Effects of carbonate content and ageing on the dynamic response of marine clays

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ABSTRACT
This paper examines the behavior of normally consolidated to lightly overconsolidated (OCR 1 to 5) marine fine grained soils tested dynamically at different levels of shear strain (γ) and presents an analysis of the effects of carbonate content and ageing on the shear modulus degradation (G/G_{max}) and damping ratio (D) characteristics. Testing was performed in both resonant column and direct simple shear equipment. The shape of the modulus degradation and damping curves was found to be significantly influenced by both the in situ overburden stress at depths greater than about 40 m and the presence of moderate carbonate content ($CaCO_3$>50%). The stress effect could also be explained by ageing, since the deeper samples at higher overburden stresses are also those subject to the greatest degree of ageing. The influence of carbonate content could be attributed principally to some possible degree of cementation or interlocking present in the soil. The outcome of these observations on seismic site response analyses of offshore sites is discussed. It was found that the use of traditional modulus degradation and damping ratio curves published in the literature could lead to unconservative results especially for moderate to high intensity seismic motions.

RÉSUMÉ
Cet article examine le comportement de normalement consolidé à légèrement surconsolidé (OCR 1 à 5) marine sols à grains fins évalués dynamiquement à de différents niveaux de déformation de cisaillement (γ) et présente une analyse des effets de contenu de carbonate et de vieillissement sur la dégradation de module de cisaillement (G/G_{max}) et facteur d'amortissement (D). L'essai a été exécuté tant dans la colonne résonnante que dans l'équipement de cisaillement simple direct. La forme de la dégradation du module et les courbes d'amortissement a été trouvé à être fortement influencé par le stress dans les morts-terrains in situ à des profondeurs supérieures à environ 40 m et la présence de la teneur en carbonate modérée ($CaCO_3$>50%). L'effet du stress pourrait aussi s'expliquer par le vieillissement, car les échantillons plus élevés à surcharger les contraintes sont aussi ceux qui sont soumis au plus grand degré de vieillissement. L'influence de la teneur en carbonate peut être attribuée principalement à un certain degré possible de cimentation ou de verrouillage présents dans le sol. Les résultats de ces observations sur les analyses de réponse de site des sites offshore sont discutées. Il a été constaté que l'utilisation du module de dégradation traditionnels et facteur d'amortissement des courbes publiées dans la littérature peut conduire à des résultats non sécuritaires spécialement pour modéré à haute intensité mouvements sismiques

1 INTRODUCTION

Of primary concern to the design of foundations for offshore structures is the site response under dynamic loading generated by storm waves and earthquakes. The free-field seismic response, i.e., the response of the site without the presence of the structure, is commonly evaluated using equivalent-linear analyses. This type of analysis requires an assessment of the cyclic soil behaviour. Soil exhibits visco-elastic behaviour at low levels of shear strain. However, at shear strains greater than a threshold value, the behaviour is non-linear. At larger strain levels, the capacity of the material to dissipate energy and the shear stiffness become dependant on the type and history of loading.

The dynamic properties of soils represented by the shear modulus (G) and damping ratio (D) have been extensively discussed during the last decades (Idriss et al. 1978, Kokusho, et al. 1982, Seed et al. 1986, Kokusho 1987, Vucetic et al. 1991, Kawaga 1992, EPRI 1993, Ishibashi et al. 1993, Lo Presti et al. 1997, Darandeli 2001). Plentiful laboratory data have been generated using various types of testing equipment such as: dynamic triaxial, resonant column, hollow cylinder, direct simple shear and torsional shear. Nevertheless, the available data for offshore cohesive soils are scarce.

There exist fewer studies concerned with the dynamic behaviour of marine clays (Koutsoftas et al. 1980, Kawaga 1992, Romo et al. 1999). In addition, during the last decade, interest in the behaviour of calcareous or carbonate soils has increased due to observed problems of foundations for offshore platforms founded on these sediments. There have been important contributions on the static and dynamic behaviour of carbonate sands (Randolph et al. 1991, Sharma and Fahey 2004). However, little information exists - or has been published - on the static and dynamic behaviour of carbonate clays.

