Non linear site response for marine deep soil sites

Réponse sismique non linéaire de sites marines profondes

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ABSTRACT

This paper presents a case history for evaluation of site response of a typical deepwater site offshore the Nile Delta. The soils comprise a thick sequence of normally consolidated highly plastic clay with a change in lithology and strong increase in stiffness profile occurring at variable depth. The non linear behaviour of the soils is examined with respect to strain and yielding of the soft upper sediments showing that deep soil profiles tend to filter out high frequencies ground motion. The procedure to develop at-grade spectra is based on a multi-linear regression model. The data for the regression are developed by propagating a number of earthquake time histories through the soil model, and computing the resulting spectral acceleration at-grade. Multi linear regression of spectral amplification ratio is a practical approach to evaluate site response for these soil conditions, providing an efficient method to develop at-grade design spectra.

RÉSUMÉ

Cet article présente un cas d'un sol typique d'un site en mer profonde au large du delta du Nile. Le sol inclut une couche épaisse d'argile fortement plastique normalement consolidée avec un changement de la litologie et une augmentation forte de rigidité à profondeur variable. Le comportement non linéaire des sols est examiné en ce qui concerne les déformations et l'écoulement des sédiments supérieurs nous prouvant que les profils de sol profonds tendent à filtrer les hautes fréquences du mouvement sismique. Le procédé pour développer des spectres en surface est basé sur un modèle de régression multilinéaire. Les données pour la régression sont élaborées en propageant un certain nombre de séismes par le modèle de sol, et en calculant l'accélération spectrale en résultant en surface. La méthode de régression multilinéaire pour le rapport spectral d'amplification est une approche pratique pour évaluer la réponse sismique locale pour ces états de sol, en fournissant une méthode efficace pour développer des spectres de réponse en surface.

Keywords : non linear site response, impedance contrast, soil yielding, multi linear regression

1 INTRODUCTION

The modification of seismic waves by unconsolidated material near the Earth's surface is usually referred to as site response. The evaluation of this phenomena is very important as it provides the designer with at-grade response spectra needed for the design of surface structures.

This paper presents an example site response analysis for a deepwater location offshore the Nile Delta. There are a number of aspects requiring special attention for an adequate evaluation of local site response. In many cases the most appropriate depth of vibrating soil column to be considered in the modelling is not clearly identified because there is no evidence of a strong impedance contrast at a fixed depth. Specific field or laboratory data regarding the modulus G/Gmax backbone reduction curves and the dissipative properties at high strain levels as those expected during seismic events are often not available. Deepwater sampling disturbance (Lunne and Andersen 2007) for very soft soils and scarcity of reliable data at surface makes shear wave velocity definition more difficult. Sensitivity analysis and comparison with similar case histories from literature are used to reduce such source of uncertainty.

Despite the variability of site response due to record to record time history variation, at-grade spectra can be obtained by mean of a bilinear regression analysis (Bazzurro and Cornell 2004). This approach allows more accurate estimation of local site response than generic ground motion predicting equations and direct evaluation of the effects caused by different soil column depths on hazard at surface.

2 SITE CONDITIONS

In order to carry out the one dimensional site amplification study the site needs to be characterized in terms of stratigraphy. The depth of the soil column considered to amplify ground motion must be identified. In most cases, this is taken as the depth to a significant change in lithology and stiffness. Furthermore, the geotechnical properties of soil mass density and shear stiffness properties at low and high strains must be established.

For the location in question it appears reasonable to consider the soil profile to be essentially normally consolidated highly plastic clay. The depth of the soil column to be considered maybe thought to be coincident with the increase in soil stiffness which represents the change in lithology associated with the base of an ancient slope movement. The depth to the sliding surface varies over the development area from 200 to 400 m, and this range of values is considered representative for the height of the vibrating soil column. Estimates of soil mass density ρ are based on direct geotechnical sampling and extrapolation with depth of the best estimate profile. Based on laboratory testing and in-situ SCP, the undrained shear strength of the soil was estimated to bwe 2 kPa at the mudline increasing linearly with depth at a rate of 1.5 kPa per meter.

