ADHESION AT JUTE GEOTEXTILE/CLAY SLURRY INTERFACE

SIEW-ANN TANⁱ⁾, NAIM MUHAMMADⁱⁱ⁾ and G.-P. KARUNARATNEⁱⁱⁱ⁾

ABSTRACT

In the use of jute fabric for the layered clay-jute geotextile-sand method for land reclamation, it is important to determine the interface behavior between the jute geotextile and various clay types commonly found in dredged seabed soils. Since jute is used to separate and support thin sand seams to form a horizontal drainage layer on top of a soft clay slurry, the interface behavior between the jute and the slurry must be examined. The adhesion on the interface between the jute and the clay slurry is measured using the incremental penetration of a suspended end-weighted jute sheet under an incremental load into a prepared clay slurry with various moisture contents, in order to obtain the interface stress value under a quasi-static condition. The effects of sheet width and sheet type were investigated earlier, and found to have a negligible effect on the interface adhesion for the water content range tested. In order to examine the effects of clay-type, several mixtures of Kaolin-Bentonite in fixed proportions were prepared to produce clays of liquid limits ranging from 100% to 400%. The interface adhesion between the jute and four samples of Kaolin-Bentonite mixes at various water contents from two to six times the liquid limits were measured using the vertical sheet test. These mixes included clay types with liquid limits from 100% to 400%, thus allowing the nature of jute/slurry interaction to be studied for a wide range of clay type. When the water contents are normalized by the liquid limits, it was observed that the interface adhesion values fall into a very narrow behaviour band, thus making it possible to estimate the available interface strength between jute and clay slurry based on water contents.

Key words: adhesion, clay slurry, jute geotextile, laboratory test, liquid limit, water content (IGC: D3/D6)

INTRODUCTION

The layered clay-sand method for land reclamation has been studied on a small scale in Singapore with the goal of replacing scarce and costly sand by seabed dredged soils as fill materials for future land reclamations projects. The method has been used with some success on a small scale (30 m × 20 m) at Pulau Tekong Besar (Lee et al., 1987), and on a large prototype project (40 ha) at Changi South Bay, Singapore (Karunaratne et al., 1990, 1991). The success of the scheme depends on the formation of thin sand seams on top of a very soft clay slurry at high water contents. For the marine clays dredged from Singapore waters, it was found that considering self-weight sedimentation and consolidation only, the water content of marine clay slurry can be reduced to around 200% to 300% in a stable suspension. For these values, large quantities of sand are lost through sand penetration as the slurry is too weak to support even a thinly spread sand layer. The amount of sand loss is dependent on the slurry strength with more sand loss occurring at higher water contents.

To overcome this problem, it has been proposed that a low cost loosely woven jute geotextile be placed on the slurry surface before carefully spreading thin layers of sand on the slurry. It is anticipated that a low cost jute geotextile placed on the slurry surface as shown in Fig. 1 will serve as a separation layer to prevent sand loss through sand penetration into the clay slurry and also enhance the bearing capacity of the clay slurry to support the weight of the sand layer. For this application, it is important to measure the jute geotextile slurry interface ad-

Fig. 1. Layered clay-sand reclamation using jute geotextile

ⁱ⁾ Senior Lecturer, Department of Civil Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 0511.

ⁱⁱ⁾ Research Student, ditto.

ⁱⁱⁱ⁾ Associate Professor, ditto.

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hesion, whose value can be used to estimate the amount of sand that can be supported for a given area of jute coverage. The jute geotextile slurry interface adhesion can be measured with a simple vertical jute sheet penetration test, where the incremental penetration of a vertically suspended jute sheet, into the clay slurry during incremental loading is determined. In order to examine the influence of different clay types, artificial clay mixtures of different proportions of Kaolin and Bentonite (Smectite mineral) powder were mixed in sea water to produce clays with varying liquid limits from 100% to 400%. Interface adhesion between the jute and these clay types were measured and some useful conclusions can be made about the influence of clay type on interface behavior.

