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The Measurement of the Undrained Shear Strength of Muds Using a Cylinder

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Abstract. Mudflows are powerful agents of degradation of natural slopes and are reported to cause loss of life and destruction of civil engineering structures. Mudflows are reported to behave as purely cohesive materials. Therefore, their stability is often analyzed in terms of their undrained shear strength (c_u). A new approach to measure the undrained shear strength of muds is called the "cylinder strength meter test" is presented. The new approach uses a cylinder as a measuring tool and the theory developed by Sokolovskii to calculate the indentation pressures developed in a Tresca plastic when a cylinder penetrates it. The implementation of the new approach is carried out in the laboratory by measuring the c_u of artificially prepared muds. The muds are made of clay alone and mixtures of clay and sand and clay and glass beads. The clay used in the experiments was kaolinite clay. The effect of the concentration by volume of the granular materials in the mixtures on their c_u is also analyzed. A review of other methods such as the vane shear test developed to measure the shear strength of muds is also presented. Advantages of using the new approach rather than the vane test is also presented.

Keywords. Undrained shear strength, vane test, cylinder strength test, muds, clay-granular mixtures.

1. Introduction

Subaerial and submarine mudslides are powerful agents of degradation of subaerial and submarine slopes and are reported to cause during their travel destruction of civil engineering structures such as buildings, oil platforms, and communication cables [1, 2]. Mudslides often take place on the shallow sections of subaerial and submarine slopes. The soil in these sections has high water contents and low shear strength [3]. According to Schapery and Dunlap [4], "the sediments are so weak that core samples sag under their own weight." Civil Engineering structures are often built on natural slopes and on sea floor areas prone to mudslides. Therefore, a knowledge of the stability against sliding of mud covered areas where structures are going to be located is of primary consideration [5].

The stability analysis of subaerial and submarine mud slopes can be made in terms of total or effective stresses. However, due to the difficulty in the measurement of pore water pressures in muds, the total stress analysis is chosen. Also, because the materials associated with muds are too soft to be tested in conventional tests such as the tri-axial

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or the direct shear tests, the vane shear apparatus has been used to obtain the undrained shear strength, c_u, of muds.

1.1. The vane shear strength test in muds

One of the methods used by geotechnical engineers to measure the c_u of muds is the vane shear test [6]. The vane consists of four rectangular paddles at right angles to each other and that are fixed at the end of a rod (Figure 1). The vane is forced into the soil and then rotated at a constant rate while the torque, T_m, is measured. The torque resistance is used in conjunction with Eq. (1) to obtain the c_u of soft cohesive soils.

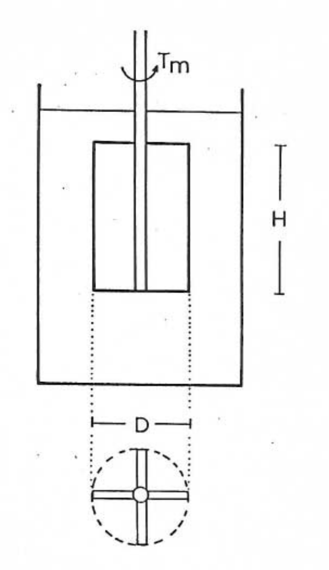

Figure 1. The vane shear apparatus.

$$c_u = \frac{T_m}{\pi D^2 H(1+\frac{D}{3H})} \tag{1}$$

In Eq. (1), H is the height of the vane blades and D is their diameter.

The vane shear tests works on the assumption that the failure surface for the cu determination in muds, is that of the cylinder with dimensions equal or slightly larger than those of the vane blades [6]. However, due to the fluidity of the muds, the failure surface induced by the vane can not rigorously be represented as that of a cylinder [7].

Also, it has been found by Krone [8] that during the rotation of the vane in muds, collisions and adhesion between the particles of clay take place that causes an increase of the muds' undrained shear strength. The above two important shortcomings of the vane shear test when applied to muds, therefore, reduces its reliability when used to measure c_u.

