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Centrifuge modeling and numerical analysis on seismic site response of deep offshore clay deposits

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A B S T R A C T

Nonlinear site response of deep offshore clay deposit plays an important role in changing the characteristics of ground motions when subjected to strong shaking, especially when different amplification behaviors of acceleration and displacement are considered. The paper describes a series of centrifuge shaking table tests and numerical simulations to investigate the behavior of deep offshore clay deposits subjected to earthquake loadings. The centrifuge model tests were performed on a slightly overconsolidated clay deposit at UC Davis. A suite of shaking tests were conducted including impulse step wave testing, frequency sweeps, a small "elastic" earthquake event and a "ductility" level large earthquake event. Accelerations, displacements and pore pressures were measured in the soils (free field) throughout the test program. For the elastic level excitations, about a 33% amplification was observed between the input acceleration at the base and the measured accelerations near the top of the clay deposit. However, for the ductility-level earthquake excitation, which had peak input acceleration at the base of 0.46g, acceleration near the top of the deposit was reduced to 0.07g. These observations are correctly simulated by DEEPSOIL with proper soil models and parameters back analyzed from the centrifuge model test. Then systematic 1-D site response analyses are performed on synthetic clay deposit models with 30 to 120 m depths using the validated DEEPSOIL program, and the amplification characteristics of acceleration and deformation induced by base excitation with different intensities and frequencies are analyzed in both time and frequency domains. The results reveal that for deep soft offshore clay deposits subjected to large earthquakes, significant acceleration attenuation may occur near the top of deposit due to soil nonlinearity and even local shear failure; however, significant amplification of displacement at low frequencies is expected regardless of the intensities of base motions, which suggests that for displacement sensitive offshore foundations and structures, such amplified low-frequency displacement response will play an important role in seismic design.

1. Introduction

The growth of the offshore industry into seismic regions requires a detailed understanding of the earthquake design of offshore facilities (e.g., oil platform, wind turbine, pipelines and other deepwater infrastructures). These facilities are usually constructed on the seabed consisting of a surface layer of soft soils overlying the stiffer materials (Randolph et al., 2011; Puskar et al., 2013). Soil effects on ground motion are a very important contributor to foundation failure and structure damage during strong earthquakes. The soil changes the characteristics of the ground motion by amplifying it and making it more destructive. Taking the seismic response of pile-supported offshore structures as an example, it is strongly affected by the nonlinear behavior of the supporting foundation to earthquake excitations, where the nature of input ground motion plays an important role (El Naggar et al., 2005; Litton et al., 2014). As the free-field analysis (acceleration–time histories at different soil layers) is used as the input excitation, the spectral accelerations of abnormal level earthquake (ALE) and extreme level earthquake (ELE) recommended by API code for simplified procedure shall be further modified to account for local soil conditions (e.g., deep soft sediment) and obtain site-specific spectral accelerations for the seismic design of the structure (Peng and Ghoneim, 2009; API 2EQ Ed. 1, 2014). In this perspective, compared to research on sandy soils in recent years (e.g., Vanzini et al., 1998; Ghosh et al., 2007; Jeanjean, 2012), much less attention has been paid to that on soft clay deposits (e.g., Tamura et al., 2015; Khosravi et al., 2016).

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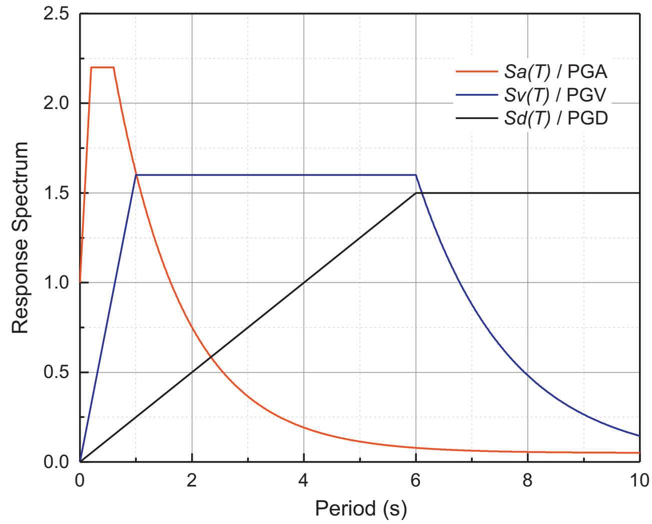

Fig. 1. Response spectra schematic of *Sa*, *Sv* and *Sd*.

