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Numerical Modeling of Failure Mechanisms in Sensitive Soft Clay—Application to Offshore Geohazards

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Abstract

The paper presents a numerical framework for stability analysis of submarine slopes of soft sensitive (strain-softening) marine clay. It is demonstrated how large slides may develop in even gently inclined slopes by the progressive failure mechanism where the shear strength is softening from its peak value down to its significant lower residual value. The typical stress-strain behaviour of sensitive clays is presented and the process of shear strain localisation is explained. The effect of local drainage and strain rate on the shear band thickness is discussed. A finite element procedure is presented, accounting for the strain softening material behaviour under undrained loading. The procedure can be applied for assessing the potential for progressive failure and identifying the critical failure mechanisms of sensitive clays. The numerical analysis of a progressive failure is demonstrated by an example for a 400 m long slope of inclination 4.2^0 where the failure is triggered by a rock fill being constructed on the crest of the slope.

Introduction

Submarine slides are a direct potential threat to sub sea infrastructure and may generate tsunamis. Slope stability analyses are therefore a key activity in offshore geohazard studies. Such analyses have traditionally been performed by limit equilibrium based calculation methods (LEM) such as the various "method of slices" (e.g. Bishop & Morgenstern, 1960; Janbu, 1973) or on the basis of infinite slope theory (Teunissen & Spierenburg, 1995). These methods assume perfectly-plastic soil behaviour. Realizing that marine clay deposits often are sensitive to some degree, and thus not perfectly-plastic but strain-softening, the traditional calculation methods have limited validity. They fail to explain the vast areas of seemingly stable slopes being engaged in submarine slides that may be triggered by some local disturbing agent. These slides can be explained by considering the progressive failure mechanism which is a direct consequence of the softening stress-strain behaviour. The Storegga slide (Kvalstad et al., 2005) is probably the best documented example of this kind.

It has since long been recognised that shear strength softening may lead to the progressive failure slide mechanism where the softening zones spread long distances along the slope. However contributions from e.g. Skempton (1964) and Bjerrum (1967) mostly refer to frictional softening in overconsolidated clay and clay shale. The mechanism of shear strength softening caused by pore pressure build up from contractancy in sensitive clays has not until recently been fully appreciated as an important factor in progressive failure of soft sensitive clays (Bernander, 2000; Andresen & Jostad, 2002).

A submarine slope may be "loaded" by various triggering mechanisms such as for example rock dumping, seismic events and erosion. This loading causes local stressing and some parts of the slope may reach the peak strength first and local failure develops. This is illustrated for a simple rotational slope failure in Figure 1. The strains increase further after local failure and the shear stresses reduce from the peak strength towards the residual strength. The capacity (failure load) is reached before a full failure mechanism has formed. With increased deformations post-peak, a fully developed failure surface eventually forms where the residual strengths have been reached along the entire surface.

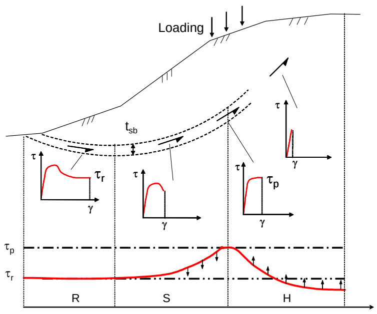

Figure 1 Illustration of rotational progressive failure mechanism in a slope with strain-softening clay with stresses and strains at failur.

The safety margin or the capacity against failure is therefore generally less for a strain-softening material compared to a perfectly-plastic material with the same strength τ_p. Because the stresses along the failure surface depend on the