Seismic site characterization and ground response analysis for an offshore site

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\textbf{ABSTRACT}

Earthquake poses significant threat to offshore and marine structure. Many earthquakes in the past have shown that local site conditions significantly affect the intensity of earthquake and so to the damages caused by those earthquakes. This study involves the seismic site characterization and ground response analysis of an offshore site in Western Yemen, based on the extensive field test results and the results of a large number of laboratory tests on undisturbed samples. Large number of seismic cone penetration tests (SCPT) were conducted as field test analysis for site characterization and evaluation of low strain soil stiffness. Dynamic properties such as shear modulus and damping ratio of soil samples corresponding to very low to high strain level were established based on laboratory tests. Peak ground acceleration (PGA) was evaluated using the generated synthetic ground motion. This study also gives a site specific design response spectrum based on Eurocode, corresponding to 475 and 2500 year return period.

\textbf{Keywords:} seismic site characterization, offshore, ground response, PGA, response spectra.

\textbf{1 INTRODUCTION}

Offshore and marine structures poses a great threat from earthquakes. These earthquake damages to marine and offshore structures have been well documented by many researchers (Wyllie et al. 1986; Iai and Kameoka, 1993; Hall 1995; Boulanger et al. 2000 etc.). As many of these structures are constructed for petroleum extraction, damage to these structures will result in a substantial economic loss. Offshore sites are generally consists of very soft to soft marine sediments to a considerable depth (even up to 50-60m). The presence of such soft sediments significantly alters the ground motion characteristics of earthquake shaking. So for the design of any offshore structure foundation system, the dynamic characterization of marine soil is essential. The present study gives a detail seismic site characterization and site response studies for an offshore site in the Western side of Yemen (Middle East).

The study area is located on the Western side of Yemen within the area of Red Sea. Figure 1 shows the geographic location of the study area along with the location of boreholes in an area of 4km × 8km within the red sea. Detailed site characterization was carried out based on the average shear wave velocity for top 30m depth ($V_{30}$), obtained using seismic cone penetration test (SCPT) data by a geotechnical company. The synthetic ground motion was generated as per the methodology suggested by Boore (2003) using regional seismo-tectonic characteristics. Dynamic soil properties such as shear modulus and damping ratio at different strain levels, using the undisturbed soil samples, were obtained from bender element tests and cyclic triaxial tests. Based on the bender element test data and cyclic triaxial test data, appropriate modulus reduction and damping curves were selected for the ground response analysis. Equivalent linear ground response analysis was done using SHAKE 2000 (Ordonez 2003), to evaluate local site response. Design response spectra at ground surface were also evaluated for the study area using Eurocode 8. Peak ground acceleration (PGA) at ground surface, predominant frequency of surface ground motion, and amplification factor for major borehole locations in the study area are also presented.

\textbf{2 GEOLOGY AND TECTONICS OF THE STUDY AREA}

The study area is located on the Western side of Yemen within the Red Sea. Republic of Yemen is an Arab country in south East Asia located in southwestern to the southern end of the Arabian Peninsula. It is bordered by Saudi Arabia to the north, the red Sea to the west, the Gulf of Aden and Arabian Sea to the south,
and Oman to the east. Geologically, Yemen constitutes a part of the Arabian Peninsula and thus forms a segment within the framework of the Arabian-Nubian Shield. The site is precisely located in the offshore parts of the Tihama Basin, in the southeastern part Yemeni Red Sea, east-west transect between Al Hundayadh and Sana’s.

Studies have shown that the tectonic movement between the Arabian and the African plates, resulting in the rifts of the Red Sea and Gulf of Aden, is considered as the principal cause of earthquakes in Yemen (Poirier and Taher 1980; Alsinawi and Al Aydrus 1999; Al Saud 2008). Davidson et.al (1994) has reported that slow subsidence of up to 1km has occurred in the region prior to the rifting, about 100 million years ago. Davison et.al (1994) has described in detail about the tectonic evolution of the southeastern part of the Red Sea Rift between Al Hudaydah and Sana’a. Significant earthquake in Yemen includes the Dhamar earthquake of 1982 (M=6) which resulted in more than 15,000 causalities. Two significant earthquakes occurred in 1941 (M=6.5) resulted in 12,000 causalities (Mohindra et.al 2012). Several researchers have performed the seismic hazard studies for Yemen and its various territories. However the present study deals with the seismic site characterization and assessment of local site effects of earthquake ground motion for an offshore site.

3 SEISMIC SITE CHARACTERIZATION

Several studies on past earthquakes has revealed the effect of local site condition on earthquake ground motions. So for the ground response analysis, the characterization of local site is necessary. Among the available methodologies of site characterization, in the present study, the seismic characterization of the study area has been carried out using the average shear wave velocity for top 30m using the seismic cone penetration test.

