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Modeling of Interface Shear Behavior between Geosynthetics
토목섬유 사이의 interface 전단 거동 modeling

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개요(SYNOPSIS) : 지오멤브레인(geomembrane)과 다른 토목섬유, 즉 지오텍스타일 또는 GCL, 사이의 interface 전단거동을 특성화하는 strain-softening 모델을 개발하였다. 본 연구에 제안된 모델은 일차적으로 smooth 지오멤브레인과 textured 지오멤브레인을 대상으로 실시한 직접전단 시험결과를 대상으로 구축되었다. 시험을 통해 측정된 변위-전단응력의 관계는 strain-softening 현상를 고려하기 위해서 최대점이 발생하는 위치를 기준으로, pre-peak과 post-peak 영역으로 나누어 분석을 실시하였다. 실험결과를 토대로 구축된 모델식은 원 자료와의 비교를 통해 본 모델의 유효성을 검증하였다. 비교 결과 높은 연직 응력에서 약간의 차이를 보이긴 하지만, 대체적으로 실험 결과와 구축된 모델을 이용한 역계산의 값이 좋은 일치를 보임을 확인할 수 있었다. 특별히 연직응력이 낮은 단계에서는 높은 일치를 보였는데, 이를 통해 제안된 식이 매립지의 최종 cover와 같이 상재 연직하중이 작은 경우에 지오멤브레인이 포함된 interface의 전단 거동에 대한 합리적인 구성 방정식이 될 수 있음을 확인할 수 있었다.

주요어(Key words) : strain-softening, geosynthetic, interface shear strength, modeling, shear displacement

1. Introduction

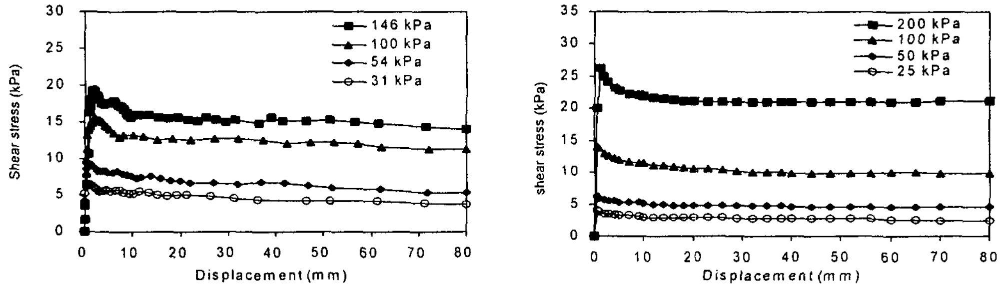
Slope stability is an important consideration in the design of containment systems. Especially, the potential for progressive failure in waste containment systems should be dealt with significantly. Many common interfaces between components in containment systems exhibit strain-softening behavior. However, conventional limit equilibrium methods used widely lack the capability to take into account stress and strain behavior and to compute displacements along the critical shear plane. Numerical simulation in geoenvironmental engineering practice requires the availability of constitutive models to describe the stress-deformation behavior of the interfaces involved. A few research on the theory of geosynthetic interface modeling for landfill liners has been published. Esterhuizen *et al.* (2001) suggested that plasticity models are more suitable than elasticity models because they correctly predict sliding displacements as a function of the total shear and normal stresses acting on the interface, and Filz *et al.* (2001) evaluated the practical significance of progressive failure using the constitutive model proposed by Esterhuizen *et al.* (2001). In this paper, a constitutive model is proposed for evaluating strain-softening effects on the stability of waste containment systems and the model is verified through comparisons between measured data from direct shear tests and predicted data through back-calculations.

2. Experimental Data for Geosynthetic Interfaces

The constitutive relationships for shear behaviors of interfaces between geomembrane(GM) and geosynthetic were developed and calibrated in this research, using the results of large-scale direct shear tests by Seo *et al.* (2002), Jones and Dixon (1998), and Triplett and Fox (2001). Two types of interfaces were modeled with a constitutive relationship in the analyses, where one interface involves smooth geomembrane and the other interface includes textured HDPE geomembrane.

