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Analysis and Design of Veneer Cover Soils with Internal Seeper

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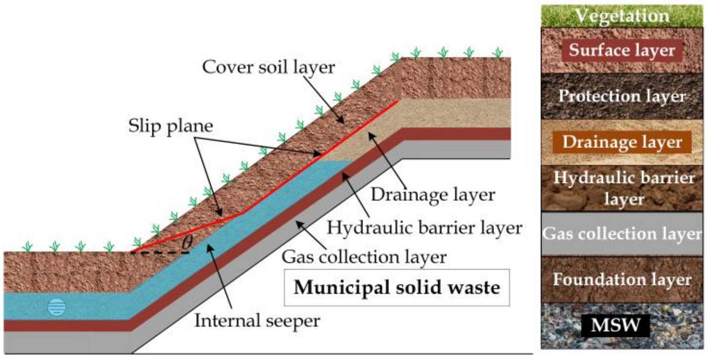
Abstract. The failure of the veneer cover soil is not an admissible condition that might affect the entire landfill mechanism. During rainfall, a poorly designed drainage layer of the cover system may get clogged and the percolated rainwater (internal seeper) can be the major factor for the cover soil layer sliding. The clogged drainage layer may exert hydraulic pressures on the overlying layers leading to the cover system instability. Two-part wedge mechanism is considered and the factor of safety expression against direct-slip failure is derived using a limit equilibrium approach. The present study compares the direct-slip stability of the veneer cover system in the presence and absence of internal seeper. The results indicate that the clogged seeper has a significant effect in reducing the stability of the final cover system. Immersion ratio is the most influencing parameter with a noticeable reduction in the factor of safety values when the internal seeper is considered. This paper also discusses the effect of slope angle (β), the ratio of cover soil layer thickness to the height of landfill (h/H), Stability number ($c/\gamma H$), and the ratio of interface friction angle to cover soil friction angle (δ/ϕ) on the stability of landfill veneer cover systems. A comparative study shows that there is a more than 50 percent reduction in the factor of safety values when the drainage layer is retained with seeper. The stability evaluation can be done more accurately by optimizing the design parameters of the final cover system.

Keywords: Veneer cover system; Internal seeper; Direct-Slip failure.

1 Introduction

One of the main and important components of landfills is the veneer cover system which prevents the direct contact of municipal solid waste (MSW) with the surrounding environment and controls the emissions from landfills. Veneer cover is a relatively thin cover soil placed above the MSW landfill. Fig. 1(a) shows the landfill veneer cover system and Fig. 1(b) shows the cover system components that include foundation layer, gas collection layer, hydraulic barrier layer, drainage layer, a protection layer, and surface layer to promote vegetation. Each layer participates in ensuring the stability of the veneer cover system. However, failures can occur due to inadequate interface shear strength between different layers of the cover system, development of excess pore pressure in the drainage layer, gas uplift in the gas collection layer, environmental factors (rainfall and earthquake), layer geometry (length, thickness, and slope), improperly designed material specifications (cohesion, friction angle, and density of the cover soil), erosion in the protection layer and other construction faults which may induce further serious disasters [1, 2, 3].

A well-designed drainage layer limits the hydraulic head on the underlying layers and drains the overlying layers. If the drainage layer is improperly designed, water may get clogged (internal seeper) during rainfall within the layer causing excess pore water pressures on the overlying layers. Due to this, the effective stress drastically reduces in the cover soil causing severe water erosion in the drainage layer and the overlying layers simultaneously. This leads to the direct-slip failure of the whole veneer cover system. The present study focusses on the stability of the veneer cover system in the presence and absence of the internal seeper in the drainage layer under static loading conditions.



(a) (b)

Fig. 1. (a) Internal seeper in the drainage layer of veneer cover system, (b) Components of veneer cover system

2 Literature Review

Koerner and Soong [4] carried out the slip failure analysis of the cover soil layer considering the seepage effect including horizontal and parallel-to-slope seepage build-up conditions. Feng and Gao [5] evaluated the seismic stability of the uniform cover system with the two seepage buildup conditions. Zhang et al. [6] evaluated the stability of the tapered cover system under the seepage build-up conditions. Khoshand et al. [7] estimated the seismic stability of the reinforced tapered landfill cover system under different seepage buildup conditions. Nadukuru et al. [8] carried out the slope stability analysis to assess the effect of drainage on the stability of a landfill veneer cover system.