The results from empirical correlations (Hardin and Drenvich 1972; Mayne and Rix 1993) available geotechnical data including seismic piezocone test (SPCPT) and laboratory test such as resonant column and bender elements were used to establish the profile of soil stiffness with depth (V_s). Unfortunately, these data were not sufficient to clearly define a

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V_{s0} profile for the upper 20 m of the profile so reference was made to technical reference reporting results from reconstituted samples, partially disturbed samples (Schulteiss 1985), undisturbed samples and from field tests (e.g. Huerta-Lopez et al. 2005). A value of 50 m/s at-grade was estimated to be adequate with linear variation down to 20 m. Below this level the shear wave velocity is proportional to the square root of the depth (Figure 1). The stiffness profile was established considering that at low strain $G_{max} = \rho \cdot V_{s0}^2$. The non linear modulus reduction curve of Vucetic and Dobry (1991) for cohesive soils with PI 50 was assumed. The influence of mean effective stress (Ishibashi 1992) on modulus decay for such value of PI is considered negligible.

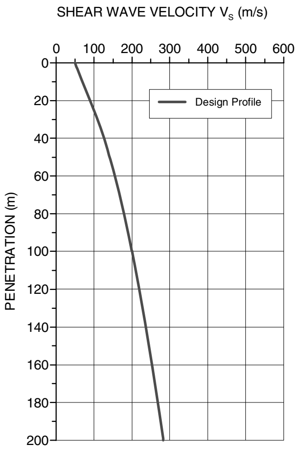

Figure 1. Design shear wave velocity profile.

The potential variation in the depth of the vibrating soil column was considered by enveloping results for 200 and 400 m soil columns.

3 SEISMIC INPUT

The seismic input for the analysis are the hazard curves and uniform hazard spectra (UHS) for ground motion on stiff soil outcrop on stiff soil defined in a probabilistic seismic hazard study. A set of 38 earthquakes time histories were selected to be representative of the seismic ground motion expected at the site. For return periods from 200 to 10000 years the peak ground acceleration (PGA) on a hypothesized stiff soil outcrop ranged between 0.07 g and 0.314 g. The set of time histories is extended to PGA ranging from 0.001 g and 0.6 g to guarantee a well constrained regression of spectral amplification. Note that when using the multi-linear regression method, the individual time histories are not scaled. The important consideration in this case is that the input time histories give complete coverage of the design uniform hazard spectrum.

4 METHODOLOGY FOR EVALUATION OF SITE RESPONSE

Seismic site response for soft marine soil is expected to cause soil strains above those for which an equivalent linear approach is adequate (Ardoino et al. 2008). Therefore the site response analysis is carried out using a non linear approach using the software NERA (Non linear Earthquake Response Analysis) (Bardet and Tobita 2001). The NERA model utilizes a one-dimensional hysteretic soil model which incorporates the concepts developed by Iwan (1976) and Mròz (1976). Each soil layer in the profile is formed of n mechanical elements, having different stiffness k_i and sliding resistance R_i. The sliders have increasing resistance (i.e. $R_1 < R_2 < \dots R_n$). The values of slider resistances and stiffness are calibrated to obtain curves which match an input G/Gmax stiffness degradation curve (Figure 2).

Damping is proportional to work performed during a single loop of the load-unload cycle and is implicitly defined by the shape of the G/Gmax backbone curve. Integration is performed in the time domain based on Newmark central difference formulation.

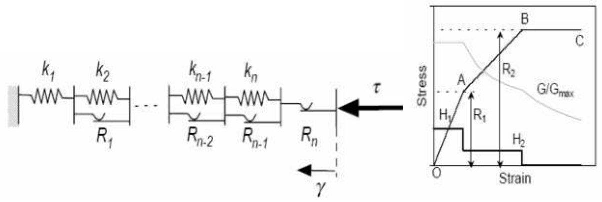

Figure 2. Schematic representation of non linear stress strain model and backbone curve.

