Preliminary tests for evaluating suitability of materials used in centrifuge modeling of slopes

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In order to use centrifuge machine to check basic parameters of sand and understand side effect of slopes or embankment in centrifuge test. A rectangular slope block and a trapezoidal slope made by Hiroshima sand were firstly set for estimation and rechecking the friction angle and cohesion of this sand. Meanwhile, a centrifuge model technique is used to preliminarily investigate the effect of seepage flow on the slope are carried out. In the estimation and rechecking tests, the results shows that the method in centrifuge machine can roughly estimate the friction angle and cohesion of Hiroshima sand. However, the exact values are suggested to use direct shear test or tri-axial test.

Keywords: *centrifuge modelling, estimation and rechecking test, permeability test*

1. INTRODUCTION

In soil mechanics problems, the basic parameters of soils, such as friction angle and cohesion, can approximate the shear stress on the failure plane as a linear function of the normal stress, which is widely used in geotechnical engineering to solve some problems in foundation, retaining wall and so on[1)]. And usually these two shear strength parameters can be determined in the laboratory primarily with two types of tests: Direct shear test and Triaxial test. Robertson and Campanella gave some interpretation about parameters in drained and undrained condition though the Cone penetration tests[2)]. Schmertmann proposed a method for determining the friction angle in sands from the Marchetti dilatometer test (DMT)[3)].

Geotechnical Centrifuge, which is a proven technique by increasing gravitational acceleration, can accomplish the simulation between the model scale and prototype scale. Ling and Wu demonstrated the use of a centrifuge modeling technique in studying slope instability[4)]. Hossein investigated undercut slope with a potential failure plane though centrifugal modeling[5)]. And the suitable materials chose in physical modeling are crucial for the model behaviors and failure patterns.

In the centrifuge modeling, it can not only make the same stress condition between the model and prototype, not also let part of soil sample fail by increasing gravitational acceleration, which can not be observed in 1 G physical modeling. Based on this distinguishing feature, some basic parameters of soil can be estimated in centrifuge tests.

In this study, the basic laboratory tests for Hiroshima sand are carried out. Some basic centrifugal experiments including a rectangular slope block and a trapezoidal slope used Hiroshima sand with 10 % water content were firstly set for estimation and rechecking the friction angle and cohesion of this sand. Meanwhile, a centrifuge model technique is used to preliminarily investigate the effect of seepage flow on the slope.

2. BASIC LABORATORY TESTS OF HIROSHIMA SAND

There are firstly three different kind of the sands (Hiroshima sand, Nara sand and Kyoto sand) from the different areas for choosing the suitable materials in centrifuge tests. Grain size distribution curves of three sand are shown Figure 1.

In centrifuge test, the soil particles should be about to prevent the higher proportion of water from draining out when subjected to a higher centrifuge acceleration. And the proportion of fine particle play an important role in keeping water. Therefore, Hiroshima sand with a smaller D_{10} are selected for the following tests. Meanwhile, in order to prevent the appearance of gravel in sand, the sand whose grain size is bigger than 1 mm are removed. Finally, the grain size distribution of the improved Hiroshima sand is also shown in Figure 1. The modified Hiroshima sand (just called Hiroshima sand later) is a poorly graded sand with D_{10} of 0.08 mm.

The relative compaction of soil affect effectively its permeability. This should be considered carefully in centrifuge tests. Figure 2 shows the compaction curve of Hiroshima sand. The maximum dry density and optimum water content is 1.75 g/cm^3 and 13.9%.

The coefficient of permeability of Hiroshima sand plays an important role in slope centrifugal modeling. The three constant head permeability tests in different relative compaction are carried out using the apparatus in Kyoto University, shown in and Figure 3 and Table 1.

From the results of permeability tests, as the relative compaction decrease, the coefficient of permeability increase. This is because the void volume increase with the decrease of relative compaction. In the 80%-100% relative compaction, the coefficient of permeability is about an order of magnitude. Finally, Hiroshima sand with the 90% relative compaction and 10 % water content are chose as a result of combining the possibility of holding water and compaction process in centrifuge tests.