A total of 20 borelog testing was conducted for the new single point mooring (SPM) system and pipeline locations as in figure 2. At the new SPM location the depth of testing in boreholes varies from 30-50m and that of pipeline location varies from 6-8m only. From the soil profile data, it has been seen that for the present study area the soil type for top 8-15m depth has fines content more than 80%, except few boreholes nearer to shore. Analyzing all the borelog data obtained from the SPM site, it can be concluded that 50m marine deposit constitute of two major types of soil layer, top silty clay to clayey silt and below that silty sand.

![Figure 1: Location of the study area](image1)

Shear wave profiling was done for the site using the seismic piezocone penetration test. The average shear wave velocity for top 30m ($V_{s30}$) was used as governing parameter for site characterization and was evaluated as per the equation (1).

$$V_{s30} = \frac{30}{\sum_{i=1}^{n} \frac{d_i}{v_i}}$$

Where $d_i$ is the depth of each soil layer, $v_i$ is the corresponding shear wave velocity for each layer and $n$ is the number of soil layers. From the borelog data, the average shear wave velocity (obtained from SCPT test) for top 30m soil was found to be 108.62 m/s to 145.55 m/s and as per NHERP classification the site falls in site class E ($V_{s30} < 180$m/s). Thus to assess the local soil effect and surface motion, ground response analysis needs to be carried out.

![Figure 2: Borehole locations within the site](image2)
4 EVALUATION OF LOW STRAIN SHEAR MODULUS

The low strain shear modulus was evaluated using SCPT data from field test and two laboratory tests such as bender element test and ultrasonic pulse velocity test. Using SCPT data the low strain shear modulus was evaluated using equation 2.

\[ G_{es} = \left( \frac{\gamma}{g} \right) V_s^2 \]  
\[ (2) \]

Where \( \gamma \) is the bulk unit weight, \( g \) is the acceleration due to gravity and \( V_s \) is shear wave velocity, measured using SCPT. The low strain shear modulus of the soil layer, which constitutes the top 15m strata, was found to be in the range of 1.7 MPa to 15 MPa. Beyond 15m depth (up to 50m), the low strain shear modulus ranging from 17 MPa to 330 MPa.

The bender element test in the present study is carried out on BH-16, 8.52m-8.70m and BH-19, 29.20m-29.34m specimens at a confining pressure of 100KPa. The shear wave velocity for the specimens specified above were of 69m/s and 224m/s respectively, which was obtained using peak to peak method (Viggiani and Atkinson 1995). Knowing the density of the specimen, the low strain shear modulus for these samples was found to be 7.67MPa and 113.42 MPa, which are comparable with the values obtained from SCPT for the same soil type.

The ultrasonic pulse velocity test was conducted on 13 undisturbed samples taken from a depth between 6.5m to 13.8m for different boreholes and shear modulus found to be in the range of 5.3 MPa to 8.3 MPa which is very similar to the values obtained from SCPT data.

5 CORRELATION OF V_s AND G_{max} WITH CONE TIP RESISTANCE (Q_c)

Shear wave velocity is an important parameter for the seismic site characterization and ground response analysis. However, at present the in-situ field measurement of shear wave velocity can only be done using geophysical field tests, which may not be viable to carry out for every location in a site. Hence, in this paper a correlation between shear wave velocity (V_s) and cone tip resistance (Q_c) was developed in the form of a regression equation, especially for the marine soils. From SCPT data, V_s and corresponding G_{max} was plotted against q_c and regression equation were developed between these parameters as given in equation 3 and 4. The regression coefficient was found to be 0.88 and 0.69 respectively.

6 EQUIVALENT LINEAR GROUND RESPONSE ANALYSIS

In the present study, ground response analysis was carried out for the marine bed based on the equivalent linear approach, proposed by Seed and Idriss (1969) using SHAKE 2000 (Ordonez 2000). Due to the non-availability of suitable earthquake records for the study area in any major database, synthetic acceleration time history is used for the site response analysis. The synthetic ground motion was generated using Boore’s methodology (Boore 2003). The ground motion was generated for a controlling earthquake of magnitude 5.5 (Mw) at a hypocentral distance of 15.42km. The modulus reduction (G/G_{max}) and damping ratio values at different strain levels for each soil layer was compared with existing curves available in SHAKE 2000 program and most appropriate ones have been selected for the ground response analysis.