VERTICAL JUTE SHEET PENETRATION TEST

Theory and Test Procedure

It is very difficult to measure the jute geotextile slurry interface adhesion (ie a constant unit stress independent of the normal force) with a conventional pull-out test in the horizontal direction, due to the large amount of self-weight sedimentation/consolidation settlement of the clay slurry at high water content. Instead, a vertical sheet penetration test to measure the interface adhesion has been proposed. The principle of this test is similar to that of a thin plate penetration test for measuring slurry strength at 150% to 300% water contents as proposed by Tan et al., 1991. This test has been extended to measure the interface adhesion between a jute coated thin plate and a Singapore marine clay slurry (Tan et al., 1993). In this paper, it has been proposed that the penetration test be conducted using the jute sheet itself, weighted at its end to allow direct penetration into the clay slurry. Figure 2 shows a schematic diagram of the test setup, which consists of a sheet of jute geotextile, stiffened at the top and bottom ends with thin perspex strip clamps, and weighted at the bottom by a lead plate used to keep the jute sheet vertical throughout the slurry penetration test. Prior to testing, the clay slurry at constant water content is thoroughly remixed to produce a uniform stable suspension. During the test, the weight of the jute sheet and end plates suspended partially in the clay slurry, are counterbalanced using a weight/pulley system (see Fig. 2).

The incremental loading is applied by removal of small weights from the pan, thus, allowing the jute sheet to penetrate into the clay slurry until a state of equilibrium is attained between the incremental load, the jute geotextile interface adhesion force, and the resultant incremental uplift buoyancy force from the volume of slurry displaced by the soaked jute sheet. The jute sheet penetration is measured using a vertical scale which is attached to the pulley line as read from a fixed horizontal pointer. Typical jute sheet penetration versus time curves are shown in Fig. 3 where it can be seen that equilibrium is reached after 5 minutes for each load increment. The jute sheets are pre-soaked in water for 5 to 6 hours before the first penetration test, and the resultant unit weight at-

tained is about 10.8 to 11.8 kN/m³ (Karunaratne et al., 1992), making it heavier than sea water, but lighter than the clay slurry. In the equilibrium state, the balance of forces will be indicated by the equation:

$$dw = \delta F + \delta B \quad (1a)$$

where δF is the incremental adhesion on the jute sheet as a result of the additional penetration of the jute sheet into the clay slurry by the amount of dz ; and δB is the incremental buoyancy gained by the jute sheet displacement of clay slurry from the additional penetration of dz into the clay slurry. These can be written as:

$$\delta F = 2(b+t)dz\tau_a \quad (1b)$$

$$\delta B = (btdz)\gamma_c \quad (1c)$$

where

dw = incremental load on jute sheet,

Fig. 2. Set-up of jute sheet penetration test into clay slurry

Fig. 3. Time for equilibrium of jute sheet penetration in clay slurry at various water contents

b, t = width, thickness of jute sheet,
 dz = incremental penetration of jute sheet,
 τ_a = interface adhesion between jute and slurry,
 γ_c = unit weight of clay slurry.

Rearranging Eq. (1) yields:

$$\tau_a = \frac{dw/dz - bt\gamma_c}{2(b+t)} \quad (2)$$

From Eq. (2), τ_a can be determined when (dw/dz) is obtained from the penetration test, and γ_c is calculated from:

$$\gamma_c = \frac{\gamma_w G_s (1+w)}{(1+wG_s)} \quad (3)$$

where

γ_w = unit weight of sea water,
 G_s = clay particle solid density, and
 w = clay slurry water content.

The ratio dw/dz applies only to the incremental weight and incremental penetration, and it is therefore essential that part of the jute sheet, the bottom horizontal perspex strip and clamps and the lead plate be submerged in the clay slurry from the start of the test. The vertical force resistances contributed by these components are therefore assumed to be constant throughout the rest of the penetration test. The thickness of the soaked jute sheet is measured by compressing it between two flat plates under 1 kPa pressure.

The water content range where the test can be performed is limited by two factors. The slurry must not be so thick that it cannot be penetrated by the dead weight of the lead plate and jute sheet, and the slurry must not be so dilute that it is not possible to maintain a constant water content for the slurry for the duration of the test because the slurry is settling too rapidly.

The penetration test begins with the clay slurry at a lower water content, say 200% for a marine clay. After sufficient data points have been obtained to determine the load-penetration relationship for that particular water content, the jute sheet is removed and washed in sea water to remove clay particles from the fibers. Additional sea water is then added to the slurry to increase its water content by mechanical mixing to produce a new stable suspension at another water content, before repeating the penetration test with the same jute sheet. This procedure is repeated until penetration data is obtained for a wide range of water contents from two to six times the liquid limits of the clay used in the test.

Jute Geotextile Used in Test

Two types of locally available natural woven jute geotextile fabrics were used in the studies. The first jute geotextile has unit mass of 500 g/cm², apparent opening sizes (AOS) of 5.5 mm, and tensile strength of about 15 kN/m. The second jute geotextile has unit mass of 600 g/cm², apparent opening sizes (AOS) of 2.7 mm, and tensile strength of about 20 kN/m (Karunaratne et al., 1992).