Table 1 Permeability tests of Hiroshima sand

Test	Water content (%)	Relative compaction (%)	Coefficient of permeability (m/s)
Test 1	13.2	100	1.55* 10^{-5}
Test 2	10	90	2.19* 10^{-5}
Test 3	10	80	3.06* 10^{-5}

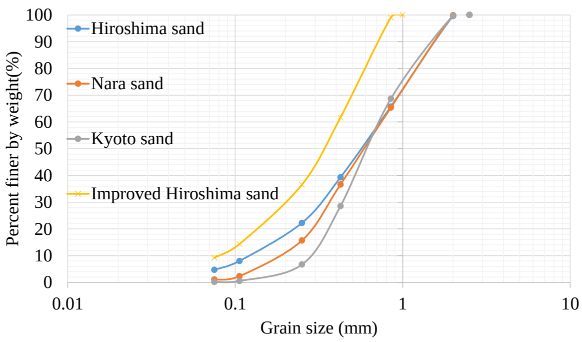


Fig. 1 Grain size distribution of three different type of sands

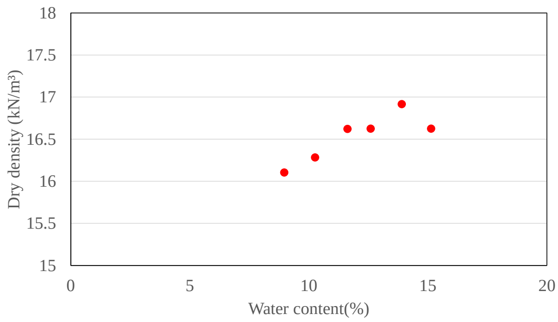


Fig. 2 Compaction curve of Hiroshima sand.

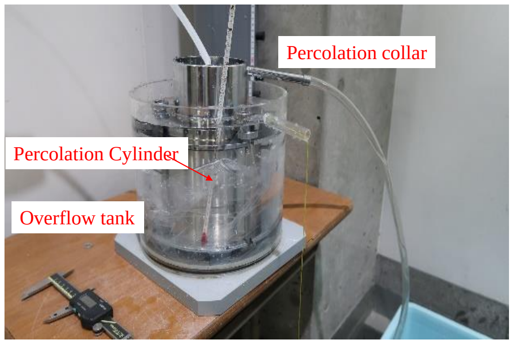


Fig. 3 Apparatus of permeability test in Kyoto University

3. ESTIMATE THE INTERNAL FRICTION AND COHESION OF HIROSHIMA SAND

A rectangular block of Hiroshima sand with a 10% water content whose basic property mentioned above, as shown in Table 2, is set in the centrifuge machine to estimate the internal friction angle and cohesion as shown in Figure 4. The sand block, with a dimension length: 100 mm, width: 197 mm, and height: 120 mm, was firstly compacted in every 20 mm with the wooden support based on the calculated volume, the schematic size of the sand block are also shown in Figure 5. After the uniform compaction process, three pieces of vertical wood were removed and the sand block without support was put into centrifuge room to allow it to fail at certain gravity as shown in Figure 6. Three important parameters including failure gravity, angle and height of failure part were recorded during and after tests, as shown in Table 3.

Table 2 Properties of Hiroshima sand

Parameter	Value
Water content (*W*)	10%
Bulk density (ρ)	1.45 kg/m^3
Relative compaction	90%

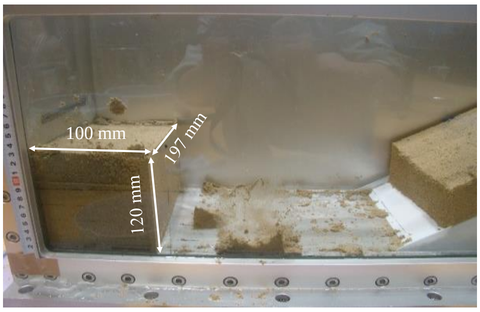


Fig. 4 A rectangular block of Hiroshima sand

Table 3. Parameter of failure part in rectangular block

Parameter	Value
Failure gravity (g)	23.1*9.8 m/s^2
Failure height (H)	7.6 cm
Failure angle (θ)	65.9°

