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FEM study on tensile force of geosynthetic liner with a change of side slope gradient

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ABSTRACT: Since the waste landfills are usually located in the valley of mountainous area in Japan, the anchor trench at side slope crest is necessary to prevent the liner from slipping. It is important to estimate the tensile force of geosynthetic in order to assure adequate performance and to design anchor trench at side slope crest. In this research, for the landfill liner composed of upper protective mat, barrier sheet and bottom protective mat, Finite Element Analysis, in which the gradient of modelled landfill side slope was changed from 1:2.0 to vertical, were conducted to evaluate the effect of side slope gradient on the tensile force of geosynthetic liner. In the FEM analysis, the stress-strain relationships of geotextile and geomembrane were modelled by linear elastic and the stress-strain relationship of ash and friction stress-relative displacement relationship of joint element were modelled by hyperbola. The centrifugal model experiments were also conducted to verify the FEM analysis. As a conclusion, the tensile force of geosynthetic liner at the slope crest decreases with increasing side slope gradient from 1:2.0 to 1:0.2 and then it increases slightly as the gradient increases up to vertical.

1 INTRODUCTION

The waste landfills in Japan are usually located in the valley of mountainous area in order to saving the plane place. The anchor trench at side slope crest is necessary to prevent the liner from slipping. Since geosynthetics used in liner are considered to experience various forces, it is important to estimate the tensile force induced in geosynthetic at the side slope crest in order to assure adequate performance and to design anchor trench. At present, the steeper side slope trend to be used to give a larger landfill void space for waste placement. However the relationship between the slope gradient and the tensile force in geosythetic at the slope crest is not clearly understood.

For the tensile force of geosynthetic liner at the side slope crest, Koerner (1994) presented a calculation method based on the limit equilibrium of frictional force between materials. Kanou et al. (1997) and Gourc et al. (1997) conducted the field experiment to study the tensile forces induced in components of liner by the compression of waste. Xu and Imaizumi (2003) conducted a series of modelled experiments under the gravitational conditions to evaluate the effect of gradient of landfill side slope on the tensile force of geosynthetic at the crest.

In this study, FEM analysis and centrifugal modelled experiments were conducted to investigate the variation of tensile force of geosynthetic at side slope crest with the change of slope gradient.

2 CENTRIFUGAL MODELLED TESTS

In order to verify the FEM analysis described later, the centrifugal modelled tests were first conducted. In the tests, the modelled landfill was constructed in a steel container having a length of 50 cm, a width of 26 cm and a depth of 35 cm as shown in Figure 1.

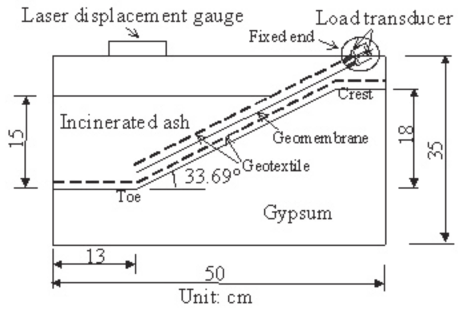

Figure 1. Configuration of the centrifugal model (1:1.5).

The foundation and slope of the modelled landfill were made of gypsum. The height of the side slope was 18 cm and the gradient was varied as 1:2.0, 1:1.5, 1:1.0 1:0.5 and vertical. Stapled non-woven geotextile was bonded to the slope as bottom protective mat and then covered by a barrier sheet of HDPE geomembrane. A piece of stapled non-woven geotextile was placed over the barrier sheet as upper protective mat. Because the scaling down of the geotextile and geomembrane is difficult, the true materials were used in the tests. The thickness and elastic modulus at 20°C of geosynthetics used in tests are listed in Table 1. The tensile forces induced at the fixed end of upper protective mat and barrier sheet were measured through load transducers.

