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Variation of Earth Pressure Acting on the Cut-and-Cover Tunnel Lining due to Geotextile Mat Reinforcement

지오텍스타일 매트의 설치에 의한 개착식 터널 라이닝에 작용하는 토압의 변화

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요 지

얕은 터널의 개착식 터널 라이닝에 발생하는 과잉토압은 라이닝의 변형과 손상을 유발하는 역학적 주요인자들 중의 하나이며(Kim, 2000), 과잉토압은 되메움토의 다짐불량, 자중에 의한 압밀, 강우의 침투에 의한 다짐, 차량에 의한 진동 등에 의해 발생할 수 있다(Komiya et al., 2000; Taylor et al., 1984; Yoo, 1997). 터널 라이닝에 발생하는 토압을 구하기 위한 많은 시험이 행해졌지만, 부등침하와 과잉토압을 줄일 수 있는 보강대책을 수립하기 위한 사례는 없다. 본 연구는 모래 지반에 1.0D～1.5D 깊이에 개착식으로 시공하는 원형의 강성 터널에 작용하는 토압에 관한 것으로 진동다짐의 영향을 모형실험에서 충분히 반영하기 위하여 100Hz의 진동주파수를 사용하였다. 본 연구에서는 개착식 터널 라이닝에 작용하는 부등침하와 과잉토압을 줄이기 위해서 지오텍스타일 매트를 설치하였다. 지오텍스타일 매트의 보강에 의한 부등침하와 토압의 감소효과를 확인하기 위해 실내모형실험을 수행하였다. 실내모형실험에서 토피, 매트 보강형태, 절취면의 거칠기 등을 달리하여 가장 효과적인 방법을 구하였다. 절취면의 거칠기 달리하기 위해 사면에 사포#100, 사포#400과 acetate 부착하였습니다. 무보강과 매트 보강에 대한 모형실험을 실시하여 구한 토압을 비교하여 매트 보강효과를 살펴보았으며, 사진분석법(Park, 2003)을 이용하여 지반의 변형을 분석하였다.

Abstract

Excessive earth pressure is one of the major mechanical factors in the deformation and damage of Cut-and-Cover Tunnel lining in shallow tunnels and portals of mountain tunnels (Kim, 2000). Excessive earth pressure may be attributed to insufficient compaction and consolidation of backfill material due to self-weight, precipitation and vibration caused by traffic (Komiya et al., 2000; Taylor et al., 1984; Yoo, 1997). Even though there were a lot of tests performed to determine the earth pressure acting on the tunnel lining, unfortunately there were almost no case histories of studies performed to determine remedial measures that reduce differential settlement and excessive earth pressure. In this study the installation of geotextile mat was selected to reduce the differential settlement and excessive earth pressure acting on the cut-and-cover tunnel lining. In order to determine settlement and earth pressure reduction effect (reinforcement effect) of geotextile mat reinforcement, laboratory tunnel model tests were performed. This study was limited to the modeling of rigid circular cut-and-cover tunnel constructed at a depth of 1.0D～1.5D in loose sandy ground and subjected to a vibration frequency of 100 Hz. Model tests with varying soil cover, mat reinforcement scheme and slope roughness were performed to determine the most effective mat reinforcement scheme. Slope roughness was adjusted by attaching sandpaper #100, #400 and acetate on the cut slope surface. Mat reinforcement effect of each mat reinforcement scheme were presented by the comparison of earth pressure obtained from the unreinforced and mat reinforced model tests. Soil settlement reduction was analyzed and presented using the Picture Analysis Method (Park, 2003).

Keywords : Cut-and-cover tunnel, Earth pressure, Geotextile, Tunnel lining, Tunnel model test

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1. Introduction

Excessive surface settlement and excessive earth pressure are the two major problems encountered after the construction of cut-and-cover tunnels and mountain tunnel portals. These problems are caused by the consolidation of backfill material due to its self-weight or external forces in the form of precipitation and traffic vibration. At present there are several case studies regarding the earth pressure acting on cut-and-cover tunnel linings (Yoo, 1997; Kim, 1999) and tunnel lining behaviour (Lee et al., 1998; Kim, 2000). Unfortunately almost no case studies regarding the earth pressure reduction method are available.

Due to the increasing cases of tunnel lining cracks and damages due to excessive earth pressure and differential settlement of the restored soil cover, there is a need to find a simple, effective, and economical remedial measure that will solve both of these problems. The use of geotextile reinforcement method was considered since it is used to prevent differential settlement and to distribute loads in the construction of other engineering structures, especially in embankments (Venkatappa Rao et al., 1995; Koerner, 1986). In order to determine the feasibility of geotextile reinforcement in cut-and-cover tunnel construction, laboratory model test using a circular 1:20 scale rigid tunnel model was installed in a plane strain soil tank covered with 1.0D~1.50D (D is the tunnel diameter) of loose sand with different geotextile mat reinforcement schemes. The plane strain soil tank was subjected to a vibration frequency of 100 Hz for a period of 10 minutes. Variation in soil cover, slope roughness and mat reinforcement schemes were applied. The soil settlement and earth pressure reduction of each mat reinforcement were determined and the most efficient mat reinforcement scheme was recommended.

2. Tunnel Model Test Equipment and Testing Method

2.1 Test Equipment

The laboratory tunnel model tests with geotextile mat reinforcement were performed using the following equipments:

2.1.1 Plane Strain Soil Tank with Vibrating Motor

The plane strain soil tank with vibrating motor was the same as the soil tank used by Im et al. (2002) and Park (2003). In this study a vibration motor was installed beneath the soil tank with a control unit that controls the vibration frequency and vibration period. The vibration frequency used was 100 Hz and the vabration frequency was 10 minutes based on the prelimenary test performed by Bautista et al. (2006). The vibration generated by the motor was used to consolidate the model soil in the soil tank. Photo 1 shows the plane strain soil tank used in this study.

2.1.2 Transverse Tunnel and Cut Slope Model

The transverse tunnel and cut slope model used in this study are shown in Photo 2. The transverse tunnel made of 8 aluminum segments with a bi-directional load cell was installed on the center of each segment (Park, 2003) while the cut slope model was made of plyboard installed at an angle of 45° on both sides of the tunnel at a distance (G) 1D from the center of the tunnel. The tunnel model

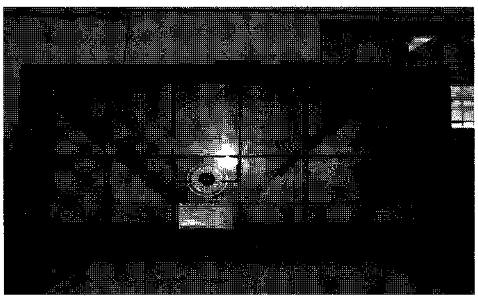


Photo 1. Plane Strain Soil Tank

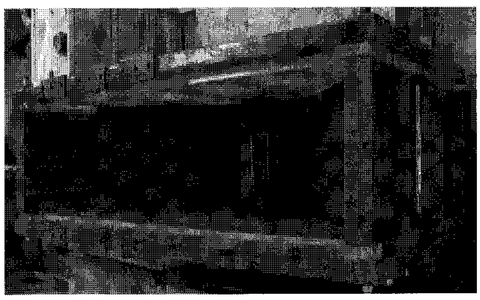


Photo 2. Cut slope and tunnel model

was a 1:20 reduction of the actual tunnel size. The friction of transverse tunnel and cut slope were considered through the attachment of sand paper #100 for the tunnel and sand paper #100, #400 and acetate on the slope surface. Double sided adhesive tape was used to attach the sand paper and acetate to the model tunnel structure and slope surface. Sand paper #100 represents soil with sufficient slope roughness, sand paper #400 represents soil with medium slope surface roughness and acetate represents soil with almost no friction resistance.

