An Experimental Study on Frictional Behavior Between Soil and Reinforcements

흙과 補强材 사이의 摩擦擧動에 관한 實驗的 硏究

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要 旨

補强土擁壁의 遠心模型實驗의 豫備實驗으로서 모래와 補强材 사이의 摩擦擧動의 特性을 調査·硏究하기 위하여 摩擦實驗을 행하였다. 補强材의 종류 및 길이를 변화시킴으로써 그들이 모래와 補强材 사이의 摩擦係數 f에 미치는 影響을 조사하였다.

한편 다른 두가지 實驗方法(直接剪斷試驗과 引拔試驗)을 택하여 어떤 방법이 실제 현장에서의 補强材의 擧動을 잘 나타내는지를 비교·검토하였다.

Abstracts

Prior to the centrifugal model experiments of reinforced earth retaining walls[15], frictional tests were performed to investigate the frictional behavior between the sand and the reinforcements. Coefficient of friction f, between the soil and the reinforcements was evaluated using different reinforcements, their lengths and testing methods. Two different testing methods, the direct shear and the pull-out tests, were adopted and their testing results were compared to determine which method better represented the actual behavior in the field.

1. Introduction

In designing a reinforced earth structure it is necessary to estimate the bond stress mobilized on the reinforcement. Since the fill used in a reinforced earth structure is generally a granular material, the bond stress is frictional and is functions of the normal effective stress, σ_v, and the coefficient of friction between the soil and the reinforcement, f. Therefore, evaluation of this coefficient is essential in designing reinforced earth structures. Considering many factors affecting the frictional behavior at the interface between soil and reinforcements, it is required to estimate properly the value of f in laboratory as well as in field. Thus, based on the previous researches on the frictional behavior between the soil and the reinforcements, the factors controlling the behavior at the interface between soil and reinforcements are reviewed and summarized. Two

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different testing methods of the direct shear and the pull-out tests are performed to investigate the feasibility of the test results to actual structures in field.

2. Factors Controlling Frictional Behavior Between Soil and Reinforcements

There are many factors affecting the frictional behavior between the soil and the reinforcement. Such factors include nature of reinforcement surface, length and width of reinforcement, stiffness of reinforcement, overburden pressure, soil density, soil dilatancy, the compaction method used to prepare, sample and testing methods employed in evaluating the coefficient f between the soil and the reinforcement.

For nature of reinforcement surface, roughness of reinforcement surface was one of the major factors controlling the frictional behavior between the soil and the reinforcement. A variety of friction angle between soil and various construction materials were obtained by performing several hundred shear tests$^{10)}$. On the other hand, for the geometry of reinforcement surface, a ribbed strip as a reinforcement showed greater peak values on tensile-displacement curves in pull-out tests than a plain strip$^{7),12)}$. The hardness of reinforcement also affected the value of f. For thin aluminum strip, the coefficient of friction was found to be very high at high normal pressure$^{3),13)}$. It was surmised that the granular sands produced a certain indentation into the surface of the aluminum.

For density of soil, at high density the measured value of f was much greater than the expected value while at low density the measured value of f was smaller than the expected value. This result was explained by the effect of dilatancy for soils with high density and the local and limited collapse of the granular structure for soils with low density$^{11)}$. On the other hand, it was also reported that the mobilized friction between the soil and the reinforcement was about the same for any relative density of the soil$^{14)}$.

For the effect of overburden pressures, test results obtained by many researchers showed that there was a linear relationship between the maximum mobilized bond stress and the normal stress, resulting in a constant angle of bond stress, δ where $\tan\delta = f$. Based on the classical law of friction, the so-called Amonton's law, the coefficlent of friction was a constant and did not depend on the normal stress. But, dilatancy of soil surrounding the reinforcements might redistribute the normal stress acting on the surface of the reinforcement.