The 1D equivalent linear ground response analysis for boreholes in new SPM site (BH-1, BH-15, BH-16, BH-17, BH-18, BH-19 and BH-20) is carried out and presented here. Typically in a 1D ground response analysis, the input motion is applied at the bedrock. The soil layer, where the shear wave velocity is about 760± 60 m/s is categorized as an engineering bedrock. However, it is observed that all the boreholes in the site have not reached the engineering bedrock. Hence, in
order to account this, two sets of ground response analysis have been performed in the present study. In the first set of studies (set-1), the analysis has been carried out for scenario where the input motion for class A type ($V_s > 1500$ m/sec) rock is directly applied to the base layer of the boreholes in SPM location and pipeline site, without assuming the existence of the bedrock. In the second set of studies (set-2), the input motion for class A type rock is first converted to site class B/C type motion according to 1997 NEHRP provisions using DEEPSOIL (Hashash et al. 2012). Assuming the existence of B-type ($V_s = 760 \pm 60$ m/sec) rock below the last soil layer, the input motion corresponding to site class B is applied at the base of last layer of the bore logs.

7 SITE SPECIFIC DESIGN RESPONSE SPECTRUM BASED ON EUROCODE

A design response spectrum is a statistically smoothed response spectrum. The irregular shape of the actual response spectrum makes it not suitable for design applications. The smoothing of the response spectrum has to be done based on the codal provisions such as NEHRP (BSSC, 2003), Eurocode-8 (2003) and BIS-1893 (2002) for design purposes. In this study the PGA and $S_a$ values were evaluated based on NEHRP site classes. The ordinates of the elastic design spectrum are calculated based on the following equations 5(a to d).

$$0 \leq T \leq T_b : S_e(T) = a_g S \left[1 + \frac{T}{T_b}(2.5\eta -1)\right]$$ 5(a)

$$T_b \leq T \leq T_c : S_e(T) = a_g S 2.5\eta$$ 5(b)

$$T_c \leq T \leq T_D : S_e(T) = a_g S 2.5\eta \frac{T_c}{T}$$ 5(c)

$$T_D \leq T \leq 4\text{sec} : S_e(T) = a_g S 2.5\eta \left[\frac{T_c T_D}{T^2}\right]$$ 5(d)

Where $S_e(T)$ is elastic response spectrum, $a_g$ is the peak ground acceleration at bedrock level, $S$ – soil parameter and $\eta$– damping correction factor ($\eta = 1$ for $5\%$) and $S$, $T_b$, $T_c$ and $T_D$ parameters that depend on seismicity of region. As per NEHRP classification, the current site falls in site class E, butas per Eurocode classification, the current site having $V_{so}$ less than 180m/s falls in site class D. Hence the values of $S$, $T_b$, $T_c$ and $T_D$ should selected corresponding to site class D of Eurocode-8.

8 RESULTS

One dimensional equivalent ground response analysis was carried out for 7 boreholes at the new SPM location (BH-1 and BH-15 to 20) and also in the pipeline region (BH-2). The PGA at the ground surface for the set-1 analysis was obtained as 0.12g to 0.23g as presented in figure 4 and that of for set-2 analysis varies from 0.12g to 0.26g as shown in figure 5. The response spectra at the ground surface from the set-1 and set-2 analysis are presented in figure 6. Figure 7 presents the amplification spectra for set-1 and set-2 ground response analysis. The amplification factor varies from 1.64 to 2.75 considering both set-1 and set-2 analysis.
and 2500 year return period. It is to be noted that the ordinates of the elastic design spectrum are available up to a time period of 4sec.

9 CONCLUSIONS

This paper presents the seismic site characterization of offshore marine soil based on extensive geotechnical field and laboratory testing. Borelog data show that engineering bedrock in study area exists at greater depth (beyond 50m).

Based on the average shear wave velocity for top 30m, the study area can be categorized as site class E as per NEHRP classification and class D as per Eurocod-8, constituting of soft clays or liquefiable soil. Hence, ground response analysis is required for the estimation of the local soil effect. From the present study, a correlation between $V_s$ and $G_{max}$ was also developed for marine clay.

In the present study, one dimensional equivalent linear ground response analysis was carried out for 6 borehole locations in the new SPM to estimate surface motion using synthetically generated input motion as perBoore’s methodology. Appropriate modulus reduction and damping curves for soil types are selected based on dynamic laboratory test results. The PGA values for the surface level was estimated and it is found to be ranging from 0.12g to 0.26g from ground response analysis. The surface level PGA value from Eurocode is found to be 0.175g. PGA profile of the site and the smoothened response spectrum at the surface, based on Eurocode-8 was developed and presented. The smoothened design response spectrum from Eurocode-8 corresponding 475 and 2500 year return period are also presented and can be used for design purpose as it is comparable with the response spectrum obtained from ground response analyses.
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