In the present study a new alternative to the vane shear test is presented. This new alternative is the cylinder strength test.

2. Theoretical approach of the alternative method to measure the c_u of muds

A new approach that will be called "the cylinder strength meter test" to measure the c_u of muds is presented. The new approach consists in slowly lowering a cylinder of known dimensions and weight into a mud sample. Measuring the depth of penetration of the cylinder into the mud, and calculating the strength of the mud required to support the cylinder at that depth.

The theory underlying the new approach is based on the support mechanism of the cylinder by the mud. It considers that the weight of the cylinder tends to cause it to sink in the mud. Whereas the undrained strength (bearing capacity) of the mud and its buoyancy tend to support the cylinder. Thus, at equilibrium conditions, the weight of the cylinder will be resisted by: (a) an upward force resulting from the c_u of the mud which can be calculated using the slip-line approach of Plasticity Theory for the case of a cylinder indenting a Tresca plastic [9], and (b) buoyancy which is equal to the weight of the displaced mud resulting from part of the cylinder penetrating the mud sample (Figures 2 and 3).

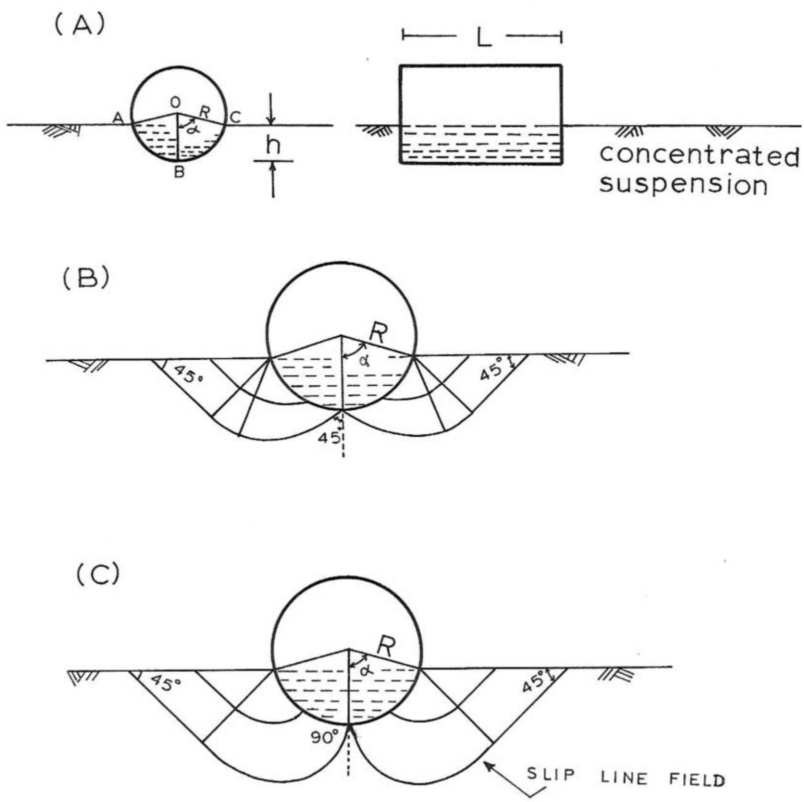

Figure 2. (A) Parameters used in the cylinder-strength test. (B) Slip-line pattern for the case of a cylinder with a smooth surface. (C) Slip-line pattern for the case of a cylinder with a rough surface [9].

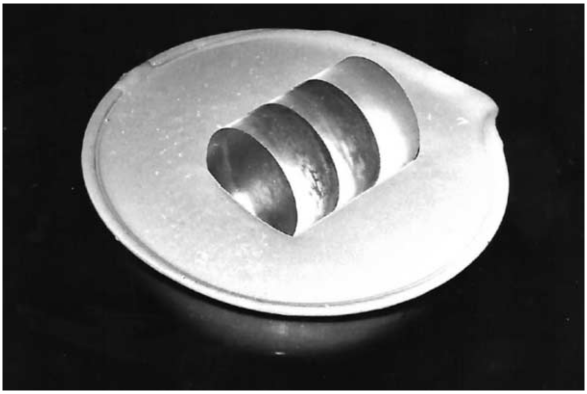

Figure 3. Cylinder with a smooth surface indenting a clay-water slurry.