If the minimum permissible size of particles to be retained in dry condition is 1/10th of the AOS, then medium to fine sand particles can easily be retained by the jute geotextile (Tan et al., 1994). To ensure uniformity, all specimens were cut from the same roll of jute geotextile. Jute sheet widths of 100, 200 and 300 mm were prepared for the penetration tests, by pre-soaking for 5 to 6 hours to attain stable unit weights of between 10.8 to 11.8 kN/m³. This is done to remove all internal air voids of the jute fibers and simulate the field condition where saturated jute denser than water will be utilized so that the jute will sink naturally in the reclamation pond under its self-weight and float just on the surface of the clay slurry with a similar unit weight to that of the soaked jute.

PENETRATION TEST IN NATURAL MARINE CLAY SLURRY

Singapore Marine Clay Used for Test

Singapore marine clay dredged from a site off Changi South Bay was used for all the laboratory tests. In order to prepare the slurry sample, the clay was first diluted with sea water to about 500% to 600% water content and all the sand sieved out using a 63 μ m sieve. In the field project (Karunaratne et al., 1991), a natural segregation of sand particles from the clay was achieved because in the sedimentation process larger sand particles settle out much more rapidly than the very fine clay particles in the reclamation pond. As a result, the hydraulically placed clay layer is a very dilute clay slurry of 500% to 600% water content without any sand within.

The properties of the marine clay used in the test are:

Specific Gravity, G_s	2.66
Plastic limit, PL	34%
Liquid limit, LL	85%
Silt content	48%
Clay content	52%
Activity	0.90

The clay mineral composition of the clay content as obtained by X-ray diffraction analysis is:

Illite-Smectite	31%
Illite	15%
Kaolinite	21%
Chlorite	16%
Smectite	17%

Discussion of Penetration Test Results

Due to the continuous nature of self-weight sedimentation of the clay slurry, it is important that equilibrium for every load increment be reached in a reasonable period of time, in order to measure the correct corresponding penetration. Figure 3 shows the jute sheet penetration versus elapsed time for different slurry water contents for a weight increment of 0.1 N over a period of 30 minutes. The data indicate that the jute sheet reached

(a)

(b)

(c)

Fig. 4(a)–(c). Load increment vs penetration plots for jute type 500 and 600 g/m² of 100, 200, and 300 mm widths

equilibrium within 5 minutes of load application in all cases, thus making it possible to measure a definite penetration value for a given slurry of the range of 200% to 600% water content.

The results of applied incremental loads to incremental penetration for the range of slurry water contents from about 200% to 600%, for the 500 or 600 g/cm² jute sheets of 100, 200 and 300 mm wide are shown in Figs. 4(a)–(c). An extremely good linear fit through the origin was obtained for most of the experiments. The good linear results implies that the assumptions that the base resistances are constant and that a uniform interface adhesion was mobilized over the two vertical faces of the jute sheet in contact with the slurry are both valid. The gradient of the best fit straight line based on least squares linear regression gives the values of (dw/dz) for the application test conditions. Using Eq. (1), τ_a can then be computed directly, and is plotted against the water contents of the clay in Fig. 5. The results imply that the interface adhesion between the jute geotextile and soft clay slurry depends only on the water content of the clay slurry, which governs the shear strength of the clay slurry. The results indicate independence of jute sheet width, and show greater scatter for the case of 600 g/m² jute type as compared to the 500 g/m² jute. In spite of the scatter, for the two jute types tested, the result indicates very low jute geotextile slurry interface adhesion increasing linearly from 0 to 5 Pa for slurry water content decreasing from 600% to 300%, with a rapid increase in interface adhesion values of 5 to 33 Pa when reduced from 300% to 200% water contents.

These results are compared to the thin perspex plate penetration into clay slurry test results of Tan et al., 1991, in the same figure. The same Singapore marine clay slurry was used for both tests, and the slurry strength which was measured using the penetration method with a thin smooth perspex plate. In order to indicate that the slurry undrained shear strength is indeed being measured by the smooth thin plate, the results were validated by comparison with good agreement of shear strength

values obtained with Swedish fall cone tests at the high end, as well coaxial viscometer tests at the low end of water contents as reported in Tan et al., 1991. Thus, the comparative results indicated that for any level of slurry water contents within 200% to 300%, the jute geotextile/slurry interface adhesion is significantly higher than the slurry strength, especially at the lower end of water contents around 200%. This may be due possibly to the greater effects of interaction between jute and clay slurry, producing a stressed zone around the interface compared to a narrow slip boundary on the smooth perspex surface. The penetration test can determine the interface stresses between the jute and clay slurry but not the rheological behaviour of the slurry. Whatever the micro-mechanism, the distinct difference between the two sets of test results is obvious.

