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ESTIMATION OF THE DYNAMIC PROPERTIES FOR GEOSYNTHETIC INTERFACES

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SUMMARY

Shaking table tests were performed on four kinds of geosynthetic interfaces. Smooth geomembrane, nonwoven geotextile, and GCL(Geosynthetic clay liner) were used in experimental tests. During the tests, the acceleration of upper and lower box and relative displacement of upper box were measured. The dynamic friction angle was calculated by measuring the yield acceleration of each interface, and the influences of normal stress, frequency of excitation, and dry/wet condition were investigated, too.

For every geosynthetic interfaces tested in this research, the normal stress and the frequency of excitation were evaluated not to influence the dynamic interface friction angle. It was found out that the peak box acceleration became to be smaller than peak acceleration of the table in the ranges where peak acceleration of the shaking table is above the yield acceleration of a geosysnthetic interface.

From geosynthetic interface testes, the dynamic interface friction angle in wet condition was 1° - 2° lower than that in the dry condition except that for GCL(B)/S-GM interface. These changes were supposed to be caused by the water existing in the interface or the intruded bentonite from GCLs into the interface.

Finally, it is identified that the maximum slip, S_d along bottom liners of landfills depends on the type of interface, the base acceleration, and the frequency of excitation. Using the relationship between normalized slip displacement and the ratio of K_y/K_a, the maximum slip equation could be calculated for a given acceleration and frequency of excitation. The normalized slip equation can be used to predict the peak displacement for the given dynamic loads.

INTRODUCTION

The friction properties at different geosynthetic/geosynthetic interfaces in composite liners are of critical importance to the stability of the entire landfill and adjoining structure. An example of the Kettleman Hill landfill failure demonstrating the seriousness of this issue has been presented by Mitchell et al. (1990) in

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the form of a case study where the slope of a 60,700 ㎡ hazardous waste failed. If any interface shear strength is lower than the slope angle, wide width tensile stress is induced into the overlying geosynthetics. This stress build up can cause the failure of the geosynthetic or pullout from the anchor trench, and finally, lead to the overall failure of landfills.

The interface shear strength between geosynthetics under dynamic loads has been the subject of recent concern due to the increased emphasis on the design of landfills against possible seismic disturbance. Until now, there have been a few case histories where landfills were subject to ground motion such as earthquake load. Twenty-two landfills were influenced by the Northridge earthquake (U.S.A.) (Augello et al., 1995), and a few solid waste landfills located in the Kobe/Osaka area of Japan were reported to be damaged by the severe earthquake (Akai, 1995). However, there is relatively a little information available regarding dynamic shear properties of waste materials and dynamic interface friction of geosynthetics.

Hushmand and Martin (1990) studied the feasibility of using geosynthetics for earthquake base isolation of structures and Kavazanjian et al. (1991) reported the results from the same study. The shaking table tests were performed using a steady-state sinusoidal excitation to determine interface behavior at different frequencies and amplitudes of vibration. The response to earthquake type excitation was also studied using a modified version of the S90W component of the 1940 El Centro earthquake ground motion. Yegian and Lahlaf (1992) used a simple experimental setup to measure the relationship between shear stress and displacement for an HDPE(high density polyethylene) geomembrane and geotextile interface. It was found from their research that normal stress and frequency of excitation did not affect the dynamic friction angle. As expected, the dynamic friction coefficient under submerged conditions was found to be slightly lower than that under dry conditions.

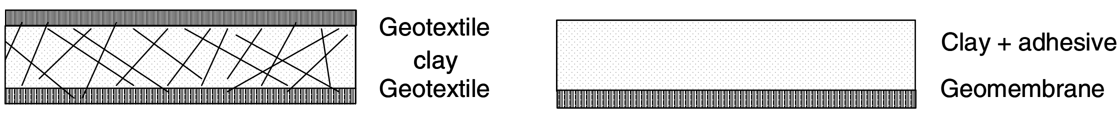
Yegian and Harb (1995) investigated the dynamic response of geosynthetic interfaces commonly used in Municipal Solid Waste Landfill (MSWL) using a shaking table facility, where geosynthetic interfaces placed horizontally and on inclined surface were tested to simulate bottom and cover liner systems. De and Zimmie (1998) estimated the dynamic frictional properties using cyclic direct shear tests, shaking table tests conducted at a normal g-level of 1g as well as at high levels, and on a 100g-ton geotechnical centrifuge. The tests revealed various important characteristics regarding the dynamic frictional properties of the geosynthetic interfaces, including a dependence of some of the interfaces on the level of normal stress and the excitation frequency. Yegian and Kadakal (1998) utilized a shaking table to investigate the frictional interface properties of a smooth HDPE geomembrane and nonwoven geotextile interface. Two test configurations were used, one for cyclic load tests, and the other for rigid block. Cyclic load tests were performed to investigate the effect of displacement rates. The difference between friction coefficients at displacement rates of 13 and 64 mm/s indicated that the friction coefficient increases with the sliding velocity.