2.1.3 Model Soil Laying Apparatus and Surface Leveling Device

Backfill soil was modeled using Sand Drop Method wherein the sand was dropped from a slot at a constant height and velocity. To ensure that the sand was layed at a uniform state close to minimum dry density ($1.378\,g/cm^3$) of Jumunjin Standard Sand, a handheld slot with an opening of 3 mm was made of acrylic plates (Refer to Photo 3). Using this slot, loose sand with relative density of 38.9% was produced.

Surface leveling device or leveler was made of 2 acrylic plates connected by bolts and nuts (Refer to Photo 4). Holes were pre-drilled on the acrylic plate based on the depth of geotextile reinforcement location or surface level.

2.1.5 Deformation Monitoring Device

Due to the test condition of this study, the use of standard devices such as dial guage to determine the surface settlement and density cans to determine density was difficult. Instead, strings with weights attached on one end were used to measure the initial and final surface settlement by lowering them from an aluminum channel placed longitudinally on the top of the soil tank (Refer to Photo 4). Markings made on the strings lowered from the aluminum channel indicate the surface level. The measured displacements were used in the calculation of the overall soil volume and density before and after the test.

Targets (Park, 2003) with a diameter of 1 cm installed at 2.5 cm × 2.5 cm square interval on the front acrylic plate were covered with acetate (Refer to Photo 5). Pictures taken before, during and after the test were interpreted using Microstation. DALT Program (Park, 2003) was used on the interpreted values to determine the behaviour of soil around the tunnel.

2.2 Modelling Materials

2.2.1 Jumunjin Standard Sand

Jumunjin Standard Sand was used in the modelling of the soil material. The physical properties and particle size information of Jumunjin Standard Sand determined through laboratory tests were presented in Table 1 and Table 2, respectively.

Mechanical properties determined by using direct shear test, standard triaxial compression test and plane strain

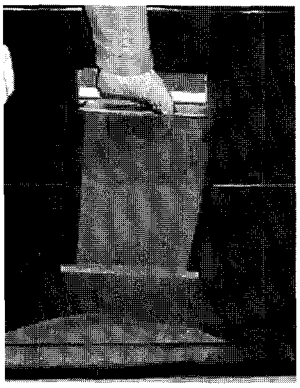


Photo 3. Handheld Slot

Photo 4. Soil Leveler

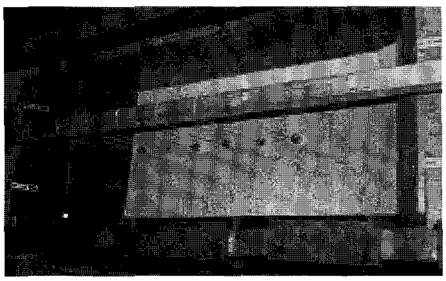


Photo 4. Settlement monitoring apparatus

Photo 5. Target installed at a square interval

Table 1. Physical Properties

Physical Properties	Symbol	Unit	Value
Max. dry density	γ_{dmax}	g/cm^3	1.652
Min. dry density	γ_{dmin}	g/cm^3	1.378
Max. void ratio	$e_{\max}$	–	0.923
Min. void ratio	$e_{\min}$	–	0.604
Water content	w	%	0.300
Specific Gravity	G_s	–	2.650

Table 2. Particle Size Information

Physical Properties	Symbol	Unit	Value
Effective Diameter	D_{10}	mm	0.443
Average Diameter	D_{50}	mm	0.595
Maximum Diameter	$D_{\max}$	mm	0.850
Curvature Coefficient	C_g	–	0.912
Uniformity Coefficient	C_u	–	1.402

compression test are shown in Table 3.

2.2.2 Geotextile Model Material

The geotextile mat reinforcements used in this experiment were polyester fabric screen and the properties are presented in Table 4 based on the study performed by Joo (2000). The experiment was performed by varying the number of mat layers and installation location. During the installation, geotextile mat reinforcements were installed with a clear distance of 10 mm from the cut slope and model tunnel. The mat reinforcement used in this experiment is shown in Photo 6 and the installation is shown in Photo 7.

2.3 Earth Pressure Monitoring and Recording Device

8 bi-directional load cells were installed on each segment transverse tunnel model to monitor the earth pressure while UCAM-10A was used to record and print-out the monitored earth pressure. Even though there were 8 loadcells installed on the transverse tunnel, only 5 loadcells located on the crown, shoulder and sidewall portion were considered. The correction coefficient test was performed in order to determine whether there is coupling effect on the vertical and horizontal direction of the loadcell. The correction coefficients determined from the test were applied on the test results obtained from the tunnel model

Table 3. Mechanical Properties of Soil using Different Tests (Park, 2003)

Parameters	Test Types																	
	Direct Shear Test								Standard Triaxial Compression Test				Plane Strain Compression Test					
Number	1	2	3	4	5	6	7	8	1	2	3	4	1	2	3	4	5	6
γ_d (g/cm^3)	1.38	1.47	1.52	1.56	1.57	1.60	1.63	1.65	1.39	1.45	1.55	1.61	1.38	1.41	1.42	1.46	1.58	1.65
Dr (%)	0	36.9	57.0	70.7	74.4	84.3	93.8	98.2	6.9	29.9	66.9	86.9	0	11.6	15.8	31.9	77.1	98.5
ϕ_{TCT} (°)	31.2	33.0	35.0	33.7	38.0	39.2	41.1	42.0	31.2	33.4	36.5	41.3	36.4	35.8	36.8	39.6	46.1	51.1

Table 4. Properties of Mat Reinforcing Material (Joo, 2000)

Geotextile	Manufacture	Polymer Fiber	Tensile Strength (tf/m)	Tensile Strain (%)	Polymer Type
	Woven	Monofilament	0.278	26.46	Polyester

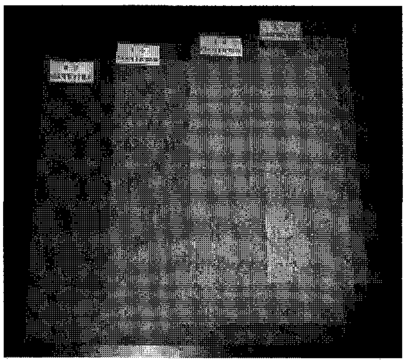


Photo 6. Geotextile reinforcements

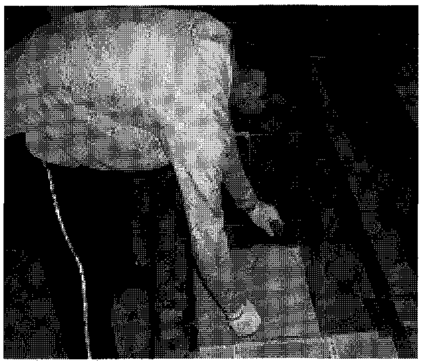


Photo 7. Geotextile Installation

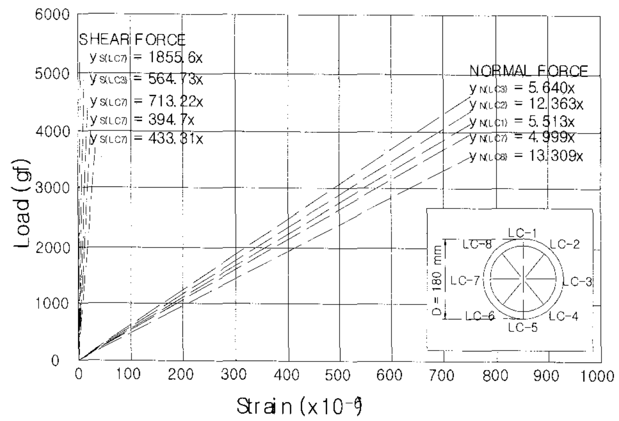


Fig. 1. Loadcell Installation Diagram and Calibration

test. The loadcell installation layout and calibration of the loadcell installed in the tunnel segment are shown in Fig. 1. The correction coeffcient test showed that there was no coupling effect on the loadcells.

