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Allowable Thickness of Veneer Cover System with Internal Seeper for MSW Landfills

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Abstract. During adverse rainfall conditions, an internal seeper formed in an improperly designed drainage layer of the landfill veneer cover system may become the cause for its sliding failure. Immersion ratio (I_r) measured from the drainage layer is the most influencing parameter that affects the stability of the landfill veneer cover system. The adequate thickness of cover soil overlying the drainage layer ensures the stability and durability of the landfill veneer cover system. The present study gives the maximum allowable design thickness of the cover system correspond to a target value of factor of safety (FS_{ds}) of 1.50 against direct sliding failure. The results are presented in the form of design charts for various values of stability numbers ($c/\gamma H$) considering the effects of the ratio of the length of cover soil to the height of landfill (L/H), internal friction angle (ϕ), and the ratio of interface friction angle to internal friction angle of cover soil (δ/ϕ) for different levels of internal seeper.

Keywords: Veneer Cover, Internal Seeper, Immersion Ratio, Design Charts, Allowable Design Thickness.

1 Introduction

A municipal solid waste (MSW) landfill is an engineered structure that is constructed to avoid the physical contact of MSW and to protect human health from contamination. Veneer cover system, the final closure of landfill controls the toxic emissions from it and acts as a barrier between MSW and the surrounding environment. Landfill veneer cover system with different components including foundation layer, gas collection layer, hydraulic barrier layer, drainage layer, a protection layer, and the surface layer is shown in **Fig. 1**. Each component plays its role in maintaining the stability of the whole veneer cover system. However, numerous cover system failures have occurred and a greater number of such failures have been reported in recent times [4]. The cause of a cover system failure may include the weak interface shear strength between individual layers, excess pore water pressure in the drainage layer, landfill gas uplift, improperly designed geometry and material specifications along with the external environmental factors like an earthquake, rainfall, etc. [2, 1].

During heavy rainfall conditions, inadequacy in draining property of improperly designed drainage layer may accomplish the rainwater to get clogged within the layer. The clogged and retained water in the drainage layer is termed as an internal seeper [1]. The overlying layers of the drainage layer are highly influenced by the excess pore pressures exerted due to retained seeper in the drainage layer. Eventually, there is a considerable reduction in the effective stress of cover soil, aiding to the simultaneous erosion in the drainage and the overlying layers. As a consequence, the whole veneer cover system may tend to fail by sliding, which is termed as the direct sliding failure. Nadukuru et al. [6], Feng et al. [2], Khoshand et al. [4], and Chen et al. [1] have discussed the cover system failures caused due to seepage buildup conditions.

Allowable design thickness of the veneer cover system ensures its safety against direct sliding failure. The behavior of any stability model can be assessed using design charts to obtain safe, optimum, and economical design. The present study aims at establishing the design charts to estimate the maximum allowable thickness of cover soil layer above the drainage layer of veneer cover system of landfill. This study predominantly considers the influence of internal seeper formed in the drainage layer under static loading conditions.

2 Literature Review

Soong and Koerner [7] stated that long-term failures in slopes have occurred due to the accumulation of seepage quantities in the drainage layer. Past studies reported that the stability of cover soils affected by the seepage forces produced in the drainage layer of the cover system. The major contributing factor for most of the reported failures of cover soils was the combined effect of rainfall-induced seepage build-up and the inadequate drainage system [6]. Koerner and Soong [5] and Feng and Gao [3] analyzed the sliding failure of the landfill cover system, considering horizontal and parallel-to-slope seepage build-up conditions. Zhang et al. [8] and Khoshand et al. [4] evaluated the stability of the tapered cover system under two seepage build-up conditions.

A veneer cover system can be protected from excess seepage forces by providing a properly designed drainage system [1]. Zhang et al. [8], Nadukuru et al. [6], Khoshand et al. [4], and Chen et al. [1] computed the factor of safety against the sliding failure of cover soil under different seepage conditions using limit equilibrium approach by dividing the veneer cover system into active and passive wedges. Past studies on the stability of landfill veneer cover system are carried out by assuming the horizontal sliding plane in passive wedge [5, 8, 4]. Chen et al. [1] performed the slip- angle analysis and reported that the sliding plane is horizontal after obtaining the lowest factor of safety at zero slip angle. Therefore, the present study assumes that the slidingplane in the passive wedge is horizontal as shown in **Fig. 2**.