5 RESULTS OF SITE RESPONSE ANALYSIS

An initial series of analyses are performed to determine the overall response of the soil column to ground shaking. The individual time histories are scaled to a single value of PGA and are propagated through the soil column. The spectral acceleration at the mudline is computed. The Spectral Amplification Ratio (SAR), defined as the frequency dependent ratio of spectral acceleration at the mudline to input outcrop spectral acceleration applied to the soil column, is evaluated for the range of frequencies of interest. To investigate the nonlinear effects with increasing intensity of ground motion, three levels of PGA are considered, 0.1 g, 0.2 g and 0.35 g. These PGA values cover return periods from 500 to slightly more than 10000 years.

Figure 3 shows spectral amplification ratio versus frequency for 0.1 g PGA. The plots show SAR values computed for the individual time histories, as well as the mean response. The plots show the response for a 400 m high soil column. Results are substantially the same for a 200 m column. The soil profile amplifies ground motion for all frequencies. Amplification is strongest below 1 Hz (as the natural frequency of the soil column is 0.17 Hz), where mean SAR reaches nearly a factor of three. The low frequency amplification reflects increased displacements of the soil column with respect to the original input record. There is little or no amplification in the mid-range, with SAR approximately 1 from 3 to 5 Hz. There is a second peak near 15 Hz for a higher mode and then the SAR returns to 1 for high frequency and PGA.

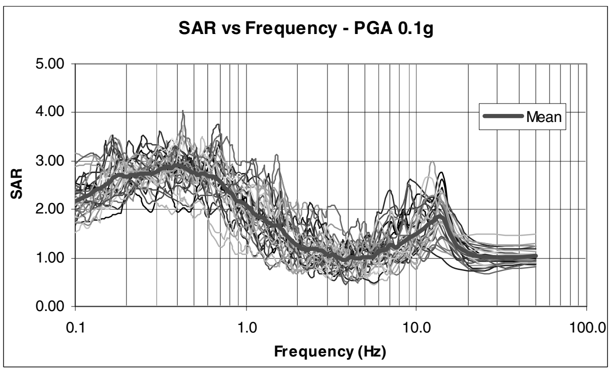

Figure 3. SAR versus frequency- PGA 0.1g, H=400 m.

Increasing the input PGA to 0.2 g lowers the overall amplification. This is to be expected, as soil yielding and degradation of shear stiffness increase with stronger shaking. The form of the mean SAR curve remains unchanged, with amplification of low frequencies and a second peak at 15 Hz.

The general lowering of the curve leads to deamplification of shaking in the mid-frequency range. For 0.35 g PGA the soil column continues to amplify frequencies below 1 Hz, but deamplifies all motions above that frequency. This is interpreted as the physical inability of the soil to transmit the high inertial forces associated with the higher frequencies.

To confirm the interpretation of soil behavior, plots of maximum shear strain γ versus depth for a 400 m column subject to an input PGA of 0.1 g and 0.35 g are compared in Figure 4.

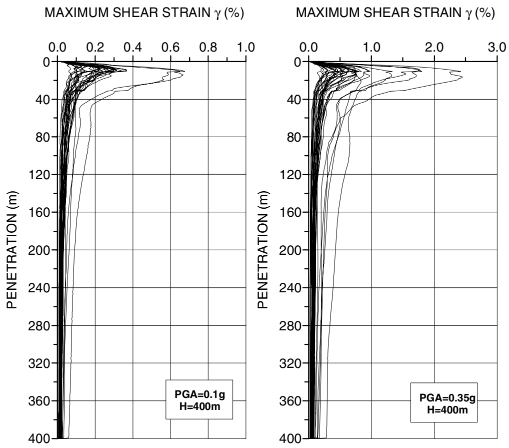

Figure 4. Maximum shear strain profiles for NERA analyses.