2.4 Test Method

In this study the earth pressure acting on an cut-and-cover tunnel with soil covers of 1.0D ~ 1.5D at a slope angle of 45° was determined through model tests. Earth pressure reduction of geotextile reinforcement (referred as mat reinforcement effect) for each reinforcement scheme was determined based on the comparison of measured earth pressure acting on the tunnel for unreinforced and reinforced model tests. Tests performed in this study can be divided into 3 major groups, namely:

(1) Model Test with Varying Soil Cover
(2) Model Test with Varying Mat Reinforcement
(3) Model Test with Varying Slope Roughness

2.4.1 Types of Tests

The types of tests and its respective test conditions are shown in Table 4 and were graphically presented in Figure 2 to Figure 4. In this study, the tests were

Table 4. Test Types and Test Conditions

Test Designation	Soil Cover (H)	Reinforcement Type & Location	Slope Surface
1.0D-NR-100	1.0D	no reinforcement	Sandpaper #100
1.0D-1T-100		1 layer top reinforcement (0.5D from top of tunnel)	
1.0D-2T-100		2 layer top reinforcement (0.3D & 0.6D from top of tunnel)	
1.0D-2S-100		2 layer side reinforcement (0.5D & 1.0D from bottom of tunnel)	
1.0D-4S-100		4 layer side reinforcement (0.5D, 1.0D, 1.3D & 1.6D from bottom of tunnel)	
1.0D-2S2T-100		2 layer top & 2 layer side reinforcement (0.5D, 1.0D, 1.3D & 1.6D from bottom of tunnel)	
1.5D-NR-100	1.5D	no reinforcement	Sandpaper #100
1.5D-1T-100		1 layer top reinforcement (0.75D from top of tunnel)	
1.5D-2T-100		2 layer top reinforcement (0.5D & 1.0D from top of tunnel)	
1.5D-2S-100		2 layer side reinforcement (0.5D & 1.0D from bottom of tunnel)	
1.5D-4S-100		4 layer side reinforcement (0.5D, 1.0D, 1.5D & 2.0D from bottom of tunnel)	
1.5D-2S2T-100		2 layer top & 2 layer side reinforcement (0.5D, 1.0D, 1.3D & 1.6D from bottom of tunnel)	
1.5D-NR-400	1.5D	no reinforcement	Sandpaper #400
1.5D-2S2T-400		2 layer top & 2 layer side reinforcement (0.5D, 1.0D, 1.3D & 1.6D from bottom of tunnel)	
1.5D-NR-ACE		no reinforcement	Acetate
1.5D-2S2T-ACE		2 layer top & 2 layer side reinforcement (0.5D, 1.0D, 1.3D & 1.6D from bottom of tunnel)	

designated by a combination of numbers and letters as shown below:

1.5D - 2S2T - 100

Soil Cover | Reinforcement Type | Slope Materail

The first two numbers represents the soil cover with respect to the diameter of the tunnel (D). The second set of numbers and letters represent the reinforcement type, the numbers representing the number of reinforcement and the letters representing the location. The letter "S" means that the inforcement is on the side of the tunnel and letter "T" meaning the reinforcement is on the top of the tunnel. "NR" is used in case there were "no reinforcements" used in the model test. The last portion of the test designation represents the type of material used on the cut slope. It can be "100" for Sandpaper #100, "400" for Sandpaper #400 or "ACE" for acetate.

2.4.1.1 Model Tests with Varying Soil Cover

Model tests representing the tunnel structure with varying soil cover were performed. The most conservative slope angle of 45° used in actual construction was selected for this study. The depth of soil cover is represented by the tunnel diameter (*D*). The test when it comes to soil cover is divided into 1.0D and 1.5D. The schematic diagram of the model test is presented in Fig. 2 and Fig. 3.

2.4.1.2 Model Tests with Varying Mat Reinforcement

In order to minimize excessive surface settlement and earth pressure, laboratory model test with different types of soil reinforcement method were performed. One un-reinforced test and five different mat reinforcement tests were performed (Refer to Fig. 4). In the figure, *D* is the tunnel diameter, *G* is the distance between slope and tunnel, *H* is the soil cover, *LC* is the bi-directional loadcell and θ is the slope angle. The reinforcement effect was determined by comparing the surface settlement and earth pressure obtained from unreinforced and mat reinforced model tests.

2.4.1.3 Model Tests with Varying Slope Roughness

To determine the effect of slope roughness on the soil behaviour of soil, earth pressure and other geometric factors, 2 types of sandpaper (#100 and #400) and acetate were used to simulate the roughness of the slope surface. The smoothness of the material used to cover the cut slope surface represents the friction resistance. Generally, the cut slope possesses friction resistance which may depend on the soil material. In this test, general types of soil was model using sandpaper #100, and slope with little friction resistance was represented by sandpaper #400, while acetate represents soil with almost zero friction resistance.

2.4.2 Test Sequence

This study was performed based on the following sequence:

a) Installation of cut slope and tunnel model
b) Initialization of Load cell
c) Laying of model soil using handheld slot and target installation on every 2.5 cm of model soil
d) Installation of geotextile model for reinforced model test
e) Surface leveling and monitoring of initial earth pressure and surface settlement
f) Picture taking of the initial soil condition before vibration
g) Vibration of soil tank at 100 Hz for 10 minutes

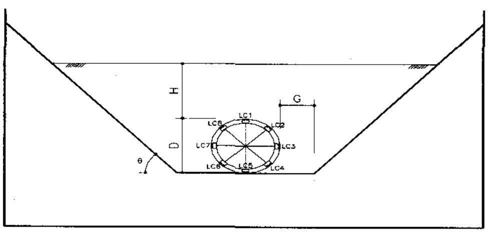


Fig. 2. Test Diagram for 1.0D Soil Cover

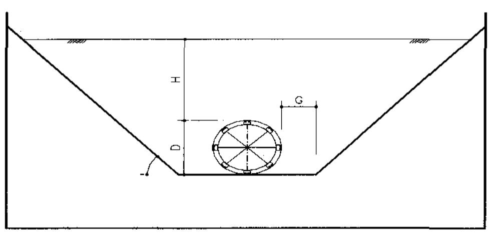
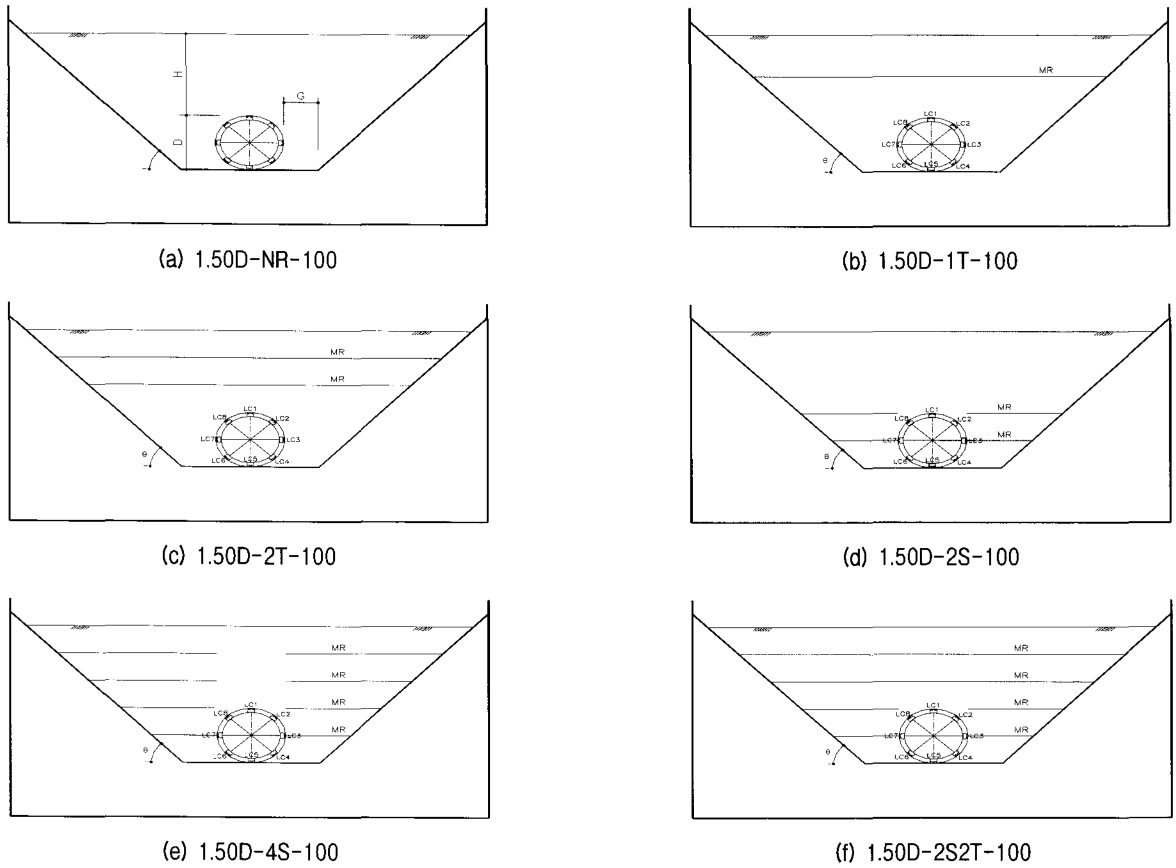