2.1 Interfaces between smooth GM (S-GM) and geotextile (GT)

Two published data were utilized for interfaces involving S-GM (Fig.1). Seo *et al.* (2002) conducted a large direct shear test (300×300mm) with a S-GM and GT. Jones and Dixon (1998) also made tests by using large direct shear testing apparatus with the S-GM and geotextile.

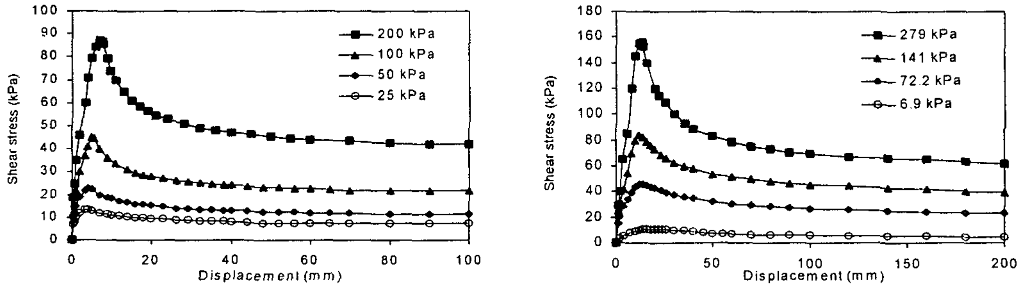


(a) Test results from Seo *et al.* (2002) (b) Test results from Jones and Dixon (1998)

Fig. 1. Interface shear testing results between S-GM and GT

2.2 Interfaces between textured GM (T-GM) and geotextile (GT)

Two published data were also analyzed for interfaces involving T-GM. The T-GM used in the testing by Jones and Dixon (1998) was manufactured with the texturing produced by impinging hot polyethylene particles on the surface of previously manufactured smooth sheets. Triplett and Fox (2001) performed direct shear tests on large (406×1,067mm) rectangular GM/GCL interfaces. GCL specimens were hydrated using four-day, two-stage procedure described by Fox *et al.* (1998). The nonwoven GT part of GCL contacted with T-GM at the interface of T-GM/GCL. The initial shear stiffness is found to vary with the normal stress employed in the tests (Fig. 2) unlike the test results of S-GM.



(a) T-GM/GT (Jones and Dixon, 1998) (b) T-GM/GCL (Triplett and Fox, 2001)

Fig. 2. Interface shear testing results between T-GM and geosynthetics

3. Interface Modeling

The determination of properties of interface shear stress-displacement behavior and shear strength parameters is essential for an accurate assessment of the composite liner interface stability. However, it is difficult to make a choice of the available shear resistance along an interface exhibiting strain-softening behavior, which make it complex to model the shear stress-displacement relationship. The entire region is divided into to two parts; (1) pre-peak region and (2) post-peak region, to take into account of shear strength degradation after peak strength is mobilized.

3.1 Shear strength determination

For the S-GM/GT interfaces, it is assumed that interface shear strength envelope for the peak and large displacement (80mm) have a zero cohesion intercept. Two types of failure envelopes, linear and nonlinear failure envelope, are assumed to ensure importance of accurate determination of failure envelopes. Table 1 provides a summary of interface shear strength for S-GM/GT.

Table 1. Interface shear strength envelopes for interfaces of S-GM/GT

Reference	Linear failure envelope			Nonlinear failure envelope		
Seo *et al.* (2002)	Peak	$\tau_p = \tan 8.2^\circ\ \sigma_n$	$r^2=0.91$	Peak	$\tau_p = 0.51\ \sigma_n^{0.73}$	$r^2=1.00$
	Large displacement	$\tau_l = \tan 5.8^\circ\ \sigma_n$	$r^2=0.97$	Large displacement	$\tau_l = 0.16\ \sigma_n^{0.91}$	$r^2=0.98$
Jones and Dixon (1998)	Peak	$\tau_p = \tan 7.6^\circ\ \sigma_n$	$r^2=1.00$	Peak	$\tau_p = 0.18\ \sigma_n^{0.93}$	$r^2=0.99$
	Large displacement	$\tau_l = \tan 5.9^\circ\ \sigma_n$	$r^2=1.00$	Large displacement	$\tau_l = 0.08\ \sigma_n^{1.05}$	$r^2=1.00$

where τ= shear strength, σ_n= normal stress, and r^2 = correlation coefficient

For T-GM/GT or GCL interfaces, peak and large displacement failure envelopes are approximately linear and characterized using Mohr-Coulomb criterion

$$\tau = c + \sigma_n \tan\delta \qquad (1)$$

where τ= shear stress, c = cohesion, σ_n= normal stress, and δ= friction angle. Table 2 lists peak and large displacement strength parameters under the range of normal stress applied in the testing.