Table 1. Properties of geosynthetics used

Materials	Thickness (mm)	Elastic modulus (MPa)
Stapled non-woven geotextile	10	6.7
HDPE geomembrane	1.5	484

The incinerated ash with a water content of 45% was poured into modelled landfill up to a height of 15 cm and resulted in an average wet density of 0.81 g/cm^3. The centrifuge acceleration was increased at a rate of 5 G/min. up to a maximum of 35 G and the model with a height of 18 cm is equivalent with prototype waste landfill with a height of 6.3 m. At first, the tensile forces of upper protective mat and barrier sheet induced by the masses of geosynthetics itself and the clamp used to connect the geosynthetic with the load cell were tested without ash. Secondly, the tensile forces with ash were tested. The difference of two measurements was considered to be tensile force induced by the compression of ash. The tests with same slope gradient were conducted twice to verify the results. The air temperature when the centrifugal modelled tests were conducted was 24.0~27.4°C.

3 FINITE ELEMENT ANALYSIS

Two dimensional FEM analysis was conducted. The finite element meshes and boundary conditions for the case where side slope gradient is 1:1.5 are shown in Figure 2. The numbers of nodes and elements are 227 and 229 respectively. The quadrilateral element and triangle element were used to model the ash. The upper protective mat and barrier sheet were modeled by bar element. The interfaces between materials were modeled by joint element. The end of the upper protective mat and barrier sheet were fixed at the crest and were connected with ash element by nodes at the toe.

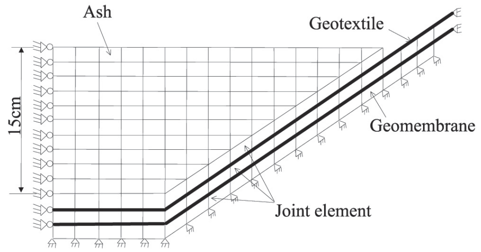

Figure 2. Finite element mesh and boundary conditions (1:1.5).

3.1 *Constitutive law of ash*

The stress-strain response of ash is modelled by Duncan-Chang model (Duncan et al. 1970). The modulus can be expressed as followings.

$$E_t = \left(1 - \frac{R_f\,(1-\sin\phi)(\sigma_1-\sigma_3)}{2c\cos\phi + 2\sigma_3\sin\phi}\right)^2 kP_a\left(\frac{\sigma_3}{P_a}\right)^n \quad (2)$$

where E_t = tangential modulus of ash; σ_1, σ_3 = maximum and minimum principal stress; R_f = failure ratio; c, ϕ = cohesion and friction angle; P_a = atmospheric pressure; k, n = experimentally determined constants. The values of the parameters determined from the result of consolidated-drained triaxial compression test are shown in Table 2.

Table 2. Parameters of ash and interfaces between materials.

	k	n	R_f	$c(kPa)$	$\phi(°)$
Ash	63.20	0.82	0.88	0.80	36.50
Ash–Protective mat	1631.92	0.83	0.82	1.02	36.20
Protective mat-HDPE barrier sheet	4877.63	0.98	0.84	0.66	12.50

3.2 *Constitutive law of geosynthetics*

The geosynthetics used in the tests were treated as a linear elastic materials and secant modulus at a strain of 1% obtained by tensile test was used. Thus, for the geosynthetic element, the relationship between tensile force T and elongation Δl can be express as follows.

$$T = \frac{E_{1\%}t}{l}\,\Delta l \quad (3)$$

where, T = tension force for unit width; $E_{1\%}$ = secant modulus at a strain of 1% as listed in Table 1; t = thickness of geosynthetic; l = length of element; Δt = elongation of element.

3.3 *Constitutive law of interface between materials*

In the finite element analysis, the shear stress-relative displacement behavior of interfaces between materials must be accurately modeled. The model using a hyperbolic relationship between shear stress and relative displacement on interface is well known.