Kim (2003) carried out an experimental study of geosynthetic interfaces on a shaking table (fixed block setup) to investigate the relationship between dynamic friction resistance and shear displacement rate of geosynthetic interfaces. The subsequent multiple rate tests showed that geotextile-involved interfaces continue to degrade as displacement increase until they reach an apparent steady-state (or residual strength). Under dry condition, the shear strengths of geotextile-involved interface were observed to increase almost linearly as the displacement rate increases in logarithm scale. However, once submerged with water, the shear strength appeared to be no longer dependent on the displacement rate. This phenomenon appeared to relate to lubrication effect of water trapped inside the interface. Finally, Kim (2003) reported that shear strength parameters are generally not sensitive to the magnitude of normal stress within the range of normal stresses tested (from 7.0 kPa to 63.3 kPa).

TESTING MATERIALS, EQUIPMENT AND PROGRAM

Testing materials

The experimental work in this research focused on the frictional behavior of smooth geomembrane-involved interfaces. Four interfaces studied here are composed of four different geosynthetic materials. Three different kinds of geosynthetics, i.e. geotextile (GT), smooth geomembrane (S-GM) and geosynthetic clay liner (GCL), were used in the testing program. Nonwoven geotextile and smooth HDPE (high density polyethylene) geomembrane were applied and two commercially available GCL, GCL(A) and GCL(B) products were also utilized. The GCL(A) is a reinforced one in which granular bentonite is held between a woven silt-film PP (polypropylene) geotextile (170g/m^2) and a nonwoven needle-punched PP geotextile (340g/m^2). To provide reinforcement, PP fibers were needle-punched through the bentonite and geotextiles. The GCL(B) is an unreinforced GCL consisting of bentonite mixed with an adhesive and bonded to a geomembrane, which is a textured 2.0mm thick HDPE material. The liquid and plastic limit are 484% and 45% for the bentonite encased within GCL(A) and 453% and 45% for the bentonite included in GCL(B), respectively. The sectional views of GCL(A) and GCL(B) are demonstrated in Fig. 1.



(a) Needle punched GCL, GCL(A) **(b) Geomembrane supported GCL, GCL(B)**

Fig. 1 Types of GCL used in the experiment

Testing equipment

Fig. 2 shows a shaking table facility used in the test to evaluate the dynamic interface frictional properties between geosynthetics. The shaking table comprises of a vibration exciter connected to a rigid aluminum table mounted on frictionless linear bearing pillow blocks moving on two stainless steel guide rails. One geosynthetic is fixed to the shaking table, and the other geosynthetic is fixed to upper hollow box. Then, weighting plates are added in the hollow box. Two accelerometers were attached to the shaking table and hollow box, respectively. The relative displacements between the bottom geosynthetic and upper geosynthetic were measured by linear variable differential transducer (LVDT) fixed on the table. The amplitude and the frequency of the table motion were controlled by a signal generator connected with the shaking table. All data acquisition and analysis were made by using a personal computer and commercially available software.

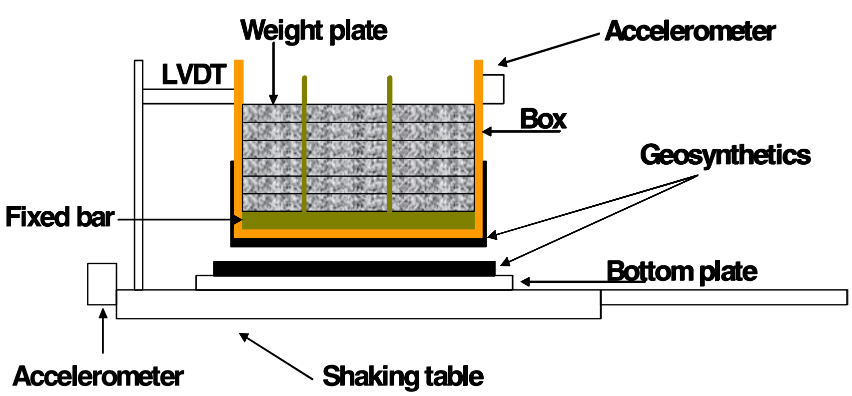


Fig. 2 Schematic diagram of shaking table with geosynthetics attached and weighting plates