A peak in maximum shear strain is found at about 10 m penetration for both cases. For the case PGA 0.1 g this strain concentration and the consequential decay in shear stiffness to about 40% of the elastic suggests that the soil is unable to pass the inertial forces generated by the seismic event. Similar trends are seen for the higher levels of ground shaking as in the case of PGA 0.35 g shown. In this case the degraded shear stiffness is estimated to be 20% of the small strain value. This is interpreted as yielding of the soil at this level.

6 REGRESSION MODEL

Recent work (Bazzurro and Cornell 2004) suggests that SAR follows a lognormal distribution, and that relation between SAR and the input spectral acceleration S_a^B can be expressed as:

$$\ln(SAR) = c_1 + c_2 \cdot \ln(S_a^B(f)) + c_3 \cdot \ln(S_a^B(f))^2 \tag{1}$$

The coefficients c_1, c_2 and c_3 can be found by a least squares quadratic regression. The number of analyses n required to obtain a given accuracy of the estimate of SAR can be established as follows. Recall that ln(SAR) is estimated by regression analysis of (1). The standard deviation of ln(SAR), conditioned on S_a^B, is of the order of 0.2 to 0.35. The number of records needed to keep the standard error of the regression curve within a specified ζ is (Bazzurro et al., 1999):

$$n = \left(\frac{\sigma_{\ln SAR}}{\zeta}\right) \tag{2}$$

Considering ζ of 0.05 and $\sigma_{\ln SAR}$ of about 0.3, a total of 36 analyses are sufficient to obtain an accuracy of 5% on the mean of ln(SAR). Figure 5 shows one example of regression plot for 0.5 Hz. Analogous plots are produced for all the frequencies of interest. For lower frequencies the SAR appears to saturate below a low threshold of input spectral acceleration and is considered constant below this threshold level.

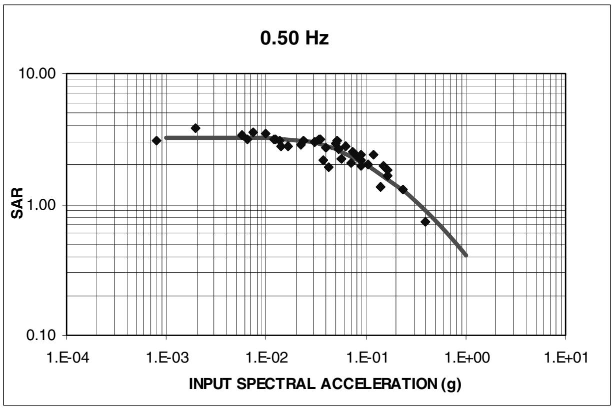

Figure 5. Regression plot 400 m soil column for 0.5 Hz spectral frequency.

The form of the ln(SAR) curves is well matched by the quadratic equation. There was a slight tendency for increasing dispersion for higher levels of ground shaking, but to a first approximation the data are homoscedastic. The values of standard deviation of the regression error range from 0.131 to 0.129 and the average value of the coefficient of multi-linear regression is acceptable.

Hazard curves for spectral acceleration at mudline (at-grade) are computed using (1) considering the mean SAR predicted by the regression model. Hazard curves for 0.5 Hz spectral frequency are shown in Figure 6 for both the 200 and 400 m soil columns. The effects of nonlinear site response are well illustrated in the at-grade hazard curves. For low levels of earthquake input there is amplification of ground motion. As the input spectral acceleration increases the at-grade curves drop below the stiff soil input and ground motion is deamplified. As expected the change between amplification and deamplification takes place at accelerations that increase with decreasing frequencies (0.1 g for PGA, 0.2 g for 5 Hz, and 0.3 g for 0.5 Hz). In the deamplification phase the hazard curves at-grade become nearly vertical, indicating a threshold value for the ground motion hazard. There is little difference in the hazard between the two column heights, although the thicker sediment column leads to marginally higher hazard.