Similarly, data related to the dynamic behaviour of cohesive soils recovered at shallow depths is more abundant than that available for soils at greater depths. It is well known that the long term consolidation effects (ageing) on deep clays cause lower porosities and higher fabric anisotropies that result in a strain-hardening response (Schmertmann 1991; Mitchell 1993). The effects of soil ageing have been mainly focused on the small strain shear modulus (Anderson et al. 1978, Kokusho et al. 1982).

When site-specific laboratory data are not available for evaluating the seismic site response, the engineer concerned with the design has to make use of data published in the literature. The characteristic soil behaviour under cyclic loads is primarily assessed from a consideration of index properties such as void ratio and in situ stresses, and plasticity index and OCR in the case of cohesive soils. The paper shows that the use of published data obtained from non-calcareous, relatively shallow samples in a seismic site response evaluation of offshore sites, may lead to unconservative estimates of the ground motions transmitted to the surface. Thus, knowledge of the dynamic/cyclic behaviour of calcareous marine clays with depth is critical for the design of costly offshore structures under earthquake or storm wave loading.

The paper presents a study of two parameters that potentially require special consideration when evaluating the seismic site response in a marine environment: ageing and carbonate content. The results and discussion would apply also to onshore sites with soils of similar characteristics.

2 CLAY SAMPLES AND TESTING PROCEDURES

As part of a geotechnical campaign performed in the Gulf of Mexico, a series of undisturbed samples were recovered at several offshore locations. These samples were retrieved using a high-quality sampling technique and recovered sample tubes were X-rayed for appropriate sample selection. More than 80 clay samples, retrieved from depths up to 120 m below mudline, were characterized by means of cyclic load testing.

The calcium carbonate contents ($CaCO_3$) presented in the clay samples were found to range from 0% to 76%. These values were measured according to ASTM D4373. The term calcareous or carbonate soils will be used throughout this work indistinctively and is employed to refer to soils with calcium carbonate contents greater than 50%.

The dynamic characteristics of clays at shear strains below ~0.1% are generally obtained in the resonant column (RC) apparatus. Dynamic soil characterization of clays at shear strains greater than 0.1% is most-conveniently done by means of cyclic strain-controlled tests using the direct simple shear (DSS) apparatus.

In the resonant column test, a cyclic torque was applied to the sample using a magnet-coil driving system. The applied force is proportional to the current flowing through the coils, and the response of the specimen is characterized by the acceleration at the top of the specimen. Recent advances in the measurement of dynamic properties of soils have shown that the moving magnets inside the coils produce a counter electromotive force that opposes the motion. This electromagnetic effect can lead to significant overestimation of damping ratio measurements if the voltage rather than the current is measured to calculate the force applied onto the specimen (Cascante et al. 2003). Hence, to obtain reliable damping measurements at low shear strains, the dynamic characteristics of the specimens were obtained by measuring the current flowing through the coils as opposed to the voltage. All the samples were reconsolidated isotropically to the best estimate of the octahedral stress.

In the cyclic strain-controlled test, N cycles of a constant shear strain γ are applied to the specimen (Vucetic and Dobry 1991). All test results reported in this study were conducted by applying up to 25 cycles of a sinusoidal excitation under strain-controlled conditions. The frequency of loading was 0.4 Hz and the shear strain levels used for the testing varied between 0.11% and 1.73%. The specimens were initially loaded to the in situ effective overburden stress and tested after the end of primary consolidation. Although the dynamic characteristics at different strain levels can be measured using only one sample, the soil response can be considerably influenced by the loading history, especially if large strain levels are employed. To remove any possible influence of the loading history, each specimen was tested only once at a predetermined shear strain level.

3 EVALUATION OF AGEING EFFECTS

The dynamic analysis of geotechnical profiles usually requires information about damping and shear modulus at different strain levels. For equivalent-linear procedures, this information is generally given by means of G/G_{max}-γ and D-γ curves. When site-specific laboratory test results are not available, published correlations have to be employed (i.e., Seed 1986, Vucetic et al. 1991, EPRI 1993, Darandeli 2001). However, published correlations for cohesive materials were mainly developed from testing conducted either on undisturbed samples recovered from the upper 20 m to 30 m of a soil profile, or on reconstituted samples. Hence, any possible effects resulting from long-term consolidation at high effective stresses are generally not reflected in the data.