The size of the shaking table is 1000mm by 1000mm, and the dimension of box is 300mm by 300mm which is the same size as is proposed for large direct shear tests in ASTM D 5321 (1998). Applied normal stress was changed by adding weight plates into hollow box. After inserting the steel plates, those plates were fixed not to move during the shaking table tests. The shaking table tests were also conducted for submerged condition to examine the change of interface friction properties as the interface condition varies from dry to submerged state.

Testing program

During each test, a sinusoidal varying horizontal acceleration was applied to the shaking table. The amplitude of vibration was varied using a dynamic signal analyzer. At low amplitudes of acceleration, the interface friction was sufficient to pass the entire vibration from one geosynthetic to the other, hence two goesynthetics moved together. Under such conditions, the accelerometers mounted on the shaking table and the box yielded the same readings for values of acceleration with time. The LVDT showed no relative displacement between two geosynthetics.

The shaking table vibration was increased continuously until relative displacement was observed between two geosynthetic layers. The acceleration level at which this displacement starts is used to calculate the dynamic friction angle of the interface. The acceleration of the shaking table was gradually increased, from low amplitude to a point when sliding was initiated. The curves of acceleration versus time provided the amplitudes of acceleration developed at the shaking table and the box at any given instant of time. The magnitudes of box and table accelerations can be plotted to provide information regarding the amplitude at which relative slip is triggered, and also to study the acceleration behavior of the interface after slip has occurred.

The testing program carried out to study the dynamic friction characteristics between the geosynthetics is presented in Table 1. The normal stresses applied in the tests correspond to the weight of final cover of landfills and the frequencies were chosen based on the fact that earthquake generally shows frequencies below 10 Hz.

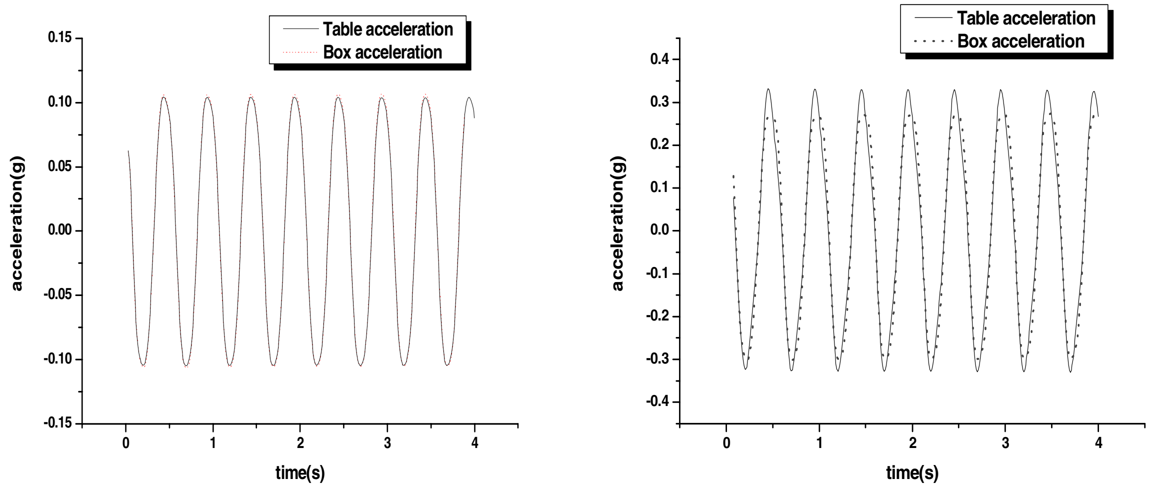
Table 1 Testing program for the shaking table tests