2.1. Support of the cylinder by the mud

When a cylinder is slowly lowered into a mud sample (Figures 2 and 3), its weight will be supported by an upward force (bearing capacity) which depends upon the c_u of the mud, and by buoyancy, this being equal to the weight of the displaced mud. The weight of the cylinder is:

$$W = \pi R^2 L \gamma_c \tag{2}$$

where R is the radius of the cylinder, L is its length, and γ_c is its unit weight.

For the calculation of the upward force (bearing capacity) resulting from the c_u of the mud, the solution developed by Sokolovskii [9] for calculating the pressure developed in a Tresca plastic when a cylinder penetrates it will be used (Figure 2). Sokolovskii [9] used the slip-line approach of Plasticity theory in order to obtain his solution. According to Sokolovskii [9] when a *smooth* cylinder indents a Tresca plastic (in our case mud), the plastic develops an upward force which is equal to:

$$P_s = 2\, c_u\, R\, L\, [(\pi + 2) \sin \alpha + 2\, (1 - \cos \alpha - \alpha \sin \alpha)] \tag{3}$$

with he parameters associated with Eq. (3) are shown in Figure 2.

The buoyancy resulting when part of the cylinder penetrates the mud can be obtained from Fig 1(A) as:

$$P_b = R^2 L\, (\alpha - \sin \alpha \cos \alpha)\, \gamma_f \tag{4}$$

where γ_f is the unit weight of the mud.

At equilibrium conditions the following relationship applies:

$$W = P_s + P_b \tag{5}$$

After replacing Eqs. (2), (3), and (4) into Eq. (5) one obtains the relationship used to obtain the cu of muds when one uses a cylinder with a *smooth* surface:

$$c_u = \frac{R[\pi\,\gamma_c - (\alpha - \sin\alpha \cos\alpha)\gamma_f]}{2[(\pi+2)\sin\alpha + 2\,(1-\cos\alpha - \alpha\sin\alpha)]} \tag{6}$$

The value of α in Figure 2 can be obtained from:

$$\alpha = cos^{-1}\left(\frac{R-h}{R}\right) \tag{7}$$

Eq. (6) apply only for values of $\alpha \leq 90^0$ (Figure 2) . In Eq. (7), h is the depth of penetration of the clay slurry by the cylinder (Figure 2).

3. Implementation of the cylinder strength test in the laboratory

For the implementation of the cylinder strength meter test in the laboratory, mud samples having the same water-clay-Calgon concentration was mixed with different volume concentration of sand and glass beads. The clay slurry for the clay-sand experiments was made by mixing 697 grams of kaolinite clay, 243 grams of distilled water, and 36 grams of Calgon (hexamethaphosphate , a dispersive agent). The clay slurry for the clay-glass beads experiments was made by mixing 730 grams of kaolinite clay, 235 grams of distilled water, and 43 grams of Calgon . The kaolinite clay and the Calgon had a specific gravity G_s = 2.65 and a unit weight equal to 26 kN/m^3. The clay-water-Calgon were placed in a prismatic container with dimensions 20x20x20 cm and the contents were mixed using an electric mixer.

3.1. Clay-water-granular material mixtures

Hutchinson [3] and Vallejo [10] have reported that many mudflows in the field are formed of a mixture of sand or rock pieces and a matrix of clay. Therefore, in order to investigate the effect of granular materials on the c_u of the clay slurry, granular materials in the form of sand and glass beads were added to the clay slurry of known volume. The clay-water-Calgon had enough bearing capacity to support the sand and the glass beads in suspension. The sand used was a uniform, rounded, medium sand size with an average diameter , d_{50}=0.3 mm, G_s = 2.7, and unit weight, γ_s =26.5 kN/m^3. The glass beads used had an average diameter equal to 5 mm, a G_s = 1.55, and a unit weight, γ_b = 15.21 kN/m^3. The results of the experiments are shown in Figures 4 and 5.