Figure 1 shows a comparison between laboratory test results of a non-carbonate clay sample recovered at a depth of about 20 m below mudline. For comparison purposes, superimposed on the figure is the relation proposed by Vucetic and Dobry (1991) for the corresponding plasticity index. In general, good agreement is observed between measured results and the Vucetic and Dobry (V&D) curve. Furthermore, examination of the data collected during the geotechnical investigations shows that, in general, the V&D relation compares favourably with measured dynamic properties of non-calcareous soils recovered within depths of up to about 40 m to 50 m below seafloor.

Similarly, Figure 2 shows the testing results of a non-calcareous clay sample recovered at a depth of about 100 m. The corresponding V&D curves are also presented in the figure. The discrepancy between the measured data and the relation proposed by V&D becomes evident for these deep samples. The threshold shear strain is clearly higher. After the threshold strain is reached, the shear modulus degrades at a higher rate. At large shear strains however, (γ>0.1%) a lower degradation rate is observed. The differences between the measured and the V&D damping ratio values are more evident. The material dissipates considerably less energy during cycling at large strains than that predicted by the V&D relationship.

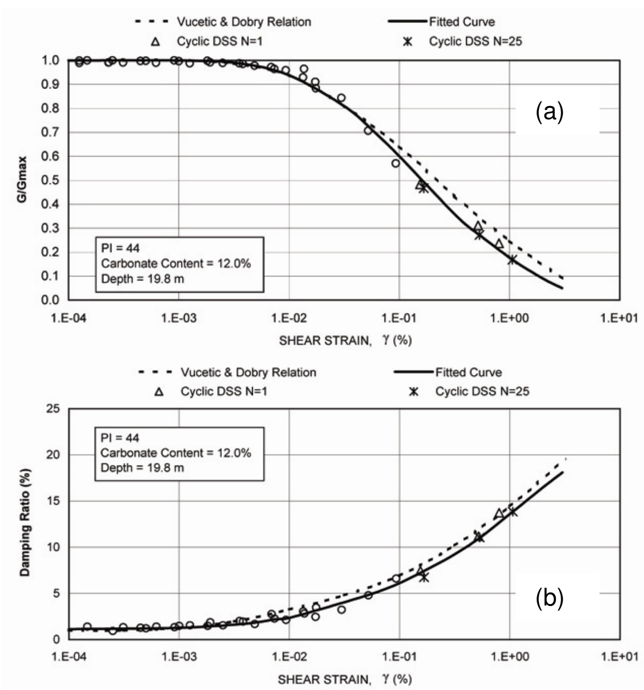

Figure 1. Comparison between measured data and the relationships published in the literature for non-carbonate relatively shallow soils

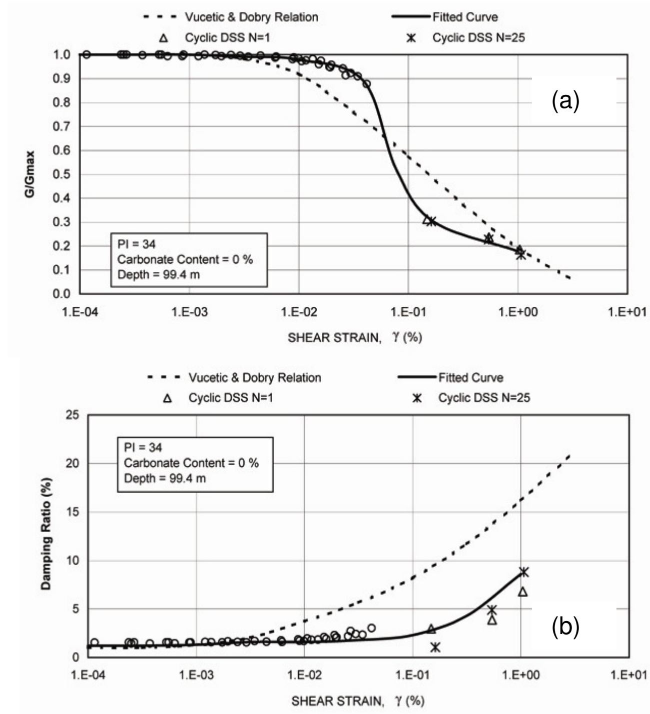

Figure 2. Modulus reduction and damping curves for a deep sample

Previous studies on the behaviour of clays from laboratory tests (Vucetic et al. 1991) have shown that the shear modulus (*G*) and damping ratio (*D*) of cohesive soils is influenced by the number of loading cycles (*N*), shear strain level (γ), the rate of strain ($\dot{\gamma}$) (predominantly at large shear strains), and the geologic age, amongst other factors.

