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Evaluation of the risk of sudden failure of a cohesive soil subjected to cyclic loading

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ABSTRACT

This paper presents a proposed methodology to evaluate the risk of sudden failure experienced by a soft cohesive soil when acted upon by combined static and dynamic loading. The research is based on the results of a comprehensive experimental study in which 155 cyclic simple shear tests were performed on undisturbed specimens recovered at the port of Barcelona, Spain. The proposed experimental program is described in detail in addition to the systematic process of analysis to properly study and interpret the results obtained for samples subjected to cyclic loading. In general, the results indicate that the combination of monotonic and cyclic stresses governs pore water pressure generation, the pore water pressure generated during cyclic loading controls the risk of sudden failure, and by means of simple correlations among the stiffness modulus, the effective stresses, the cyclic strains and the number of cycles, it is possible to combine families of curves to allow for an evaluation of the risk of sudden failure.

1. Introduction

Researchers and geotechnical engineers have paid more attention to the study and understanding of granular materials than to the analysis of cohesive materials. This is mainly because most reported failures that are induced by dynamic loads correspond to the performance of seismic action on this type of soil. Thus, potentially dangerous areas are identified as loose and saturated granular soils, where the phenomenon of liquefaction can occur. Liquefaction involves a cancellation of the effective stress so that the ground is not able to withstand any load.

However, in the case of cohesive soils, the phenomenon is different from liquefaction and sudden failure is identified when the strains grow uncontrollably. In general, this failure does not correspond to the situation of null effective stress and should be properly identified to assess the risk of sudden failure.

For proper study of the dynamic phenomenon caused by repeated loads acting on a soil, it is first necessary to identify the factors influencing the response of the soil. According to Hardin and Black [1], the dynamic shear modulus (G) that defines the deformability of soil submitted to a cyclic shear load depends on multiple variables, including the initial effective normal stress, void ratio, history of vibrations, degree of saturation, initial shear stress, grain characteristics (i.e., shape and size), amplitude of the cyclic loading, vibration frequency, soil structure and temperature.

However, under theoretical conditions, a saturated and normally consolidated soil is assumed, the temperature is neglected and factors representing other properties, such as the soil structure and characteristics of the grains, are considered to be parameters of the fit curves. The research 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 Barcelona harbour. Thus, this work focuses more on cyclic actions with high periods and does not significantly consider the influence of the frequency of the load on soil.

Based on the above, the number of variables to be considered for an appropriate cyclic characterization can be reduced to the dynamic shear modulus (G), initial effective normal stress (σ'_{v0}), static shear stress (τ_O), cyclic shear stress (τ_c) and number of cycles (N). For each value of the shear stress (τ_c), the corresponding values of cyclic deformation (γ_c) and excess pore water pressure (u) must be predicted.

It is necessary to consider the different combinations of static and cyclic shear stresses because the state induced by the initial load predisposes the stress-strain response of soil conditions in a manner that is clearly distinguishable from any other response.

The main topic studied in this investigation is the sudden failure that affects soft cohesive soils subjected to dynamic loading. Sudden failure is a phenomenon in which cohesive soils experience, under dynamic loading, a radical loss of shear strength and consequent large deformations.

This investigation studies the influence of the combination of static

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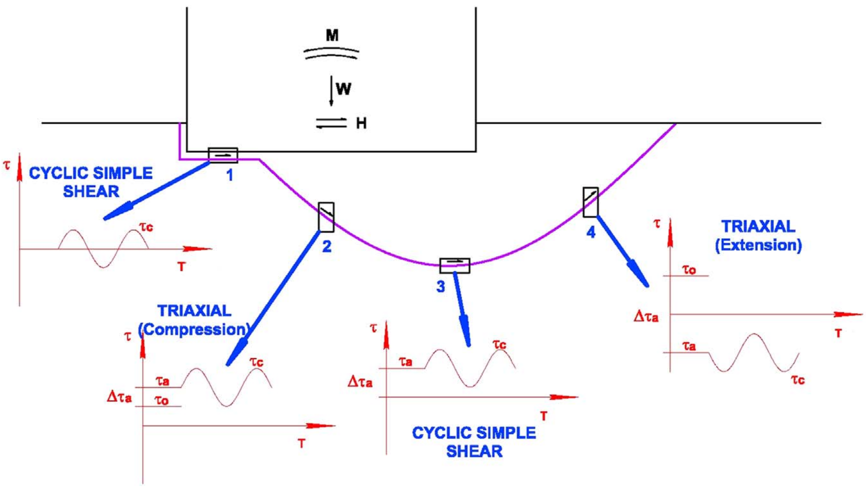

Fig. 1. Schematics to idealize the stress conditions developed along a hypothetical failure surface and that can be simulated by means of cyclic simple shears tests and triaxial tests.

and dynamic shear stresses on the behaviour of a cohesive soil subjected to dynamic stresses under a structure supported by such soil, and as a result, the stress distribution is quite complex. It includes idealizations such as that shown in Fig. 1, in which it can be observed that some of the stress conditions can be simulated in the laboratory by means of cyclic simple shear tests and others can be simulated through the execution of cyclic triaxial tests of a compressive nature in some cases and of extension conditions in others.

