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Static and seismic stability of sensitive clay slopes

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ABSTRACT

Many sensitive clay slopes exist that have a factor of safety greater than one based on the peak strength, and a factor of safety less than one based on the remolded strength. Obviously, it is possible for shaking from an earthquake to remold and soften a sensitive clay, but there is no criteria available to help engineers determine the extent of seismic loading required to induce sufficient strain softening to trigger instability. Slopes of varying sensitivity, produced by adding a small amount of Portland cement to clays of different plasticity were tested in a centrifuge to study the static and dynamic failure mechanism for sensitive clay slopes. The properties of the clay were determined by rudimentary laboratory tests. Results are interpreted in the context of existing literature to further our understanding of the factors controlling the potential for dynamic loading to trigger the instability of sensitive clay.

The findings are based on a few key concepts. First, it must be recognized that structured sensitive clay is typically stiffer than remolded clay and hence, unless softening is triggered, sensitive clay may be expected to perform better than insensitive clay of the same residual strength. Second, softening behavior, which leads to localization on a thin shear band, is counteracted to some extent by strengthening associated with increase in strain rate. The rate effect favors thick shear bands, while softening leads to thin shear bands. Another factor affecting shear band behavior is that thick bands may be undrained during dynamic shear while thin shear bands are expected to be drained during static shear. Thirdly, the slope failure mechanisms for static and dynamic loading are quite different. During static (constant) loading, large deformations initiate precisely when one failure mechanism has a factor of safety $FS < 1.0$. But, during dynamic loading, strains may be limited by the inertia of the slope and the short duration of the loading, even if $FS \ll 1$ on a multitude of adjacent overlapping mobilized failure mechanisms. Thus, dynamic loading can lead to diffuse (wide) shear zones composed of a continuous band of the mobilized failure mechanisms. One conclusion is that the deformation required to soften a sensitive clay slope is expected to be larger for dynamic deformation than for static deformation.

1. Introduction

Static and/or cyclic softening and strain localization of sensitive clay are important in the stability of coastal and submarine slopes or levee embankments. Instability of sensitive clay slope may be triggered by factors such as leaching, external loading, internal weathering, physico-chemical activity, and earthquakes. Because of volumetric collapse during the remolding process, significant deformation may occur when drainage is allowed.

Evidence indicates that for sensitive clay, after a fraction of a meter of sliding deformation under static gravity loading the shear strength on a shear plane degrades dramatically and catastrophic failure can result [13,26]. A typical example of a recent devastating event can be found in the sudden collapse of Leda clay, Saint-Jude, Quebec in Canada, May 2010 [26]. Strain softening of sensitive clay under static loading has caused extensive submarine or in-land landslides [3,6,12,17,25,33]. Researchers have shown that significant damage in the 1989 Loma Prieta earthquake occurred in areas underlain by the young bay mud deposit [32,36]. The Turnagain Heights landslide which occurred due to the Alaska earthquake in 1964 is one example of how sensitive clay slopes can made unstable by seismic loading [29,30,35]. There have been well-known case histories about cyclic softening such as in Anchorage from 1964 Alaska earthquake [20] and Wufeng in Taiwan, from 1999 Chi-Chi earthquake [11]. But few other examples exist in the literature.

The question is: if the ground moves a fraction of a meter due to earthquake shaking, could sensitive clays be just as easily remolded and hence be expected to trigger a catastrophic failure? Two reasons why we expect different relationships between deformation and strength loss are: seismic (dynamic) failure mechanisms are fundamentally different from gravity driven (static) failure mechanisms, and rate dependent shear strength

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hinders localization of deformations into distinct shear planes. To study the behavior of strain softening slopes under dynamic and static loading conditions, physical model tests using a 1 m radius geotechnical centrifuge were performed on clay slopes of varying sensitivity. High plasticity remolded San Francisco Bay Mud with 3–5% cement is used to match target strength levels and moderate sensitivity range [28]. A low plasticity Yolo Loam with 2–3% cement is used for mimicking highly sensitive clay behavior [27,28]. To help characterize the material, vane shear tests were conducted and uniaxial compression tests were executed for some cement treated and untreated clay samples.

2. Background

2.1. Softening and strain localization in clay

Softening results in localization of strains in a thin shear zone. For a given displacement, as the thickness of the shear zone reduces, shear strains in the shear band (displacement/thickness) increase and the rate of remolding with respect to displacement increases [1,4,5,21].