The dependency of *G* and *D* on *N* and γ results in part from the non-linearity of the soil, whilst the dependency on the rate of strain is mainly a consequence of the viscosities of the soil skeleton and the pore fluid. These studies suggest that increasing the geologic age produces an increase of the shear modulus at low strain (G_{max}), a decrease of damping ratio (*D*) and the possibility of an increase in the shear modulus degradation (G/G_{max}), especially in high plasticity clays.

Ageing effects are intrinsically related to the consolidation history (OCR) as well as the effective state of stresses (σ'_0) to which the material has been subjected. Hence, ageing is inherently related to depth since the effective stress state increases with depth. It is also expected that deeper samples would present a different fabric structure (inherent anisotropy) than newly deposited sediments; thus the response of deep soils to cyclic loading should differ from that of shallow soils.

A typical stress-strain hysteresis loop corresponding to a non-calcareous sample recovered at a depth of 52 m is presented on Figure 3. Examination of the stress-strain loops reveals that more than 50% of the total shear modulus degradation occurs in the first 5 cycles. After a few loading cycles the sample starts to exhibit a strain-hardening behaviour that is reflected as loops with a “banana” shape. This strain-hardening feature results in the lower shear modulus degradation rates observed at high strains. When calculating damping coefficients from the geometrical form of the loops, it is found that most of the energy is elastically stored in the soil and little energy is dissipated during cycling, resulting also in low damping ratios.

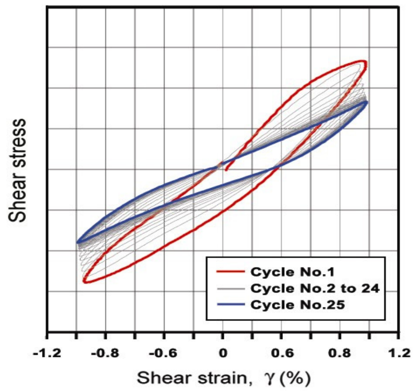

Figure 3. Hysteretic loop showing slight tendency to “banana-shape” type behaviour

Deeper samples are more likely to present higher fabric anisotropy. The plate-shaped clay particles will tend to align in the direction of the bedding plane with the driving energy provided by the high in situ effective stresses. This particle arrangement could perhaps be responsible for the observed increase in shear strength mobilization and a reduction of energy as suggested by Schmertmann (1991).

Long term overburden stresses acting on these deep clays are responsible for lower porosities. Vucetic et al. (1991) have mentioned also the effects of void ratio (*e*) on the shape of the G/G_{max} and *D* curves; as *e* decreases the G/G_{max} curve tends to shift upwards while the *D* curve moves downwards. The test results are in agreement with these observations

The combination of inherent anisotropy and low void ratios caused by ageing are believed to be responsible for the observed behaviour shown on Figure 2. The tendencies of shear modulus degradation and reduced damping values were observed for clay specimens recovered at depths greater than about 40 m to 50 m.

4 EVALUATION OF EFFECTS OF CARBONATE CONTENT

The evaluation of soil-structure interaction problems for offshore structures often requires an assessment of soil stiffness degradation during cyclic loading. In general, the shear strength and the stiffness of clays degrade with the number of cycles when subjected to cyclic loading and shear strains greater than a certain elastic limit (γ_e); thus G/G_{max} decreases as the number of cycles *N* increases. Similar to ageing, the presence of calcium carbonate ($CaCO_3$) can significantly influence the behaviour of the soil skeleton and hence the strength and stiffness degradation.

Figure 4 shows the G/G_{max}-γ and D-γ curves for a shallow (17.1 m depth) sample of calcareous clay. The V&D relations for the corresponding plasticity indexes are also shown for comparison purposes. The effects of carbonate content can clearly be observed in Figure 4. The shear modulus degrades at a higher rate at shear strains greater than the threshold shear strain when compared to the V&D relation. The observed increased rate of stiffness degradation agrees with conclusions drawn by Sharma and Fahey (2004) for two cemented calcareous soils. Although Sharma and Fahey (2004) concluded that the presence of carbonates results in higher strain thresholds, the authors did not register consistent test results in the calcareous clays tested that could support this observation. However, the observed increase of strain threshold observed by Sharma and Fahey (2004) can be related to the higher particle interlocking of the granular material.