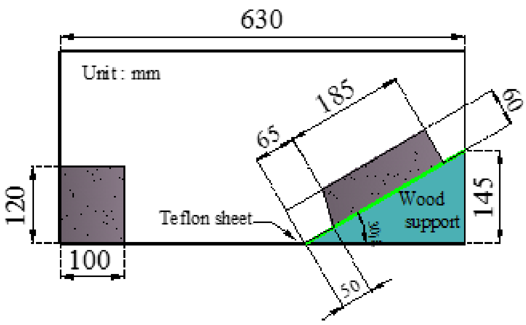


Fig. 5 The sizes of the rectangular block sand and the trapezoidal slope

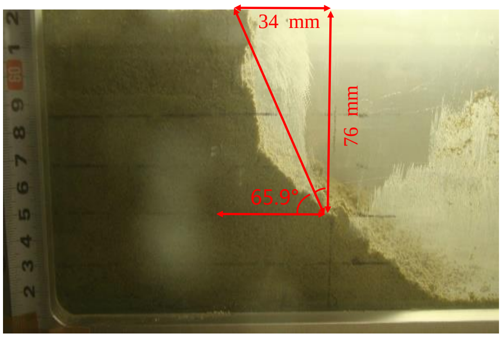


Fig. 6 Partial failure of the rectangular block

The fiction angle and cohesion can be assessed by the three known parameters with some calculation and the force diagrams are shown in Figure 7.

The weight of failed mass can be expressed as equation (1),

$$W = \frac{1}{2}\rho g H^2 \frac{\sin(\alpha-\theta)}{\sin\alpha\sin\theta} \qquad (1)$$

Where,

ρ: density of Hiroshima sand, H: failure height, α: block angle before the test, θ: failure angle, g: gravity

The factor of safety can be defined as equation (2),

$$FS = \frac{R}{F} = \frac{W\cos\theta\tan\phi + cA}{W\sin\theta} = \frac{W\cos\theta\tan\phi + H\csc\theta}{W\sin\theta} \qquad (2)$$

Where,

R: resisting force, F: driving force, A: area of sliding surface, ϕ: friction angle, c: cohesion

At the failure condition, FS=1, we can get the equation (3),

$$H = \frac{4c}{\rho g}\frac{\cos\phi\sin\alpha}{\cos(2\theta-(\alpha+\phi))-\cos(\alpha-\phi)} \qquad (3)$$

Therefore, the friction angle and cohesion can be derived at failure height,

$$\phi = 2\theta - \alpha$$
$$c = \rho g H\left(\frac{1-\cos(\alpha-\phi)}{4\cos\phi\sin\alpha}\right) \qquad (4)$$

Finally, the estimation friction angle and cohesion of Hiroshima sand are 41.8° and 2.80 KPa, respectively based the the parameters we measured and the equation (4).

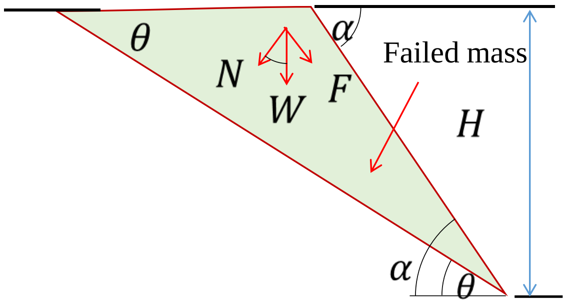


Fig. 7 Force diagram of a sand block

4. RECHECK THE INTERNAL FRICTION AND COHESION OF HIROSHIMA SAND

Another trapezoidal slope made of same Hiroshima sand was built for checking its properties of internal friction angle and cohesion as shown in figure 8. Its sizes also are given in figure 5 and the experimental procedures are same with the rectangular sand block. The sand slope is located on a wooden base with a 30° angle. In this checking test, failure gravity, angle and length of failure part are also recorded during and after tests, as shown in Table 4.

Figure 9 shows the force diagram of a trapezoidal slope. In a same way, the weight of failed mass in the trapezoidal slope are,

$$W = \frac{1}{2}\rho \mathrm{glb}\sin(\theta-\beta) \quad (5)$$

Where, $l = H \csc\theta$ $b = \frac{\sin(\alpha-\theta)}{\sin(\alpha-\beta)} l$

b: upper length of failure mass, l: length of sliding plane, β: angle of base, θ: failure angle, α: angle of slope from horizontal, h: failure height

The factor of safety can be express as,

$$FS = \frac{R}{F} = \frac{\tan\phi}{\tan\theta} + \frac{2c\sin\alpha\sin(\alpha-\beta)}{\rho gH\sin(\alpha-\theta)\sin(\theta-\beta)\sin\theta} \quad (6)$$

Where,
R: resisting force, F: driving force, A: area of sliding surface, ϕ: friction angle, c: cohesion

