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A study on the durability of a triple liner system – Stress and deformation analysis by finite element method

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ABSTRACT: The authors have developed a new type of geomembrane sheet with a threefold impermeable formation, taking aim at seepage control in the industrial waste disposal area. In order to study the durability of the sheet under a large load, we made non-linear finite element models of the sheet and analyzed the stress-deformation characteristics in detail. From the analysis results, it was confirmed that, when even subjected to a large reclamation load on a rubble mound, the sheet is able to demonstrate a good deformation performance, securing the thickness necessary for maintaining sufficient impermeability. Consequentially, it is concluded that the applicability of this geomembrane sheet to control seepage is sufficiently high.

1 INTRODUCTION

Reliable method for seepage control of pollutant is requested in order to construct a sea area landfill site. The authors have developed the integrated three-layer geomembrane sheet, named Triple Liner System (herein it is called TLS), in which the polyurethane elastomer, as a intermediate protection material of 10 to 20 mm in thickness, is inserted between the PVC geomembranes. This intermediate material can form an impermeable layer without growing voids because it is filled keeping liquidity moderately. After stiffened, the polyurethane elastomer also shows high performance for both of flexibility and chemical resistance, and moreover it mobilizes shear strength equal to the outer PVC geomembranes. Akai et al. (2004) and Satoh et al. (2005) confirmed that TLS had an excellent threefold impermeable function compared to a conventional double sheet, with high deformability and impermeability ($\leq 10^{-13}$cm/s in coefficient of permeability, *k*).

It is difficult to estimate the durability, especially stress-deformation characteristics of TLS under in-situ stress condition only by laboratory element or model tests. Therefore, the stress-deformation relationship of TLS was analyzed by non-linear finite element method, assuming when laid on the slope of a rubble mound at a landfill site located in the sea. We hereby report the applicability of TLS which is used as the seepage control method in the site.

2 ANALYSIS METHOD

2.1 *Finite element model*

The analyzed model is modelled a part of a TLS sheet using 2D finite elements as shown in Figure 1. All elements for the sheet consist of plain-strain rectangular elements with nine nodes. The polyurethane elastomer and PVC geomembranes share nodes each other at the boundaries and assumed to be adhered completely. The lateral boundaries of the model are confined by perpendicular roller supports.

Maximum value of applied uniform load is defined as 350 kN/m^2, taking into account an assumed reclamation load of a landfill site.

The 50 loading steps with the increment of 0.2 kN/m^2 will be applied firstly up to 10 kN/m^2 and the

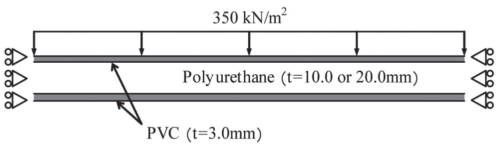


Figure 1. Finite element model of TLS.

170 loading steps with the increment of 2.0 kN/m^2 will follow the primary steps up to 350 kN/m^2.

The rubble mound laid under TLS made of solid elements, combining some octagons with a radius of 350 mm, is assumed to never move and deform. TLS contact the rubble mound in coefficient of friction of 0.4 based on the friction test result.

2.2 *Material models*

The material characteristics of the polyurethane elastomer are modelled by the Ogden model which is applied to rubber in general. Ogden (1997) proposed the strain-energy function, W as follow, using n-th order series:

$$W = \sum_{n=1}^{N} \frac{\mu_n}{\alpha_n} (\lambda_1^{\alpha_n} + \lambda_2^{\alpha_n} + \lambda_3^{\alpha_n} - 3)$$

Where, λ_1, λ_2 and λ_3, are extension ratios and μ_n and α_n are constants. The stress-strain relationship in the simple tension test for the polyurethane elastomer is simulated as shown in Figure 2.

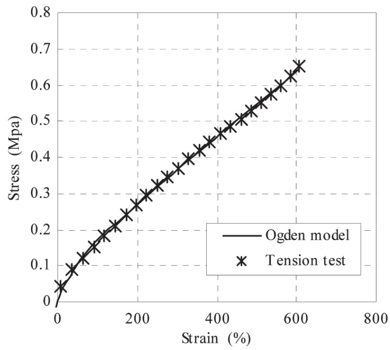


Figure 2. Material model (Polyurethane elastomer).

On the other hand, bilinear model is applied to PVC as shown in Figure 3 with the test result.

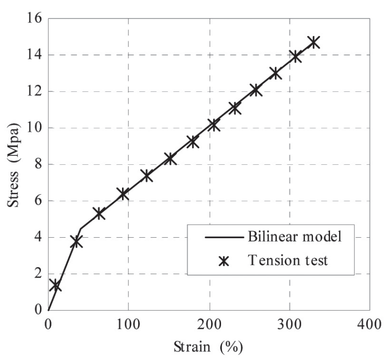
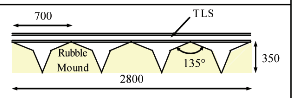
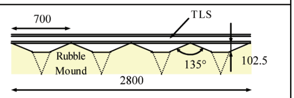
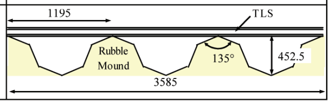


Figure 3. Material model (PVC geomembrane).

