Impact of double defects on seepage behavior of geomembrane lined earth-rock dams

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Abstract. In this study, the unsaturated seepage theory was employed to analyze the effect of different elevations and separations of double defects in geomembrane barrier on the seepage behavior of geomembrane lined earth-rock dams. The results indicated that the separation between the defects has a significant influence on the defect-induced leakage. The increasing separation results in the increase of defect-induced leakage. When the separation reaches 3 m, the defect-induced leakage tends to decrease. The defect-induced leakage increases again when the separation is greater than 3.5 m. And defect-induced leakage increases gradually with decreasing elevation of defect, but is still in the same order of magnitude. In addition, the wetted area near the defects expands with the increasing separation between double defects. The wetted areas can be delineated by a circle, by an ellipse or by two discrete circles depending on the separation and elevation of double defects.

1. Introduction

Geomembranes are made from relatively thin continuous polymeric sheets or the impregnation of geotextiles with asphalt, elastomer or polymer sprays. Due to their low permeability, geomembranes mainly act as synthetic membrane liner or barrier used to control fluid (or gas) migration in the hydraulic, environmental, geotechnical, and transportation engineering projects [1-4]. In addition, to prevent the leakage, geomembranes can be generally placed on the upstream surface of an earth-rock dam as impervious barrier [5], (Figure. 1). However, geomembrane liners of the earth-rock dam are effective only when the liners retain their physical integrity. Unfortunately, geomembranes used in earth-rock dams often have holes due to inadequate seaming, punctures, tears, etc., which will have negative effect on the impervious performance.

Figure 1. A typical earth-rock dam with geomembrane barrier on dam surface.
Foose et al. used three-dimensional numerical models to analyze leakage through circular defects and two-dimensional numerical models to analyze leakage from defective seams [6]. The results showed that existing equations and analytical models all have limitations and no universal equation or method is available for predicting leakage rates. Saidi et al. performed a numerical study to investigate the impact of defects of finite length on the resulting flow rates [7]. Results obtained show that the impact on the flow rate of the shape of the defect end is negligible. Cen et al. employed the unsaturated seepage theory to calculate the seepage field of geomembrane faced sandy-gravel dams with one defect and found that the seepage flux decreases with increasing defect elevation in geomembrane [8]. However, according to results of leak detection surveys presented by Nosko and Touze-Foltz where damages by stones occur in the geomembrane, various holes are often grouped in the same area of the geomembrane [9]. The question then arises of the impact of double defects on seepage properties of geomembrane lined earth-rock dams.

In this study, 3D finite element model is developed to investigate the effect of double defects on the seepage field of geomembrane lined earth-rock dams. The influences of elevations and separations of double defects on the seepage flux and shape of wetted areas near the double defects in cushion layer are presented. The results of this study provides the reference for engineering design of geomembrane lined earth-rock dams.

2. Seepage behavior of geomembrane and dam material
As the low permeability of geomembranes, most of the dam body is in the unsaturated condition when geomembranes are intact on upstream dam surface. Thus, the unsaturated seepage theory can be employed for the seepage field calculation of the dam in this paper [10].

There are many tiny granular particles and potential permeation zones on the surface of geomembranes under high-power microscope. The water flowing through the geomembranes can be inferred as laminar for the reason that the water flows through these potential permeation zones with a quite small velocity (about 10^-9 m/s). Thus, it is assumed that Darcy’s law for macroscopic seepage can be also employed to analyze the geomembrane seepage behavior at the micro level. In addition, as the thickness of geomembranes is quite small, it is difficult to simulate the anti-seepage behavior of geomembranes on millimeter level by finite element method for practical engineering. In finite element analysis, the geomembranes are usually treated as porous medium, and the thickness of geomembranes is magnified to a certain value. According to the assumption of identical seepage flux [10], the magnified thickness of geomembrane can be calculated as follows:

\[ t = \frac{k_y}{k_y'} \delta \]  

where \( t \) is the magnified thickness of geomembrane, \( \delta \) is the actual thickness of geomembrane, \( k_y' \) is the coefficient of permeability of porous medium, \( k_y \) is the coefficient of permeability of geomembrane.

3. Model and calculation
To investigate the effect of double defects on the seepage field of geomembrane lined earth-rock dams, 3D finite element model of a geomembrane lined earth-rock dam is developed for calculation, as shown in Figure 2 (a). The dam height is 56.0 m and the crest length is 136 m. The upstream and downstream dam slope ratios are 1:1.7 (V:H). The thicknesses of cushion layer and transition layer is 2.5 m and 1.5 m, respectively. In the finite element modeling of seepage field, the geomembrane barrier with a thickness of 1 mm is treated as porous medium with a thickness of 30 cm. The permeability of porous medium is set as \( 3 \times 10^{-9} \) cm/s. Figure 2 (b) shows the 2D mesh on the geomembrane face. The double defects are assumed to locate at the upper, middle or lower elevation of the geomembrane, respectively, with the separations of 0.25 m, 0.5 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m, 3.0 m, 3.5 m and 4.0 m. Figure 2 (c) shows the element of geomembrane double defects, considered as square defects with the side length of 10 cm instead of circular holes for the convenience. The permeability of defects is magnified to 1 cm/s.
The permeabilities of the transition layer and dam body are $1 \times 10^{-4}$ cm/s, $2 \times 10^{-3}$ cm/s, and $2 \times 10^{-1}$ cm/s, respectively.

