were further screened to avoid the need for strong baseline corrections. Figure 1 compares the UHS and mean (5% damped) acceleration response spectra of the selected records, for each return period and reference soil condition.

3 NUMERICAL MODELLING

The SSRAs in this study consisted in one-dimensional, non-linear, time-domain, ground response analyses performed with the software Deepsoil (v7.0) (Hashash, 2024). The analyses aimed to capture the effect of different valid assumptions regarding the reference soil conditions found at the base of the soil column, as will be later presented.

The thickness of the soil layers comprising the numerical models ensured the transmission of mechanical waves up to 30 Hz. Soil non-linearity was modelled by means of the general quadratic/hyperbolic model proposed by Groholski et al. (2016). The model was calibrated to match the reference shear modulus degradation (G/G_{max}) and damping ratio curves ($D_{(\%)}$), while respecting the target shear resistance. A total of eight reference G/G_{max} and $D_{(\%)}$ curves were derived from resonant column tests and assigned to the respective soil layers distinguishing by soil type (i.e., cohesion-less or cohesive) and depth.

The numerical analyses performed with Deepsoil are summarised in Table 1 and Figure 2. Table 1 reports the combinations considered between reference soil conditions and height of the 1D soil models (H), while Figure 2 illustrates the extent of the modelled soil columns and the measured and interpreted shear wave velocity profile considered. For models with H>150 m the shear wave velocity profile was extended by means of a power-law analytical expression akin to those employed by Régnier et al. (2016) and Shi and Asimaki (2018). The input motions compatible with the UHS derived for $V_{S,30}$=350 m/s were not used for H>150 m, as this implies unrealistic impedance contrasts, lower than the unity.

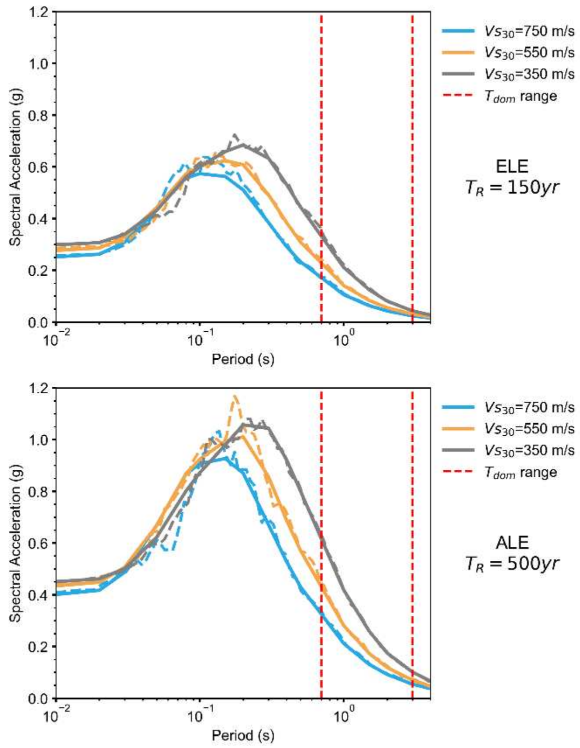

Figure 1 – Solid lines: uniform hazard spectra (UHS) obtained from the PSHA at three reference $V_{S,base}$. Dashed lines: average (5% damped) response spectra of suites of 7 records per reference soil condition.

Table 1. Combinations of reference of $Vs_{.base}$ and H considered for the SSRAs.

Reference Soil conditions $V_{S.base}$ (m/s)	Model height H (m)
350	90 and 150
550	150, 200 and 300
750	150, 200 and 300

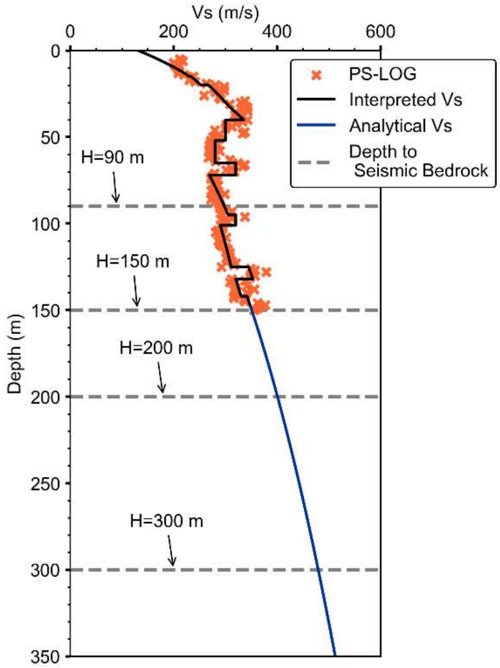

Figure 2 – Measured and interpreted shear wave velocity distribution.