Fig. 3. Test Diagram for 1.50D Soil Cover



(a) 1.50D-NR-100 (b) 1.50D-1T-100

(c) 1.50D-2T-100 (d) 1.50D-2S-100

(e) 1.50D-4S-100 (f) 1.50D-2S2T-100

Fig. 4. Mat Reinforcement Scheme

h) Picture taking of the final soil condition after vibration
i) Monitoring of the final earth pressure and surface settlement
j) Test data arrangement and analysis

3. Result of the Tunnel Model Test

After the soil tank was subjected to a vibration of 100 Hz for a period of 10 minutes an average dry density of $1.537\,g/cm^3$ and a relative density of 66.9% were

Table 5. Variation of Earth Pressure with 1.0D Soil Cover

Load Cell Location		Earth Pressure Before Vibration (gf/cm^2)						Earth Pressure After Vibration (gf/cm^2)					
		NR	1T	2T	2S	4S	2S2T	NR	1T	2T	2S	4S	2S2T
Crown		41.110	35.765	34.532	33.504	30.421	33.093	57.142	54.676	56.937	55.087	55.909	51.593
Shoulder	Right	15.924	16.332	15.720	16.332	14.290	14.903	19.394	22.661	22.252	23.477	22.252	22.456
	Left	18.578	19.394	23.477	23.273	24.090	26.744	25.723	23.477	24.294	24.294	19.803	20.823
Sidewall	Right	16.740	16.944	21.027	26.948	27.356	29.602	20.415	21.027	18.872	14.903	16.332	15.311
	Left	15.515	15.924	16.740	13.066	14.903	14.903	22.456	37.768	23.681	31.847	41.034	43.280

Table 6. Variation of Earth Pressure with 1.50D Soil Cover

Load Cell Location		Earth Pressure Before Vibration (gf/cm^2)						Earth Pressure After Vibration (gf/cm^2)					
		NR	1T	2T	2S	4S	2S2T	NR	1T	2T	2S	4S	2S2T
Crown		50.770	49.126	46.659	50.976	49.537	47.687	96.608	90.852	89.002	96.197	80.896	79.753
Shoulder	Right	24.702	23.886	24.702	26.131	20.415	22.661	30.418	34.705	34.297	36.135	36.339	33.889
	Left	21.232	21.640	21.844	23.477	39.809	30.214	30.214	31.031	34.501	34.501	30.010	32.256
Sidewall	Right	31.235	37.155	42.463	38.788	30.418	33.072	19.803	18.169	17.761	12.045	14.086	12.861
	Left	30.214	33.276	27.152	38.788	20.415	18.986	35.318	40.626	42.055	40.013	39.605	39.401

Table 7. Variation of Earth Pressure with Slope Roughness at 1.50D Soil Cover

Load Cell Location		Earth Pressure Before Vibration (gf/cm^2)						Earth Pressure After Vibration (gf/cm^2)					
		100		400		ACE		100		400		ACE	
		NR	2S2T	NR	2S2T	NR	2S2T	NR	2S2T	NR	2S2T	NR	2S2T
Crown		50.770	47.687	49.126	46.043	50.154	45.837	96.608	79.753	90.236	88.591	66.803	83.658
Shoulder	Right	24.702	22.661	22.456	21.232	22.252	23.273	30.418	33.889	33.072	38.993	37.972	41.034
	Left	21.232	30.214	20.619	19.598	20.007	21.232	30.214	32.256	32.664	35.930	33.276	33.685
Sidewall	Right	31.235	33.072	37.768	38.176	38.788	41.442	19.803	12.861	35.114	14.086	25.110	46.138
	Left	30.214	18.986	32.868	40.830	36.747	40.422	35.318	39.401	47.159	47.363	62.062	140.659

obtained. The measured earth pressures before and after vibration for model tests with 1.0D and 1.50D soil cover are shown in Table 5 and Table 6, respectively. The measured earth pressures for each model test with different slope roughness at 1.50D soil cover are shown in Table 7.

3.1 Analysis of Earth Pressure Reduction Around the Tunnel

Earth pressure reduction is determined by comparing the different reinforcement model tests with the unreinforced model test (NR). Difference in earth pressure and mat reinforcement effect due to the installation of geotextile reinforcement for each reinforcement scheme is presented below. In this test a negative value indicates increase in earth pressure and a positive value indicates reduction in earth pressure.

3.1.1 Model Test with Different Soil Cover

3.1.1.1 Model Test with 1.0D Soil Cover

Table 8 shows the difference in earth pressure and mat reinforcement effect of each mat reinforcement scheme after vibration with the earth pressure of the unreinforced test (NR) as the basis. Considering the reduction in earth pressure due to reinforcement type, it can be seen that there is a reduction in reinforcement effect as the mat reinforcement increase. This is visible in the comparison of the values of 1T and 2T and in the values of 2S and 4S. For 1D, the reinforcement effect is not only affected by the number of reinforcement but also by the location of mat reinforcement.

3.1.1.2 Model Test with 1.50D Soil Cover

Table 9 shows the reduction in earth pressure for each mat reinforcement scheme after vibration. For 1.5D, the mat reinforcement effect was influenced by 3 factors,

Table 8. Earth Pressure Reduction with Reinforcement Type (1.0D Soil Cover)

Load Cell Location		Earth Pressure in gf/cm^2 (Reinforcement Effect in %)				
		1T	2T	2S	4S	2S2T
Crown		2.47 (4.3)	0.21 (0.4)	2.06 (3.6)	1.23 (2.2)	5.55 (9.7)
Shoulder	Right	−3.27 (−16.8)	−2.86 (−14.7)	−4.08 (−21.1)	−2.86 (−14.7)	−3.06 (−15.8)
	Left	2.25 (8.7)	1.43 (5.6)	1.43 (5.6)	5.92 (23.0)	4.90 (19.0)
Sidewall	Right	−0.61 (−3.0)	1.54 (8.0)	5.51 (27.0)	4.08 (20.0)	5.10 (25.0)
	Left	−15.31 (−68.2)	−1.22 (−5.5)	−9.39 (−41.8)	−18.58 (−82.7)	−20.82 (−92.7)