Interface type	Normal stress (kPa)	Frequency (Hz)	Testing Condition
GT/S-GM	1.6, 3.6, 6.8	2, 5, 10	Dry / submerged condition
GCL(A)NW[1)]/S-GM			
GCL(A)W[2)]/S-GM			
GCL(B)/S-GM[3)]			

1) GCL(A)NW : nonwoven part of the GCL(A), 2) GCL(A)W : woven part of the GCL(A), 3) the bentonite part of GCL(B) contact the smooth geomembrane

TEST RESULTS

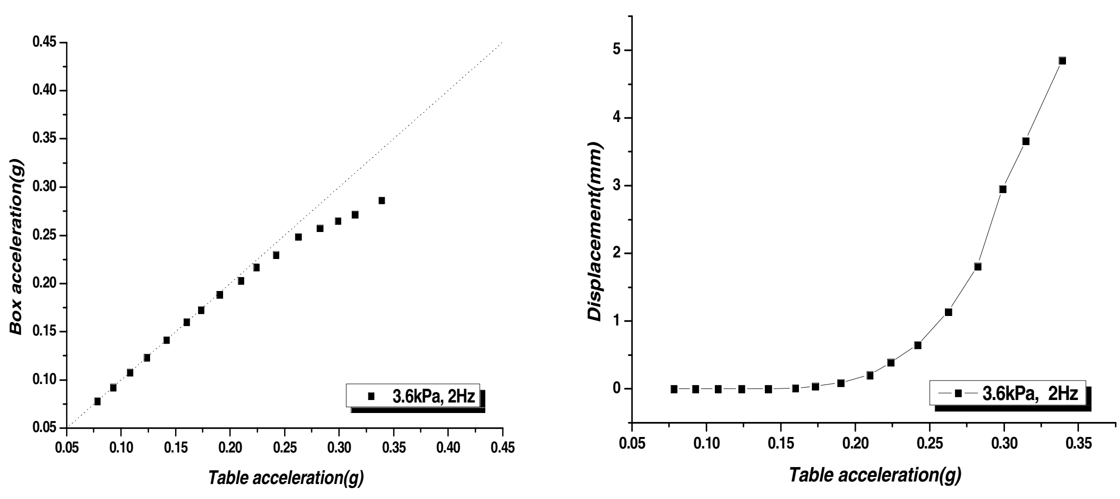
Fig. 3(a) shows the typical accelerations of the table and box measured at the very low amplitude of table vibration. At this amplitude of the table vibration, the peak table acceleration was 0.10g (g : gravity acceleration) and the box acceleration was almost identical to that of the table. Fig. 3(b) shows the results from another test performed under the same conditions as shown in Fig. 3(a) except that the amplitude of table vibration was larger. As is observed in Fig. 3(b), the peak table acceleration was 0.33g and the peak box acceleration was 0.27g. It was found that the acceleration of the box was smaller than that of the table.



(a) Low table acceleration, 0.10g (left figure)   (b) High table acceleration, 0.33g (right figure)

Fig. 3 Table and box accelerations with time

Similar tests were performed for the value of peak table acceleration ranging from 0.05g to 0.4g with a same normal stress and the frequency of excitation. Fig. 4(a) shows a plot of the peak table acceleration versus the peak box acceleration. Fig. 4(b) shows the maximum relative displacement, S_d of box with increasing table accelerations. As is shown in Fig. 4(a) and Fig. 4(b), the accelerations of table and box was almost identically increased before the sliding occurred. However, after sliding was initiated, the peak box acceleration was smaller than the peak table acceleration. It means, under the dynamic excitation, the shear stress that can be transmitted from a smooth geomembrane to geotextile is limited. The same tests were also performed with the interface submerged.



(a) Table and box acceleration   (b) Table acceleration versus relative displacement