Table 2. Interface shear strength envelopes for interfaces of T-GM/geosynthetic

Reference	Interface	Peak interface strength (τ_p)			Large displacement interface strength (τ_l)		
		friction angle (°)	cohesion (kPa)	r^2	friction angle (°)	cohesion (kPa)	r^2
Jones and Dixon (1998)	T-GM/GT	22.9	2.5	1.00	11.3	1.9	1.00
Triplett and Fox (2001)	T-GM/GCL	28.1	7.7	1.00	11.7	6.6	0.98

where r^2 = correlation coefficient

3.2 Pre-peak region modeling

As mentioned previously, the modeling is performed, dividing the entire region into two regions, pre-peak region and post-peak region, to describe the strength reduction after peak strength is mobilized. Linear and non linear relationships between displacement and shear stress at the pre-peak region are formulated into one constitutive equation.

For interfaces involving S-GM, the interface shear stiffness is the same regardless of the level of normal stress. For interfaces with T-GM, however, the initial shear stiffness is dependent on the magnitude of normal stress. The tangent shear modulus value is found to vary with the normal stress employed in the tests. The procedure proposed by Duncan and Chang (1970) is modified in this modeling at pre-peak region. This hyperbolic relationship describes the nonlinear and stress dependent interface shear stress-shear displacement relationship at an interface.

(1) Approximation of nonlinear stress-displacement relationship by using hyperbolic equation; The hyperbolic equation is considered for interface shear behaviors. The hyperbolic formulation (Kondner, 1963) is given by

$$\tau = \frac{d}{a + bd} \tag{2}$$

where τ = interface shear strength, d = shear displacement, 1/a = initial shear modulus (E_i), and 1/b = ultimate shear strength (τ_{ult}). From the value of b, the failure ratio (R_f) which is defined as the ratio of τ_p/τ_{ult} , is calculated. On the other hand, the failure ratio is evaluated to be zero for interfaces of S-GM as the ultimate shear strength is not converged to one value.

(2) Consideration of stress dependency; Experimental studies show that the relationship between initial shear modulus and normal stress may be expressed as (Janbu, 1963; Reddy *et al.* 1996)

$$E_i = K \gamma_w \left(\frac{\sigma_n}{P_a}\right)^n \tag{3}$$

where E_i = the initial shear modulus, σ_n = normal stress, γ_w = unit weight of water, K = dimensionless shear coefficient, P_a = atmospheric press, and n = modulus exponent. Values of the parameters K and n may be determined readily from the testing results. The values of E_i/γ_w and σ_n/P_a are plotted using logarithmic (log-log) axes. The slope of the best-fit line gives the value of n, and the intercept of the line gives the value of K. However, the value of n is evaluated to be zero at the interfaces with S-GM because shear modulus shows no dependency on normal stress.

(3) Determination of tangent modulus value; The tangent modulus, E_t, may be expressed as

$$E_t = \frac{\partial \tau}{\partial d} \tag{4}$$

Duncan and Chang (1970) proposed that tangent modulus value for any stress condition may be expressed as

$$E_t = K \gamma_w \left(\frac{\sigma_n}{P_a}\right)^n \left(1 - R_f \frac{\tau}{\tau_p}\right)^2 \tag{5}$$

and maintained that this expression for tangent modulus may be employed very conveniently in incremental analyses.

The hyperbolic interface model parameters calculated from previous mentioned procedures are summarized in Table 3 for the interfaces of S-GM/GT and T-GM/geosynthetic. Increasing value of n implies that the dependency of tangent modulus on normal stress increases at pre-peak region.