Table 9. Earth Pressure Reduction w/ Reinforcement Type After Vibration(1.5D Soil Cover)

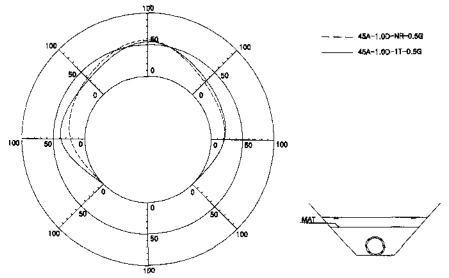
Load Cell Location		Earth Pressure in gf/cm^2 (Reinforcement Effect in %)				
		1T	2T	2S	4S	2S2T
Crown		5.76 (6.0)	7.61 (7.9)	0.41 (0.4)	15.72 (16.2)	16.86 (17.4)
Shoulder	Right	−4.29 (−14.1)	−3.88 (−12.8)	−5.72 (−18.8)	−5.92 (−19.5)	−3.47 (−11.4)
	Left	−0.82 (−2.7)	−4.29 (−14.2)	−4.29 (−14.2)	0.20 (0.7)	−2.04 (−6.8)
Sidewall	Right	1.63 (8.2)	2.04 (10.3)	7.76 (39.2)	5.72 (28.9)	6.94 (35.1)
	Left	−5.31 (−15.0)	−6.74 (−19.1)	−4.70 (−13.3)	− 4.29 (−12.1)	−4.08 (−11.6)

namely: (a) number of mat reinforcement, location of mat reinforcement and soil cover. The mat reinforcement effect has the tendency to increase with the increase in the number of mat reinforcement and soil cover. This phenomenon was visible in the comparison of the results of 1T and 2T, and 2S and 4S. Similar to 1.0D, the location of mat reinforcement was also a significant factor.

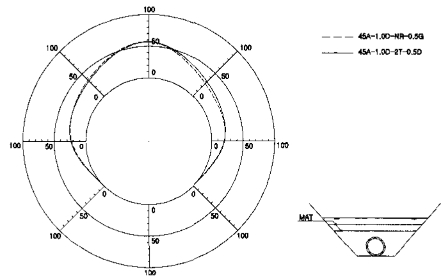
3.1.2 Model Test with Different Reinforcement Scheme

3.1.2.1 Model Test with Different Reinforcement Scheme at 1.0D Soil Cover

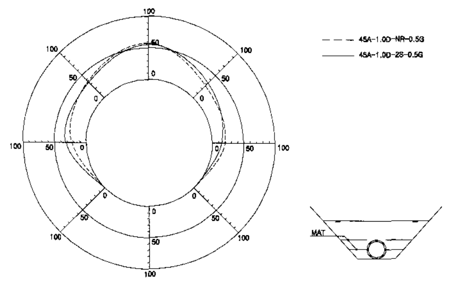
Based on Table 8, the earth pressure acting on the crown portion was reduced by 2～10% except for 2T wherein there was almost no reduction. By comparing the numerical values tabulated in Table 8 it can be seen that 2S2T reinforcement is the most efficient reinforcement scheme when it comes to the reduction of earth pressure acting on the tunnel crown. On the shoulder portion, reduction of 5～23% was measured on the left side while there was an increase of 14～21% on the right side. If we were to consider the reduction of earth pressure, 4S and 2S2T are the most efficient reinforcement scheme with a reinforcement effect of 23% and 19%, respectively. For the left sidewall portion, there was 8～27% reduction in earth pressure for all reinforcement types except for 1T wherein there was a 3% increase. For the right sidewall portion, there was 5～92% increase in earth pressure for all reinforcement types. Considering only the reduction of earth pressure it can be seen that 2S and 2S2T are the most effective reinforcement schemes in the reduction of earth pressure acting on the tunnel sidewalls with a reinforcement effect of 27% and 25%. Considering the overall reduction on the earth pressure acting on the tunnel structure, 2S2T is the most effective reinforcement scheme



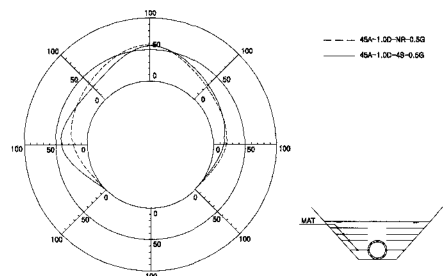
(a) 1.0D-1T-100



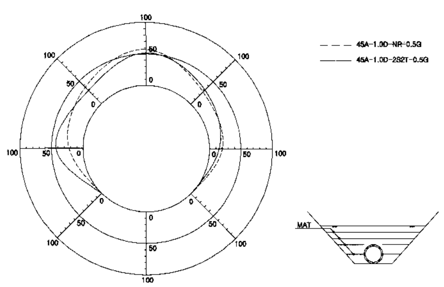
(b) 1.0D-2T-100



(c) 1.0D-2S-100



(d) 1.0D-4S-100



(e) 1.0D-2S2T-100

Fig. 5. Earth Pressure Reduction with Reinforcement Type (1.0D Soil Cover)

for soil model tests with 1.0D soil cover.

Fig. 5 shows the graphical representation of the mat reinforcement effect on the earth pressure acting on the tunnel structure for model tests with 1.0D soil cover. The broken line represents the earth pressure of the unreinforced soil acting on the tunnel structure while the solid lines represents the reduced earth pressure for each type of reinforcement.

3.1.2.2 Model Test with Different Reinforcement Scheme at 1.50D Soil Cover

Based on the examination of the numerical values presented in Table 9 and the plots shown in Fig. 6, it can be seen that 2S2T is the most effective reinforcement scheme in the reduction of earth pressure acting at the tunnel crown with a reinforcement effect of 17%. This was followed by 4S with 16%, 2T with 8%, 1T with 6% and 2S with 0.4% which has almost no reinforcement effect. For the shoulder portion, there was an overall increase in the earth pressure for all reinforcement. An increase of 2~18% was measured. When it comes to the sidewall portion, 2S and 2S2T are the most efficient reinforcement schemes when it comes to the earth pressure acting on the sidewalls with 39% and 35% earth pressure reduction.

Similar to what was obtained from the results of the model tests with 1.0D soil cover, 2S2T was the most effective reinforcement scheme in reducing the overall earth pressure acting on the tunnel structure. An increase in earth pressure for some portions of the tunnel was monitored.

3.1.2.3 Model Test with Varying Slope Roughness at 1.50D Soil Cover

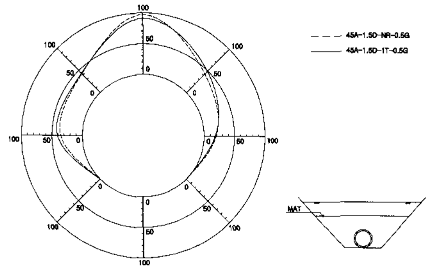
Table 10 shows the earth pressure reduction effect of 2S2T with the slope roughness for tunnels with 1.50D soil cover. It can be seen in this table that 2S2T is very effective when it comes to 100, with 17% and 35% reduction on the crown and sidewalls, respectively. The mat reinforcement effect was not seen for 400 and ACE. For 400, there was only a 2% reduction at the crown portion while there was a 10~18% earth pressure increase at the shoulder portion. For ACE, 2S2T increased the earth pressure in all portions of the tunnel. This is due to the roughness of the cut slope. When there is low friction resistance (400) and zero resistance (ACE) excessive shear strain occurs between the boundary of the original soil and the backfill material (Refer to Fig. 12 (e) & (g)). The mat reinforcement fails to distribute the load and the load has the tendency to concentrate on the shoulder and sidewall portions of the tunnel.

