Seismic stability of geosynthetic barrier on landfill slope

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ABSTRACT

The interfaces of geosynthetic barrier are considered to be structurally weak surfaces when the barrier is installed in the landfill slope. However, dynamic behaviors of geosynthetic barrier under seismic excitation have not been clarified sufficiently. In the present study for the purpose to assess the seismic risk of the landfills with respect to the sliding failure along the geosynthetic barriers, the dynamic behaviors of geosynthetic barrier slope were investigated experimentally by means of shaking table tests. Firstly the dynamic behaviors of geosynthetic interfaces were investigated by sliding block experiments to evaluate dynamic friction. Secondly, the surface and global sliding failure modes of the geosynthetic barrier slope were observed depending on the thickness of bottom protection layer. Finally the stability analysis method was proposed so as to predict the failure of geosynthetic barrier slope reasonably.

Keywords: dynamic interface property, geosynthetic barrier, shaking table test, stability analysis

1 INTRODUCTION

The static and dynamic behaviors of geosynthetic barriers are very important to keep the stability of the whole landfill that is necessary to function as hydraulic barrier systems and minimize the contamination risk due to leachate leakage. The geosynthetic barrier has multi-layer configuration that consists of geomembrane sheet, non-woven geotextile protection sheet, geosynthetic clay liners and others. The interfaces of layers are considered to be structurally weak surfaces when the barrier is installed in the slope of landfill because the interface friction or shear resistances between different geosynthetics and geomaterials are relatively small compared to the shear strength of each material.

Fig. 1 shows a typical configuration of geosynthetic barrier with double geomembrane (GM) protected by nonwoven geotextile (N-GT) that is often adopted in coastal landfills and has common features with ordinary inland landfills. When the barrier is installed in the inclined surface for lateral and cover barriers, due to self-weight of the soil for protection layer and the solid waste disposed into the landfill, the sliding force will arise along the barrier system that results in shearing force applying the barrier.

Stability analyses on geosynthetic barrier slope have been often conducted by limit equilibrium method. Seismic forces can be considered in the limit

equilibrium methods. However, dynamic behaviors of geosynthetic barrier under seismic excitation have not been clarified sufficiently.

In the present study for the purpose to assess the seismic risk of the landfills with respect to the sliding failure along the geosynthetic barriers, the dynamic behaviors of geosynthetic barrier slope were investigated experimentally by means of shaking table tests. Firstly the dynamic behaviors of geosynthetic interfaces were investigated by sliding block experiments to evaluate dynamic friction. Secondly, the surface and global sliding failure modes of the geosynthetic barrier slope were examined by model slope experiments. Finally the stability analysis method was proposed so as to predict the failure of geosynthetic barrier slope reasonably.

Fig. 1. Typical configuration of geosynthetic barrier.

2 SLIDING BLOCK EXPERIMENTS

2.1 Equipment for sliding block experiments

For the purpose to analyze dynamic frictional properties of geosynthetic interfaces, a series of sliding block experiments were conducted by applying the sinusoidal horizontal motions as input excitation to a block on a shaking table (Kotake et al, 2014). Considering the configuration of the geosynthetic barrier system as shown in Fig.1, the experiments were performed basically on two types of interfaces that are “geomembrane and geotextile”, and “geotextile and geomaterial”. In relation to the model slope experiment as described later, the interface between geomembrane and geomaterial is also examined though it is not a practical case. Figs. 2 and 3 show a schematic diagram and the setup of the sliding block experiments for geomembrane and geomaterial interface.

Fig. 2. Schematic diagrams of sliding block experiments.

Fig. 3. Setup of sliding block experiments.

The sandy soil was filled and compacted in a wooden box with the inner dimension of 410 mm × 400 mm × 70 mm that was fixed on the shaking table. The steel block with a geomembrane sheet attached on the bottom surface was placed at the middle position on the soil surface for the initial setup. The block was made of 20mm thick steel plates, and they were folded and unified by instant glue. The bottom plate was 310 mm long and 200 mm wide, and the weight was 0.16 kN. The whole weight of the block was made 0.21 kN and 0.26 kN by increasing the number of upper plates.

The measuring instrumentation consisted of two accelerometers and three displacement transducers as seen in Figs. 2 and 3. An accelerometer was installed

on the shaking table, and another on the top of the block. The displacement transducer, fixed on the shaking table, allowed the measurement of relative displacements between the shaking table and the block. The other two displacement transducers were set to monitor flatness of the block.

2.2 Material properties of components

The geomaterial used in the present experiments was the sandy soil that was used in the model slope experiment as described later. The sandy soil was compacted to have the density of approximately $\rho=1.45 \text{ g/cm}^3$. The geomembrane used here was HPDE geomembrane sheet with smooth surface and 1.5mm thickness. The tensile strength of the geomembrane was 540 N/cm at elongation of 650%. Static friction between the geomembrane and the sandy soil was measured by sliding test under the similar conditions using the same steel blocks as used in the shaking table experiments. The static friction coefficient was $\mu_s=0.436$.