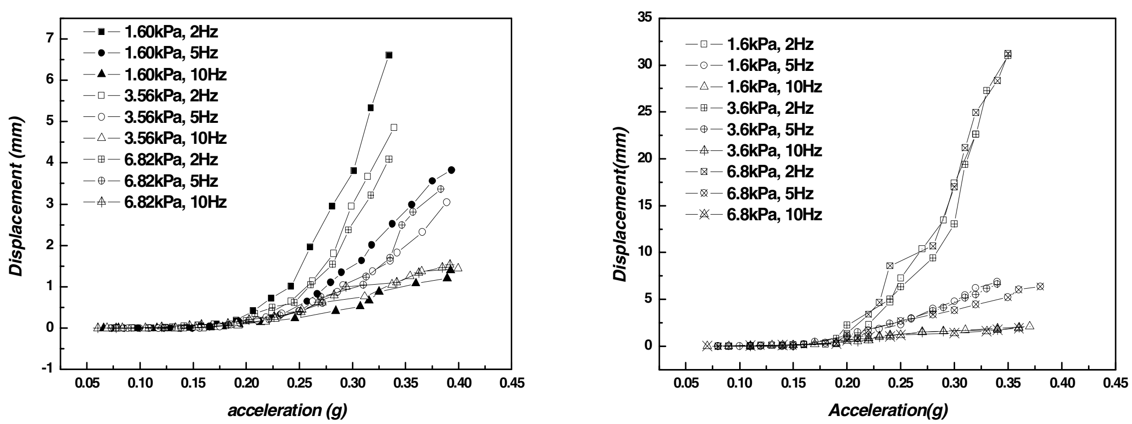
Fig. 4 Test results of the GT/S-GM interface

Fig. 5 shows maximum relative displacements measured by using LVDT with increasing acceleration. As shown in Fig. 5, when the acceleration of table was relatively small, the relative displacement was not measured. However, once slip was initiated, peak slip displacements (peak to opposite peak displacement) was exponentially increased as the table acceleration increased. The magnitudes of slip displacements at the same normal stress were almost consistent and it was just observed that the relative displacements were dependent on the frequency of excitation. The measured slip displacements under the low frequency of excitation were larger than those under the high frequency. The higher slip displacements were observed for wet condition, comparing those for dry condition except for the GCL(B)/S-GM interface.

The maximum (peak to peak) slip displacements shown in Fig. 5 were normalized using Equation (1) as a function of the ration of K_y/K_a . It was found that S_{nor} was decreased with increasing K_y/K_a ratio and the functions were calculated for each frequency (Fig. 6).

$$S_{nor} = \frac{S_d f^2}{K_a} = \frac{S_d}{K_a T^2} \qquad \text{(Equation 1)}$$

Where, S_{nor} : normalized slip, S_d : measured maximum slip displacement (mm), f : frequency (Hz), K_a : base acceleration (g), K_y : yield acceleration (g), and T : period of the base acceleration (sec.)



(a) Dry condition (b) Wet condition

Fig. 5 Relative displacements with the table accelerations for GT/S-GM interface

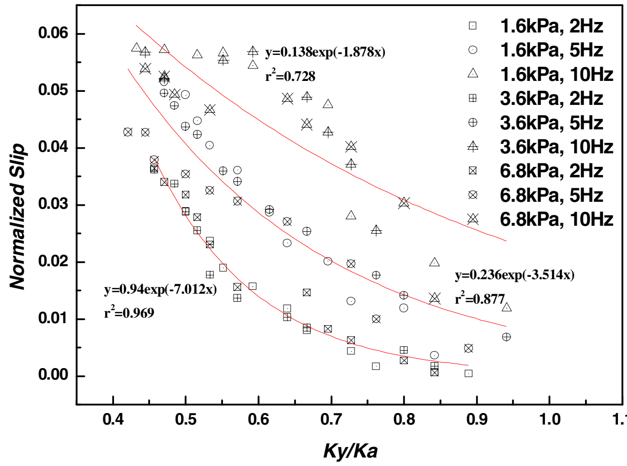


Fig. 6 Normalized slip displacements with increasing K_y/K_a ratio (Wet condition, GT/S-GM interface)