Considering dependency of dilatancy on the level of applied normal stress, the effect of dilatancy on the friction mobilized at the interface was more significant at low stress than at high stress. This result was confirmed by the fact that the coefficient of friction for the upper region of reinforced earth structure was found considerably greater than for the lower region. In addition, results from pull-out tests with full-scale reinforced earth walls indicated that the value of peak friction angle decreased with increasing overburden pressure$^{11)}$. For low pressures this value in granular soils was often very high (the cofficient of friction at soil/reinforcement interface, $f = 2$ to 6). A more feasible explanation of this behavior was presented by Guilloux, et al (1979) performing the constantvolume shear box tests. As strip reinforcements embedded in a soil were pulled, dilatancy might occur in a small zone in the vicinity of the reinforcing strip. Arching would occur across the strip by which the soil suppressed the

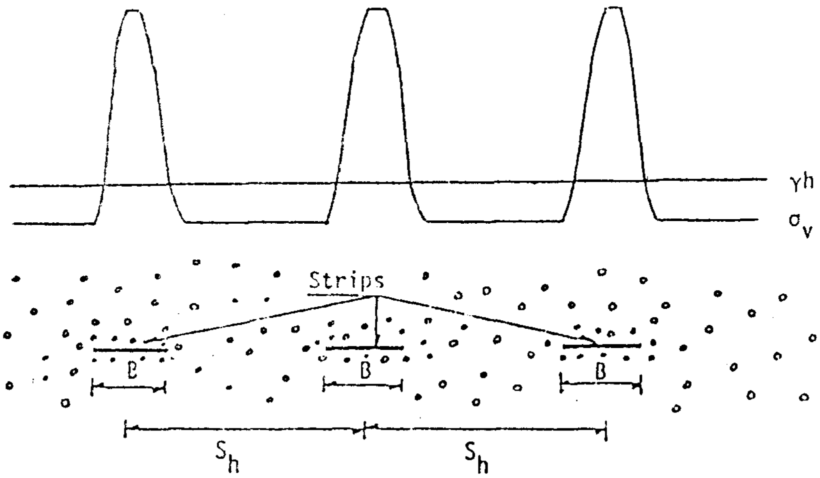


Fig. 1 Arching over reinforcing strips (Guilloux, et al 1979).

volumetric expansion normally associated with dilatancy. This suppressed dilatancy resulted in a locally enhanced vertical stress as illustrated in Fig. 1, causing an increased pull-out resistance and hence an increased value of *f*

For dimensions of reinforcing matreials, their effects on the frictional behavior at the soil-reinforcement interface were investigated by many researchers.1,2,11,12) The measured value of *f* generally increased with the length of the reinforcements. This phenomenon was explained by considering the edge effect which decreased the normal stress acting on the face of the reinforcement at the edge of the structure11) or by the undulation of reinforcements which developed an extra resisting force proportional to the length of reinforcement.1,12)

There were contradicting test results about the influence of the reinforcement width to the value of *f*. While the pull-out test in full scale1) showed that the value of *f* decreased with an increase in the reinforcement width, other researchers12) reported that this value increased as the reinforcement width increased. In fact, the width of the reinforcement affected different factors which influenced the value of *f*. Two major factors were considered11): (1) the deformability of the reinforcement which decreased with the reinforcement width, and (2) the dilatancy effect which had to decrease beyond a critical value of the width. For deformability of reinforcement, higher values of *f* were expected for wider reinforcement. It was possible that more undulations of reinforcement had been formed with increasing width of reinforcement. The effect of arching on the value of *f*, described previonsly, might also be significant for a certain range of strip width.

Since frictions mobilized at the soil-reinforcement interface depended on relative strains between a soil and reinforcement, the relative stiffness between them was a factor controlling the frictional behavior at the interface. The effect of relative stiffness was examined by using a plane strain unit cell apparatus9) and by performing the pull-out tests8). Tests with an extensible reinforcement of non-woven fabric showed that strains were high at the end of the sample subject to pull-out, dropping rapidly to zero or near zero values towards the free end of the sample. This result indicated that the relative strain and consequently mobilized friction along the fabric were not uniform. As the stiffness of the reinforcement increased, the relative strain distribution became uniform.