3.1.3 Analysis of Results

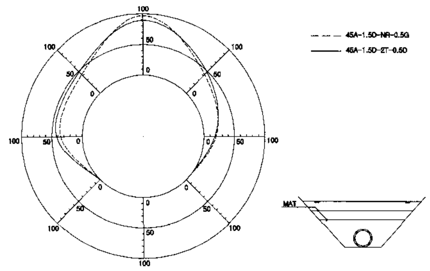
The numerical and graphical results show considerable differences between the values monitored from the left side and the right side of the tunnel. Reduction in earth pressure occurred on the left side while an increase in earth pressure occurred on the right side of the tunnel. Since the soil tank was subjected to vibration in order to induce soil settlement, the difference in the result can be attributed to transmission of vibration influenced by several factors. These factors are: (a) rigidity of the soil structure, (b) soil tank structure and supporting elements and (c) location of vibrator (due to the frame of the soil tank the vibrator was installed slightly to the left of the tunnel).

Table 10. Earth Pressure Reduction w/ Slope Roughness After Vibration (1.5D Soil Cover)

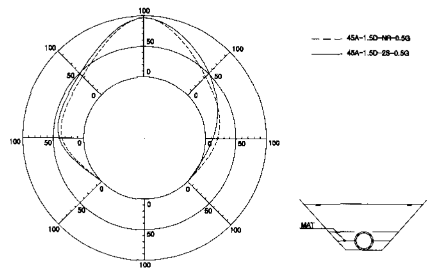
Load Cell Location		Type of Reinforcement (Reinforcement Effect, %)		
		100-2S2T	400-2S2T	ACE-2S2T
Crown		16.86 (17.4)	1.65 (1.8)	-16.86 (-25.2)
Shoulder	Right	-3.47 (-11.4)	-5.92 (-17.9)	-3.06 (-8.1)
	Left	-2.04 (-6.8)	-3.27 (-10.0)	-0.41 (-1.2)
Sidewall	Right	6.94 (35.1)	21.03 (59.9)	-21.03 (-83.7)
	Left	-4.08 (-11.6)	-0.20 (-0.4)	-78.60 (-126.6)



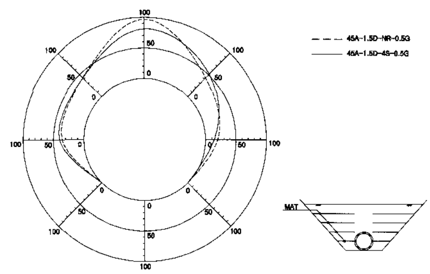
(a) 1.5D-1T-100



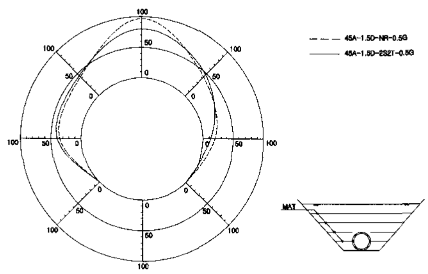
(b) 1.5D-2T-100



(c) 1.5D-2S-100



(d) 1.5D-4S-100



(e) 1.5D-2S2T-100

Fig. 6. Earth Pressure Reduction with Reinforcement Type (1.50D Soil Cover)

The numerical differences and the percentages were presented. In this test, the magnitude of earth pressure reduction or increase is not important. What is important is the fact that the installation of mat reinforcement effectively reduces the soil settlement and earth pressure acting on the tunnel lining.

3.2 Picture Analysis

Pictures of the model test were taken before, during and after the test to determine the behaviour of soil around the tunnel. Pictures were interpreted using Microstation and analyzed using DALT Program(Park, 2003). The results are presented below.

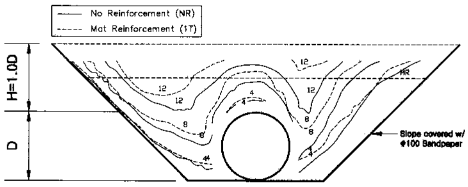
3.2.1 Behaviour of Soil around the Cut-and-Cover Tunnel

3.2.1.1 Model Test with 1.0D Soil Cover

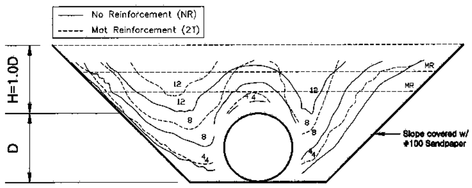
Fig. 7 shows the mat reinforcement effect on the settlement of soil around the tunnel structure for model tests with 1.0D soil cover. When it comes to the reduction of soil settlement around the tunnel at 1.0D soil cover, 2T was the most effective as can be seen from the figures below, followed by 1T and 4S with similar soil settlement reduction and 2S2T with the less soil settlement reduction effect.

3.2.1.2 Model Test with 1.50D Soil Cover

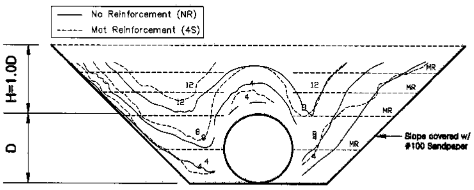
Fig. 10 shows the mat reinforcement effect on the settlement of soil around the tunnel structure for model tests with 1.50D soil cover. For model tests with 1.50D soil cover, 1T, 2T and 2S can be considered the most



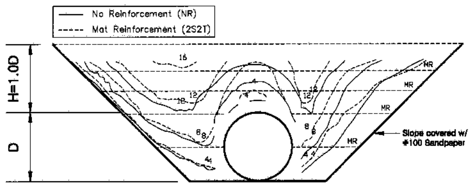
(a) 1.0D-1T-100



(b) 1.0D-2T-100

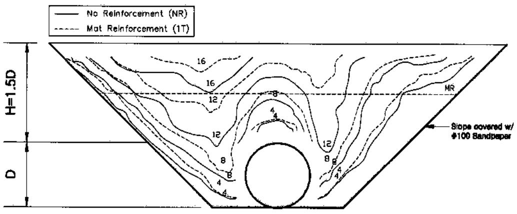


(c) 1.0D-4S-100

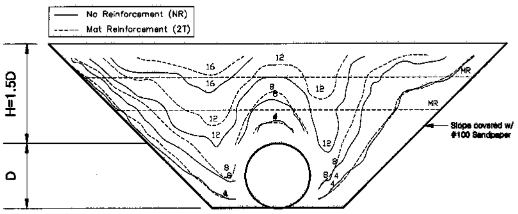


(d)1.0D-2S2T-100

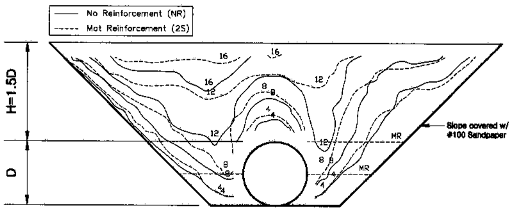
Fig. 7. Partial soil displacement contour at 1.0D Soil Cover