2.3 *Analysis cases*

Six cases of analysis shown in Table 1, combining two types of polyurethane elastomer thickness and three types of rubble mound configuration, were computed. Each case of the mound configuration expresses the existence of gaps or inequalities assumed to be caused by differences between levelling work qualities.

Table 1. Analysis cases.

Case	Polyurethane Elastomer Thickness	Rubble Mound Configuration		
		Gap	Inequality	Sketch (unit: mm)
A1	10mm	○	×	
A2	20mm			
B1	10mm	×	×	
B2	20mm			
C1	10mm	○	○	
C2	20mm			

○: existent ×: not-existent

3 RESULTS AND CONSIDERATIONS

3.1 *Relation between load and stress in TLS*

As the uniform load increases, the tensile stresses in the elements of polyurethane elastomer and the compression stresses in the elements of PVC geomembrane at the apex on the central rubble in Case A1, A2, B1 and B2 increase similarly as shown in Figure 4. The magnitude of stress generated in the polyurethane elastomer is much smaller than that in the lower PVC geomembrane.

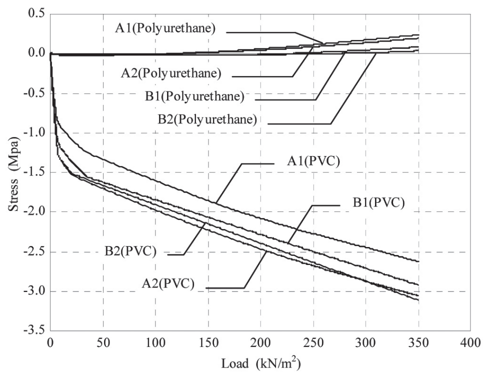


Figure 4. Load-stress curves (at apex – compression).

The stress distribution of TLS around the apex, where compressive stress of PVC is predominant, is shown in Figure 5.

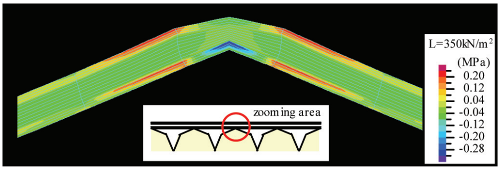


Figure 5. Stress distribution (at apex – compression).

On the other hand, the tensile stresses developed 18.0 in the upper PVC elements at the apex of rubble adjacent to the central one are shown in Figure 6. The tensile stresses in Case B1 and B2 decrease after the whole of TLS contacts the rubble mound completely at a load of 24 to 28kN/m^2, while those in Case A1 and A2 increase monotonously. The difference between the load-stress curves seems to be made whether TLS is forced into the gap between rubbles or not. The stress distribution of TLS around the apex where tensile stress of PVC is predominant is shown in Figure. 7.

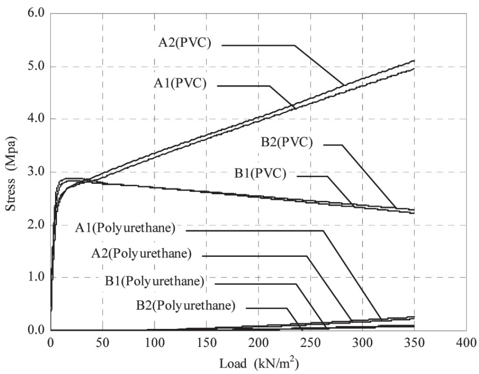


Figure 6. Load-stress curves (at apex – tension).

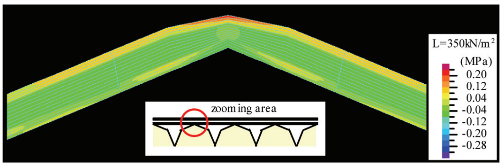


Figure 7. Stress distribution (at apex – tension).

In Case A1 and A2, TLS is forced into gap between rubbles as shown in Figure 8. The tensile stresses of 15 MPa or more which are much greater than the stresses at the apex are generated in the lower PVC geomembrane elements as shown in Figure 9. On the other hand, the tensile stresses in the polyurethane elastomer elements are much smaller than those of the PVC's, showing value of approximately 0.1 MPa.

In Case C1 and C2, the tensile stresses converge on about 1.7 MPa in the PVC geomembrane layers at all apexes, while the stresses of the polyurethane layers

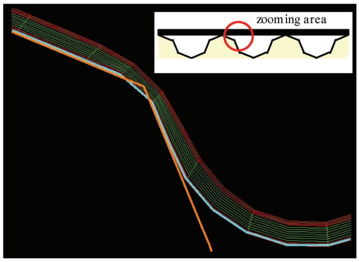


Figure 8. Deformation into gap.

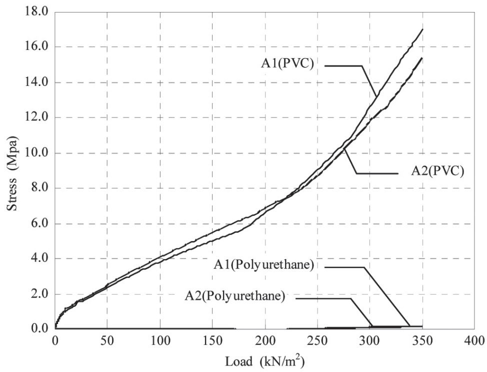


Figure 9. Load-stress curves (at gap).