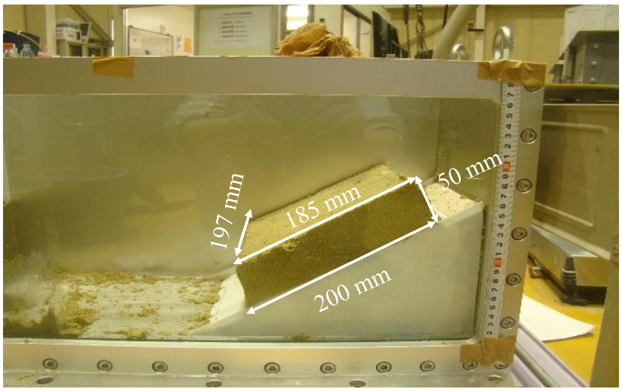
Setting FS=1, we can get the failure height as,

$$H = \frac{2c}{\rho g}\frac{\cos\phi\sin\alpha\sin(\alpha-\beta)}{\sin(\theta-\phi)\sin(\alpha-\phi)\sin(\theta-\beta)} \quad (7)$$

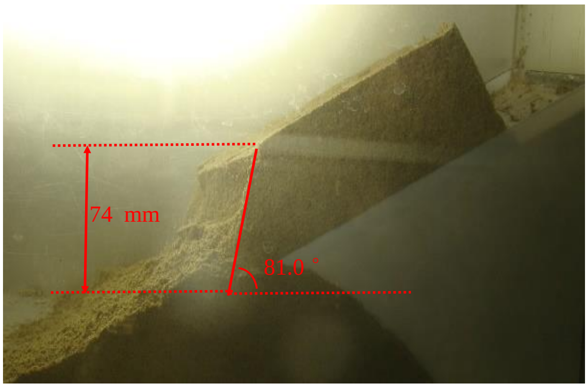
The estimated friction angle and cohesion in sand block test as well as two measured parameters which are failure angle and failure gravity are put into equation (7), the failure height is 6.6 cm. on the other hand, the failure height is 7.4 cm by checking after test. The method in centrifuge machine can roughly estimate the basic properties of Hiroshima sand. However, the exact values should be use direct shear test or tri-axial test.

Table. 4 Parameter of failure part in the trapezoidal slope

Parameter	Value
Failure gravity (g)	20.0*9.8 m/s^2
Failure height (H)	7.4 cm
Failure angle (θ)	81.0°



(a) A trapezoidal slope before test



(b) A trapezoidal slope after test

Fig. 8 A trapezoidal slope before and after experiment.

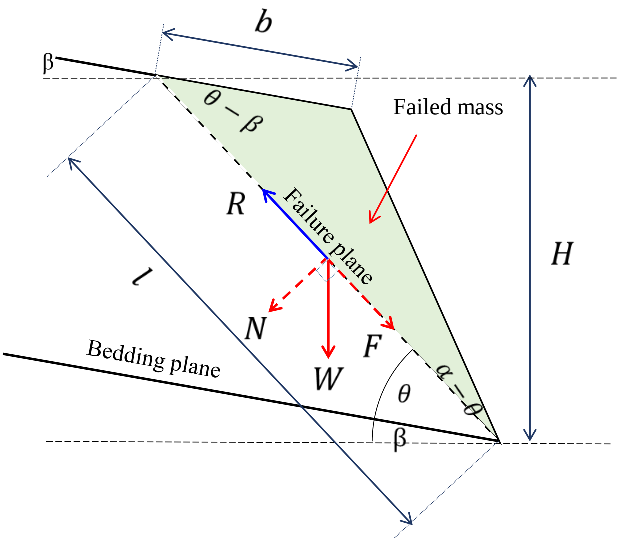


Fig. 9 Force diagram of a trapezoidal slope

5. PRELIMINARY TEST OF SLOPE WITH SEEPAGE.

The soil chamber using in the centrifuge machine is shown in Figure 10. Three sides of steel plates and one front side made of acrylic glass in order to observe the failure process of slope are fixed firmly. This soil chamber mainly consist of three parts which has each function. A central hollow part with a size (length: 630 mm, height: 300 mm, width: 200 mm) is used to build the sand slope.

In the preliminary test, homogenous model of slope was constructed in the one corner of soil chamber as shown schematically in Figure 11. The Hiroshima sand with the water content of 10% was laying on a wood support with a 50° angle as a simulation of a ledge. Every layer was tamped uniformly by a wooden rod to reach the designed height in the condition that the soil chamber was rotate 50° degree to allow compaction in horizontal as shown in figure 10. This procedure was continued until the designed height of the slope got. The four pressure gauges were embedded in the lateral acrylic plate at the specific locations, as shown in Figure 11.