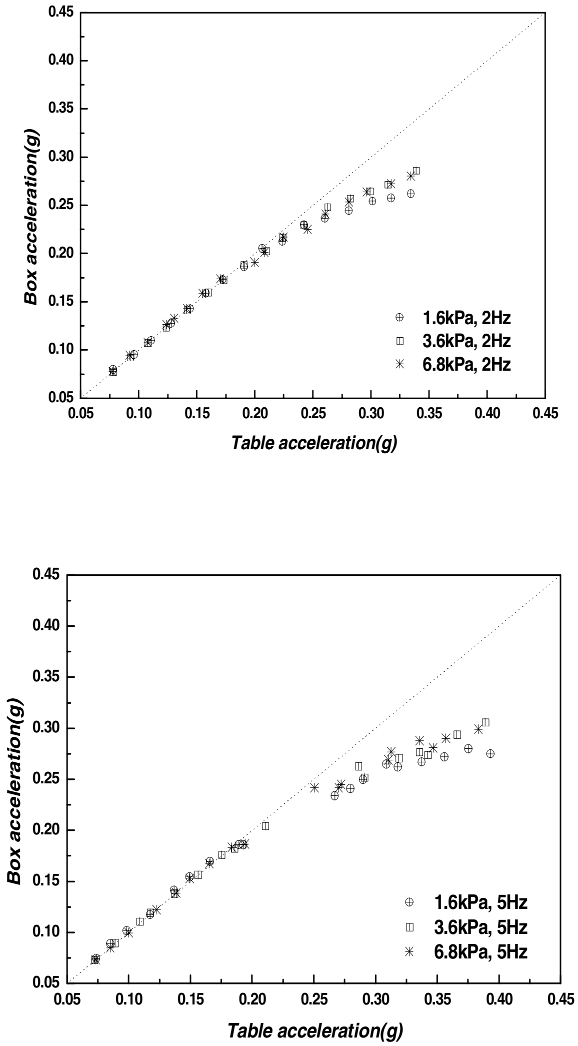
Normalized slip equations were calculated for other geosynthetic interfaces, i.e. GCL(A)NW/S-GM, GCL(A)W/S-GM, and GCL(B)/S-GM interface. Test results for another three interfaces are summarized in Table 2 and some comments on testing results are addressed in later discussion part.

DISCUSSION

Effect of normal stress, frequency, and submergence

Effect of the normal stresses applied

Shaking table tests were conducted with increasing weighting plate. The normal stresses applied in this research were 1.6 kPa, 3.6 kPa, and 6.8 kPa. The accelerations of the table and the box for geotextile/smooth geomembrane (GT/S-GM) interface are shown in Fig. 7.



(a) f = 2 Hz (b) f = 5 Hz

Fig. 7 Effect of normal stress on the dynamic friction angle for GT/S-GM interface (dry condition)

As shown in Fig. 7, at the constant frequency of excitation, the dynamic interface friction angle was constant with varying normal stress. Therefore, it was found that the dynamic interface friction angle is not influenced by the normal stress applied in this study. The same results were found for all interface combinations conducted in the tests.

Effect of frequency of the excitation

Tests were performed for three kinds of frequencies (2, 5, 10 Hz) in this experiment. Fig. 8 shows the accelerations of the table and box for the interfaces of smooth geomembrane with woven geotextile part of GCL(A), i.e. GCL(A)W/S-GM interface.

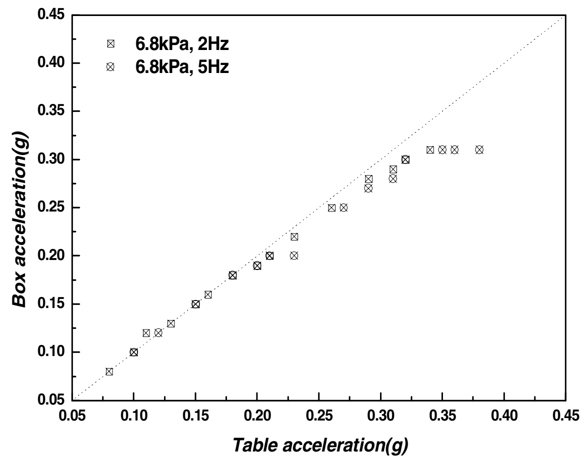


Fig. 8 Effect of frequency on the dynamic friction angle for GCL(A)W/S-GM interface (dry condition, σ_n =6.8 kPa)

As shown in Fig. 8, the dynamic interface friction angle of GCL(A)W/S-GM interface was not changed with varying frequency, which indicates that the frequency of excitations has little effect on the dynamic friction angle in this study. Therefore, it was concluded that the dynamic interface friction angle is not influenced by the frequencies applied in this study. The same results were found for all the interface combinations conducted in this study.

Effect of the submergence on dynamic interfaces properties

As the geosynthetic interfaces submerged, the dynamic interface properties were changed. As listed in Table 2, the dynamic friction angle or yield acceleration was reduced by 1.1° ~ 2.2° due to the lubricant effect of the water except for GCL(B)/S-GM interface. For the GCL(B)/S-GM interface, on the contrary, the friction angle increased with bentonite part of GCL(B) hydrated due to the cohesive effect of hydrated bentonite.