Sensitive clay has a metastable structure at a large void ratio, but upon remolding during undrained shear, the structure is destroyed and the material approaches the remolded critical state at very low effective stress. The collapse to very low effective stress results in very small residual shear strength.

For a sensitive strain softening material, after reaching the peak strength, the p′–q path approaches the origin; shear stress drops to the residual strength (Fig. 1(a)) and positive pore pressures develop on the shear plane. The positive pore pressures on the shear plane dissipate with time and hence from this point of view residual strength increases as the rate of loading decreases [4,5,19]. Thakur and Nordal [34], explain why the softening rate in the shear band is less remarkable if displacements are slow enough to allow excess pore pressure to drain. Gylland et al. [19] showed that the strain softening response and the shear band thickness are strongly affected by rate dependency through local drainage that occurs between the shear band and the surrounding intact clay. On the other hand, if shear is very rapid and the shear band is essentially undrained, then the strength increases as rate increases.

In dilatant material (e.g., heavily overconsolidated clay), water content and void ratio can tend to increase, leading to softening associated with dilation on the shear band. Outside of the shear band, stress–strain behavior is like elastic unloading (Fig. 1(b)).

Global measurement of strain behavior can only show the average strain inside and outside of localized shear band. Therefore, the global rate of softening is affected by the thickness of the shear band (Fig. 1(c)) relative to the specimen size. For a given Δd, as the thickness of the shear band decreases the global rate of softening increases.

Several factors affect the rate of softening. And, the different causes of sensitivity will result in structures that are more easily broken down. A plastic clay with sensitivity due to thixotropic hardening alone, for example, may soften slowly while an open fabric of rigid silty particles connected by brittle cement might be broken with a relatively small amount of remolding energy (Fig. 2).

2.2. Strain rate effect

It has been well established that undrained shear strength of clay increases with shear strain rate [14,18,23,24,37]. According to many researchers [2,7–9,18,23,31,38], undrained shear strength of clay increases with strain rate at about 5–15%/log cycle of strain rate. Geotechnical failures driven by static loading may occur in hours or years, and hence strain rates might be on the order of 10^0–10^{-4}%/h. Insitu tests such as the CPT may produce strain rates on the order of the penetration velocity divided by the cone diameter V_{cone}/D_{cone}=(20 mm/s)/35 mm=10^5%/h and laboratory tests being about 10^0%/h [12].

3. Test program

3.1. Program design

A series of static and dynamic centrifuge experiments were performed to study softening for both moderately and highly

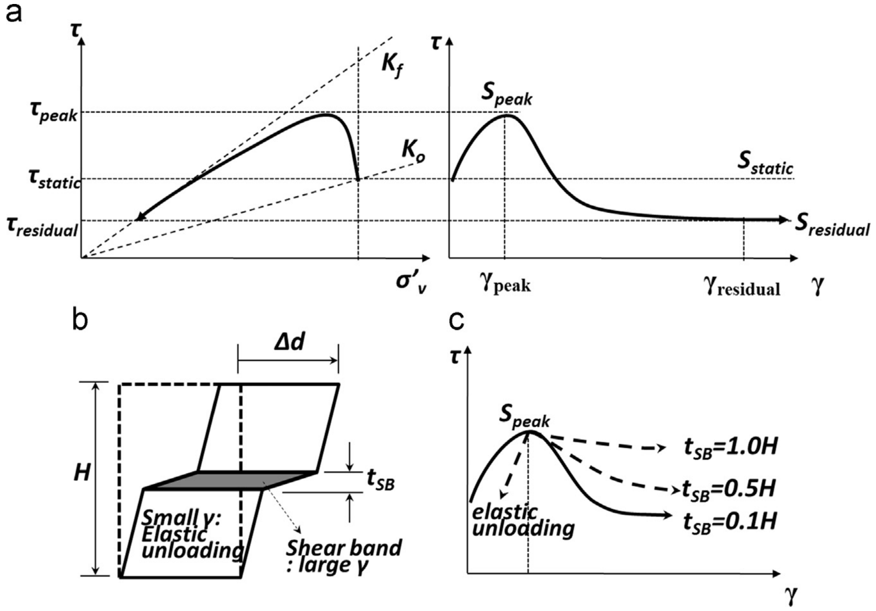

Fig. 1. Strain softening behavior and its relation to the shear band formation. Note, σ'_v=vertical effective stress, τ=shear stress, S=shear strength, γ=shear strain, K_o=earth pressure coefficient at rest, K_f=earth pressure coefficient at failure, H=initial height of the soil element before shearing, Δd=horizontal displacement by shearing, t_{SB}=thickness of shear band.