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Earthquake response and sliding displacement of submarine sensitive clay slopes

Yan-Guo Zhou[a,*], Jie Chen[a], Yu She[a], Amir M. Kaynia[b], Bo Huang[a], Yun-Min Chen[a]

[a] *MOE Key Laboratory of Soft Soils and Geoenvironmental Engineering, Institute of Geotechnical Engineering, Zhejiang University, Hangzhou 310058, PR China*
[b] *Norwegian Geotechnical Institute, Norwegian University of Science and Technology, Norway*

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ABSTRACT

Many submarine landslides occur through marine sensitive clay layers, and the strain softening behavior plays a key role. The changing soil properties induced by various disturbances will have marked impact on earthquake performance of submarine clay slopes. In the present study, undrained triaxial compression tests on reconsolidated samples of a soft sensitive marine clay were conducted, and a soil disturbance dependent simple constitutive model is proposed for describing post-peak nonlinear strain softening behavior of sensitive clays based on experimental results, and then is implemented in QUIVER code to perform one-dimensional seismic response analysis of mild infinite slopes, to address the relative importance of soil disturbance effect on the site response and sliding displacement of submerged slopes during seismic loading. Detailed laboratory test descriptions and results of a soft sensitive marine clay, model formulations and comprehensive computational efforts are presented. Parametric study of site response analysis focusing on the effects of soil disturbance degree and depth on generic clay grounds with varying sloping angles subjected to harmonic and earthquake loadings are performed. The predicted acceleration amplification, maximum shear strains and permanent displacements provide insight of earthquake performance of submarine sensitive clay slopes.

The main findings are drawn based on several key concepts. First, undisturbed sensitive clay is typically stiffer and stronger than disturbed clay consolidated at the same stress level and hence, unless strain softening is triggered, structured sensitive clay will perform better than insensitive clay of the same residual strength. Second, post-peak softening at shallow depth will lead to strain localization on a thin layer, which is the main cause of sudden change of upward wave propagation characteristics and large permanent displacement at seabed surface of mild submarine clay slope. Thirdly, soil disturbance degrees and depths have very marked effects on seismic response and displacement performance of sensitive clay slopes, and such effect will be further enhanced by slope angle or earthquake intensity, which should be cautiously treated in engineering design.

1. Introduction

Submarine landslides of the shelf break and the continental slope are a major threat to many offshore facilities, such as pipelines, foundation systems, and wellheads because of the large displacements and forces associated with such failures. The response of submerged slopes to seismic or storm loadings has become an important element in the risk assessment for offshore structures. Offshore slopes are generally very mild ($< 10^\circ$) and relatively sensitive (DeGroot et al., 2007), and the geological profile typically includes normally consolidated to lightly overconsolidated soft clays with layer thickness ranging from a few meters to hundreds of meters (Hadj-Hamou and Kavazanjian, 1985; Jackson et al., 2004). Post-slide investigations suggest that many submarine landslides occur through marine sensitive clay layers, and the strain softening behavior of the weak layer plays a key role (Dan et al., 2007; Sultan et al., 2010; Locat et al., 2014). Sensitive clay has a metastable structure at a large void ratio formed by aging effect, but upon remolding during undrained shear, the structure is destroyed and the material approaches the remolded critical state. The shear strength of sensitive clay layer might be decreased due to various disturbances, such as geological activities, pore pressure generation, earthquakes, and plastic shear deformation (Kayen and Lee, 1991; Lastras et al., 2004; Puzrin and Germanovich, 2005; Schroeder et al., 2008). The episodic nature of offshore cyclic loadings can cause significant soil disturbance and even remolding, and the recovery of soil strength through reconsolidation can be comparable to the reduction during remolding (Randolph et al., 2011). Besides, historical evidence suggests that the majority of large submarine landslides are triggered by or coincided

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* Corresponding author.
E-mail address: qzking@zju.edu.cn (Y.-G. Zhou).

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with earthquakes (Fine et al., 2005; Masson et al., 2006; Lee et al., 2006). Thus there is a strong need for suitable methods to evaluate the seismic risk posed by submarine slides and evaluating permanent displacements of sensitive clay slopes (i.e., catastrophic failure or soil slumping), and the changing soil properties induced by disturbance will have impact on earthquake response and performance of submarine clay slopes.

In this regard, besides a few good researches of site investigation (e.g., Tappin et al., 2003) and physical modeling (e.g., Kutter, 1984; Park and Kutter, 2015), the seismic response of slopes is mainly assessed by using analytical or numerical approaches that utilize limit equilibrium methods (e.g., Kvalstad et al., 2005; ten Brink et al., 2009; Feng et al., 2010) or the finite element method (FEM) or finite difference methods (FDM) (e.g., Biscontin et al., 2004; Azizian and Popescu, 2005; Feng and Gao, 2012; Dey et al., 2016a; Boulanger and Montgomery, 2016). The limit equilibrium approach considers the shear stresses along a failure surface and computes a factor of safety (FS) based on the available shear strength and the shear stresses required for equilibrium, but does not provide any meaningful information about slope performance when the pseudostatic factor of safety is less than unity. A dynamic FEM captures the entire nonlinear stress-strain-strength properties of the soil, and computes the deformation patterns throughout the slope under the earthquake excitation. However, sophisticated and robust nonlinear stress-strain-strength models of the soil are required to produce reliable numerical results (Ishikawa et al., 2015).

