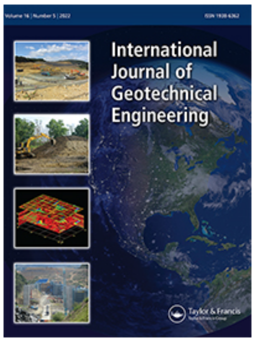

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Discussion on stability analysis of embankment dams with defective internal geomembrane liners

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ABSTRACT

Demirdogen et al. (2022) show that the effect of the elevation of upstream geomembrane defects on the downstream safety factor is different from that of internal geomembranes. This discussion explains the reasons for the above difference.

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Downstream safety factors of geomembrane-protected dams have been computed in Demirdogen et al., 2022 as seen in Table 1. It is seen that when the defect location is elevated the safety factor of upstream geomembrane cases reduces monotonically while in the cases of internal geomembranes, it reduces at first and then increases. The above two trends can be explained here.

Upstream geomembrane (Figure 1)

At the steady state, the head difference that drives water through defects depends on the head difference between the entrance to the defect (upstream surface) and the head at the outlet (blanket) drain. The total (hydraulic) head (sum of pressure and the elevation heads) at the inlet of each defect is constant for all three cases at the upstream surface of the dam which, in fact, is an equipotential surface. The following expression can be written using D'Arcy's law for the flow rate (Q) in each case.

$$Q = \left[kA_{eff} \frac{(H - h_{outlet})}{L} \right] \tag{1a}$$

Where

H = Hydraulic head at the upstream dam surface
h_{outlet} = Hyd. head at the outlet drain
L = Length of average flow path from upstream to outlet
A_{eff} = Effective area of the flow domain
k = Average hydraulic conductivity of soil

Because A_{eff} is a function of the elevation of the defect (e),

$$A_{eff} = G(e) \tag{1b}$$

Substituting from Eqn. (1b) in Eqn. (1a)

$$Q = \left[k\mathbf{G}(\mathbf{e}) \frac{(H - h_{outlet})}{L} \right] \tag{2}$$

Because H, h_{outlet}, L and k are more less constants for any defect position, From Eqn. (2), Q would be proportional to $G(e)$. $G(e)$ is a nonlinear function that monotonically increases with e, because when the starting point of water flow is elevated as the defect is raised, the effective area of the flow domain increases (Figure 1). Therefore, from Eqn. (2), it follows that the flow rate (Q) must increase monotonically, as the defect location is raised.

As Q increases with the defect elevation, the sub-phreatic flow region expands in size by moving towards from the downstream slope. Now, if one visualizes a downstream critical zone (Figure 1) which contains most of the critical failure circles or slip surfaces that correspond to low safety factors, it is realized that the area of overlap between the above critical zone and the sub-phreatic flow region (with **positive pore pressures**) also increases in size as Q is increased with the raising of the defect location. Because pore pressures have an adverse effect on safety, this demonstrates why the safety factor decreases with the raising of the defect elevation, verifying the results seen in Table 1.

Internal geomembranes (Figure 2)

In this scenario, as seen in Figure 2, there are two seepage domains (pre-geomembrane and post-geomembrane). At the steady state, flow rates in the two domains must be equal (Eqn. 3).

$$Q = Q_{pre} = Q_{post} \tag{3}$$

Furthermore, for each domain, D'Arcy's eqn. can be applied as follows

$$Q_{pre} = \left[kA_{eff-1} \frac{(H - h_1)}{L_1} \right] \tag{4}$$

$$Q_{post} = \left[kA_{eff-2} \frac{(h_1 - h_{outlet})}{L_2} \right] \tag{5}$$

Where

h_1 = Unknown hydraulic head at the defect (defect entrance and defect exit can be assumed to be of the same head because of free flow inside the defect)

$A_{eff\text{-}1}$ and $A_{eff\text{-}2}$ = Effective areas of the pre and post geomembrane flow domains

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Table 1. Safety factors for the downstream slope of the dam associated with a geomembrane with a defective seam/s at different locations and frequencies (Table 8, Demirdogen et al, 2022).