Table 3. Summary of the hyperbolic interface model parameters at pre-peak region

Interface	R_f	K	n	Reference
S-GM/GT	0	809	0	Seo *et al.* (2002)
	0	1,318	0	Jones and Dixon (1998)
T-GM/GT	0.88	5,314	0.18	Jones and Dixon (1998)
T-GM/GCL	0.67	1,540	0.65	Triplett and Fox (2001)

3.3 Post-peak region modeling

The displacement softening model developed by Esterhuizen *et al.* (2001) is used to describe the interface shear behavior at post-peak region in this research. Esterhuizen *et al.* (2001) followed the method outlined by Turnbull and Hvorslev (1967) to model a nonlinear displacement softening behavior for geosynthetic interfaces after peak strength is mobilized.

As strain-softening displacement, d_s, increases, the strength reduction, τ_s, increases until it equals the full difference between peak and large displacement strengths. It is assumed that the normalized curves can be approximated as nonlinear hyperbolic relationship between shear strength degradation, τ_s, and strain-softening displacement, d_s. The procedures for displacement softening modeling used by Esterhuizen *et al.* (2001) are as follows.

(1) Transformation of the initial stress vs. displacement curves into new curves that relate the strength degradation, τ_s, to the strain-softening shear displacement d_s, which can be calculated from subtracting the shear displacement at peak shear strength from the large displacement at post-peak region.

(2) Calculation of the strain-softening factor, S, and the displacement ratio, D; S can be calculated by normalizing the post-peak strength degradation by the shear strength degradation from the peak to the large displacement value. D also can by calculated by normalizing the strain softening shear displacement, d_s, by the maximum strain softening shear displacement, d_s, that take place at large displacement, d_l.

(3) Plotting the relationship between S and D; The normalized curves can be approximated by a hyperbolic relationship which is described by following equation.

$$S = \frac{D}{\frac{1}{k} + \frac{D}{c}} \qquad (6)$$

where k=initial slope of the curve and c=intercept of the horizontal asymptote with the S axis.

(4) Determination of the equation relating to S and D; The Eq.(6) can be determined by using the fact that the curve passes through (1,1) and approximating the testing results. Table 4 shows a hyperbolic parameters of Eq.(6) together with a value provided by Esterbuizen *et al.* (2001) to

compare parameters.

The larger values of k are observed for interfaces of S-GM, comparing the values for T-GM, which means that interface shear strength decrease significantly at the early stage after peak strength is mobilized. However, the magnitude of strength degradation are significant for interfaces between T-GM/geosynthetic (Seo *et al.* 2002, Triplett and Fox, 2001).

Table 4. Summary of the hyperbolic interface model parameters at post-peak region

Interface	k	c	Reference
S-GM/GT	14.22	1.08	Seo *et al.* (2002)
	29.17	1.04	Jones and Dixon (1998)
S-GM/Clay	20.00	1.05	Esterhuizen *et al.* (2001)
T-GM/GT	5.82	1.21	Jones and Dixon (1998)
T-GM/GCL	6.51	1.18	Triplett and Fox (2001)

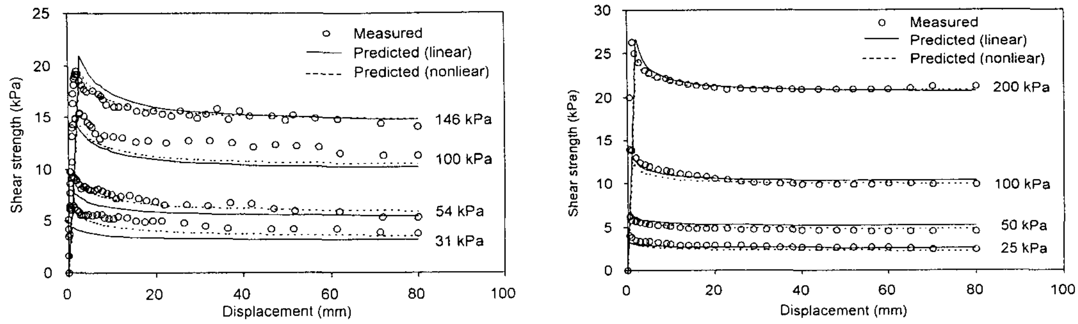
4. Comparison of results from developed modeling and testing data