4 RESULTS AND DISCUSSION

4.1 Response spectra at mudline

It is worth to note that, for the sake of brevity, the discussion herein presented is limited to the period range of interest. Figure 3 shows the outcomes of the SSRAs performed at the site in terms of 5% damped mean response spectra at the mudline level ($\overline{Sa}$) for each model presented in Table 1, considering both ELE and ALE scenarios. Figure 3 reports shaded areas formed by the upper and lower estimates of $\overline{Sa}$ for each reference soil condition.

The input motions selected for $V_{S.base}$=350 m/s yielded the largest spectral ordinates within the period range of interest (i.e., 0.7 – 3.0 s). For both ALE and ELE events. $\overline{Sa}$ for $V_{S.base}$=350 m/s are 0.09 g to 0.10 g larger than those obtained for the other two values of $V_{S.base}$, approximately. $\overline{Sa}$ for $V_{S.base}$=550 m/s and 750 m/s are separated by a smaller margin.

To measure the sensitivity of the estimated $\overline{Sa}$ with respect to $V_{S.base}$ and H, we employed a simple metric referred to as Δ_{max}, which is expressed in Equation 1. $\overline{Sa}^{UB}_{(T,Vs30,H)}$ and $\overline{Sa}^{LB}_{(T,Vs30,H)}$ represent the upper and lower estimates of $\overline{Sa}$ for a given period, reference soil conditions and model thickness. This approach is similar to the one-at-a-time measures of sensitivity such those represented by the well-known tornado diagrams. Results are reported in Table 2 and Table 3. Note that Δ_{max} is not strictly a sensitivity index; rather, it serves as a convenient proxy.

$$\Delta_{max} = max\left(\overline{Sa}^{UB}_{(T,Vs30,H)} - \overline{Sa}^{LB}_{(T,Vs30,H)}\right) \quad (1)$$

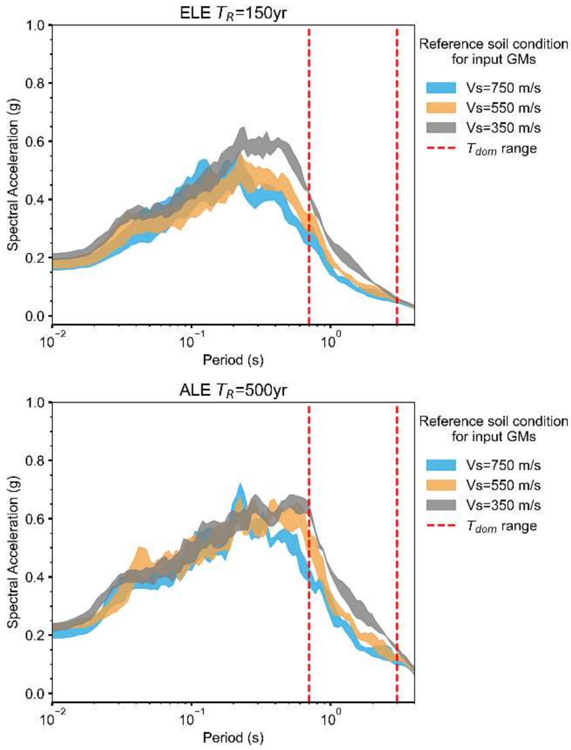

Figure 3 – Upper and lower estimates of mean response spectra for each type of reference soil condition.

In general, $V_{S.base}$ induced the largest variations of $\overline{Sa}$ for structural periods within 0.7 – 3.0 s. This was even more pronounced for the analysis that considered H = 150 m, for which Δ_{max} attained values of approximately 0.086 g and 0.106 g, for ALE and ELE respectively (see Table 3). In contrast, for each reference site conditions, the maximum variations given by the different values of H are no larger than 0.043 g and 0.064 g for ALE and ELE events respectively (see Table 2).

Table 2. Maximum ranges of variation of $\overline{Sa}$ for fixed values of $V_{S.base}$.

$V_{S.base}$ (m/s)	Δ_{max} (g)	
	ELE	**ALE**
350	0.043	0.064
550	0.029	0.055
750	0.028	0.052

Table 3. Maximum range of variation of $\overline{Sa}$ for fixed values of H.

H (m)	Δ_{max} (g)	
	ELE	**ALE**

150	0.086	0.106
200	0.038	0.056
300	0.036	0.043

4.2 Comparison with ISO 19901-2

Figure 4 compares the results obtained from the SSRAs against the design response spectra proposed by ISO 19901-2, which is the main reference for offshore structures within the context of petroleum and natural gas industries. Concerning the mapped spectral acceleration at 1 s reported by the code, the region at study is located at the sharp boundary between the lower and the upper values of Seismic Zone 3. Given this, Figure 4 reports both the upper and lower ISO response spectra.