The slope is 150 mm long in base, 175 mm wide and 40 mm thickness. After preparing the slope model, the soil chamber was sent to centrifuge room and firstly increased to 50 G, then the seepage water was simulated by supplying water into the silt acting just on the top of the slope from the water supply tank until the slope failed. Meanwhile, the drain valve also was turned on when starting to supply water.

Figure 12 shows the time history four pressure gauges at each position. From 180 seconds to 900 seconds, it is process of increasing gravity from 1 G to 50 G. a, which cause the increase of the lateral force. However, there is a short decrease of the gravity maybe due to the small change of the lateral support. Then the state kept for 300 seconds to make slope uniform. Here, we just use the lateral earth pressure at rest in equation (8) to estimate roughly the result based on the estimated friction angle of Hiroshima sand and the results are shown in table 5 comparing with the measured values. And the estimated values is reasonable with the measured values.

$$\sigma_l = K_0 \rho g h \tag{8}$$

where

σ_l : lateral pressure, K_0 : coefficient of lateral pressure at rest ($K_0 = 1 - \sin\phi$)

After the water supply, four pressure gauge sew a sudden decrease due to the failure. The observed slope failures after a larger quantity of water as shown in Figure 13. A arch shaped of the failures occurs in the the top of slope after a very short time of water supply, which also has an agreement with the sudden decrease of lateral pressure near the top of slope. This is because the speed of water supply is fast in the 50 G condition and this need to be exactly control by specific valve.

Table 5. Parameter of failure part in the trapezoidal slope

Pressure gauge	Estimated value (Pa)	Measured value (Pa)
P1	3.6	2.9
P2	12.6	14.0
P3	5.4	6.8
P4	18.0	15.8

Fig. 10 Soil chamber and rotation for the compaction process

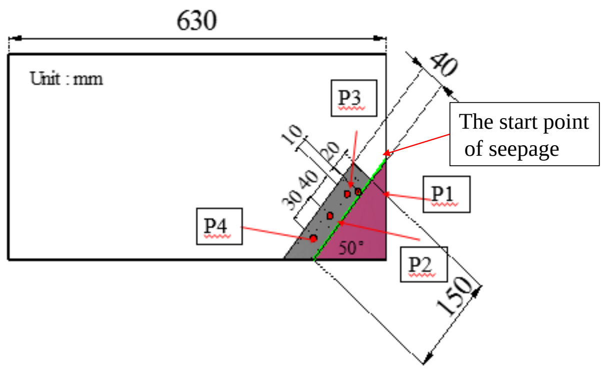


Fig.11 Schematic diagram of the experimental slope model and the pressure gauges locations

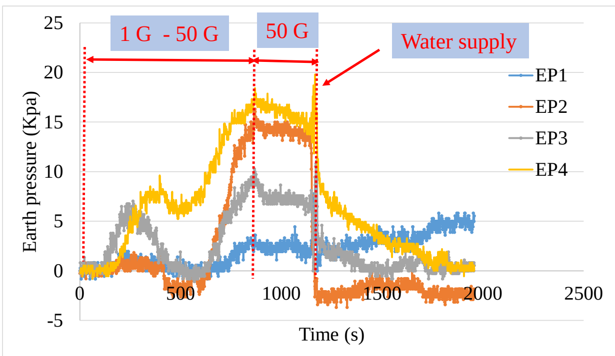


Fig.12 Time histories of four gauges

Fig.13 Slope failure along a bedding plane due to seepage.

6. CONCLUSIONS

In this paper, basic laboratory tests are carried out as well as basic experiments for estimation the friction angle and cohesion of Hiroshima sand. Meanwhile, a centrifuge model technique is used to preliminarily investigate the effect of seepage flow on the slope.

Hiroshima sand is selected as the material for centrifuge tests in grain size distribution test. In the compaction tests and permeability test, Hiroshima sand with 10% water content and 90% relative compaction are applied in centrifuge tests due to the possibility of holding water the availability of compaction process.

In the estimation and rechecking tests, the results shows that the method using centrifuge machine is a way to roughly estimate the friction angle and cohesion of Hiroshima sand. However, the exact values should be used a direct shear test or tri-axial test.

The slope due to seepage water occurs failure in the preliminary test. While too much water aggregated on the top the slope cause this special slope failures.

Aiming at the existing problem in speed of water supply, speed control valves are suggested to install to keep a slow water supply. Other sensor including laser sensor and pore water pressure gauge also will be employed. In addition, different conditions with regard to slope thickness, slope angle, toe angle will further investigate to understand comprehensively the effect of seepage water for slope along the ledge.

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