The stress-displacement relationship may be used very conveniently for incremental analyses of nonlinear behavior. Though the load is generally divided into some increments to estimate the deformations induced by load, the displacements, on the contrary, induce interface shear stress in case of displacement controlled interface shear testing. Therefore, the displacement to be analyzed is divided into a number of increments enough to describe the behavior in detail. For the purposes of analysis, the interface is assumed to behave linearly under each increment of displacement. These steps are repeated until the estimated shear strength reach the peak shear strength determined by equations developed by test results. Once the peak interface shear strength is developed, the interface shear behavior becomes to be transferred into the post-peak region. Then, the relationship between S and D is applied until the shear behaviors reach large displacement, d_l.

4.1 Interfaces between smooth GM and GT

Fig. 3 presents the measured and predicted curves using the determined parameters at interfaces of S-GM involved. As the smaller incremental displacement at pre-peak region can made a exact prediction, the value of 0.01 mm is selected for incremental displacement, when the limit of increment is 0.01.

Though the overall agreement may be seen to be quite good, it may be also observed that as a result of these approximations there is some difference between the measured and predicted stress-displacement curves in Fig. 3. Especially, some discrepancy is found in Fig. 3 (a). The comparison results of nonlinear failure envelope (Fig. 3 (a)) demonstrate good agreement between measured and predicted data, which corresponds to the fact that the correlation coefficient of nonlinear failure envelope is bigger than that of linear failure envelope. However, good agreement is observed, in general, in Fig. 3 irrespective of linear or nonlinear envelope. It can be concluded from the comparisons that it is much significant to characterize accurately the relation between the normal stress and shear strength for exact prediction. It is very essential, of course, to perform the laboratory tests accurately to evaluate the parameters.

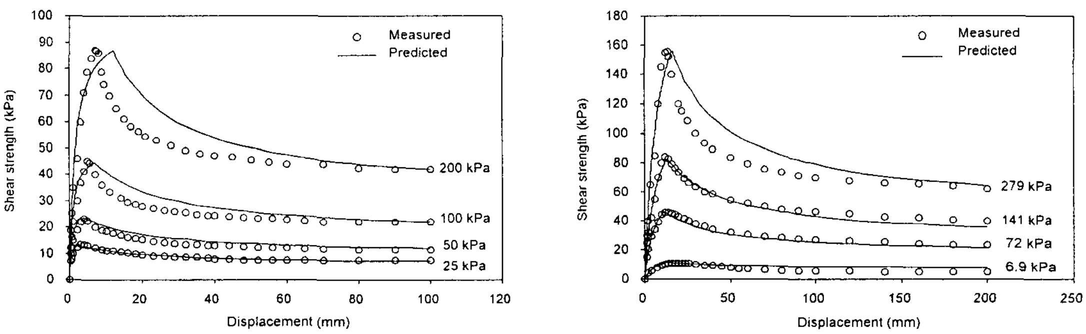


(a) Comparison with data of Seo *et al* (2002)   (b) Comparison with data of Jones and Dixon (1998)

Fig. 3. Comparison of measured data and predicted data for S-GM/GT interfaces

4.2 Interfaces between textured GM and GT

Back-calculation is performed using the same method as is done for the case of S-GM/GT interfaces. Fig. 4 displays the measured and predicted curves using the determined parameters. The value of 0.1 mm is selected for incremental displacement because the lower increment causes increasing displacement errors between predicted and measured value, where displacement error means the difference between measured and predicted displacement at peak strength, d_p. Although lower increment predicts peak interface shear strength more accurately, the increasing displacement error gives more influence on the total accuracy.