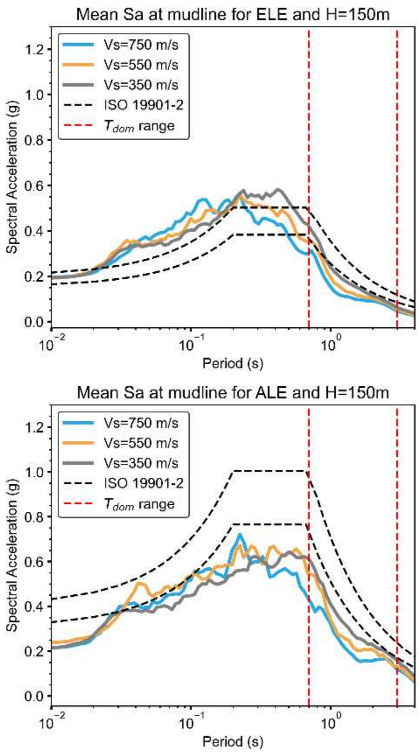

Figure 4 – Comparison between ISO 19901-2 design spectra and mean acceleration response spectra at mudline level obtained from the SSRAs, using input motions compatible with three values for $V_{S,base}$ and H=150 m.

For the range of periods of interest (i.e., 0.07 – 3.0 s) SSRAs produced comparable or lower response spectra ordinates for all three values of $V_{S,base}$, for both ELE and ALE scenarios. However, for shorter periods (i.e, T<0.7 s), different results were obtained for ELE and ALE scenarios. For the former, the estimated mean response spectra at the surface are higher than the design spectra of ISO, while the PGA values are in agreement with the code. Conversely, in case of ALE, ISO design spectra are considerably higher than the estimated response at the surface. We can conclude that the site-specific assessment is therefore advantageous in this case, since any conservatism is introduced. It is worth recalling that, according to ISO 19901-2, a simplified seismic action procedure based on mapped spectral accelerations, could be, in most cases, more conservative than a detailed assessment, being the former based on regional studies. Moreover, besides the fact that the site under study is in a high seismicity area, the employment of the simplified seismic action procedure should be discouraged given the uncertainty introduced by the sharp transition of mapped spectral acceleration at the site of interest.

5 CONCLUDING REMARKS

This paper presented some insights for an informed selection of the reference $V_{S,base}$ at offshore deep-water sites with unknown depth-to-bedrock. The analyses performed aimed at investigating the influence of the reference soil conditions, represented by the $Vs_{.base}$ and the height of the investigated soil column (H). Results presented suggest that the choice of the reference $Vs_{.base}$ is associated to larger variations of the spectral acceleration at mudline level, particularly for intermediate-to-long structural periods, which can be identified as the range of interest for the wellhead platform to be constructed at the investigated site. In lights of the results, adopting $Vs_{.base}$=550 m/s represents a reasonable compromise for engineering practices. Softer reference soil conditions could lead to biased results. In such a case, the site amplification factor of the GMPEs becomes more predominant, which results in input ground motions with stronger spectral ordinates at long periods. This could be an acceptable situation for SSRAs performed for relatively short soil columns, whereby soil non-linearity is expected even at reference conditions. However, for the soil profile investigated in this study, any significant mobilization of soil-nonlinearity below 150 m depth is highly unlikely.

Despite the different assumptions made in terms of reference soil condition, SSRAs consistently produced lower or comparable spectral acceleration with respect to the design response spectra prescribed by ISO 19901-2, meaning that the adopted approach did not introduce any additional conservatism. In light of this, we can conclude that the proposed approach is suitable to define the mudline design response spectra for deep-water sites with insufficient depth-wise site characterization.

It is worth to mention that the findings of this study pertain to a site located in a region of high seismic hazard. Therefore, future studies could aim at testing whether the findings presented in this document are valid for sites located in regions characterized by low-to-moderate seismic hazard. In such a context we can expect a minor influence of the GMPEs site amplification factor, particularly for what concerns the non-linear term. Moreover, the present study can also be refined by examining the effects of an unknown depth-to-bedrock on the site-amplification factors and seismic hazard at the mudline level.

AUTHOR CONTRIBUTION STATEMENT

Ricardo Rodriguez-Plata and **Francesca Ioele**: Conceptualization, Data curation, Formal Analysis, Writing Original draft. **Erika Schiappapietra**: Conceptualization, Methodology. **Pamela Poggi, Fabrizio Panico** and **Domenico Gioffrè**: Conceptualization, Supervision and Review.

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