The research is oriented to the effect, in the evaluation of the risk of sudden failure, of the combination of stresses identified as 1 and 3 in Fig. 1 because these conditions are idealized by means of the cyclic simple shear test.

The contribution of this research is to present a proper analysis methodology for assessing the risk of sudden failure using novel empirical functions that can be commonly applied; however, constants for these expressions must be obtained for each particular location. This methodology incorporates appropriate experimental characterization and sample handling and a particular form of analysis and presentation of results that identifies a new structure of empirical formulas that should be adjusted to the available soil samples.

For cohesive soils, the effects of static stress history on the behaviour of static stiffness have been well studied (Atkinson et al. [2]; Finno and Chung [3]; Jovicic and Coop [4]; Cho and Finno [5]; Lings et al. [6]; Santagata et al. [7]; Finno and Cho [8]). However, there are few studies concerning the effects of the number of cycles and of static stress on the shear modulus of saturated clays submitted to cyclic loading.

Cyclic softening of clays is commonly understood to be a reduction in soil stiffness and strength due to repeated cyclic loading, as discussed in [9]. The behaviour of clays under cyclic loading has also been investigated by Matsui et al. [10], Kokusho et al. [11], Ansal and Erken [12], and Subramaniam and Banerjee [13]. Idriss et al. [14] and Patiño et al. [15] showed that the initial shear stiffness of soft clay is reduced after several cycles, whereas Matasovic and Vucetic [16] further discussed the coupling of the cyclic softening of clay and pore water pressure generation. They proposed a model to predict the softening behaviour based on the cyclic shear strain amplitude using a threshold strain concept. The test results of Soroush and Soltani-Jigheh [17] suggest that the post-cyclic undrained shear strength and secant deformation modulus of the specimens of mixed clayey soils are comparatively reduced from the pre-cyclic behaviour. The reduction level depends on the granular material content, cyclic shear strain level, and effective confining pressure.

The strength of clays under earthquake loading conditions was investigated by Seed and Chan [18], Idriss et al. [19], Lee and Focht [20] and Tsai et al. [21]. Chang and Hong [22], Huang and Chuang [23], El Takch et al. [24] and Kim et al. [25] analysed the effect of the percentage of fines. The strength of three marine clays was the object of investigations by Koufsoftas [26], Koufsoftas and Fischer [27] and Moses and Rao [28].

Some of the most interesting cases of damage involve ground failure in areas underlain by low plasticity clayey soils [29]. Martin et al. [30] concluded that elastic silt and a lean clay layer exhibited a radical loss of shear strength under dynamic loading, but a definitive explanation for significant earthquake-induced settlements in a high-plasticity clay stratum has not yet been found.

Over the course of the last few years, this subject has been the source of study by researchers who in the past had focused their attention on the liquefaction phenomenon only. Boulanger and Idriss [31] oriented their investigations on the study of silts and clays. They proposed to estimate, as a function of the seismic magnitude, the equivalent number of uniform cycles leading to softening. Recently, Boulanger and Idriss [32] developed a procedure for evaluating the potential for cyclic softening in clay-like fine-grained soils during earthquakes. Their procedure uses a stress-based approach comparable to that used in semi-empirical procedures (e.g., [33]). The procedure is to assess the factor of safety (possibility of onset of significant strains or strength loss) in saturated silts and clays during earthquakes.

Seed and Chan [18] discovered that upon increasing the magnitude of the sustained static stress under the same magnitude of the cyclic stress, there is a significant decrease in the number of cycles necessary to reach failure. Andersen and Hoeg [34] found that the level of effective stresses governs the behaviour of clays subjected to cyclic loading and that it might be related to the generation of pore water pressure, to the development of cyclic strains and to the number of cycles necessary to reach failure. Hyodo et al. [35] investigated the effect of a combination of static stress and cyclic stress on the behaviour of clays under triaxial loading.

2. Description of the tested cohesive soil

The soil deposit where the samples used for the experimental stage of this investigation were recovered is located in the subsoil of the Port of Barcelona in the mouth of the Llobregat River discharging into the Mediterranean Sea. The deposit is part of the Llobregat Delta, which has an alluvial origin that dates back to the Recent Quaternary and, more specifically, to the Holocene era.

Undisturbed samples were recovered from subsoil at the Port of Barcelona, as shown in Fig. 2, from exploratory borings SA-1 and SA-2 in particular. These borings were advanced from the deck of Prat Pier.

According to Alonso et al. [36], the stratigraphic profile of an area close to the Prat Llobregat Pier is depicted in Fig. 3. As can be observed