A final cover system should ensure to have a balance on certain design challenges including hydraulic conductivity, internal drainage, stability, constructability, and erosion resistance [9]. A properly designed drainage layer gives adequate drainage to restrict seepage pressure to protect the veneer cover system [10]. Koerner and Soong [4] computed the factor of safety against sliding failure of cover soil using the limit equilibrium method under the different seepage conditions in a drainage layer. Koerner and Soong [4] divided the sliding block into active and passive wedges and the slip plane of the passive wedge was assumed horizontal. The slip plane of the passive wedge may be inclined at a certain angle with horizontal [3]. The present study used the sliding model with a slip angle $\theta = 0^o$ as shown in Fig. 2. Chen et al. [3] established a modified sliding model and computed the factor of safety against direct-slip failure when the drainage layer is accumulated with water.

3 Objective of The Study

It can be noted from the review of the literature that the comparative study on the stability of the veneer cover system considering the presence and absence of internal seeper is not given due consideration. Therefore, the objective of the present study is to investigate the effect of internal seeper on the veneer cover system stability against direct–slip failure under static loading with and without internal seeper.

4 Methodology

4.1 Analysis of direct-slip (*ds*) failure in the presence of internal seeper

Fig. 2 is the analysis model of direct-slip failure and PNR is the slip plane along which the cover soil is prone to slip. The cover soil along the slip plane is divided into two wedges as an upper wedge (MQRN) and a lower wedge (PMN). The upper wedge MQRN always tends to slide under loading conditions and the lower wedge PMN always resists the loads coming from the upper wedge. Hence the upper and lower wedges are termed as the active and passive wedges respectively, θ is the slip angle made by the slip plane PN with the horizontal. The parameters, h, c, ϕ, c_o, δ, β, θ, L, h_w, H, l_{MN}, l_{PN}, l_{NR}, A_{active}, and $A_{passive}$ are defined in Fig. 2. The intensity of the seepage in the drainage layer which is termed as immersion ratio (λ) can be expressed as

$$\lambda = h_w / \left(L \sin \beta \right) \quad (1)$$

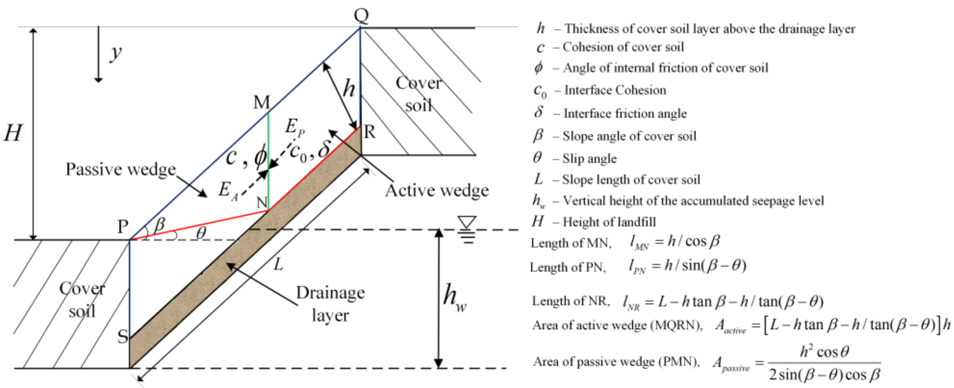


Fig. 2. Direct slip (***ds***) failure in veneer cover soil in the presence of internal seeper.

Hydraulic pressure distribution on the slip plane PNR

Hydraulic pressures on the slip plane PNR depends on the relationship between the position of point N and the height of the seepage level h_w [3]. The two different cases are described as follows.

