Large-scale Tests of Leachate through Defects in Geomembrane Underlain a Soil Layer

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Abstract: Large-scale model tests of leachate through defects in geomembrane underlain a soil layer had been conducted. The effects of overburden pressure ($p$) on the leachate flow rate and the leachate flow mechanism have been investigated. The test and analysis results indicate that increasing $p$ value on geomembrane reduces the leachate flow rate significantly. This reduction is mainly due to the reduction of geomembrane/soil interface transmissivity ($T$). Comparing the measured data with predicted values using existing equations shows that assuming a perfect contact condition between geomembrane and soil is not applicable in practice. Giroud et al.’s (1997) empirical equations for good contact (imperfect) condition can provide a reasonable prediction of the flow rate through a defect in geomembrane of composite liner under lower overburden pressure (less than 10 kPa). However, the effect of overburden pressure is not considered, and modification is required.

1 INTRODUCTION

Geomembrane/clay composite liner is widely used in landfill construction. However, in the field, defects in geomembrane cannot be completely avoided, and most of them are seam defects (Giroud and Bonaparte, 1989). Therefore, to evaluate the leachate through a defect in geomembrane underlain a clayey layer is necessary for designing landfill and assessing the potential impact of a landfill to surrounding environment. There are several equations proposed for this problem (Foose et al., 2001). However, the predicted values are varied in a wide range. Large-scale model test data as well as the field data are desirable for validating the prediction methods.

Only few reported large-scale model tests on leachate through a defect in geomembrane (e. g. Fukuoka, 1986; Jayawickrama et al., 1988). Also, the effect of overburden pressure ($p$) on geomembrane to the leachate flow rate and the mechanism of leachate migration in composite liner had not been investigated experimentally. In this study, large-scale model tests on leachate through defects in geomembrane underlain a soil layer had been conducted, and the effect of $p$ and the leachate migration mechanism have been investigated. Test condition, measured data as well as analysis results are presented in this paper.

2 TEST SETUP AND TEST MATERIALS

Test setup is shown in Fig. 1. The model mainly consists of two sets of steel cylinders with an inner diameter of 1173 mm. The heights of the cylinders are 363 mm and 1000 mm, respectively, and the thickness of the cylinder wall is about 10 mm. The test procedures are as follows:

(1) Place three layers of non-woven geotextile at the bottom of the model as drainage layers. Then put soil into lower part of the model and compact the soil in three (3) layers by a rammer at wet side of optimum water content to desired degree of compaction.

(2) Level the surface of the soil carefully and place geomembrane with a defect in proper position on top of the soil.

(3) Set the upper part of the model. Put about 20 mm thick fine sand on the top of the geomembrane, which transfers applied load uniformly to the geomembrane and serves as drainage layer also. “O” rings are placed between geomembrane and model cylinders to prevent leakage.

(4) Set the loading frame (a porous loading plate and a permeable inner load transfer system), and put the leachate into upper cylinder.

(5) Set the piston and air pressure system and apply desired pressure on the geomembrane. Between the piston and the cylinder, three “O” rings are fixed to achieve air-proof.

(6) Maintain the level of the leachate in the model. After leachate flow becomes steady, measure the flow rate.

Fig. 1 Illustration of model test setup
Fig. 2 Grain size distribution of soil used

(7) After termination of the test, sample the soil at designed places and measure the concentration of target contaminant. The soil used was passing 2 mm sieve decomposed granite (in Japan it is called Masado). The grain size distribution of the soil is given in Fig. 2 with a $D_{50}$ of about 0.4 mm. Compaction test (JIS A 1210) yielded a optimum water content of about 13% and maximum dry density of 19.7 kN/m$^3$. Compaction water content was 15%. The dry density of compacted soil in the model was 18.0 kN/m$^3$. With these conditions, falling head test resulted in a hydraulic conductivity of $3.57 \times 10^{-8}$ m/s.

The geomembrane used was 1.5 mm thick high-density polyethylene (HDPE). Two tests were conducted. Test-1 had a defect of a 10 mm in diameter hole, which was opened at the center of the geomembrane. Test-2 had a defect seam of 1 mm wide and 30 mm long. The duration of Test-1 was about 3 months and about 6 months for Test-2. The leachate used was salt water with a salt content of 10 g/l. Leachate head above the geomembrane was kept as 0.5 m throughout the tests.

3 RESULTS OF TEST-1, A CIRCULAR DEFECT

3.1 Measured Leachate flow rate

After setup Test-1, an overburden pressure ($p$) of 50 kPa was applied on the geomembrane. The flow became steady after about 2 weeks and the flow rate was measured for about 1 month. Then, to investigate the effect of $p$ on the leachate flow rate, the applied pressure was reduced to 10 kPa. After the flow steadied, the measurement was continued for another month. The frequency of the measurement was once per two-days. Figure 3 shows the measured flow rate ($Q$). It can be seen that increase $p$ on the geomembrane reduced $Q$ significantly. $Q$ corresponding to $p=50$ kPa is about 55% of that for $p=10$ kPa.