A simple model used in slope response analysis is the sliding block model that was originally proposed by Newmark (1965). This type of analysis attempts to quantify the sliding displacement of a sliding mass during these instances of instability. Earthquake-induced displacement is the parameter most often used in assessing the seismic stability of slopes, could be from a few millimeters to as large as a few meters depending on the slope conditions and the earthquake excitation (Jibson, 2007; Nadim et al., 2007). Various researchers have proposed equations based on the sliding block model that predict the slope displacement as functions of ground motion parameters and slope characteristics (e.g., Bray and Travasarou, 2007; Saygili and Rathje, 2008; Saygili and Rathje, 2009), where displacements were calculated using the equivalent-linear, fully-coupled, stick-slip sliding model of Rathje and Bray (2000). More recently, Kaynia (2012) developed one-dimensional nonlinear dynamic slope stability analyses in QUIVER code, based on a simple nonlinear model consisting of a visco-elastic linear loading/unloading response together with strain softening and a kinematic hardening yield function of post peak strength. The model is implemented in a one-dimensional slope consisting of soil layers with infinite lateral extensions under vertically propagating shear waves. The strain softening turns out to have a considerable impact on the nonlinear response of the soil once the soil reaches the peak shear strength, especially for sensitive marine clay (Kaynia and Saygili, 2014; Carlton et al., 2016). Therefore the capability of this model could be considerably improved if the effect of soil disturbance on strain softening behavior of sensitive clay could be properly considered.

The aim of this study is to present a soil disturbance dependent constitutive model for describing post-peak nonlinear strain softening behavior of sensitive clays based on experimental results, and then implemented it into QUIVER code to perform one-dimensional seismic response analysis of mild infinite slopes, to address the relative importance of disturbance affecting the response of submerged slopes during seismic loading. Detailed laboratory test descriptions and results of a soft sensitive marine clay, model formulations and comprehensive computational efforts are presented. Results of parametric study of site response analyses focusing on the effects of disturbance degree and disturbing depth in a generic soft clay ground with varying sloping angles and input ground motion characteristics are given. The predicted acceleration amplification/attenuation, maximum shear strains, permanent deformations and displacement time histories provide insight of earthquake performance of sensitive clay slopes.

2. Experimental study and strain softening model

2.1. Site condition and soil sampling

The construction site where the clay samples retrieved is located at the southern part of Hangzhou (i.e., Xiaoshan district), and the sampling location is about 50 m away from the excavation and therefore it could be assumed that there is no construction induced disturbance. It is a recent Holocene deposit and consists of soil of alluvial and marine origins, with the ground water table at a depth of about 2.0 m. The upper 2.5 m at the site is fill material below which the in situ soil consists of 2.25 m of clayey silt (CL lean clay) overlying a soft mucky clay (OH) to 20.7 m and a soft mucky clay to mucky silty clay (OL) to 33.5 m. Undisturbed samples were retrieved throughout the whole depth using the Japanese 75 mm thin-walled piston sampler (JSSMFE, 1977). By using the unconfined compression test and the field vane test, the measured sensitivity of the predominant clays mainly ranges from 4 to 8, which is consistent with the results reported by Chen et al. (2015) and Li (2015). And the clay can be classified as a sensitive clay according to the classification proposed by Skemption and Northey (1952). The basic soil properties of the Xiaoshan soft clay are given in Table 1, which shows a typical soft sensitive clay.

2.2. Undrained triaxial compression test

As the main data required for establishing the strain softening model of sensitive clay for QUIVER code is the undrained shear strength (S_u) of both intact and disturbed samples, isotropically consolidated undrained triaxial compression tests (i.e., CIU) were conducted in this study by using soil samples with 80 mm height and 39.1 mm diameter.

Table 1
Basic soil properties of Xiaoshan clay (to be continued).

Soil strata	Depth (m)	Soil type (USCS)	Specific gravity Gs	Water content (%)	Mass density (g/cm^3)	Void ratio $e0$	Liquid limit ω_L%	Plastic limit ω_P(%)
Silty clay	2.5–4.75	CL lean clay	2.69	29.6	1.91	0.83	33.6	26.2
Mucky clay	5.5–20.7	OH to OL	2.74	47.1	1.73	1.34	39	21.2
Mucky silty clay	21.5–33.5	CL lean clay	2.73	47.3	1.75	1.25	35.4	20.6

Soil strata	CIU test				Sensitivity
	c_{cu} (kPa)	φ_{cu} (°)	c' (kPa)	φ' (°)	S_t
Silty clay	–	–	–	–	–
Mucky clay	23.5	10.6	7.2	26.4	3.8–9.1
Mucky silty clay	22.7	12.0	8.2	28.7	3.5–8.6