For the use of different testing methods, a peak value of friction at the soil-reinforcement interface depended on the testing methods. Results from the pull-out tests generally showed higher values of f than the direct shear box tests. It was caused by the fact that some undulations formed by the comparative flexibility of the reinforcements gave a higher pull-out resistance than a perfectly horizontal planar one.6) The pull-out tests in full scale gave higher values of f than the reduced scale tests in the laboratory.1),11) This result was associated with effects of reinforcement dimensions and dilatancy of soil on the value of f. Friction tests with a constant volume showed greater friction than with constant normal stresses.5) The tendency of diliation caused by shear stresses mobilized at the interface resulted in an increase of normal stress. Such a tendency was significant for dense soils with relatively low normal stresses.

Finally, a compaction method used in the field was known to affect the pull-out force in determining the value of f at the interface.1) The use of a vibratory compactor made the surface of each layer in a reinforced earth structure flatter. As a result, the reinforcements in the compacted zone were not as deformed by undulation of the surface as the reinforcements in the uncompacted zone. Thus, test results showed that the mobilized friction at the interface was smaller in a compacted zone than in a noncompacted zone. This effect was also investigated by monitoring the lateral movements of the facing in a reinforced retaining wall and by measuring the tension distribution in the strips during the construction operations.4) Appreciable pressures transmitted to the facing panels from the action of the compaction equipment increased the friction at the interface as well as the lateral movement of the facing panels.

3. The Direct Shear and the Pull-out Tests

Two different laboratory testing methods were used to evaluate the frictional coefficient between the soil and the reinforcement ; the direct shear and the pull-out tests. Test results obtained from these methods were compared to determine which method better represented actual behaviors of reinforced earth structure in fields.

The soil used for tests was a cohesionless sand called Coyote Concrete Sand from Nevada in the U.S.A. The grain size distribution of this sand is shown in Fig. 2. The basic soil properties are summarized in Table 1.

Tests were conducted on soil samples having a relative density of 90%. This density was achieved by vibration using a shaking table. Three different aluminums and a brass were used as reinforcing materials. Their properties are also listed in Table 1. Tensile tests were performed to obtain the tensile strength of reinforcements using an Instron testing machine. Tensile strengths shown in the table are for strips with 0.25 in. width.

For the direct shear testing device which a conventional direct shear testing device was modified, as shown in Fig. 3, the lower half of the shear box consisted of a wood block on which the reinforcement was attached and fixed with strong epcxy. The upper half of the box

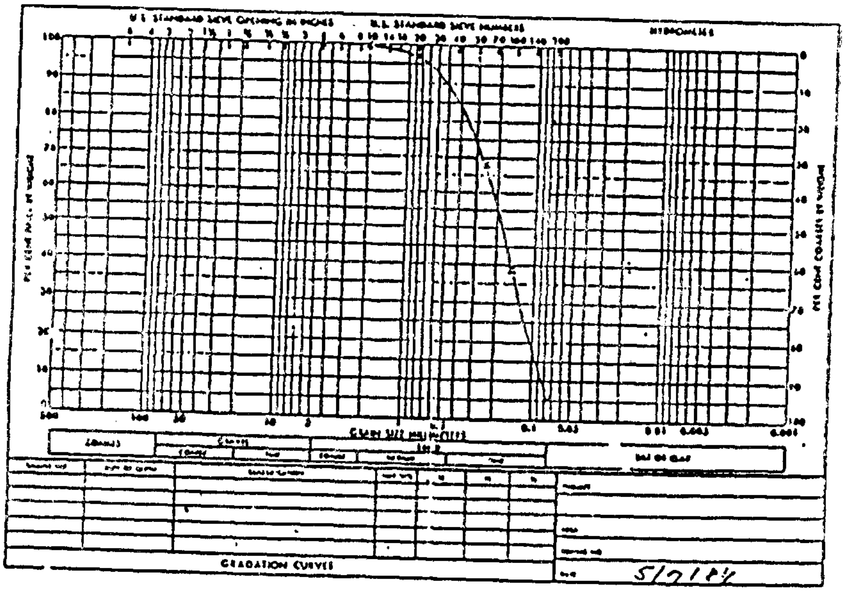


Fig. 2 Grain size distribution.