3.2 Prediction

There are several equations proposed to predict the leachate flow rate through a defect in geomembrane underlain a soil layer. The equations can be divided into two groups according to assumed contact conditions between geomembrane and underlain soil, namely, perfect contact and imperfect contact. The main difference between perfect and imperfect contact conditions is that the former assumes there is no flow at geomembrane/soil interface but later assumes there is.

(1) Perfect contact condition. The representative equations for perfect contact condition are as follows.

\[ Q = 4r_o k_L h_w \]  

\[ Q = 2\pi r_o h_w \]  

where $r_o$ = radius of a circular defect, $k_L$ = hydraulic conductivity of underlain soil, and $h_w$ = head on geomembrane. Eq. (1) was proposed by Forchheimer (1930) and Eq. (2) by Giroud and Bonaparte (1989).

(2) Imperfect contact condition. The imperfect contact condition can be further divided into good and poor contacts (Giroud and Bonaparte, 1989). Assuming there is flow at geomembrane/soil interface and a head distribution at the interface as in Fig. 4. Giroud et al. (1997) proposed an empirical equation as follows:

\[ Q = 1.12C_{wp}[1 + 0.1(h_w / H_L)^{0.95}]^{0.5} k_L^{0.74} h_w^{0.9} \]  

where $C_{wp}$ = a constant, 0.21 for good contact and 1.15 for poor contact. $H_L$ = thickness of underlain soil layer. Equation (3) should only be used with the unit specified (m for $h_w$, $H_L$, $r_o$, and m/s for $k_L$). Other parameters are as defined previously. Rowe (1998) derived an analytical solution based on a model as illustrated in Fig. 5.

\[ Q = \pi k_L (r_o^2 + 2\Delta_1 + 2\Delta_2 - 2h_w/\Delta_1) h_w/H_L \]  

where $h_w$ = total head drop across the composite liner, and $\Delta_1$ and $\Delta_2$ = expressions involving Bessel functions, with variables of the radius of a circular defect, $r_o$, the thickness of soil layer, $H_L$, the hydraulic conductivity of soil layer, $k_L$, the head on geomembrane, and the overburden pressure.$p$. 

\[ Q = 10^{-3} \frac{h_w}{H_L} \]  

where $Q$ is the leachate rate, $h_w$ is the head on geomembrane, $H_L$ is the thickness of underlain soil layer, $k_L$ is the hydraulic conductivity of underlain soil, and $p$ is the overburden pressure.
brane, $h_\infty$, and transmissivity, $T$, at geomembrane/soil interface (see Rowe (1998) for detail). To use Rowe’s equation, the value of $T$ must be pre-specified.

The predicted values by Eqs. (1) – (3) are included in Fig. 3 also. Two points can be observed from Fig. 3. (a) Perfect contact condition (Eqs. (1) and (2)) is inapplicable to the test condition. (b) Equation (3) with good contact condition yields a fair prediction of test data. However, it does not consider the effect of overburden pressure, and over-predicted the flow rate under higher overburden pressure.

With measured flow rate ($Q$), the transmissivity ($T$) and the radius of “wetted” area ($R$) at geomembrane/soil interface around the defect were reversely estimated by Rowe’s (1998) solution and given in Table 1. It shows that $T$ value is influenced by $p$ value significantly. Rowe (1998) used the flow rate from Eq. 3 to back-calculate $T$ value, for $k_L = 10^9$ m$^2$/s, $T = 1.6 \times 10^8$ m$^2$/s and $k_L = 10^8$ m$^2$/s, $T = 8.6 \times 10^7$ m$^2$/s. With a higher $k_L$ value in this study, the $T$ values in Table 1 seem reasonable. Another point is that the estimated $R$ values of Test-1 are larger than the radius of the model (about 0.6 m), which implies that the test results might be influenced by boundary of the model.

Table 1 Estimated $T$ and $R$ values

<table>
<thead>
<tr>
<th>Test</th>
<th>Overburden pressure, $p$ (kPa)</th>
<th>Transmissivity, $T$ (m$^2$/s)</th>
<th>Radius of “wetted” area, $R$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>10</td>
<td>$1.6 \times 10^5$</td>
<td>0.878</td>
</tr>
<tr>
<td>-1</td>
<td>50</td>
<td>$7.2 \times 10^5$</td>
<td>0.658</td>
</tr>
<tr>
<td>Test</td>
<td>50</td>
<td>$1.2 \times 10^7$</td>
<td>0.69*</td>
</tr>
<tr>
<td>-2</td>
<td>100</td>
<td>$1.5 \times 10^8$</td>
<td>0.26*</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>$2.0 \times 10^8$</td>
<td>0.10*</td>
</tr>
</tbody>
</table>

*RADIUS of wetted area at the ends.*

3.3 Concentration Distribution in Soil Layer

After termination of Test-1, the soil was divided into 4 layers (90 mm thick for each layer), and in each layer 17 samples were taken from different locations. The salt contents in pore water of samples were measured by using an ion meter. The salt concentration distribution on a cross-section through the center of the model is given in Fig. 6. Generally, the simultaneously downward as well as laterally flow pattern can be observed. In this sense, the measured results in Fig. 6 support the proposal of Fig. 5. A relative lower concentration directly under the defect is considered as the scatter of the data.

