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Failure of a soft cohesive soil subjected to combined static and cyclic loading

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Abstract

This paper describes the type of failure that a soft cohesive soil can exhibit when acted upon by combined static and cyclic loading. The conclusions are based on the results of a comprehensive experimental research in which, in addition to identification and classification testing, 15 monotonic simple shear tests and 138 cyclic simple shear tests were carried out in which, prior to the cyclic shear stresses, different levels of monotonic shear stresses were applied. Laboratory tests were performed on undisturbed samples taken from the southern area of the port of Barcelona, Spain. In general, the results thus obtained indicate that the undrained shear strength for a given number of cycles is clearly affected by the initial shear stress, as it is explained in this paper.

Keywords: Simple shear test; Biased shear stress; Cohesive soils; Dynamic load; Effective stress; Failure; Laboratory test; Liquefaction; Porewater pressure; Shear strength; IGC: D01; D06; D07

1. Introduction

Generally speaking, the international geotechnical community has focused its attention on the study and comprehension of the knowledge acquired in the cyclic behaviour of granular materials, particularly loose sand, since this implies a high risk of liquefaction and, on the contrary, little attention has been paid to investigating some aspects of the response of cohesive soils when subjected to cyclic loading.

The Spanish Ministry of Public Works (2005) indicate the need to investigate the cyclic behaviour of the foundation soils when they support structures subjected to repeated loading conditions, similar to those created by the action of waves during a storm. The work described in this paper was performed to study the foundation of a structure that was designed to withstand the effect of waves in the southern part of the Barcelona harbour. In particular, the investigation deals with the influence of the combination of static and cyclic shear stresses in the behaviour of the foundations of vertical breakwaters on soft cohesive soils that are subjected to cyclic wave forces. Foundation shear stresses may be idealised as shown in Fig. 1. It can be observed that some of the stress conditions can be simulated in the laboratory by means of cyclic simple shear tests while others would require the execution of cyclic triaxial tests under compression or extension conditions.

The research is oriented to investigate the strength of the soil under the combination of stresses identified as 1 and 3 in Fig. 1, since these conditions are reproduced by means of the cyclic simple shear test.

The strength of clays under earthquake loading conditions was investigated by Seed and Chan (1966), Idriss et al. (1978) and by Lee and Focht (1976) for regular cyclic loading. Chang and Hong (2008) and Huang and Chuang (2011) analysed the effect of the percentage of fines on liquefaction. The strength

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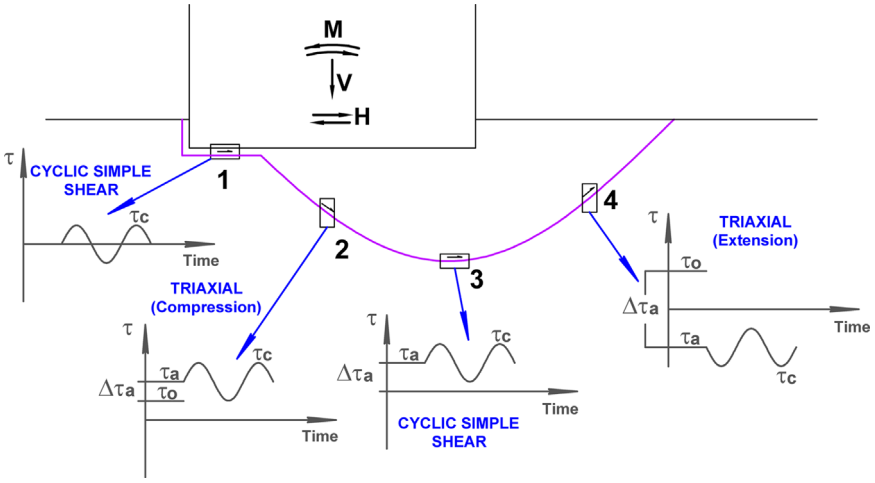

Fig. 1. Idealised diagram of the stress conditions developed along a hypothetical failure surface and that can be simulated by means of cyclic simple shears tests and triaxial tests.

of three marine clays was the object of investigation by Koutsoftas (1978), Koutsoftas and Fischer (1980) and Moses and Rao (2007). The behaviour of clays under cyclic loading has also been investigated by Matsui et al. (1980), Kokusho et al. (1982) and Ansal and Erken (1989).

The main parameter to quantify the strength of a given clay subjected to impulsive or cyclic loading has been the undrained shear strength, but some authors like Sangrey et al. (1969) have approached the problem in terms of effective strength parameters.

Some local studies of typical clay response to repeated or cyclic loadings have been published by Andersen (1975 and 1976) (Drammen clays) or by Stokoe and Lodde (1978) (San Francisco Bay mud) or Díaz-Rodríguez (1989) (Mexico City clays).

More recently, detailed studies of the response of clays to cyclic loading have been undertaken to investigate the effects of some particular aspects, like the effect of combined static and cyclic loading that has been studied by Andersen and Hoeg (1992) or the effect of irregular loading cycles as reported by Andersen et al. (1992) or Idriss et al. (1978), who – based on the results of a series of controlled-strain cyclic tests – developed a nonlinear model that takes into account the degradation in soft soils due to cyclic loading; this degradation was studied by means of undrained cyclic triaxial and cyclic simple shear tests.

Over last few years, this matter has been studied by researchers who in the past had focused their attention on the earthquake-induced liquefaction phenomenon only. Boulanger and Idriss (2004) oriented their investigations to the evaluation of the liquefaction potential of silts and clays. They proposed to estimate the equivalent number of uniform cycles leading to softening as a function of the seismic magnitude (M_w). They imply that, from a practical point of view, the equivalent number of uniform cycles leading to softening of clays is somewhat larger, one to three times larger, than that corresponding to liquefaction of sands.

Boulanger and Idriss (2006, 2007) refer to the similitude existing between the liquefaction phenomenon that affects loose sands and cyclic softening induced on silts and clays. To estimate if a cohesive soil tends to develop a behaviour similar to that of loose sands and, therefore, is susceptible to be affected by the liquefaction phenomenon, they proposed a criterion based on the location of the soil within Casagrande's Plasticity Chart; in addition, they provided a hands-on approach to assessing whether a soil is susceptible of being affected by liquefaction or by cyclic softening.

With the exception of some investigations, the specialized literature reports very few cases in which the cyclic behaviour of cohesive soils has been studied under stress combinations.

Authors such as Seed and Chan (1966), Andersen and Hoeg (1992) and Hyodo et al. (1994) have performed laboratory tests in which sustained static stresses have been combined with cyclic stresses. Seed and Chan found out that upon increasing the magnitude of the sustained static stress, under the same magnitude of the cyclic stress, there is a significant decrease of the number of cycles necessary to reach failure. Andersen and Hoeg found that the level of effective stresses governs the behaviour of clays subjected to cyclic loading and it might be related to the generation of porewater pressure, to the development of cyclic strains and to the number of cycles necessary to reach failure. Hyodo et al. (1994) investigated the effect of a combination of static stress and cyclic stress on the behaviour of clays under triaxial loading.

The experimental investigation described in this paper is part of the doctoral thesis of Patiño (2009) at the Universidad Politécnica de Madrid.

The effect of biased cyclic loading on the liquefaction of sands under simple shear has been published by Soriano et al. (2011).

2. Description of the tested soil

All of the tests, including the classification tests and the monotonic and cyclic simple shear tests, were executed with specimens cut from undisturbed samples recovered from the subsoil at the port of Barcelona, in particular those obtained