Case 1*: The seepage level is below point N.* Fig. 3(a) shows the condition of case 1. The condition when the seepage level is below point N is expressed below both in terms of h_w and λ.

$$h_w < h[\tan\beta + \cot(\beta-\theta)]\sin\beta \;\Rightarrow\; \lambda < \frac{h}{L}[\tan\beta + \cot(\beta-\theta)] \quad (2)$$

From Fig. 3, it is clear that hydrostatic pressure on the face NR under case 1 is zero i.e. $U^1{}_{NR} = 0$. The hydrostatic pressure on the face PN can be computed by calculating the hydrostatic pressure on the micro-element surface at the point *u* (*du*) at a depth of *y* from the height of seepage level. The term *du* can be obtained from the hydrostatic pressure calculated at point g (*dg*) using the law of similarity as follows.

$$dg = \rho_w g\left(h_w - \frac{h}{\cos\beta} - y\right)\frac{dy}{\sin\theta} \quad (3)$$

$$du = \frac{y}{\sin\theta . l_{PN}}dg = \rho_w g\left(h_w - \frac{h}{\cos\beta} - y\right)\frac{y}{l_{PN}\sin^2\theta}dy \quad (4)$$

Subsequently, the hydrostatic pressure on the face PN under case 1 ($U^1{}_{PN}$) is given by.

$$U^1{}_{PN} = \int_0^{h_w - h/\cos\beta} du = \frac{\rho_w g\left(h_w - \dfrac{h}{\cos\beta}\right)^3}{6 l_{PN}\sin^2\theta} \quad (5)$$

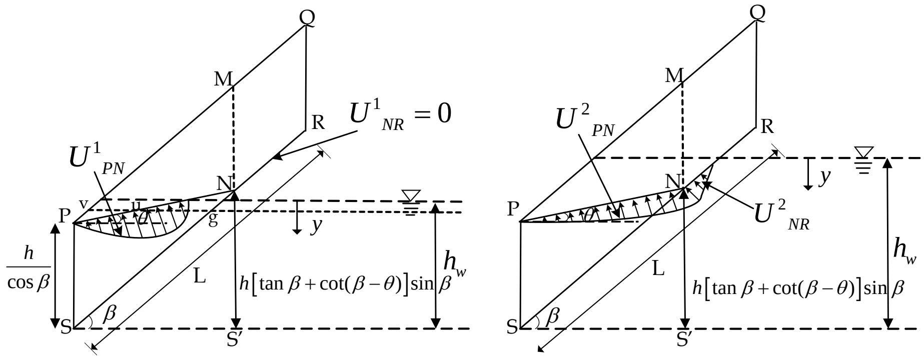
Case 2: The seepage level is above point N. Fig. 3(b) shows the condition when the seepage level is above point N and the expression for the condition is shown below in terms of both h_w and λ

$$h_w \geq h[\tan\beta + \cot(\beta-\theta)]\sin\beta \ \Rightarrow \lambda \geq \frac{h}{L}[\tan\beta + \cot(\beta-\theta)] \tag{6}$$

The hydrostatic pressures on the faces NR and PN under case 2 are derived and expressed as follows.

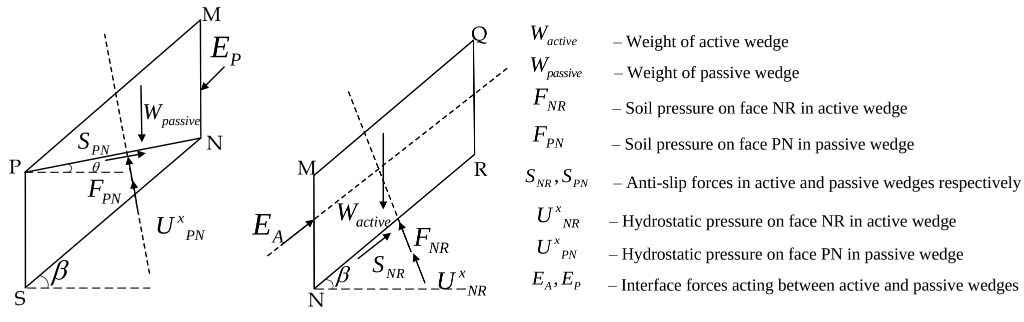
$$U^2{}_{NR} = \frac{1}{2\sin\beta}\rho_w g\left(h_w - \frac{h}{\cos\beta} - l_{PN}\sin\theta\right)^2 \tag{7}$$

$$U^2{}_{PN} = \int_0^{l_{PN}\sin\theta} du = \rho_w g l_{PN}\left(\frac{1}{2}\left(h_w - \frac{h}{\cos\beta}\right) - \frac{1}{3}l_{PN}\sin\theta\right) \tag{8}$$



(a) Seepage level is below point E (b) Seepage level is above point E

Fig. 3. Computation models for ***ds*** failure in veneer cover soil with the presence of internal seeper under two different conditions.



