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Revisiting the Bjerrum's correction factor: Use of the liquidity index for assessing the effect of soil plasticity on undrained shear strength

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ABSTRACT

The undrained shear strength (s_u) of fine-grained soils that can be measured in situ and in laboratory is one of the key geotechnical parameters. The unconfined compression test (UCT) is widely used in laboratory to measure this parameter due to its simplicity; however, it is severely affected by sample disturbance. The vane shear test (VST) technique that is less sensitive to sample disturbance involves a correction factor against the soil plasticity, commonly known as the Bjerrum's correction factor, μ. This study aims to reevaluate the Bjerrum's correction factor in consideration of a different approach and a relatively new method of testing. Atterberg limits test, miniature VST, and reverse extrusion test (RET) were conducted on 120 remolded samples. The effect of soil plasticity on undrained shear strength was examined using the liquidity index instead of Bjerrum's correction factor. In comparison with the result obatined using the Bjerrum's correction factor, the undrained shear strength was better represented when s_u values were correlated with the liquidity index. The results were validated by the RET, which was proven to take into account soil plasticity with a reliable degree of accuracy. This study also shows that the RET has strong promise as a new tool for testing undrained shear strength of fine-grained soils.

1. Introduction

The shear strength of fine-grained soils generally can be divided into two parts as drained and undrained shear strengths depending on whether the pore water pressure dissipates or not. In situ shear strength of soils is recorded almost unexceptionally in undrained conditions. There are other cases such as the short-term stability analysis of slopes requiring the undrained shear strength.

The most common tool used to measure the in situ undrained shear strength is the field vane shear test (VST_F). The laboratory techniques for this test briefly include the unconsolidated-undrained test (UUT), unconfined compression test (UCT), direct shear test (DST) and vane shear test (VST_L).

The VST technique was originally developed by the British Army to measure the cohesion of clay sediments, which is the shear strength in certain special cases (Skempton, 1949; Boyce, 1983). The laboratory version of VST, or the miniature VST, may be used to obtain the undrained shear strength of fine-grained soils. The test provides a rapid determination method for the shear strength of undisturbed, remolded and reconstituted soils. It is recommended for use on soils with undrained shear strength less than 100 kPa (ASTM D4648–00, 2000). Essentially, the miniature VST is capable of measuring undrained shear strength of soils from a few kPa to about 100 kPa, which roughly represents the plastic range for most fine-grained soils.

Sample disturbance is one of the most important factors influencing the undrained shear strength of fine-grained soils measured by laboratory techniques. The UCT is one of the most common tools used to determine the undrained shear strength of soils. The undrained shear strength determined in this way is highly sensitive to disturbance caused by the sampling process, compared to other means such as consolidation or triaxial tests (Tanaka et al., 1992; Lacasse et al., 1994; Tanaka, 1994). Based on the conclusion that the undrained shear strength obtained from VST_L is nearly the same as that from VST_F, Tanaka (1994) showed that the vane shear strength is not significantly influenced by the mechanical disturbance caused by sampling, release of overburden pressure, or increase in the confining pressure when the vane is inserted. This important conclusion can be considered as the basis of the VST's superiority over the UCT, and thus the underestimation of undrained shear strength caused by the sample disturbance during the UCT can be prevented.

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Various researchers have pointed out that the undrained shear strength determined by the VST is influenced by various factors, such as over-consolidation ratio (OCR) (e.g. Jamiolkowski et al., 1985), pre-consolidation pressure (e.g. Skempton, 1957; Larsson, 1980), and particularly the soil plasticity.

Skempton (1957) found that the ratio of undrained shear strength to vertical effective stress of normally consolidated clays is a linear function of the plasticity index for the VST:

$$\frac{s_u}{\sigma'_v} = 0.11 + 0.0037PI \tag{1}$$

where s_u is the undrained shear strength, σ'_v is the vertical effective stress, and *PI* is the plasticity index. Watson et al. (2000) examined factors such as rotation rate and waiting time that may influence VST results. They also introduced a new form of 'helical' VST in which the standard vane apparatus is continuously rotated during penetration into the soil sample, resulting in a complete profile of soil strength.

Bjerrum (1954) stated that the normally consolidated Norwegian clays show a linear increase in undrained shear strength with depth, which can be expressed by a constant ratio of shear strength to effective overburden pressure. If this ratio is determined for various clays, a close correlation can be found between the ratio and the plasticity index.

Bjerrum (1973) proposed a correction factor μ (Fig. 1) for shear strength obtained from the VST_F, based on many failure cases. In his proposal, as the effects of anisotropy and strain rate on the shear strength were considered, the factor μ can be determined from the plasticity index. This correction factor is still in use to date.