Usually the strain softening properties can be found in conventional direct shear tests. But, in this analysis, such simplifications are made as shown in Figure 3 that shear stress is assumed to keep the constant beyond peak value. Through calculating, it is found that the part ahead of the peak shear stress is well according with the hyperbolic relationship.

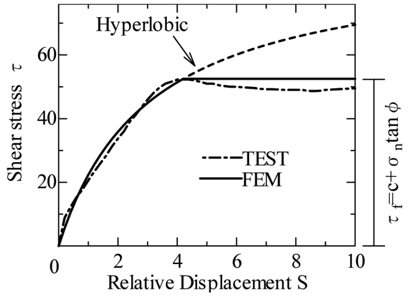

Figure 3. Diagrammatic sketch of shear characteristic on interfaces.

The shear stiffness K_{st} of interfaces ahead of the peak shear stress can be expressed as follows:

$$K_{st} = \left(1 - R_f \frac{\tau}{\tau_f}\right)^2 k\gamma_w \left(\frac{\sigma_n}{P_a}\right)^n \tag{4}$$

where: τ, σ_n = shear stress and normal stress on interface; R_f = failure ratio; τ_f = shear stress at failure; γ_w = unit weight of water; k, n = experimentally determined constants.

The Coulomb failure criterion is generally used to represent the shear strength of interfaces between materials and is expressed as:

$$\tau_f = c + \sigma_n \tan \phi \tag{5}$$

where: c and ϕ = cohesion and friction angle of interface. Substituting Equation (5) into Equation (4), the shear stiffness of interface can be expressed as Equation (6). The values of parameters for various interfaces determined from the results of conventional direct shear tests are shown in Table 2. The normal stiffness of interface, K_{sn}, was assigned a very large value of 10^7 kPa/m^3 to avoid overlapping of the joint element.

$$\left.\begin{aligned} &K_{st} = \left(1 - R_f \frac{\tau}{c + \sigma_n \tan \phi}\right)^2 k\gamma_w \left(\frac{\sigma_n}{P_a}\right)^n \\ &(\tau < c + \sigma_n \tan \phi) \\ &K_{st} = 0\ (\tau \geq c + \sigma_n \tan \phi) \end{aligned}\right\} \tag{6}$$

4 CALCULATED AND TESTED RESULTS

The variation of tensile forces at the fixed ends of protective mat and barrier sheet at a centrifugal acceleration of 35G versus the side slope gradient are shown in Figure 4. It is found that the tensile forces calculated by FEM are very similar to the values obtained by centrifugal modelled tests. This means that the FEM analysis is very useful to estimate the tensile force creating at the shoulder of the liner.

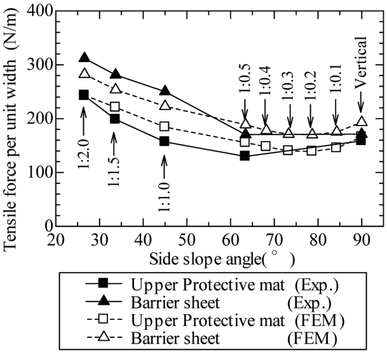

Figure 4. Tensile forces at the fixed end versus slope gradient.

It is also found that both the calculated and tested values of tensile forces at the fixed ends of the upper protective mat and barrier sheet decrease as the side slope gradient increases from 1:2.0 to 1:0.5 and then increase slightly as the gradient become to vertical, which is similar with the results tested under the gravity condition (Xu and Imaizumi, 2003). In addition, it is clear by the calculated results that the tensile forces at the fixed ends of the upper protective mat and barrier sheet achieve the minimum value at the side slope gradient of 1:0.2. To explain this fact, the relative displacement and shear stress on the interface are considered. The FEM calculated results for 1:2.0, 1:1.0, 1:0.2 and vertical slopes are given in followings.

The calculated normal stresses on the interface between materials are shown in Figure 5. It is found that the maximum normal stress at the toe of slope decreases with increasing slope gradient but the change is not evidence for 1:0.2 to vertical side slope.