3 Objective of the study

Literature review reveals that the maximum allowable thickness of the veneer cover system in the presence and absence of internal seeper, for the safety against direct sliding failure mode are not established. Therefore, the present study aims to recommend the maximum allowable thickness of the veneer cover system of MSW landfill. The present study considers the effect of an internal seeper formed in the drainage layer of the cover system. The direct sliding failure analysis is carried out to obtain the expression for the factor of safety. The present study also provided a comparative study on the maximum required thickness of cover soil in the absence of an internal seeper. An illustrative design example is provided at the end to understand the applicability of the design charts.

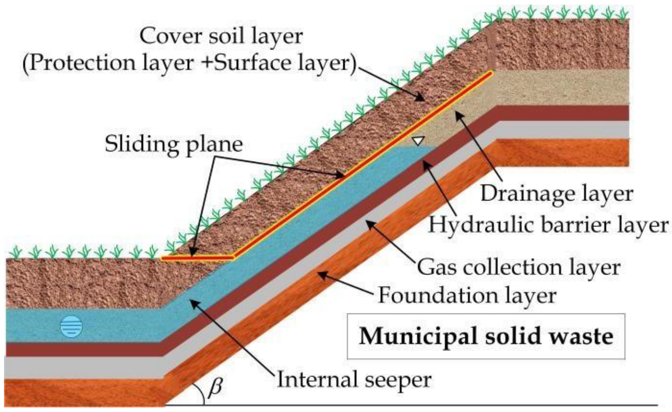

Fig. 1. Veneer cover system and its components with internal seeper.

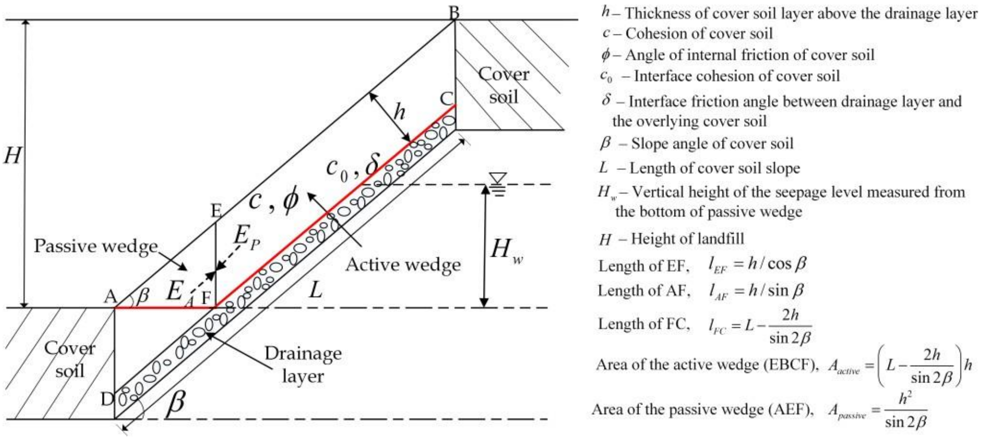

Fig. 2. Active and passive wedges for direct sliding (*ds*) failure.

4 Direct sliding (*ds*) failure in the presence of internal seeper

The analytical model of direct sliding failure with internal seeper is shown in **Fig. 2**. The two-wedge mechanism is used by dividing the cover soil above the drainage layer into active and passive wedges. The wedge 'EBCF' is the active wedge, which is always prone to slide. The wedge 'AEF' is the passive wedge, which tries to resist the load from the active wedge. The cover soil layer is susceptible to slide along the sliding plane 'AFC'. The present study assumes that the cover soil in the passive wedge slides along the horizontal plane 'AF'. The symbols used in the analysis and the area of active and passive wedges are described in **Fig. 2**. The degree of seepage in the drainage layer is defined by the term immersion ratio (I_r) and can be expressed as follows.