Figure 2. Calculation model. (a) 3D finite element model; (b) 2D mesh on the geomembrane surface; (c) Element of geomembrane defects.

4. Result analyses

4.1. Influence of double defects on the seepage flux

Table 1 lists the defect-induced leakage and seepage flux through geomembrane for different separations between the defects. It can be observed that the defect-induced leakage increases with increasing separation. When the separation reaches 3 m, the defect-induced leakage tends to decrease. The defect-induced leakage increases again when the separation between the defects is greater than 3.5 m. In addition, the defect-induced leakage increases gradually with decreasing elevation of defect, but is still in the same order of magnitude. Due to the low permeability of intact geomembrane, the seepage flux through geomembrane is very small with a stable value of $39.13 \pm 0.01$ m$^3$/d.

| Separation between the defects (m) | Upper defects | Middle defects | Lower defects |
|-----------------------------------|---------------|----------------|--------------|
|                                   | Defect-induced leakage (m$^3$/d) | Seepage flux through geomembrane (m$^3$/d) | Defect-induced leakage (m$^3$/d) | Seepage flux through geomembrane (m$^3$/d) | Defect-induced leakage (m$^3$/d) | Seepage flux through geomembrane (m$^3$/d) |
| 0.25                              | 11.33         | 39.14          | 12.20        | 39.14          | 12.64         | 39.14          |
| 0.50                              | 12.24         | 39.14          | 13.17        | 39.14          | 13.65         | 39.13          |
| 1.00                              | 14.12         | 39.14          | 15.18        | 39.13          | 15.73         | 39.13          |
| 1.50                              | 16.16         | 39.13          | 17.36        | 39.13          | 17.99         | 39.13          |
| 2.00                              | 17.76         | 39.13          | 19.15        | 39.12          | 19.88         | 39.12          |
| 2.50                              | 18.18         | 39.13          | 19.63        | 39.12          | 20.40         | 39.12          |
| 3.00                              | 15.25         | 39.13          | 16.53        | 39.13          | 17.21         | 39.13          |
| 3.50                              | 15.76         | 39.13          | 17.10        | 39.13          | 17.80         | 39.13          |
| 4.00                              | 18.96         | 39.13          | 20.25        | 39.12          | 21.06         | 39.12          |
4.2. Hydraulic head distribution near the double defects

The cushion layer under the geomembrane is in unsaturated zone except the area near the double defects. Figure 3 shows hydraulic head distribution near the leaks at the upper elevation of the geomembrane. It can be observed that the separation of double defects has a significant influence on the shape of wetted areas near the leaks. In the case of the minimum separation of double defects, the wetted area can be delineated by a circle. As the separation increases, the shape of wetted areas changes from a circle to an ellipse. When the separation reaches 3 m, the shape of wetted area becomes to two independent circles.

Figure 3. Hydraulic head distribution near the upper double defects in the geomembrane (Unit: m).

Figure 4 shows the hydraulic head distribution near the middle double defects of the geomembrane. The wetted areas can be delineated by a circle when the defects are very close to each other, and by an ellipse when the separation between double defects increases. The shape of wetted area becomes two independent circles when the separation reaches 3.5 m.

Figure 4. Hydraulic head distribution near the middle double defects in the geomembrane (Unit: m).

In Figure 5, the hydraulic head distribution near the leaks are presented for the double leaks located at the lower elevation of the geomembrane. It shows that the wetted area expands with the separation between double defects increasing. The wetted area can be delineated by a circle when the separation is equal to 0.25 m. As the separation increases, the wetted area is better approximated by an ellipse than by a circle. The shape of wetted area is still an ellipse when the separation reaches 4 m.
5. Conclusions

The 3D finite element model of geomembrane lined earth-rock dams is developed to investigate the effect of double defects on the seepage field of dam. The following conclusions can be drawn.

- The separation between the defects has a significant influence on the defect-induced leakage. With increasing separation between the double defects, the defect-induced leakage increases. When the separation reaches 3 m, the defect-induced leakage tends to decrease. The defect-induced leakage increases again when the separation between the defects is greater than 3.5 m. In addition, the seepage flux increases gradually with decreasing elevation of defect, but is still in the same order of magnitude.

- For the case of double defects at the upper or middle elevation of geomembrane face, the wetted areas can be delineated by a circle when the defects are very close to each other, and by an ellipse when the separation between double defects increases. And the shape of wetted area eventually changes to two independent circles for the relatively large separation.

- For the case of double defects at the lower elevation of geomembrane, the wetted area can be delineated by a circle when the separation is equal to 0.25 m. As the separation increases, the wetted area is better approximated by an ellipse than by a circle. The shape of wetted area is still an ellipse when the separation reaches 4.0 m.

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