(a) Passive wedge (b) Active wedge

Fig. 4. Stress analysis diagrams of active and passive wedges when there is an internal seeper.

Stress analysis of active and passive wedges

The forces acting on the active wedge (MQRN) and the passive wedge (PMN) are shown in Fig. 4. The terms W_{active}, $W_{passive}$, F_{NR}, F_{PN}, S_{NR}, S_{PN}, U_{NR}^{x}, are U_{PN}^{x} defined in Fig. 4. Equations from (9) to (13) are the forces acting on the active wedge.

$$W_{active} = A_{active}\gamma_{sat} \tag{9}$$

where, γ_{sat} is the saturated unit weight of cover soil.

$$F_{NR} = W_{active}\cos\beta - U_{NR}^{x} \tag{10}$$

$$S_{NR} = (l_{NR}c_0 + F_{NR}\tan\delta)/FS_{ds} \tag{11}$$

$$E_A = W_{active}\sin\beta - S_{NR} \tag{12}$$

Incorporating the equations from (9) to (11) into the equation (12), we obtain the equation (13) as follows.

$$E_A = \frac{W_{active}\sin(\beta)FS_{ds} - \left[l_{NR}c_0 + \left(W_{active}\cos(\beta) - U_{NR}^{x}\right)\tan\delta\right]}{FS_{ds}} \tag{13}$$

Similarly, (14) to (18) are the equations of the forces acting on the passive wedge.

$$W_{passive} = A_{passive}\gamma_{sat} \tag{14}$$

$$F_{PN} = W_{passive}\cos\theta + E_P\sin(\beta-\theta) - U_{PN}^{x} \tag{15}$$

$$S_{PN} = (l_{PN}c + F_{PN}\tan\phi)/FS_{ds} \tag{16}$$

$$E_P\cos(\beta-\theta) = S_{PN} - W_{passive}\sin\theta \tag{17}$$

Substituting the equations from (14) to (16) into the equation (17), we obtain the equation (18) as follows

$$E_P = \frac{l_{PN}c + \left(W_{passive}\cos\theta - U_{PN}^{x}\right)\tan\phi - W_{passive}\sin\theta FS_{ds}}{\left(FS_{ds}\cos(\beta-\theta) - \sin(\beta-\theta)\tan\phi\right)} \tag{18}$$

where x is the case number that depends on the position of point N and the height of the seepage level (h_w).

Calculation of factor of safety

Considering both active and passive wedges together, the interface forces acting between the wedges are equal and opposite in direction. As a result, the following equation is obtained.

$$E_A = E_P \tag{19}$$

On solving, the factor of safety of the cover soil slope against direct-slip failure (FS_{ds}) can be obtained.

4.2 Analysis of direct-slip (*ds*) failure in the absence of internal seeper

Analysis of direct-slip failure with no seeper condition can be carried out similarly as discussed in section 4.1 by incorporating the following changes in the expressions. The total unit weight (γ_t) is used in the place of saturated unit weight (γ_{sat}) in the equations (9) and (14). The hydraulic forces, $U^x{}_{NR}$ and $U^x{}_{PN}$ acting on the active and passive wedges respectively, would remain zero in the equations (10), (13), (15), and (18).

5 Results and Discussion

The effect of parameters that include β, *h/H*, $c/\gamma H$, and δ/ϕ on the direct-slip failure is analyzed and the comparative study is carried out with the presence and absence of internal seeper. As immersion ratio (λ) is playing a crucial role in offering stability to the final cover system, the present study examined the effect of λ to understand the impact of seepage level on FS_{ds}. With reference to the past studies and the practical engineering experience, the geometric and shear strength parameters considered in the present study are $L = 30m$, $h = 0.8m$, $\beta = 30^o$, $c = 15$ kPa, $c_0 = 2c/3$, $\phi = 20^o$, $\delta = \phi/2$, $\gamma_{sat} = 21 \text{kN/m}^3$, and $\gamma_t = 18.9 \text{ kN/m}^3$. In this study, the critical value of the factor of safety is taken as 1.5 and the parametric studies are presented in Figs. 5, 6, 7, 8, 9, and 10.