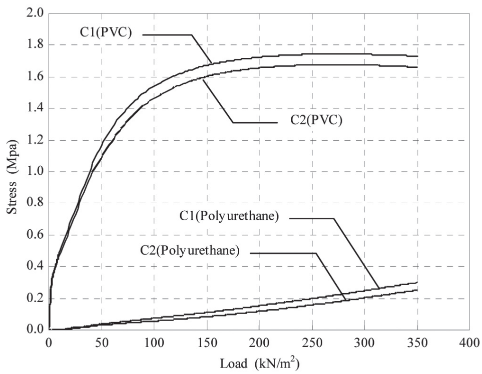


Figure 10. Load-stress curves (at apex).

reach 0.2 to 0.3 MPa finally as shown in Figure 10. The entire TLS is pushed toward the concave between rubbles and the tensile stresses are developed there in these cases.

The load-stress relationships at the concave in Case C1 and C2 are shown in Figure 11. The maximum value of tensile stress about 6 MPa and compressive stress less than 1 MPa are generated in the PVC geomembrane layers at the concave. TLS can be deformed along the inequalities of the rubble mound smoothly and then it is concluded that the sheet has a deformation performance sufficiently.

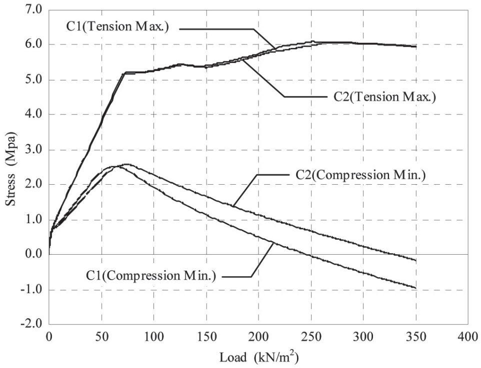


Figure 11. Load-stress curves (PVC geomembrane at concave).

3.2 *Relation between stress and strain in TLS*

The stresses and strains under loading 350 kN/m^2 are shown in Table 2. In all the cases, there is no significant difference of the strain caused by the thickness of polyurethane elastomer and the strain in the polyurethane layer is smaller than in the PVC's. In Case B1 and B2, it shows the smallest value of both stress and strain compared with other cases. Anyway, the analyzed strains for both the materials are found to show much small value in comparison with the ultimate strains confirmed in the simple tension tests (about 600% for polyurethane and about 300% for PVC).

Table 2. Tensile stress and strain under loading 350 kN/m^2.

Case	Polyurethane		PVC	
	Stress Mpa	Strain %	Stress Mpa	Strain %
A1	0.26	56.4	4.94	61.3
B1	0.10	17.5	2.21	34.4
C1	0.30	44.5	5.93	79.5
A2	0.21	52.8	5.11	62.5
B2	0.07	15.8	2.28	34.4
C2	0.25	42.9	5.95	81.1

3.3 *Relation between load and thickness of TLS*

In all the cases, the thickness of TLS becomes the minimum under loading 350 kN/m^2 at the apex as shown in Table 3. However, the decreasing rate of TLS thickness, which is defined as percentage of the decrement to initial thickness, is less than 40% in all the cases. On comparing Case A and Case B, it is found that TLS can keep thicker when the rubble mound is filled. Because *k* of TLS is very small, the thickness of 10 mm or more after loading is estimated to be effective in controlling seepage.

4 CONCLUSIONS

From a series of the analysis results, it was confirmed that TLS was able to demonstrate a good deformation performance without broken when even subjected to large reclamation load on a rubble mound. It also can secure the thickness necessary for keeping sufficient impermeability after deformed. As a result, it is concluded that the applicability of TLS for seepage control method is sufficiently high.

On the other hand, a gap between rubbles may cause much damage to TLS if the sheet is forced into the gap. TLS could be also maintained somewhat thicker on a well-levelled mound than on that without filling in gap. Therefore filling and levelling works in construction of the mound are very important to maintain the performance and to improve the durability of the sheet.

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Table 3. Thickness under loading 350 kN/m^2.

Case	TLS Thickness			Polyurethane elastomer thickness		
	Initial	350 kN/m^2	Decreasing rate	Initial	350 kN/m^2	Decreasing rate
A1	16.0 mm	10.5 mm	34 %	10.0 mm	5.5 mm	45 %
B1	16.0 mm	12.1 mm	24 %	10.0 mm	6.2 mm	38 %
C1	16.0 mm	10.9 mm	32 %	10.0 mm	5.5 mm	45 %
A2	26.0 mm	15.8 mm	39 %	20.0 mm	10.8 mm	46 %
B2	26.0 mm	17.8 mm	32 %	20.0 mm	11.9 mm	41 %
C2	26.0 mm	16.2 mm	38 %	20.0 mm	10.8 mm	46 %