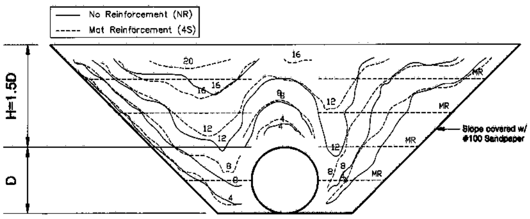
1.5D-1T-100



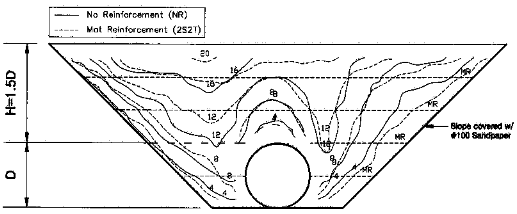
1.5D-2T-100



1.5D-2S-100

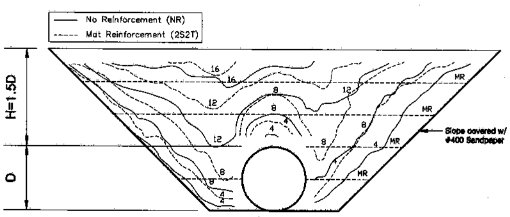


1.5D-4S-100

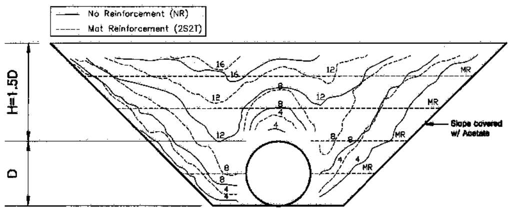


1.5D-2S2T-100

Fig. 8. Partial soil displacement contour at 1.50D Soil Cover



(a) 1.5D-2S2T-400



(b) 1.5D-2S2T-ACE

Fig. 9. Partial soil displacement contour at 1.50D Soil Cover

effective in the reduction of soil settlement around the tunnel as can be seen from the figures below, followed by 4S and 2S2T with similar soil settlement reduction. 2S2T was the most effective mat reinforcement scheme in the earth pressure reduction and it has the least soil settlement reduction effect around the tunnel.

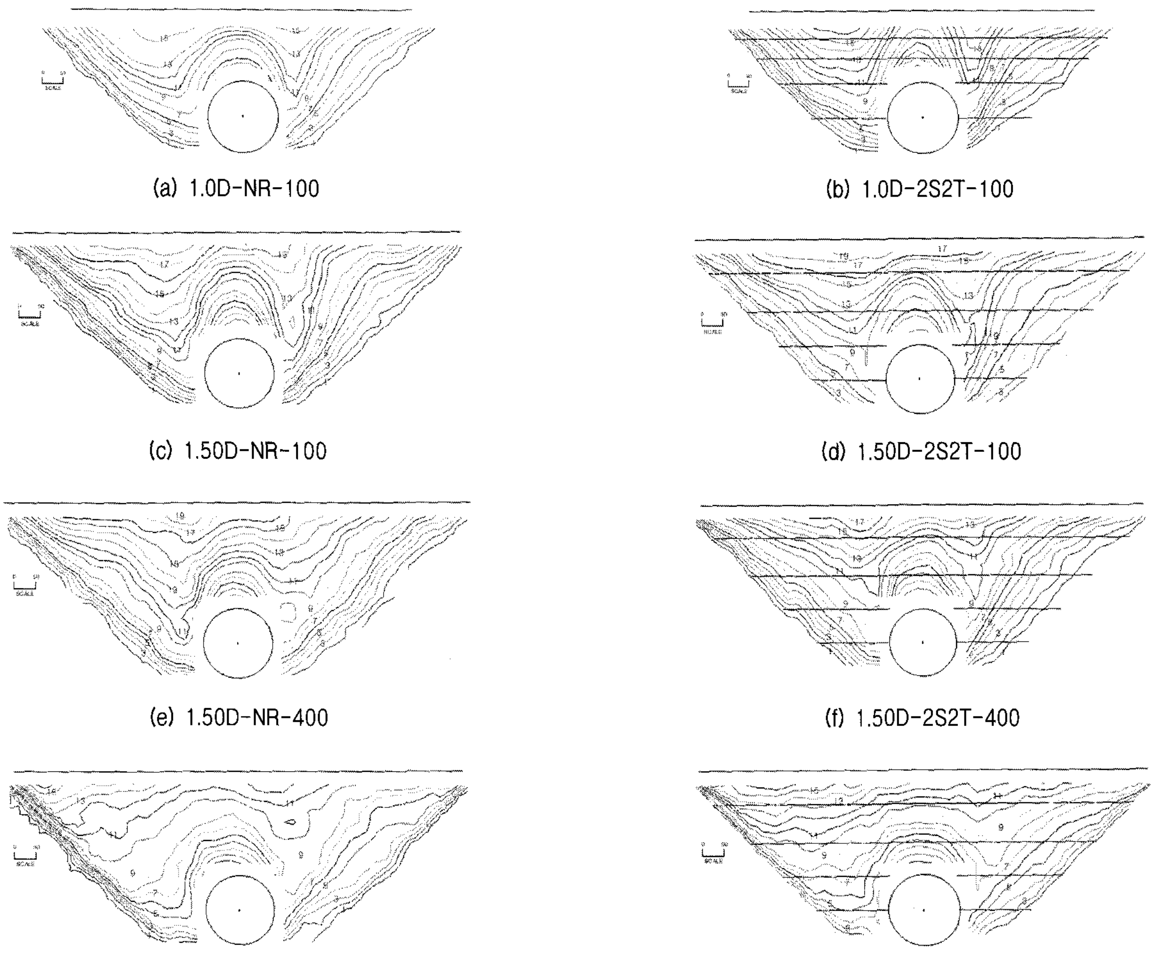
3.2.1.3 Model Test with Varying Slope Roughness at 1.50D Soil Cover

Fig. 9 shows the mat reinforcement effect on the settlement of soil around the tunnel structure for model tests with varying slope roughness at 1.50D soil cover. The following figures show that there was less settlement for the mat reinforced soil (2S2T) as represented by the broken line compared to the unreinforced soil (NR) represented by the solid lines for both 400 and ACE.

Even though 2S2T was not effective in reducing the earth pressure acting on the tunnel lining with varying slope roughness, it can be seen in the following figures that the mat reinforcement was effective in reducing the soil settlement around the tunnel.

3.2.2 Other Results

Results which include soil displacement contour diagram, soil displacement vector, zero extension direction and maximum shear strain contour diagram are presented in the figures below. For comparison purposes the unreinforced and reinforced model tests results are presented side by side. Fig. 10 shows the soil displacement contour diagram of the unreinforced test (NR) and most effective reinforcement scheme (2S2T). To clearly show the mat reinforcement effect, the soil behaviour around the tunnel was redrawn from the soil displacement contour and presented in Fig. 7. On the left side was drawn model



(a) 1.0D-NR-100 (b) 1.0D-2S2T-100

(c) 1.50D-NR-100 (d) 1.50D-2S2T-100

(e) 1.50D-NR-400 (f) 1.50D-2S2T-400

(g) 1.50D-NR-ACE (h) 1.50D-2S2T-ACE

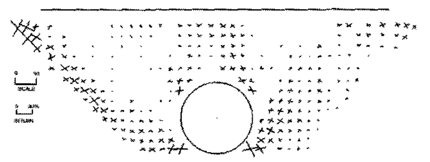
Fig. 10. Soil Displacement Contour Diagram

test with no reinforcement (NR) and model test with 2S2T reinforcement on the right side. It can be seen from the figures on the left that the mat installation has reduced the soil displacement. The mat reinforcement effect can be seen on the contour diagram on the right side. There was an overall reduction in soil displacement on all the tests performed.

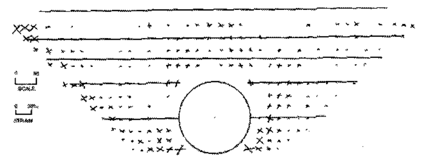
Fig. 11 shows the zero extension direction diagram. Zero extension direction diagram shows the location of the failure plane. The point with a concentration of x represents the failure plane. In the case of this test the failure plane occurs between the original soil and backfill material. It can be seen that with installation of mat reinforcement the concentration of "x" was greatly reduced (Refer to Fig. 11 (b), (d), (f) & (h)). The installation of mat reinforcement prevents the occurrence of the failure surface.

Fig. 12 shows the maximum shear strain contour diagram. This diagram shows the concentration of shear strain location where failure will occur. Based on the zero extension direction and maximum shear strain contour diagram the location of failure surface can be determined. Comparing tests with different slope roughness at 1.50D soil cover shows excessive concentration shear strain along the slope with little friction resistance (400) and zero friction resistance (ACE). Diagrams in Fig. 12 (b), (d), (f) & (h) show a reduction of shear strain due to the installation of mat reinforcement.