Effect of immersion ratio (λ) on *FS*$_{ds}$

Fig. 5 shows the effect of λ when the drainage layer is clogged with seeper. It can be noticed that FS_{ds} values decrease significantly with the increase of λ. This is because when the seepage level in the drainage layer increases, the effective stress of the cover soil reduces considerably due to the increase of buoyancy forces. It finally leads to the slip failure of the cover soil system.

Effect of slip-angle (θ) on FS_{ds}

Fig. 6 gives an idea about the position of the slip plane in passive wedge along which the cover soil system is prone to slide. It is evident from Fig. 6 that the lowest value of FS_{ds} is achieved at $\theta = 0^o$ for all the cases. It indicates that the slip plane is horizontal, which is also reported by Feng et al. [5]. Hence the present study considers $\theta = 0^o$ throughout the analysis. It can also be noticed that the presence of internal seeper reduces the FS_{ds} values significantly from 8.6% to 54% when λ increases from 0.1 to 0.7.

Effect of slope angle (β) of cover soil

Fig. 7 compares the effect of slope angle (β) of cover soil on FS_{ds} without seeper and with seeper under different values of immersion ratio (λ). It can be observed from Fig. 7 that the increase in slope angle reduces the value of FS_{ds} for all conditions. It can be attributed to the increase of slip force of active wedge and the simultaneous reduction in the anti-slip force of passive wedge. Lower values of FS_{ds} are noticed under the presence of internal seeper when compared with no seeper condition. About 8% to 72% reduction in FS_{ds} value is observed with the increase of λ from 0.1 to 0.7.

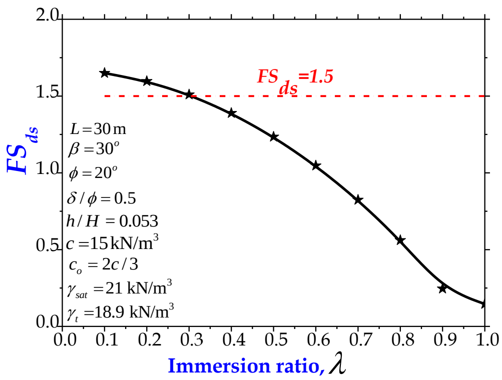


Fig. 5. Effect of immersion ratio on FS_{ds} in the presence of internal seeper.

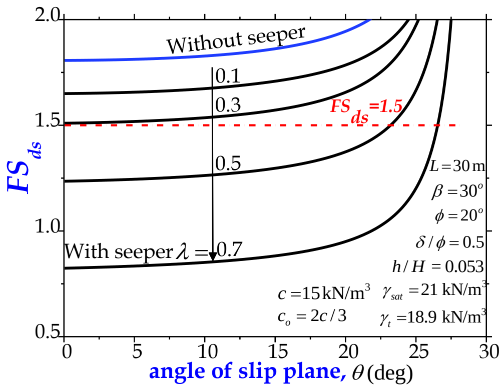


Fig. 6. Effect of slip angle on FS_{ds}.

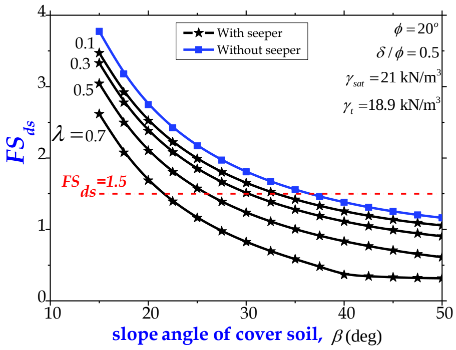


Fig. 7. Influence of slope angle on FS_{ds}.

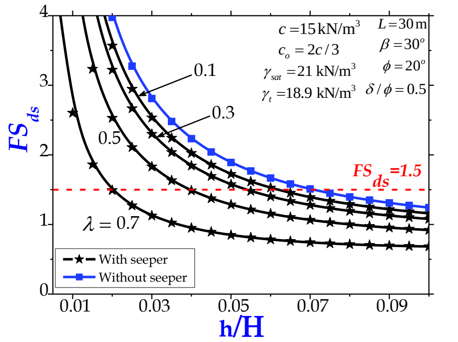


Fig. 8. Influence of the ratio of cover soil layer thickness to the height of landfill on FS_{ds}.