Table 1. Properties of soil and reinforcing materials.

SOIL		REINFORCING MATERIALS				
Maximum dry density Minimum dry density	113.3 pcf 90.8 pcf	Materials	Width (in.)	Thickness (in.)	Tensile strength (lbs.)	
Maximum void ratio Minimum void ratio	0.89 0.49				Yield	Break
Specific gravity	2.71	Brass	0.25	0.0051	57.5	62.5
Relative density (%)	Internal friction angle (degrees)	Aluminum	0.25	0.0155	85.0	102.5
70	41.0		0.25	0.0037	17.0	19.0
80	41.8		0.25	0.0022	14.0	15.0
90	45.2					

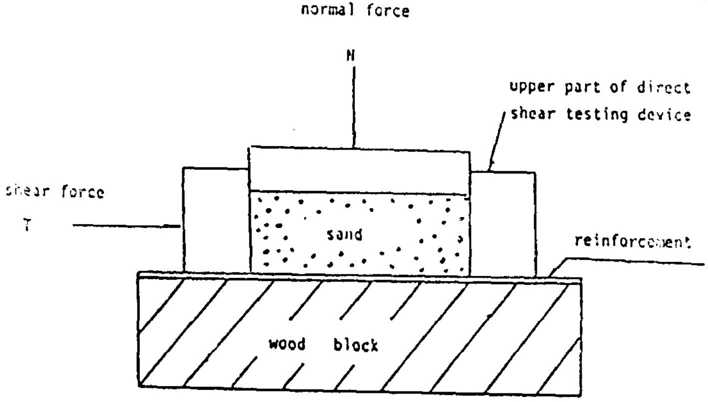


Fig. 3 A schematic of the direct shear testing device.

was filled with sand and was placed on the top of the lower half. The inner dimensions of the upper half were 2.5 in. by 2.5 in. by 1 in.. A proving ring and a dial gauge were used to monitor the shear forces mobilized at the interface between the sand and the reinforcement and the relative displacements of the sand to the reinforcement, respectively. The normal forces were applied to the sand by surcharging dead weights. A constant rate of displacement of 0.012 in./min. was applied during tests.

Typical shear stress-displacement curves and peak shear stresses with normal stresses to determine the coefficient of friction, $f = \tan\delta$, between the sand and the reinforcements are shown in Fig. 4.

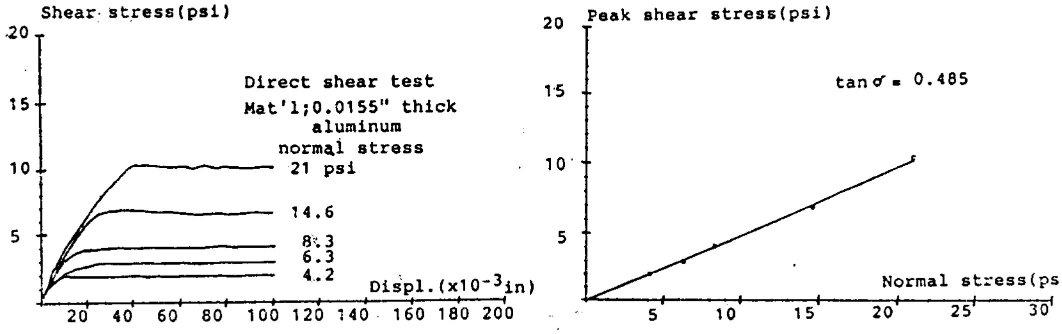


Fig. 4 Direct shear test results with aluminum of 0.0155 in. thick.