	Safety factor of the downstream slope						
			Internal				
Status of defective seam	Homogenous	Upstream	Inclined	Vertical	Zig-zag with large lifts	Zig-zag with small lifts	Double*
Unlined	1.46	-	-	-	-	-	-
No damage	-	1.83	-	1.83	-	-	-
Low	-	1.77	1.71	1.68	1.73	1.75	-
Middle	-	1.68	1.70	1.67	1.72	1.74	1.78
High	-	1.64	1.75	1.76	1.81	1.82	-
Two defective seams	-	1.60	1.63	1.63	1.66	1.66	-

It was assumed that both geomembrane liners have a defect in double liner systems.

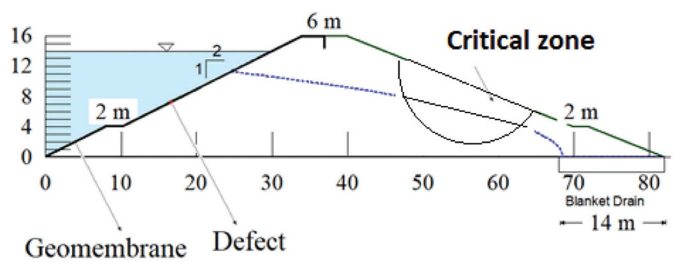

Figure 1. Upstream geomembrane defects (Modified Figure 7(b) Demirdogen et al., 2022).

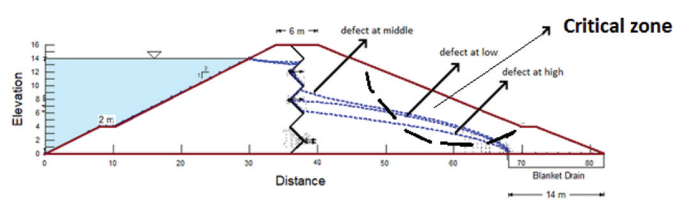

Figure 2. Flow pattern with internal geomembrane (Modified Figure 9 Demirdogen et al., 2022).

L_1 and L_2 = Average distances between the upstream surface and the geomembrane and the geomembrane and the outlet, respectively.

By applying Eqn. (1b) for this case,

$$A_{eff-1} = G_1(e) \tag{6}$$

$$A_{eff-2} = G_2(e) \tag{7}$$

Where e is the elevation of the geomembrane defect.

On substituting from Eqns. (6) and (7) in Eqns. (4) and (5) respectively, and combining the result with Eqn. (3) to determine the **unknown h_1**, the following expression is obtained:

$$h_1 = \left[\frac{HL_2G_1(e) + h_{outlet}L_1G_2(e)}{L_2G_1(e) + L_1G_2(e)}\right] \tag{8}$$

Finally, when h_1 is substituted in Eqn. (5),

$$Q = Q_{post} = Q_{pre} = k\left[\frac{\mathbf{G}_1(\mathbf{e})\mathbf{G}_2(\mathbf{e})\{H - h_{outlet}\}}{\{L_2\mathbf{G}_1(\mathbf{e}) + L_1\mathbf{G}_2(\mathbf{e})\}}\right] \tag{9}$$

Based on the more rigorous nature of Eqn. (9) compared to Eqn. (2), one *cannot* expect Q to have a monotonically increasing trend as the defect elevation *e* is raised, as in the case of the upstream geomembrane defects. A finite element (FE) analysis conducted in Demirdogen et al. (2022) demonstrates that Q increases when the defect location is raised from 'low' to 'mid' elevation and then decreases when it is raised further from 'mid' to 'high' elevation. Consequently, the sub-phreatic flow region can also be expected to follow the same trend (Q). These FE analysis results are illustrated in Figure 2.

Again, if one visualizes a downstream critical zone (in Figure 2) which contains most of the critical failure surfaces that correspond to low safety factors, it is realized that the area of overlap between this critical zone and the sub-phreatic flow region (with **positive pore pressures**) will exhibit the above trend of Q, i.e. increasing and then decreasing when the defect elevation is raised. This will result in the non-monotonic trend of first decreasing and then increasing safety factor, upon the elevation of the defect location in internal geomembranes, as seen in Table 1.

Disclosure statement

No potential conflict of interest was reported by the authors.

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