Carbonates appear to have a greater effect on the damping ratio. The measured damping ratios begin to diverge from the V&D relation at strains greater than the threshold shear strain. The stress-strain behaviour is similar to the (“banana” shape) behaviour observed on Figure 3; most of the energy is stored elastically in the soil and little energy is dissipated during cycling, resulting in low damping ratios. However, it is considered that the strain-hardening (dilation) behaviour observed in the carbonate sample is a result of the higher particle interlocking caused by the carbonate structure, similar to the behaviour observed in carbonate granular materials.

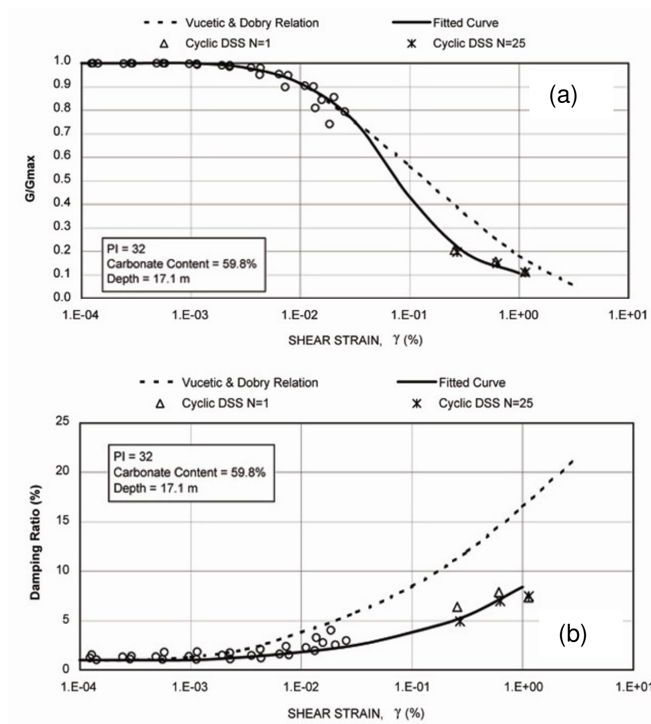

Figure 4. Modulus reduction and damping curves for a shallow carbonate sample

The combined effects of the effective stresses (ageing) and carbonate content are depicted in Figure 5.

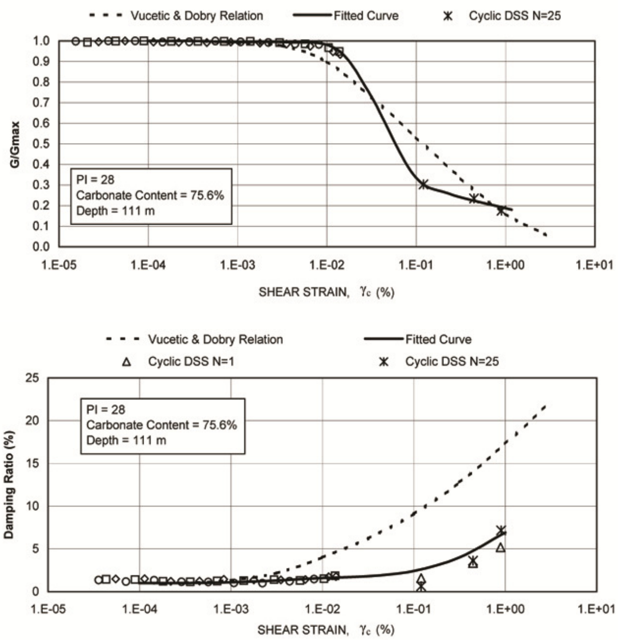

Figure 5. Combined effects of calcium carbonates and effective stresses (ageing) in the shear modulus and damping curves

The results presented summarize the different dynamic responses of marine clays obtained by the authors during the geotechnical investigations conducted in the Gulf of Mexico. There is a consistent increase in the threshold shear strain with depth, attributed principally to ageing rather than carbonate effects. The modulus degradation rates consistently increase with depth, whilst the damping ratio considerably decreases. Carbonate soils can present a certain degree of cementation caused by precipitation of minerals (i.e., calcite or aragonite) between the particles. The degree of bounding or cementation enhances the loading resistance of the soil. This bonding however may be lost during cyclic loading, causing an important loss of shear strength or modulus degradation as shown on Figure 5.