PENETRATION TEST IN KAOLIN-BENTONITE MIXTURES

For this study, four artificial clay types were produced by having different proportions of Kaolin, mixed thoroughly with different proportions of Bentonite (Smectite mineral) using sea water. The liquid limits (LL) of these clays were determined using the cone penetration method in accordance with BS1377–1990. It is noted, however, that the slurries conform to the linear mixture law with the liquid limits varying as a linear function of the mix proportion as shown in Fig. 6. The slurries were prepared at 2.5 times liquid limit to ensure that all air voids were removed by thorough mixing, and stored in covered test bins to be dried out or remixed at different water contents for the jute sheet penetration test.

For these tests, only the 500 g/m² jute sheets 250 mm wide and 300 mm long were used. The jute sheets were cut from the same roll, cleaned and pre-soaked in sea water overnight to saturate all air voids in the fibers. Af-

Fig. 5. Interface adhesion vs water content of jute/slurry

Fig. 6. Liquid limits of Kaolin-Bentonite mixes

(a)

(b)

(c)

(d)

(e)

Fig. 7(a)-(e). Load increment vs penetration for various clay types

ter each penetration test the jute sheet was thoroughly washed in sea water to remove clay particles from its fibers. The water content of the clay slurry was then increased by adding more sea water and mixing mechanically to produce a stable suspension before starting the next penetration test. The typical behavior of the jute sheet penetration time behavior was found to be similar to that shown in Fig. 3 thus allowing equilibrium penetration to be observed after a period of 5 minutes.

The incremental load versus sheet penetration plots for the marine clay, and four of the artificial clay mixtures are shown in Figs. 7(a)–(e). It is obvious that the trend of the data is linear passing through the origin, indicating that the penetration tests work for the different clay types. Applying Eq. (2) to the data, τ_a for these test conditions can be computed, and plotted as a function of water content as shown in Fig. 8. The results indicated that the interface adhesion is strongly dependent on water content, with its value decreasing from 30 Pa to zero at the very high water contents.

When the water contents are normalized by the liquid limits, it can be seen that the interface adhesion plot is a narrow band as shown in Fig. 9. In the liquid limit test us-

ing a cone apparatus, the undrained shear strength is defined when the cone causes a bearing failure as it sinks under its own weight 20 mm into the clay for a time period of 5 seconds. The liquid limit represents a slurry consistency at the same shear strength of about 1 kPa as determined by Atkinson and Bransby (1978). Therefore, a plot based on water content normalized by the liquid limit, represents clays at the same shear strengths, and it is also not surprising to observe that this results in the same interface adhesion values for the same jute type. The interface adhesion between the jute sheet and any clay slurry at any water content can therefore be estimated from Fig. 9 once water content and liquid limit have been determined. The results indicate that for between 2 to 6 times the liquid limit, the slurry behaves as a Bingham fluid with a threshold shear strength at zero strain rate. Beyond 6 times the liquid limit, the shear strength reduces to zero, where Newtonian fluid behavior is more likely the case.

CONCLUSIONS

The jute sheet vertical penetration test into clay slurry at various water contents was shown to be a simple and direct method to determine the interface adhesion between jute geotextile and clay slurry of a very low shear strength. The method is applicable to all clay slurries from 2 to 6 times their liquid limits. The method is not affected by the width of the jute sheet, nor is it significantly dependent on the jute mass density. The general result suggests that there is a good correlation between the interface adhesion value and the slurry w_c/LL ratio. For a w_c/LL ratio of 2 to 3, the interface adhesion reduces rapidly from 30 Pa to 7 Pa. Beyond a ratio of 3, the interface adhesion reduces from 7 Pa to zero at w_c/LL of 6. Based on these results, the interface adhesion of any clay slurry with the 500 g/m² jute sheet can be estimated from the relationship shown in Fig. 9, once the water content and liquid limit have been determined.

Fig. 8. Interface adhesion vs water contents for various clay types

Fig. 9. Interface adhesion as a function of w_c/LL ratio

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