2.3 Results and discussions

The experimental results were summarized in terms of time histories of accelerations of the shaking table α_T and the sliding block α_B and relative displacements u_{B-T} in order to examine the acceleration transfer to the block through the interface and the relative displacement between the shaking table and the block that arose while the block was sliding.

Fig. 4 shows the acceleration time histories in the steady states under $f=5\text{Hz}$ excitation. It is seen that the maximum acceleration of the block was 4.47 m/s^2 while that of the shaking table was 5.10 m/s^2 . When the acceleration of the block was smaller than that of the shaking table as seen in this case, the relative displacement between the block and the shaking table u_{B-T} appeared. The block moved back and forth in a distance of 0.8mm in each excitation, and the relative displacements u_{B-T} accumulated constantly on the whole to the same direction as seen in Fig. 5. Similar tendency was observed in the other test cases in which the different patterns of acceleration were applied (Kotake et al. 2011).

Suppose that the slippage between the geomembrane and geotextile interface be similar to the solid friction, the dynamic friction coefficient μ_{dyn} can be given as $\mu_{\text{dyn}}=\alpha_{\text{crit}}/G$, where α_{crit} is the critical acceleration at that the block begins to slide and G is the gravity acceleration. From the test results of $\alpha_{\text{crit}}=4.47 \text{ m/s}^2$ obtained for the interface, the dynamic friction coefficient is evaluated to be $\mu_{\text{dyn}}=0.456$ and the friction angle was $\delta=\tan^{-1}(\mu_{\text{dyn}})=24.5^\circ$ that is a little larger than the static one ($\mu_s=0.436$). From the test cases with different block weight and excitation frequency of 3.5 to 5.0 Hz, the values of dynamic friction coefficients ranged $\mu_{\text{dyn}}=0.44 - 0.47$ ($\phi=24\text{-}25^\circ$).

Fig. 4. Acceleration time histories.

Fig. 5. Relative displacement time histories.

3 MODEL SLOPE EXPERIMENTS

3.1 Methodology for model slope experiments

Shaking table tests on the geosynthetic barrier slope models were conducted using the apparatus equipped with hydraulic servo control system. Fig. 6 shows the model slope of 1/30 scale that was made inside a stainless steel container. The container had the dimension of width 101 cm $\times$ height 61 cm $\times$ depth 29 cm and was placed on the steel shaking table. The height of slope model was 30 cm and assumed to be 9 m of real height.

For the model barrier, the HDPE geomembrane sheet having the thickness of 1.5mm was steadily attached along the bottom and the side slope that was made of foamed styrol as a fixed rigid base. The gradient of the geosynthetic lateral barrier was 1:1.5, and that of the surface of the lateral protection layer was 1:2.0. For the geomaterial of the model slope, silica sand No.8 was used. NSF kaolin, 2% in weight, was mixed with the silica sand and the water content was adjusted to be $w=2\%$ so that the geomaterial could have relatively small cohesion. By the effects of cohesion the model slope could behave as soil lumps when it collapsed. The model slope was made in stages from bottom to top by compacting the spread soil of approximately 5cm thick with a woodcut and a wooden hammer. The density of soil in the model slope was $\rho=1.45\sim1.52\text{ g/cm}^3$.

The shaking table was excited in the sinusoidal horizontal motions with the target acceleration

amplitude by the hydraulic servo control system. The acceleration was increased in stages by an increment of 0.50 to 1.00 m/s^2 with a constant frequency of 5Hz until the remarkable collapse of the slope was observed. In each stage of excitation, duration time was approximately 5 second.

Three accelerometers were installed at the top of the shaking table to measure the excitation directly, the bottom of the container and the top of the model slope to examine the response acceleration. In the present experiments, the acceleration monitored at the slope top was similar to that of excitation measured at the table. The behaviors of the model slopes during the tests were visually observed and recorded by means of a digital video camera and a high-speed camera with more than 200 frames per second.

Fig. 6. Geosynthetic barrier slope model for shaking table test.

3.2 Experimental results and discussions

Two failure modes were observed in the slope model experiments; the surface slope failure and the global sliding failure occurred due to the difference of the thickness of bottom protection layer.

The surface slope failure was observed when the thickness of bottom layer was relatively large. Figs. 7 and 8 show the surface slope failure mode observed in the test case with the bottom thickness of $t_2=6\text{ cm}$ that corresponded to the typical dimension of the landfill section. Firstly an initial sliding surface was observed at the toe of the slope that crossed the white marking line at the acceleration of $\alpha=9.20\text{ m/s}^2$. (Fig. 8a), and then the soil lump of the whole slope slid perfectly along the geomembrane sheet at $\alpha=9.70\text{ m/s}^2$. (Figs. 7 and 8b). At the toe of the slope a clear shear sliding surface was generated nearly horizontally while no particular deformation was observed in the bottom layer. (Fig. 8b).