The consequences of theses observations on seismic site response analyses are presented in the following section.

5 EFFECTS ON SEISMIC RESPONSE ANALYSES

The effects of carbonate content and soil ageing in marine clays described above could be important and should be considered in the evaluation of seismic response of offshore sites. Figure 6 presents the results of seismic response analyses for a typical offshore profile using the computer program SHAKE (Schnabel et al., 1972). The soil profile comprises a 33-m layer of soft to stiff high plasticity clay underlain by 13 m of medium dense clayey fine sand followed by stiff to very stiff calcareous/carbonate clay to the final depth of investigation at about 130 m below mudline. The dynamic properties of the typical profile were studied in great detail; a complete characterization of the profile was achieved by means of laboratory and field test results. The figure shows the response spectra calculated at the mudline for a structural damping of 5%.

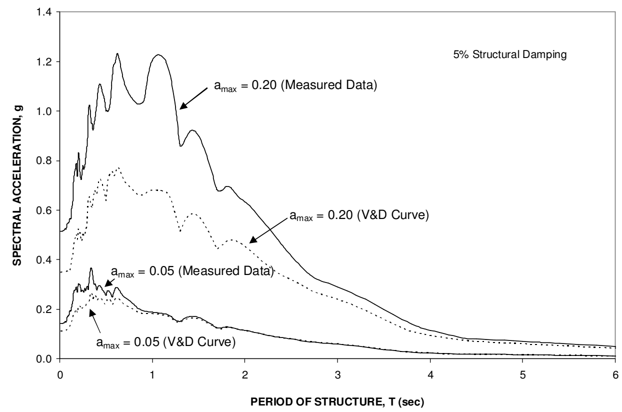

Figure 6. Influence of carbonate content and ageing on seismic site response

The spectra correspond to two different peak firm ground acceleration levels of 0.05 g and 0.20 g. The curves labelled “measured data”, correspond to the results of simulations using G/G_{max}-γ and D-γ curves measured in the laboratory whereas the curves labelled “V&D” correspond to simulation using the modulus and damping curves proposed by Vucetic and Dobry (1991).

The results illustrate that the two spectra corresponding to a peak firm ground acceleration of 0.05 g produce very similar spectra at the mudline. The low level of seismic excitation induces low shear strains in the layers and hence SHAKE uses shear moduli and damping values corresponding to these low strains. In the low strain range, the G/G_{max} and D curves measured in the laboratory and proposed by Vucetic and Dobry are very similar irrespective of the ageing or carbonate content. As a result, the seismic responses at the mudline for both soil characteristics are very similar. However, for the case of a peak firm ground acceleration of 0.2 g, the shear strains induced in the soil profile increase and over the range of expected strains, the laboratory-determined and V&D G/G_{max} and D curves differ considerably.

The degree of cementation observed in calcareous clays could result in a higher threshold shear strain indicating elastic soil behaviour at higher levels of cyclic shear strain leading to higher amplifications of seismic motions. Similarly, for the case of damping, the use of curves published in the literature might lead to un-conservative results if the intensity of the seismic motion analyzed is high enough to induce deformations above the threshold shear strain. Therefore, depending on the characteristics of the soil profile, lower damping could translate into higher seismic energy transmitted to the surface and thus, higher accelerations acting on the structure. The combination of these two effects could lead to the high amplifications of the seismic motion observed on Figure 6.

5.1 Closing Discussion

Many of the offshore projects being developed around the world are located in tectonically active areas where earthquake effects may be the principal loading condition that needs to be incorporated into the foundation and structural design.

Seismic input data for the dynamic analysis are provided by a probabilistic seismic hazard assessment whereby the design requirements are expressed in the form of a target response spectrum. A two-tier approach is generally employed. The lower level of hazard generally corresponds to a return period of around 200-years (SLE or ELE) during which the structural response is conditioned to be elastic. At the higher DLE or ELE level, usually corresponding to a return period of several thousand years, structural non-linearity is provided for in the design (API, 2003).

For geotechnical engineers, the seismic design response spectra provided from the probabilistic seismic hazard assessment (PSHA) are applied at bedrock level and it is the responsibility of the geotechnical engineer to propagate the input motions to the surface (or depth of soil-structure interaction) in order to provide input spectra for the soil-structure interaction and structural analyses.