A schematic of the pull-out testing device is shown in Fig. 5, A shear box was made of plywood, having three small slots on each of the two opposite sides of the wall. These slots were separated from each others by a distance of 1 in. in the vertical direction. Two different boxes of 5 in. and 10. in. length of inner dimmension were used to evaluate the effect of reinforcement length on the friction coefficient at the soil-reinforcement interface. The smaller box had the inner dimensions of 5 in. by 5 in. by 6 in. The larger one was 5 in. bv 10 in. by 6 in. Smooth plastics were placed on the inside face of box wall to reduce wall frictions.

Reinforcing strips were embedded in the sand placed in the box and were protruded through slots on opposite walls of box. Since the box was stationary and the strips were moving, the

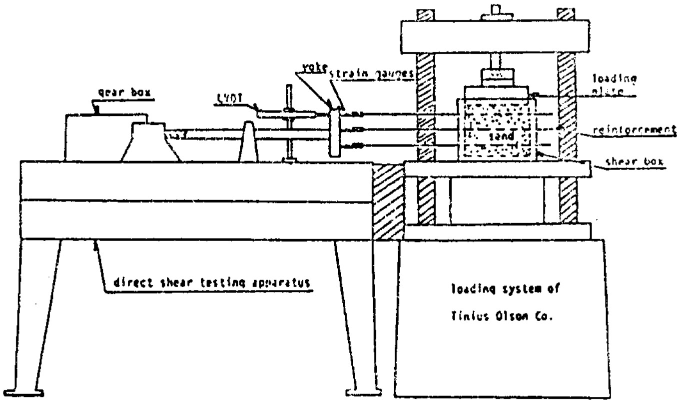


Fig. 5 A schematic of the pull-out testing apparatus.

length of strip subjected to normal loading could be kept constant during tests. Pulling forces on these strips were measured by load cells. The load cell was made of full-bridged strain gauges put on prongs on the aluminum yoke. A LVDT was installed to measure displacement of strip. All outputs of signal were stored in a IBM pc and data was reduced to be plotted by using a HP plotter.

Based on the assumption that shear stresses mobilized at the interface between soil and strip were uniform, shear stresses, τ, were calculated by monitoring tensions registered in the load cell as follows.

$$\tau = T/2\,BL$$

where T is the measured tension, B is width of strip, and L is length of strip.

Normal loads were applied by a Tinus Olson universal testing machine. Different numbers of strip were embedded to investigate group effect of strip on the overall frictional behavior at the soil-strip interface. All of pull-out tests were conducted with soil samples having a relative density of 90% which was achieved by using a vibration technique. The same rate of displacment, 0.012 in./min., as used in the direct shear tests was applied during pull-out tests. Fig. 6 represents typical results from pull-out tests with three layers of strip being 5 in. long. Pull-out tests were conducted by changing the layer (single, double and triple layers) and the spacing between strips (1 in. and 2 in. apart between strips in the vertical direction).

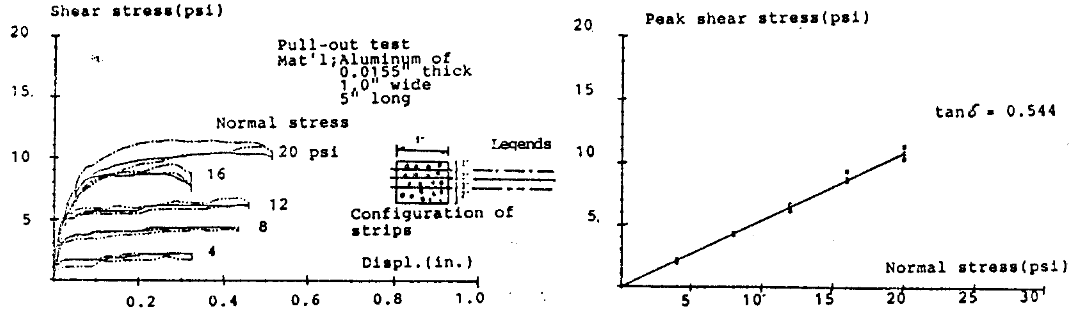


Fig. 6 Pull-out test results with aluminum of 0.0155 in. thick and 5 in. long and triple layers.