Table 2 Yield acceleration (dynamic friction angle) for the geosynthetic interfaces tested

Interface type	Interface combination	Dynamic friction angle (friction angle, yield acceleration)		Variation (°) (+ : increase, - : reduction)
		Dry condition	Wet condition	
Ⅰ type	GT/S-GM	10.2° (0.18g)	9.1° (0.16g)	- 1.1 °
Ⅱ type	GCL(A)NW/S-GM	10.2° (0.18g)	8.0° (0.14g)	- 2.2 °
Ⅲ type	GCL(A)W/S-GM	10.8° (0.19g)	9.1° (0.16g)	- 1.7 °
Ⅳ type	GCL(B)/S-GM	10.2° (0.18g)	10.8° (0.19g)	+ 0.6 °

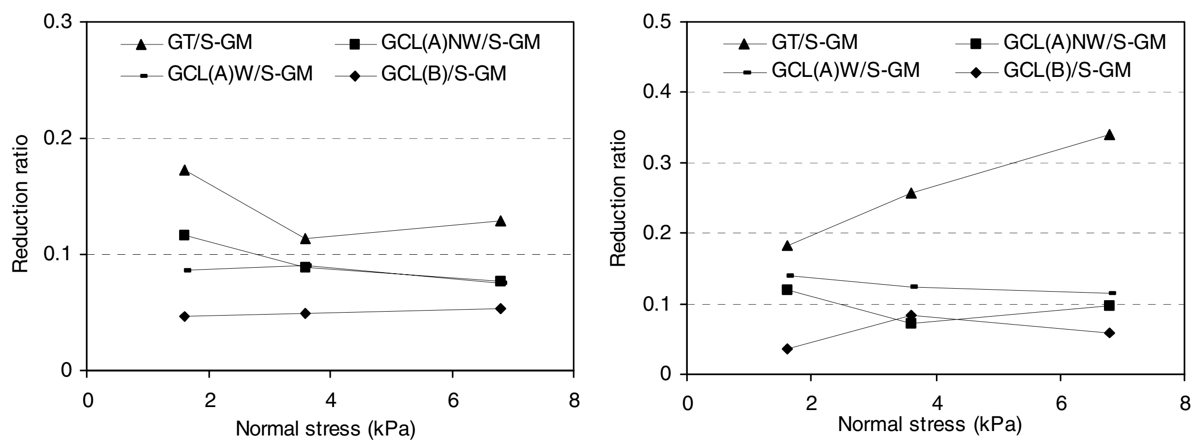
However, in case of maximum relative displacements under high level of accelerations, the magnitude of displacements was significantly increased as the interface gets to be submerged due to same lubricant effect of the water. However, the GCL(B)/S-GM interface showed the opposite behavior.

Reduction of acceleration transferred to the upper box

As previously mentioned, the peak box acceleration became to be smaller than peak acceleration of the table in the range where peak acceleration of the shaking table is above the yield acceleration of a geosysnthetic interface. The reduced shear force is supposed to be dissipated into relative displacement of upper box. The average reduced amount is demonstrated in Fig. 9 with the normal stresses applied. In this experiment, the reduced amount was highest in the GT/S-GM interface and the lowest in the GCL(B)/S-GM interface, which was supposed to be caused by cohesive effect of the bentonite attached in the GCL(B). Especially, for the GT/S-GM interface, the transmitted shear force decreased as a normal stress increased under submerged condition. The average reduction value is summarized in Table 3.

Table 3 Average reduction ratio of peak acceleration transmitted into the upper box

Interface type	Interface combination	Average reduction ratio	
		Dry condition	Wet condition
Ⅰ type	GT/S-GM	0.14	0.26
Ⅱ type	GCL(A)NW/S-GM	0.09	0.10
Ⅲ type	GCL(A)W/S-GM	0.08	0.13
Ⅳ type	GCL(B)/S-GM	0.05	0.06



(a) Dry condition (b) Wet condition

Fig. 9 The Reduction of accelerations transmitted into the upper box for the ranges above the yield acceleration of each interface

Summary of test results (dynamic friction angle and normalized slip equation)

All the dynamic friction angles and normalized slip equations are summarized in Table 4. For dry condition, the dynamic interface friction angles between geosynthetics were 0.18g or 0.19g. However, for wet condition, the dynamic interface friction angle became to be smaller by 0.02g ~ 0.04g except for GCL(B)/S-GM interface. The reason why dynamic friction angle decreased is supposed to be caused by the hydrated bentonite intruded into the interface from the GCL(A) or the water existing in the interface act as lubricant.