4 RESULTS OF TEST-2, A DEFECT SEAM

4.1 Measured Leachate flow rate

Test-2 was conducted with $p$ values from 50 kPa to 200 kPa. After setup of the test, a $p$ value of 50 kPa was applied. The flow became steady after about three weeks and the measurement was continued for about one month. Then the pressure was increased to 200 kPa. The flow rate became steady after about one month and the measurement continued for another month. Then the pressure was reduced to 100 kPa. This time the flow stabilized in about two weeks and the measurement was continued for about three weeks. After that the flow rate was reduced sharply and the reason is not clear yet. The data reported in this paper are up to the sharp reduction under 100 kPa overburden pressure. The measured data are presented in Fig. 7. The flow rate under 200 kPa is about 3% of that under 50 kPa and about 20% of that under 100 kPa. The reasons considered are the reduction of geomembrane/soil interface transmissivity and the densification of the soil layer under pressure. With a measured strain increment of about 1% (about 3 mm vertical deformation) for pressure increase from 50 kPa to 200 kPa, the densification effect is considered not significant and a quantitative investigation is under going. At present, the main reason considered is the reduction of the interface transmissivity ($T$).

4.2 Prediction

The same as for a circular defect, there are prediction equations for perfect contact and imperfect contact conditions for a defect seam.

(1) Perfect contact condition. There are theoretical equations for the problems analogous to leakage through composite liners.
having defect seams with perfect contact condition (Foose et al., 2001). However, the equations either include infinite series or elliptic integrals and not convenient for practical use. Foose et al. (2001) proposed an empirical equation for a defect seam with perfect contact condition as the follows:

$$Q_l = \frac{1}{0.52 - 0.76 \log(w/H_L)} \cdot k_L h_w$$  \hspace{1cm} (5)

where $Q_l$ = leakage rate per unit length of a seam, and $w$ = width of a seam. Other parameters are as defined previously.

2) Imperfect contact condition. Giroud et al. (1997) also proposed an equation for infinite long defect seams as the follows:

$$Q_l = C_l [1 + 0.2 (\frac{H_w}{H_L})^{0.95}] w^{0.14} h_w^{0.45} k_w^{0.87}$$  \hspace{1cm} (6)

where $C_l$ = a constant, 0.52 for good contact and 1.22 for poor contact. In case of the length of a seam is finite and the effect of ends can not be ignored, as illustrated in Fig. 8, the effect of two ends can be approximately evaluated as a circular defect with a radius of $w/2$.

Test-2 was analyzed using Eqs. (2) and (5) for perfect contact condition and Eqs. (3) and (6) for good (imperfect) contact condition, respectively. In the analysis, the effect of $p$ value on the hydraulic conductivity of the soil layer was not considered. The results are included into Fig. 7 also. It indicates that under lower $p$ value, Giroud et al.’s (1997) equations provides a reasonable prediction. With the increase of $p$, the flow rate tends to approach the predicted perfect contact condition. Another interesting point revealed by the analysis is that for perfect contact condition, plane flow of a 29 mm ($B-w$) long and 1 mm wide seam (exclude the ends effect) is about 4 times of a circular hole with a diameter of 1 mm, and contrastively, for imperfect (good) contact condition, the former is only about 2.5% of the later. This is because under imperfect contact condition, the radius of ‘wetted’ area of a defect hole is much larger than 29 mm and the leachate can flow more easily for a radial flow rather than a plane flow.

Rowe (1998) proposed an equation for a defect on a wrinkle (will be called Rowe’s wrinkle equation). Following Foose et al. (2001), Rowe’s wrinkle equation was used to calculate the flow rate of a seam defect (exclude the ends effect). Using Rowe’s wrinkle equation, geomembrane/soil interface $T$ value needs to be predefined. Reversely using a know flow rate, the $T$ value can be back evaluated. Combining Rowe’s wrinkle equation for plane flow and Rowe’s (1998) equation for a circular defect, the $T$ values of Test-2 were evaluated. The back-calculated values are given in Table 1 also, which reduced significantly with increase of $p$ value.

5 CONCLUSION

Large-scale model tests of leachate through defects in geomembrane underlain a soil layer had been conducted. The effects of overburden pressure ($p$) on the leachate flow rate and the leachate flow mechanism have been investigated. Based on the test and analysis results, the following conclusions can be drawn.

1) Increasing $p$ value on geomembrane reduces the leachate flow rate significantly. This reduction is mainly due to the reduction of the geomembrane/soil interface transmissivity ($T$).

2) Assumption of perfect geomembrane/soil contact condition is not applicable to the leachate flow through a defect in the geomembrane underlain a soil layer. Giroud et al.’s (1997) empirical equations for good contact condition can provide a reasonable prediction for this problem under lower overburden pressure (<10 kPa). However, the effect of overburden pressure is not considered and the modification is required.

ACKNOWLEDGMENT

The financial support for this study has been provided by Japanese “Grant-in-Aid for Scientific Research” program with a grant number of 13650545.

REFERENCES