Results of the direct shear and the pull-out tests are summarized in Table 2. Values of f obtained from pull-out tests could be noticed to be always higher than those obtaind from direct shear tests. This might be caused by indentation of particles on surface of strip, undulation of strip, and dilatancy associated with arching action as described previously.

For a reinforcing material of brass having very hard surface, the value of f from the direct shear test was very close to that from the pull-out test. On the other hand, for the strips of aluminum whose surface hardness was lower than brass, the value of f increased with decreasing thickness of reinforcement for both the pull-out and the direct shear tests. This trend was more significant in the pull-out tests than in the direct shear tests since normal stresses in pull-out tests acted on both surfaces of strips,

On the other hand, the higher value of f in the pull-out tests might be explained by the dilatancy effect of the soil on the frictional behavior at the soil-reinforcement interface, associated with arching as described previously. But, from the observation that the value of f

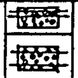
Test / Mat'l	Direct-Shear Test	Pull-out Test					
Length of Reinforcement	2.52"	5"			10"		
		Layers of Reinforcements					
Configuration of Reinforcement		Single 	Double 	Triple 	Single 	Double 	Triple 
Brass	0.369	0.370					
Aluminum of 0.0155" Thick	0.485	0.502	0.523 0.513	0.544	0.579	0.607 0.590	0.765
Aluminum of 0.0037" Thick	0.510	0.638					
Aluminum of 0.0022" Thick	0.520	0.685					

Table. 2 Values of frictional coefficient, *f*, obtained from the direct shear and the pull-out tests.

of brass from the pull-out tests was very close to that from the direct shear tests, the dilatancy effect was unlikely to be significant. This could be explained by dilatancy of soil in conjunction with particle indentation into the surface of strips. Less tendency of particle penetrating in hard surface of strip like a brass would result in less tendency of soil dilating around strips. Thus, the value of *f* for a brass having hard surfaces would be less than that of aluminum.

For pull-out tests with double layers of aluminum strip, the closer the spacing between strips was, the higher the value of *f* was. This trend was more significant for the pull-out tests with triple strips. Such a phenomenon might also be explained by the dilatancy effect of the soil on the frictional behavior at the interface.

Comparing values of *f* from the pull-out test with strips of 5 in. length to those of 10 in length, the effect of strip length on the value of *f* was likely to be very significant. This effect could be explained in terms of particle indentation into surfaces of strip and an undulation of strip. It could not be overlooked that the value of *f* increased with the number of strips and with decreasing the spacing between strips. In this case the value of *f* would increase with dilating tendency of soil.

4. Conclusions

Comparisons of the results between the direct shear test and the pull-out test indicated that the value of frictional coefficient, *f*, obtained from the pull-out test was usually higher than that from the direct shear test. This value was also dependent on the density of reinforcements, associated with the dilatancy of the soil. The hardness of reinforcement was an important factor determining the value of *f*, related to indentation of soil grains. It was also observed that the value of *f* increased with the reinforcement length. In conclusions, considering the fact that both surfaces of reinforcements were exposed to a soil and dilatancy effect might be involved between adjacent reinforcement, the pull-out test was preferred to be used to evaluate correctly the frictional behavior between the soil and the reinforcement in field.

Acknowledgements

This study is a part of author's Ph, D. dissertation in the University of Colorado at Boulder. Great appreciation is extended to Professor Hon Yim Ko, author's advisor, for his thoughtful guidance and supports given to him during the course of this study.

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(접수일자 1989. 9. 5)