On the other hand, using the relationship between normalized slip, S_{nor} and K_y/K_a ratio, the normalized slip equations were calculated for each interface and the values of coefficients, a and b are also listed in Table 4 according to the frequency of excitation. The coefficient, a, is the interceptor of y axis, and the coefficient, b, is the curvature in the normalized slip curve. The normalized slip equation can be used to predict the peak displacement for the given dynamic loads. Namely, this equation can be utilized to predict the amount of shear displacement when the representative frequency of dynamic loads and the yield acceleration for the weakest interface are known. The value of b is found to be dependent upon the frequency. However, the value of "a" was almost constant regardless of the frequencies applied. Therefore, from the relationships in Table 4, the value of "b" can be induced with respect to the expected representative frequency.

Table 4 Yield acceleration and normalized slip equation for geosynthetic interfaces tested

Interface combination	Dynamic friction angle (g and degree)	Normalized slip equation		
Dry condition		**y = a exp (bx)**		
		f (Hz)	**a**	**b**
GT/S-GM	0.18g (10.2°)	2	0.298	-7.153
		5	0.347	-5.840
		10	0.191	-3.473
GCL(A)NW/S-GM	0.18g (10.2°)	2	0.562	-9.030
		5	1.880	-10.110
		10	0.358	-5.658
GCL(A)W/S-GM	0.19g (10.8°)	2	3.245	-12.593
		5	1.034	-9.710
		10	0.629	-7.037
GCL(B)/S-GM	0.18g (10.2°)	2	0.246	-7.863
		5	0.066	-4.082
		10	0.048	-2.958
Wet condition		**y = a exp (bx)**		
		f (Hz)	**a**	**b**
GT/S-GM	0.16g (9.1°)	2	0.940	-7.011
		5	0.236	-3.515
		10	0.138	-1.878
GCL(A)NW/S-GM	0.14g (8.0°)	2	5.093	-16.160
		5	0.538	-8.025
		10	-	-
GCL(A)W/S-GM	0.16g (9.1°)	2	3.620	-12.701
		5	0.650	-6.901
		10	0.244	-3.075
GCL(B)/S-GM	0.19g (10.8°)	2	0.002	-2.831
		5	0.004	-2.064
		10	0.007	-0.479

CONCLUSIONS

Shaking table tests were performed to investigate the dynamic interface frictional properties of a landfill cover systems. The influences of normal stress, frequency of excitation, and dry/wet condition were examined for given geosynthetic interfaces. During tests, when the magnitude of table acceleration was small, the table and box moved together. However, when acceleration reached a certain level, the peak acceleration of the box became smaller than that of the table. At this level called the yield acceleration, the slip displacement of box was initiated. The dynamic friction angle of each interface was evaluated by using the yield acceleration.

For every geosynthetic interfaces tested in this research, the normal stress and the frequency of excitation were identified not to influence the dynamic interface friction angle. From the measured relative slip displacements, the measured slip displacement under low frequency of excitation is larger than that under high frequency. The peak box acceleration became to be smaller than peak acceleration of the table in the range where peak acceleration of the shaking table is above the yield acceleration of a geosysnthetic interface. The reduced shear force is supposed to be dissipated into relative displacement of upper box.

For every geosynthetic interfaces tested, the dynamic interface friction angle in the wet condition was 1°2° lower than that in the dry condition except that for GCL(B)/S-GM interface. Also, the amplitude of relative displacement in the wet condition was higher than that under the dry condition. These changes were supposed to be caused by the water existing in the interface or the intruded bentonite from GCLs into the interface.

It was identified in the tests that the maximum slip, S_d along bottom liners or final covers of landfills depends on the type of interface, the base acceleration, and the frequency of excitation. Using the relationship between normalized slip displacement and the ratio of K_y/K_a, the maximum slip equation could be calculated for a given acceleration and frequency of excitation. The normalized slip equation can be used to predict the peak displacement for the given dynamic loads. Namely, this equation can be utilized to predict the amount of shear displacement when the representative frequency of dynamic loads and the yield acceleration for the weakest interface are known.

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