The soil models employed for propagating the bedrock input motion are usually based on soil parameters determined from a variety of in situ or laboratory tests. Based on code recommendations, for routine onshore assessments, the dynamic characteristics of the material down to a depth of about 30 m are considered adequate to model the influence of the local behaviour of the soil profile. Furthermore, most of the seismic design codes presently in use are based on foundation factors related to the characteristics of the upper 30 m of the soil profile.

However, the results from the cyclic/dynamic laboratory tests performed in this study and those reported in the available literature indicate that soil response at greater depth may not be similar to that obtained from tests on shallow samples at relatively low confining stresses. In essence, the laboratory results suggest that both the G/G_{max} and D curves are modified such that higher levels of energy can be transmitted to the upper layers of deep soil profiles. The consequences of this may result in higher relative levels of acceleration at mudline and associated higher demands on the structure itself.

Consequently, for more important onshore projects and generally all offshore projects, where the propagation of the seismic input need to be examined over a greater depth - usually 100 m or more - special care needs to be exercised when selecting the appropriate dynamic properties with depth for the soil profile. Apart from the potential effects of ageing, the carbonate content of clay soils may further accentuate the tendency for extended elastic response and reduced damping.

The results presented herein have been attributed to ageing effects and also large carbonate content in marine clays. Note that we have not obtained the modified G/G_{max} and D curves when testing carbonate soils at shallow depth (and low confining stresses). However, the modified response has been measured in deep marine clays which do not have carbonates. As a result, it is not possible to clearly separate the potential effects of ageing and carbonate content.

Ageing, however, does seem to be the controlling mechanism. In the laboratory, surface samples have been consolidated to confining stresses equivalent to depths of about 100 m. Both normally consolidated and lightly overconsolidated samples have been prepared but the modified response has not been evidenced in the laboratory. Conversely, deep samples that do exhibit the modified G/G_{max} and D response, do not lose the characteristic curve shape when consolidated to stresses in excess of the maximum pre-consolidation stress. This may be because stresses large enough to break to ageing effects were not achieved. It would appear that the modified dynamic response is not simply related to stress level, but that secondary ageing effects are involved.

6 CONCLUSIONS

Recent laboratory results on the dynamic and cyclic behaviour of marine clays from the Gulf of Mexico have been reviewed. The effects of ageing or *in situ* state of stresses and calcium carbonate content on the G/G_{max}-γ and D-γ was emphasized. The following conclusions can be drawn from the analysis of the experimental data:

- Soil ageing or *in situ* effective stresses affect both the shear modulus degradation and damping curves. It was found that the threshold shear strain increases with depth. Comparisons of the patterns of shear modulus degradation with those obtained from the experimental data showed that deeper soils experience higher modulus degradation at strains higher than the threshold strain. At large strains however, the rate of modulus degradation decreases. Damping values measured at high strains decrease considerably with depth.
- Examination of the behaviour of calcareous clays showed that carbonates are responsible for lower damping ratios at strains higher than the threshold. As opposed to other experimental data on calcareous soils (i.e., Sharma and Fahey, 2004), the threshold shear strain was found not to be affected by the presence of carbonates.
- The effects of ageing and carbonate content on seismic site response analyses were presented by examining the response of an offshore site. A comparison between the seismic response obtained using measured G/G_{max}-γ and D-γ and

curves and those proposed by V&D was carried out using the program SHAKE. The results show that response spectra calculated at the mudline are not significantly affected when low levels of seismic excitation occur. When the input excitation is increased, however, a considerable difference in the response spectra was obtained. Therefore, depending on the characteristics of the input motion and the soil profile, the seismic energy transmitted to the surface can be under-predicted.

Additional work is needed to examine the effects of anisotropic confining stresses and loading rates over the low range of shear strains of the resonant column. The geotechnical engineer concerned with the seismic response of offshore sites should consider the possible effects of calcium carbonates and soil ageing when performing site response analyses for structures on deep soil profiles. Traditional modulus and damping curves from near-surface samples may lead to an under-prediction of the surface motions.

The testing program discussed herein is not considered to be exhaustive. However, during other studies for structures on deep soil profiles, similar modulus and damping curves have been measured, similar to those discussed in this paper. These results have been obtained for marine clays with little or no carbonate content.

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