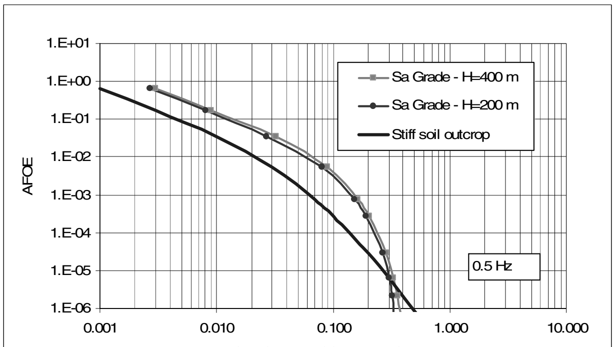

Figure 6. Seismic hazard curve at-grade for 0.5 Hz spectral frequency.

(Note: AFOE is annual frequency of exceedance).

As for the hazard curves, the UHS clearly show the effects of nonlinear response. At low return periods the stiff soil UHS are amplified, while at longer return periods there is a strong deamplification. Frequencies below 1 Hz are amplified in all cases. The particular characteristics of the soil column lead to a flattening of the at-grade UHS, with an extended plateau from 0.6 to 10 Hz for the longer return periods (Figure 7).

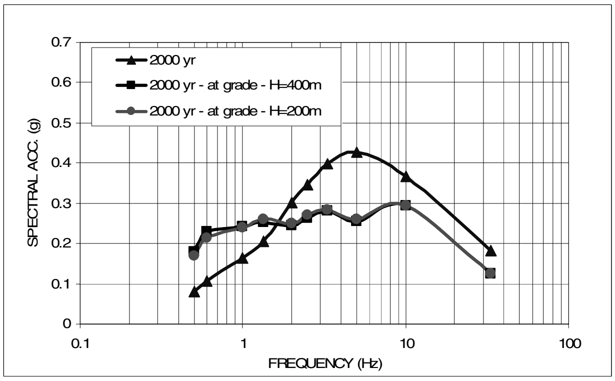

Figure 7. 5% damped UHS at-grade, 2000 year return period

7 CONCLUSIONS

This work presents the results of a nonlinear site response analysis for a deep water field offshore the Nile Delta. The purpose of the study is to determine the effect of the soft sediments present in the area on ground motion and develop a site response model to predict the seismic hazard curves at-grade.

Soil response is generally non linear with deamplification for stronger levels of ground shaking. For ground shaking with return period up to 10000 years amplification can be expected frequencies below 1Hz, whereas for higher frequencies the amplification reduces for increasing shaking intensity. For mild shaking the profile is either neutral or shows moderate amplification for mid range frequencies (from about 1Hz to 15 Hz). As input acceleration increases the profile deamplifies this range. Finally for mild shaking the column produces slight amplification for high frequencies. In this range stronger input motion is deamplified.

Strong deamplification of high frequencies associated to stronger shaking is interpreted as failure or yielding of the soft upper sediments which are not able to transmit the inertial forces. Examination of profiles of maximum shear strain with depth indicates a maximum strain at 10 m penetration, this is considered to be the zone of soil yielding which leads to filtering of high frequency accelerations.

Regression models are developed to predict mean spectral amplification as a function of input spectral acceleration at the base of the soil column. A multi-linear quadratic regression provides a good fit ln(SAR). Residuals of the regression are acceptable, and the average standard deviation of the residuals ($\sigma_{\ln SAR}$) is of the order of 0.18.

The regression model was used to compute at-grade UHS. The effect of the soft soil was to significantly reduce the plateau suction of the UHS, and increase spectral acceleration at low frequencies. This response is typical of deep normally consolidated locations in the marine environment.

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