The global slope failure was observed in a case that the thickness of bottom layer was decreased as thin as the half of the basic dimension, i.e. $t_2=3\text{ cm}$. A clear sliding surface with a steep angle from the bottom part of the slope toe was observed at the acceleration of $\alpha=7.00\text{ m/s}^2$, as shown in Figs. 9 and 10b. The whole soil mass of the slope from bottom to top moved along the geomembrane sheet and the large part of the soil mass of the bottom layer moved horizontally along the

bottom geomembrane. At the end of the bottom soil mass a clear sliding surface generating upward to the surface was observed and the soil was heaving as shown in Fig. 10a. Therefore, it can be thought that the sliding surface at the slope toe was the interface between the sliding block and the resisting block, or active and passive blocks. The sliding surface firstly generated at $\alpha=6.20 \text{ m/s}^2$ and gradually developed as the active block was sliding downward associated with the increase in excitation magnitude until it was brought to the perfect failure.

Fig. 7. Surface slope failure observed at $\alpha=9.70 \text{ m/s}^2$.

a) $\alpha=9.20 \text{ m/s}^2$ b) $\alpha=9.70 \text{ m/s}^2$
Fig. 8. Sliding surface generated at slope toe.

Fig. 9. Global slope failure observed at $\alpha=7.00 \text{ m/s}^2$.

a) Bottom end b) Slope toe
Fig. 10. Sliding surfaces at bottom end and slope toe.

4 STABILITY ANALYSIS

4.1 Stability analysis by limit equilibrium method considering seismic force

Two failure modes with respect to the sliding soil mass were considered as used in the static analysis as shown in Fig. 11. One is the surface slope failure mode in which only the lateral protection layer slides as proposed by Koerner and Soong (1998) for the sliding

failure of cover soil. The other is the global slope failure mode in which the soil mass in both the lateral and the bottom protection layers slide along the geosynthetic barrier layer proposed by Kotake et al (2002).

The sliding protection soil layers are separated to active and passive soil blocks as defined by Koerner and Soong (1998). The forces applying in each soil block for both sliding and resisting are shown in Fig. 11, where W_A and W_P are weight of active and passive soil blocks, N_A and N_P are respective reaction forces acting to the right angles to the slope. H_A and H_P are respective seismic forces applying horizontally as body forces to the soil blocks. That is, $H_A = K_h \times W_A$ and $H_P = K_h \times W_P$ where K_h is the horizontal seismic coefficient. P_p is the passive earth pressure applying to the passive soil block in the bottom protection layer. As the material properties, c and ϕ are cohesion and internal friction angle of the soil for protection layer, and C_i is the resisting forces by cohesion and δ is friction angle at the interface between the geosynthetic barrier layer and the protection soil layer. Then, balancing the forces in the vertical and horizontal directions, the safety factor F_s can be calculated (ex. Koerner 2005).

Fig. 11. Schematic diagrams of failure modes and forces involved with soil blocks of landfill slope.

4.2 Stability analysis on experimental results

Stability analyses were conducted so as to explain the results of model slope experiments by shaking table. The strength parameters of the soil that had been made for the model slope in the experiments were estimated to be cohesion $c=0.8 \text{ kN/m}^2$ and internal friction angle $\phi = 38^\circ$ that were obtained from direct shear tests on the soil having the similar density of $\rho=1.45 \text{ g/cm}^3$ to the model slope. The interface strength parameters were assumed to be $c_i=0$ and $\delta=25^\circ$ that were typical values obtained from the sliding block experiments as described before.

Fig. 12 shows the relations between the horizontal seismic coefficient K_h and the safety factor F_s for the cases of the surface and global failure modes having the thickness of the bottom layers $t_2=3 \text{ cm}$ and $t_2=6 \text{ cm}$, respectively. The K_h values at which the calculated safety factor became $F_s=1.0$ were approximately $K_h=0.9$ and 0.7 for the analysis cases of surface and global modes, respectively. It was found that the analysis results agreed with the experimental results

with respect to the acceleration at failure. This suggests that the suitable selection of parameters may lead to reasonable prediction for the actual structures.

Fig. 12. Stability analysis to predict experimental results.

4 CONCLUSIONS

In the present study for the purpose to assess the seismic risk of the landfills with respect to the sliding failure along the geosynthetic barriers, the dynamic behaviors of geosynthetic barrier slope were investigated experimentally by means of shaking table tests. The findings from the present research are as follows:

- 1) In the sliding block experiments, the sliding at the geomembrane and sandy-soil interface occurred at the critical acceleration, and the dynamic friction coefficient was slightly larger than the static friction. During sliding the peak acceleration of block was not exceeding the critical acceleration and the relative displacements were accumulated.
- 2) In the model slope experiments, each of surface and global failure modes could be clearly observed, depending on the interface friction and thickness of the bottom protection layer. It was found that the global failure could occur when the interface friction was relatively low and the bottom protection layer is thin.
- 3) The safety against sliding failure could be reasonably predicted by limit state stability analysis considering seismic forces and using the strength parameters for the geomaterial and the interface obtained from the dynamic tests.

ACKNOWLEDGEMENTS

This research was supported by Grant-in-Aid for Scientific Research (C) 22560506.

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