(a) Comparison with data of Jones and Dixon (1998)   (b) Comparison with data of Triplett *et al.*, (2002)

Fig. 4. Comparison of measured data and predicted data for T-GM/geosynthetic interfaces

The predicted shear stresses are compared with measured data in Fig. 4, which illustrate good agreement between two kinds of results especially on the range of low normal stress. Good consistency for this stress range points out the possibility that this model can be a good constitutive model in the case such as cover soil for landfills, where normal stress is very low. This good consistency is partially attributed to highly correlation between the normal stress and shear strength of testing data. However, some differences could be seen on high normal stress (≥ 200kPa), which is caused by some reasons. First, when the value of n which is normal stress dependent parameter is very small, the increasing magnitude of shear strength becomes to be limited on the high normal stress. Second, if the initial slope, k, at post-peak region is greater than average value of k, the interface shear strength decreases dramatically at initial stage of post-peak region. Finally, the increment of displacement has also effect on the accuracy of back-calculation.

Therefore, new methods are required to be developed to solve the discrepancy of interface shear behavior between T-GM/geosynthetic on high normal stress.

5. Summary and conclusions

The simple and efficient model for the interface shear behavior between geosynthetics is proposed. The model proposed in this paper has the advantage that shear strength degradation or strain softening effect along geosynthetic interfaces can be taken into account. The model is calibrated by using four published testing data.

Four relationships are evaluated to develope this strain softening model: (1) the peak strength envelop, (2) the large displacement strength envelop, (3) the hyperbolic or linear equation for pre-peak region, and (4) the hyperbolic strength reduction versus displacement ratio relationship.

The back-calculation results based on modeling are generally in good agreement with the experimental results for smooth geomembrane / geotextile and textured geomembrane / geosynthetic interfaces. However, it is found that the accuracy of back-calculation is significantly influenced by the relationship between normal stress and peak or large displacement interface shear strength. Good agreement between predicted and measured data is observed especially for low normal stress. This model is expected to be a good constitutive model in a finite-element analysis, which should include strain-softening behavior or slope failure along landfill liner interfaces.

References

1. Duncan, J.M. and Chang, C.Y. (1970). "Nonlinear analysis of stress and strain in soils." *Journal of Soil Mechanics and Foundations Division*, ASCE, Vol. 96, No. SM5, pp. 1629-1653
2. Esterhuizen, J.J.B., Filz, G.M. and Duncan, J.M. (2001). "Constitutive behavior of geosynthetic interfaces." *J. Geotech. and Geoenvir. Engrg.*, ASCE, Vol. 127, No. 10, pp. 834-840.
3. Filz, G.M., Esterhuizen, J.J.B. and Duncan, J.M. (2001). "Progressive failure of lined waste impoundments." *J. Geotech. and Geoenvir. Engrg.*, ASCE, Vol. 127, No. 10. pp. 841-848.
4. Fox, P.J., Rowland, M.G. and Scheithe, J.R. (1998). "Internal shear strength of three geosynthetic clay liners." *J. Geotech. and Geoenvir. Engrg.*, ASCE, Vol. 124, No. 10. pp. 933-944
5. Janbu, N. (1963). "Soil compressibility as determined by oedometer and triaxial tests." *European Conference on Soil Mechanics & Foundations Engineering*, Wiesbaden, Germany, Vol.1, pp. 19-25
6. Jones, D.R.V. and Dixon, N. (1998). "Shear strength properties of geomembrane / geotextile interfaces." *Geotextiles and Geomembranes*, Vol. 16, pp. 45-71.
7. Kondner, R.L. (1963). "Hyperbolic stress-strain response: cohesive soils." *Journal of Soil Mechanics and Foundations Division*, ASCE, Vol. 89, No. 1, pp. 289-324
8. Seo, M.W., Park, J.B. and Kim, O.Y. (2002). "The evaluation of interface shear strength between geomembrane and geotextile." *Journal of the Korean Geotechnical Society*, Vol. 18, No. 1, pp. 79-89.
9. Triplett, E.J. and Fox, P.J. (2001). "Shear strength of HDPE geomembrane / geosynthetic clay liner interfaces." *J. Geotech. and Geoenvir. Engrg.*, ASCE, Vol. 127, No. 6, pp. 543-552.
10. Turnbull, W.J. and Hvorslev, M.J. (1967). "Special problems in slope stability." *Journal of Soil Mechanics and Foundations Division*, ASCE, Vol. 93, pp. 499-528