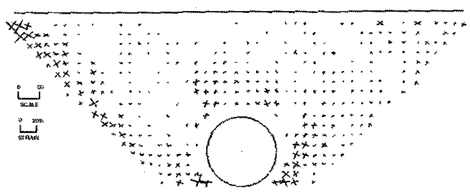
Considering the zero extension direction and maximum shear strain contour diagram, it can be seen that failure surface occurs in the boundary between the original soil and backfill material. This can be seen in model tests with 1.0D and 1.5D soil cover. This phenomenon can be clearly seen in the 1.5D-ACE wherein the slope is covered with



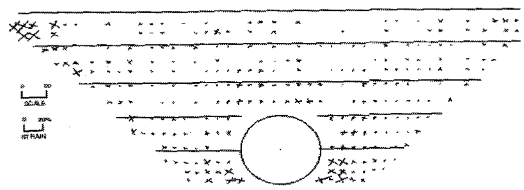
(a) 1.0D-NR-100



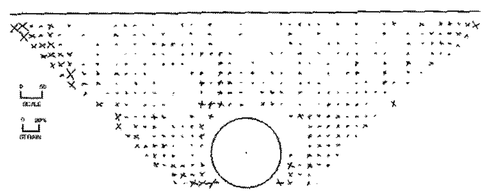
(b) 1.0D-2S2T-100



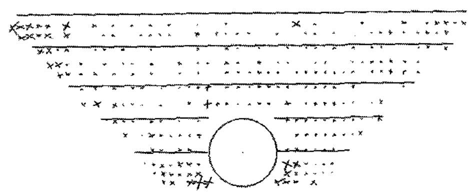
(c) 1.50D-NR-100



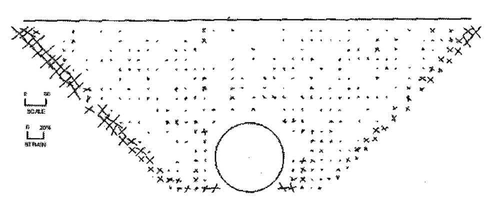
(d) 1.50D-2S2T-100



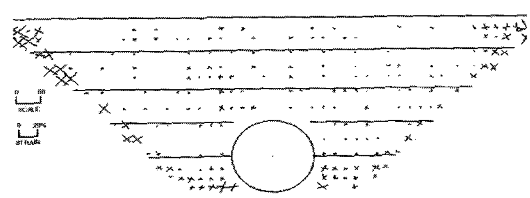
(e) 1.50D-NR-400



(f) 1.50D-2S2T-400

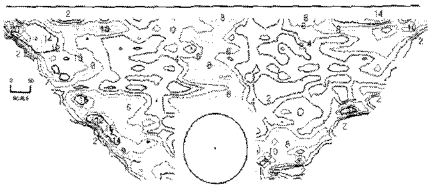


(g) 1.50D-NR-ACE

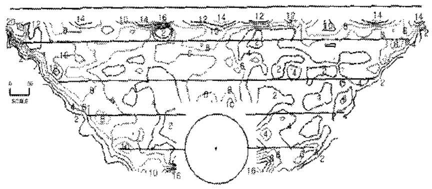


(h) 1.50D-2S2T-ACE

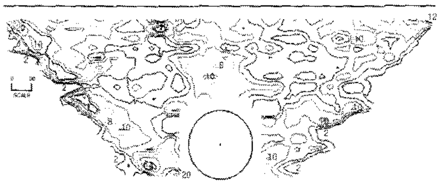
Fig. 11. Zero Extension Direction Diagram



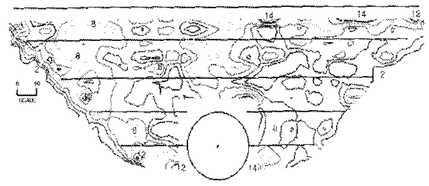
(c) 1.50D-NR-100



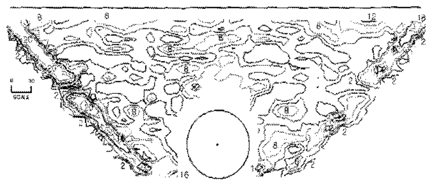
(d) 1.50D-2S2T-100



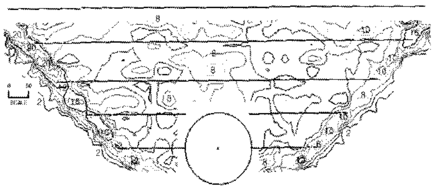
(e) 1.50D-NR-400



(f) 1.50D-2S2T-400

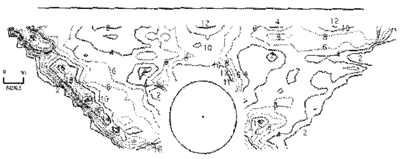


(g) 1.50D-NR-ACE

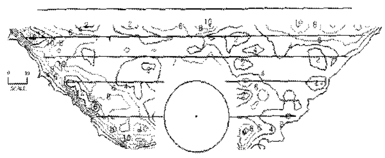


(h) 1.50D-2S2T-ACE

Fig. 12. Maximum Shear Strain Contour Diagram



(a) 1.0D-NR-100



(b) 1.0D-2S2T-100

Fig. 13. Maximum Shear Strain Contour Diagram

acetate.

4. Conclusion

Installation of geotextile mat reinforcement has been applied in other engineering construction like embankments and reclamations but there were no case histories wherein geotextile mat reinforcement was applied in cut-and-cover tunnel construction. In this study the application of geotextile mat reinforcement was recommended to reduce excessive surface settlement and earth pressure acting on the cut-and-cover tunnel lining through laboratory model test. In order to determine the feasibility of geotextile reinforcement in cut-and-cover tunnel construction, laboratory model test using a circular rigid 1:20 scale tunnel model was installed in a plane strain soil tank covered with 1.0D ~ 1.50D (D is the tunnel diameter) of loose sand with different geotextile mat reinforcement schemes. The plane strain soil tank was subjected to a vibration frequency of 100 Hz for a period of 10 minutes. Through the comparison of the results obtained from the unreinforced and reinforced model tests, the most effective mat reinforcement scheme for different soil cover and slope roughness was recommended. The following conclusion were obtained from this study:

(1) Mat reinforcements installed above and beside the tunnel significantly reduced the earth pressure acting on the lining.
(2) For tunnels with 1.0D soil covers, the mat reinforcement effect was affected by 2 major factors: namely, number of mat reinforcement and location of mat

reinforcement. Increase of mat reinforcement in the same location has the tendency to reduce the reinforcement effect as can be seen in the reduction in reinforcement effect between 1T and 2T, and 2S and 4S.

(3) Among all the mat reinforcement schemes implemented, 2S2T was the most effective mat reinforcement scheme for tunnels with 1.0D soil covers.

(4) For tunnels with 1.50D soil covers, the mat reinforcement effect has the tendency to increase with the number of mat reinforcement. Among all the reinforcement schemes 2S2T and 4S were the most effective. But when it comes to overall earth pressure reduction effect 2S2T was considered as the most effective.

(5) For 2S2T, earth pressure reduction of as much as 10%, 19% and 25% on the crown, shoulder and sidewall portions was monitored for tunnels with 1.0D soil cover while earth pressure reduction of as much as 17% and 35% on the crown and sidewall portions was monitored for 1.50D.

(6) 2S2T was not effective when it comes to slopes with model tests with varying slope roughness but it was very effective in reducing the settlement of soil around the tunnel.

(7) Based on the zero extension direction diagram and maximum shear strain diagram, it was found that the failure surface occurred between the original soil and the backfill material.

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