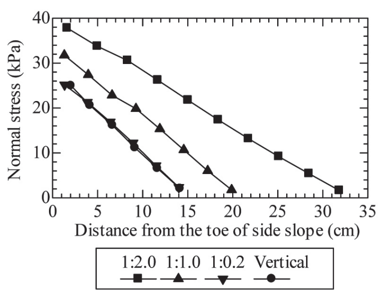

Figure 5. Normal stress on the interface between materials.

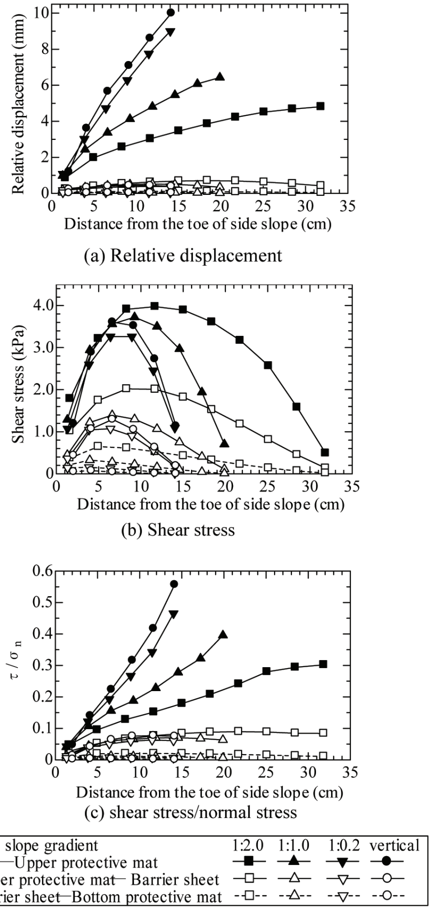

Figure 6. Relative displacement, shear stress and ratio shear stress/normal stress along the interfaces.

The distribution of relative displacement and shear stress along the interface are shown in Figure 6(a) and 6(b). From Figure 6(a), it is found that for the interface between ash and upper protective mat, the relative displacement at the toe is similar, but near the fixed end, the relative displacement increases with increasing slope gradient. It can be found from Figure 6(b) that the maximum shear stress on the three interfaces decreases as the slope gradient increases from 1:2.0 to 1:0.2. Since the difference of the integrations of shear stresses between the upper and bottom surface of geosynthetic along the length can be consider to mainly cause the tensile force at the fixed end, furthermore considering the change of side slope length, the decrement of tensile force from 1:2.0 to 1:0.2 can be understood.

From 1:0.2 to vertical, it is found that there is an increment in maximum shear stress. In addition, the side slope lengths are almost same. Therefore, an increment of tensile force at the fixed end is seen for the vertical side slope.

The ratios between shear stress and normal stress along the interfaces are shown in Figure 6(c). According to the results of conventional direct shear tests between the materials, the peak frictional coefficient (tan ϕ) is 0.76 for the interface between ash and upper protective mat and 0.22 for the other two interfaces. From Figure 6(c), it is found that the ratios between shear stress and normal stress (τ/σ_n) are not mobilized to peak value in all three interfaces. For the interface between ash and upper protective mat, the ratio between shear stress and normal stress is mobilized to a larger value with the increasing slope gradient. For the interface between barrier sheet and bottom protective mat, the ratio between shear stress and normal stress is mobilized to a very low value.

5 CONCLUSIONS

In this paper, FEM analysis and centrifugal model experiments were conducted to investigate the variation of tensile force of geosynthetic liner with the change of side slope gradient. The results of centrifugal model tests verified the numerical model. As a main conclusion, it is found that the tensile force at the fixed end of geosynthetic decreases as the slope gradient increases from 1:2.0 to 1:0.2 and then it increases slightly as the gradient increases up to vertical.

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