3.2. Cylinder used

For the implementation of the new test in the laboratory, a smooth Plexiglass cylinder with a length, L = 4 cm, and a diameter, D = 3.48 cm, was used in thee laboratory experiments. The weight of the cylinder was, W = 0.45 N. The value of cu was obtained using Eq. (6).

4. Analysis of the results

Figure 4 shows the values of the c_u for different volume concentrations of sand in the mixture measured by both the vane shear apparatus and the cylinder strength meter test.

Figure 5 shows the c_u results using both the, the vane shear test and the cylinder strength meter test for different volume concentrations of glass beads in the mixtures.

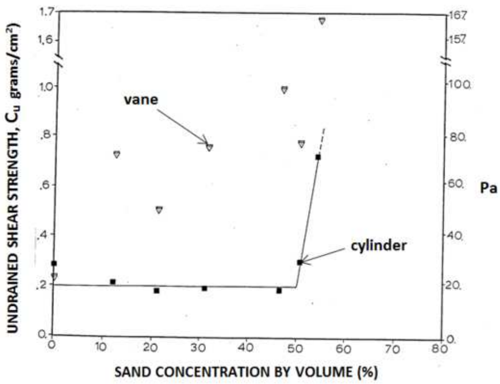

Figure 4. Relationship between the c_u and the volume concentration of sand in the mixtures for both the vane shear test and the cylinder strength test.

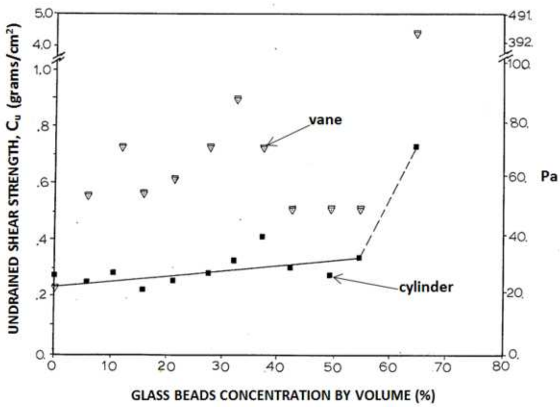

Figure 5. Relationship between the c_u and the volume concentration of glass beads in the mixtures for both the vane shear test and the cylinder strength test.

Figures 4 and 5 show the results of the cu measurements in the mixtures containing granular materials. The results show that for the clay slurry-sand or clay slurry–glass beads mixtures, the addition of sand and glass beads into the clay slurry did not substantially affect the c_u of the clay slurry up to a sand or beads volume concentration equal to 50%. Beyond this point, there was a sudden increase in the measured values of c_u. The reason for this sudden increase seems to reflect the fact that as sand and beads concentration increased beyond 50%, the individual particles begin to come into contact with each other, adding an additional structural support to the cylinder and frictional resistance to the rotation of the vane. The vane gave values that were larger than the c_u values measured by the cylinder. The reasons for this seems to be: (a) in the larger surface area (> πDH in Figure 1) induced by the vane when inserted and rotated in the mud, and (b) the large disturbance produced by the vane during its penetration and rotation in the mud.

5. Conclusions

A new approach for the measurement of the undrained shear strength (cu) of muds which were made of a mixture of clay and granular materials in the form of sand and glass beads is presented. The new approach uses a cylinder to measure cu and the results are compared with those measured using the vane shear apparatus. The results indicated the following:

a) For volume concentrations of sand and glass beads less than 50%, the cu of the mixtures was essentially that of the clay matrix. For volume concentration > 50% of granular materials, the shear strength of the mixture was increased by the presence of the granular materials in the mixture.
b) The values of the cu using the vane were much larger than those measured by the cylinder.

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