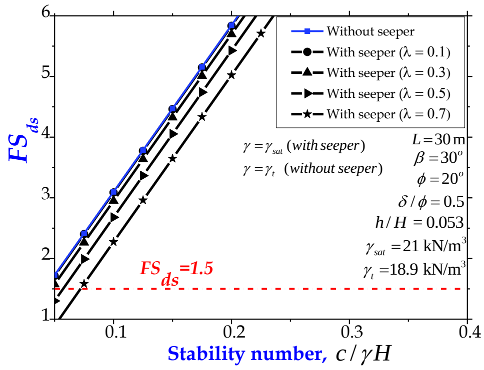


Fig. 9. Influence of Stability number on FS_{ds}.

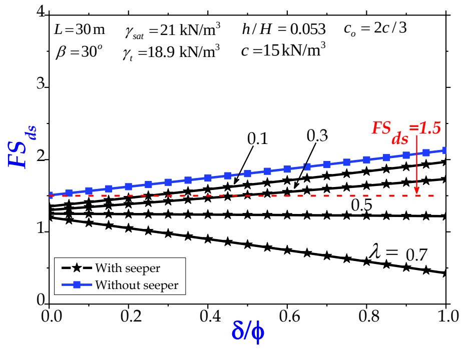


Fig. 10. Influence of the ratio of interface frict -ion angle to cover soil friction angle on FS_{ds}.

Effect of *h/H* ratio on FS_{ds}

Fig. 8 illustrates and compares the effect of h/H on FS_{ds} in the presence and absence of internal seeper. It is clear from Fig. 8 that the increase of h/H ratio reduces the FS_{ds} values. This is because, as the cover soil thickness increases, the weight of active wedge also increases, which causes the need for more anti-slip force from the passive wedge. When the drainage layer is clogged with seeper, a significant reduction in the values of FS_{ds} can be observed ranging from 6.75% to 67% when λ increases from 0.1 to 0.7.

Effect of stability number $(c/\gamma H)$ on FS_{ds}

Fig. 9 shows the effect of stability number ($c/\gamma H$) on FS_{ds} with and without the presence of internal seeper. It is evident that the increase in stability number ($c/\gamma H$) increases the values of FS_{ds}. This is due to the increase of shear strength with soil cohesion as per Mohr-Coulomb law, which further increases the resisting force of the cover soil layer. It can also be noticed that the presence of internal seeper reduces FS_{ds} values when compared with values of FS_{ds} with no seeper condition. The negligible effect can be noted when $\lambda = 0.1$. The reduction in FS_{ds} about 8% to 48% values is observed with the increase of λ from 0.2 to 0.7.

Effect of δ/ϕ on FS_{ds}

Fig. 10 illustrates the effect of δ/ϕ on FS_{ds} under the presence and absence of internal seeper. It can be observed from Fig. 10 that FS_{ds} values increase with the increase of δ/ϕ when $\lambda < 0.5$ which is due to the increase of resisting forces against slippage. However, the values of FS_{ds} reduce gradually when $\lambda > 0.5$ as the buoyancy effect is dominant than the anti-slip forces**.** Similar behavior is reported in Chen et al. [3]. A comparative study also reveals that the presence of internal seeper reduces the FS_{ds} values which ranges from 7.5% to 80% when λ increases from 0.1 to 0.7.

6 Conclusions

The failure of the veneer cover soil due to direct–slip failure is discussed in this study. An analytical model is established in this study for the computation of the factor of safety. The effect of clogged seeper in the drainage layer on the factor of safety values against direct–slip failure (FS_{ds}) is studied and compared with no seeper condition. The conclusions drawn from the study are as follows.

1. Immersion ratio is the most influencing parameter affecting the stability of the veneer cover soil against direct-slip failure. FS_{ds} values decrease with the increase of the immersion ratio.
2. The most critical angle of the slip plane is zero which shows that the slip plane is horizontal as the lowest value of FS_{ds} is obtained at $\theta = 0^0$.
3. The parameters β, h/H, $c/\gamma H$, and δ/ϕ have a significant effect on the stability of veneer cover system. The presence of internal seeper reduces the FS_{ds} values significantly when compared with no seeper condition.
4. Considering all the parameters, the percentage reduction in the FS_{ds} values due to clogged seeper varies from 8% to 80% when the immersion ratio increases from 0.1 to 0.7.

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