Tanaka (1994) stated that the shear strength modified by Bjerrum's correction factor is considerably conservative for Japanese marine clay, in comparison with the unconfined compressive strength. In this regard, Dolinar (2010) pointed out that the normalized undrained shear strength can be correlated with the plasticity index (*PI*) for non-swelling clays, while in swelling clays, the plasticity index does not influence the undrained shear strength of normally consolidated soils. Thus, there is no uniform criterion to determine the normalized undrained shear strength from the plasticity index for all fine-grained soils. Kayabali and Tufenkci (2010) stated that, although the VST_L provides a reasonable undrained shear strength value at the plastic limit (*PL*), it overestimates the undrained shear strength at the liquid limit (*LL*). They recommended that care should be taken when the laboratory VST is used to determine the undrained shear strength at water contents near the liquid limit.

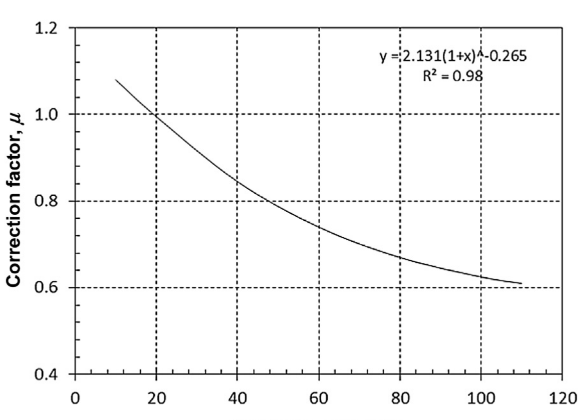

Fig. 1. Bjerrum's correction factor with respect to plasticity index (Bjerrum, 1973).

In an attempt to compare natural plastic clays to remolded ones, Graham and Li (1985) examined how the general concepts of soil behavior developed from remolded samples can be applied to samples of a complex, natural clay. They found that, in terms of stress–strain behavior, strengths and yielding, the natural and one-dimensionally consolidated remolded samples of Winnipeg clay show similar though not identical results. In this investigation, we consider this conclusion and the similarity between the undrained shear strengths obtained from VST_L and VST_F on remolded fine-grained soils as noted by Tanaka (1994), the results of which are intended to be applied to fine-grained natural soils.

Kayabali and Ozdemir (2013) proposed the reverse extrusion test (RET) as an alternative to the UCT. By applying this technique on 60 remolded and 75 natural soil samples, they showed that the RET yields a consistent ratio of 14–15 for the extrusion pressure over the unconfined compressive strength. They stated that the RET is likely to eliminate the difficulties involved in the testing of soft to very soft soils, as well as the strength anisotropy for fissured soils using the conventional UCT owing to the confinement provided by the testing apparatus. In conclusion, they pointed out that the RET can better represent the undrained shear strength of soil than the UCT, and that the results may be improved further by taking into account soil plasticity.

The scope of this investigation is to revisit Bjerrum's correction factor in assessing the effect of soil plasticity on the undrained shear strength of fine-grained soils by using a different approach, as well as employing a relatively recent technique to validate the use of the proposed alternative.

2. Materials and methods

The soil samples used in this investigation include remolded soil samples brought from different regions of Turkey to the university laboratory. All samples are oven-dried, pulverized and sieved through a #40 mesh.

The first tool used to assess the undrained shear strength of remolded fine-grained soils is the laboratory miniature vane shear device which is a Wykeham Farrance model WF2350. Regarding test standards, the guidelines of the ASTM D4648–00 (2000) are followed. The starting water content for the remolded samples to be tested using the VST_L is somewhat smaller than the liquid limit. The soil sample is wetted at this water content and mixed homogeneously prior to shearing. The next test is carried out by adding small amount of dry soil sample to the previous wet mixture and the new sample is remixed presumably at slightly lower water content. The VST_L has four torque springs for different levels of soil stiffness. The appropriate spring is selected for each test so that shear failure will occur between 20° and 90° of sample rotation. The test is repeated 10 times for each soil sample at different water contents. A plot showing the relationship between undrained shear strength (s_u) and water content (w) obtained from the VST_L is presented in Fig. 2 for sample No. 12.

The second tool used in the investigation is the reverse extrusion device whose principle was first introduced by Whyte (1982). While more details can be found in Kayabali and Tufenkci (2010) for this new test in soil mechanics, a brief summary is presented here for convenience. The container has an inner diameter of 38 mm. The top cap is removable for sample extraction after the test is finished. The rammer has a die orifice of 6 mm, which controls the plastic failure of the sample. There is a small clearance between the rammer and the container to prevent metal friction between parts. A general view for this simple setup is shown in Fig. 3. The homogeneous wet mixture of remolded soil is placed in the container and tapped gently with the rammer. The height of sample inside