On the other hand, previous studies have shown considerable amplification of surface ground accelerations for low bedrock accelerations of the order of 0.05*g* to 0.10*g* and significant attenuation of accelerations in soft soil sites subjected to large earthquakes (Idriss, 1990; Stewart and Liu, 2000; Dobry and Iai, 2000), which seems favorable for the traditional force-based seismic design. There are several fine works about the effect of the deposit thickness on site response of clay or soft soil deposits (e.g., Dobry and Vucetic, 1987; Romo, 1995; Rodriguez-Marek et al., 2001). However, less data is available to evaluate the effect of deep deposits of clay on amplification or attenuation of ground deformations. For example, the seismic displacements of the deep sea well-head manifold are potentially a cause of distress to connections between jumpers and the manifold. As the seismic displacement of the jumpers is driven by the free field soil response in the far field, the free field soil response is of particular interest in seismic design (e.g., Zheng et al., 2015). In consideration of the very different response spectra from acceleration to displacement of the same input motion (see in Fig. 1), the study on amplification or attenuation characteristics of ground deformation of deep soft clay sediment subjected to earthquakes becomes quite necessary for obtaining a realistic displacement demand, assessing the performance of foundations and even the development of displacement-based seismic design procedures (Deng et al., 2014; Palermo et al., 2014).

To address the abovementioned problems, the present study carried out both physical modeling and numerical simulation on seismic response of deep soft clay deposits subjected to earthquake loadings. Firstly, a series of centrifuge shaking table tests were performed in a slightly overconsolidated clay deposit, and the considerable amplification of peak acceleration under weak excitation and significant attenuation under large excitation were observed. Secondly, these observations are correctly simulated by DEEPSOIL program with proper soil models and appropriate parameters back calculated from model test data. Then systematic 1-D site response analyses are performed on synthetic clay deposit models with 30, 60, 90 and 120 m depths using the validated DEEPSOIL program, and the results of site response are analyzed in both time and frequency domains. Important amplification characteristics of both acceleration and displacement of deep soft clay deposit were revealed, which shed light on developing seismic design parameters for foundations of offshore structures.

2. Centrifuge model test

The geotechnical centrifuge is a useful tool for modeling large-scale nonlinear problems for which gravity is a primary driving force. The centrifuge applies an increased “gravitational” acceleration to physical models in order to produce equivalent self-weight stresses in the model and prototype. Garnier et al. (2007) provide detailed discussions on the procedures and model scaling in a geotechnical centrifuge. For earthquake problems, dynamic centrifuge model testing provides data to improve the understanding of basic mechanisms of dynamic response and failure, and further provides benchmarks useful for verification of numerical models (e.g., Kutter et al., 2016; Manzari et al., 2016; Hakhamaneshi and Kutter, 2016).

A series of centrifuge shaking table tests was conducted at the University of California at Davis (UC Davis) to simulate 1-D site response in a slightly overconsolidated marine clay deposit (30 m depth in prototype). The soil model was spun to a centrifugal acceleration of 58*g*, and it took several hours until approximately 95% of the settlement had occurred. Following the completion of the consolidation phase, several testing activities were carried out. All experimental parameters discussed below are presented in prototype scale, unless stated otherwise.

2.1. Soil properties and model configuration

The model ground was constructed in a flexible shear beam (FSB) container with internal dimensions of 95.7 m in length, 44.4 m in width and 34 m in height under 58*g*. The FSB container with a low natural frequency provides less additional lateral stiffness to the soil layer, which is particularly advantageous when modeling a liquefiable soil deposit. And because of its simple and continuous boundaries, the FSB containers are widely used to model SSI problem on soft soil ground (Kutter, 1995; Ghayoomi et al., 2013). During model construction, clay layers were consolidated in 4 sublayers in a hydraulic press to pre-consolidate the soil before loading on the centrifuge. Target consolidation stress was set to equal 1.1 times the in-flight vertical stress at the base of the respective sublayers. The ultimate OCR profile at 58*g* was lightly over-consolidated. These layers and their consolidation stress are marked in Fig. 2. In order to

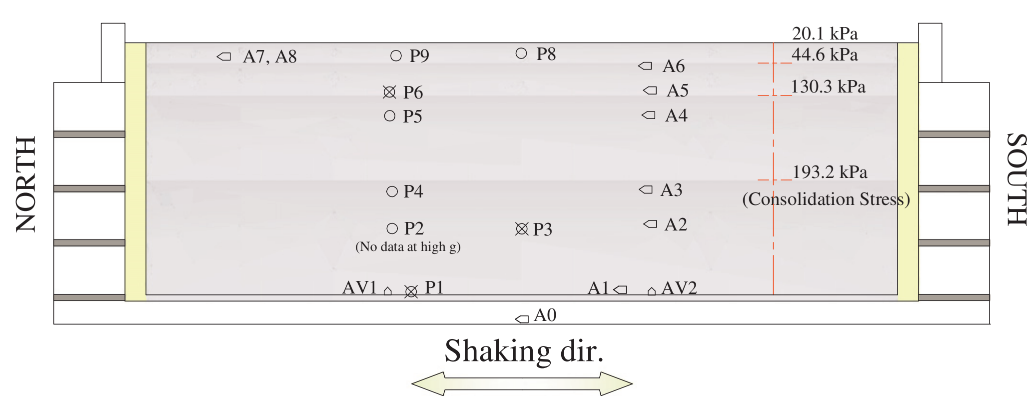

Fig. 2. Arrangement of instruments in centrifuge model.