$$I_r = H_w / L \sin\beta = H_w / H \tag{1}$$

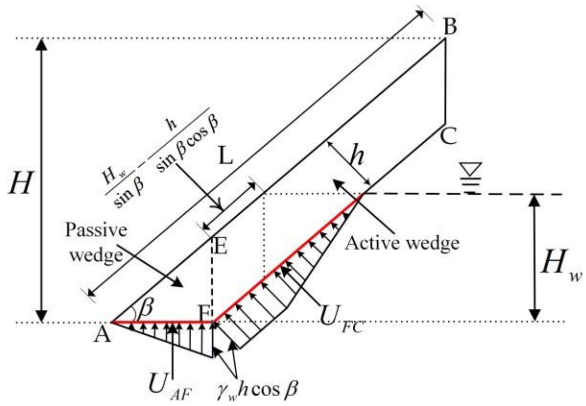

Fig. 3. Hydraulic pressure distribution on the sliding planes 'AF' and 'FC'.

4.1 Hydraulic pressure acting on the sliding plane, AFC

Horizontal seepage build-up condition is assumed in the analysis. The sliding plane, AFC is subjected to hydraulic pressures as shown in **Fig. 3**. The expressions for hydrostatic pressures on the faces 'AF' and 'FC' are given by U_{AF} and U_{FC} as shown below

$$U_{AF} = \frac{1}{2}\gamma_w h^2 \cot\beta \tag{2}$$

$$U_{FC} = \frac{\gamma_w h \cos\beta}{\sin 2\beta}\left(2H_w \cos\beta - h\right) \tag{3}$$

4.2 Force analysis of active and passive wedges

The forces acting on the active wedge (EBCF) and the passive wedge (AEF) are shown in **Fig. 4**, which are given by W_{active}, $W_{passive}$, F_{FC}, F_{AF}, S_{FC}, S_{AF}, U_{FC}, and U_{AF}. The forces acting on the active wedge (EBCF) are given by the equations (4) to (8).

$$W_{active} = A_{active}\gamma_{sat} \tag{4}$$

where γ_{sat} is the unit weight of cover soil layer in a saturated state

$$F_{FC} = W_{active}\cos\beta - U_{FC} \tag{5}$$

$$S_{FC} = \left(l_{FC}c_0 + F_{FC}\tan\delta\right) / FS_{ds} \tag{6}$$

$$E_A = W_{active} \sin\beta - S_{FC} \tag{7}$$

The inter-wedge force (E_A) is obtained by substituting the equations (4) to (6) into the equation (7) as follows:

$$E_A = \frac{FS_{ds} W_{active} \sin\beta - \left[L_{FC} c_0 + \left(W_{active} \cos\beta - U_{FC} \right) \tan\delta \right]}{FS_{ds}} \tag{8}$$

Similarly, the forces of the passive wedge (AEF) are given by the equations (9) to (13):

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

$$F_{AF} = W_{passive} + E_P \sin\beta - U_{AF} \tag{10}$$

$$S_{AF} = \left(L_{AF} c + F_{AF} \tan\phi \right) / FS_{ds} \tag{11}$$

$$E_P \cos\beta = S_{AF} \tag{12}$$

The inter-wedge force (E_P) is obtained by substituting the equations (9) to (11) into the equation (12) as follows:

$$E_P = \frac{L_{AF} c + \left(W_{passive} - U_{AF} \right) \tan\phi}{FS_{ds} \cos\beta - \sin\beta \tan\phi} \tag{13}$$

The force equilibrium is used to obtain the equations (5), (7), (10), and (12). The equations (6) and (11) (anti-sliding forces) are obtained from the general Mohr-Coulomb criteria.

4.3 Calculation of factor of safety

As shown in **Fig. 2**, the inter-wedge forces (E_A and E_P) between the active and passive wedges, which are equal in magnitude and acting opposite to each other can be represented using the following equation.

$$E_A = E_P \tag{14}$$

The factor of safety against direct sliding failure (FS_{ds}) of the veneer cover system can be obtained by solving the equation (14) using the Newton-Raphson iteration technique in MATLAB.

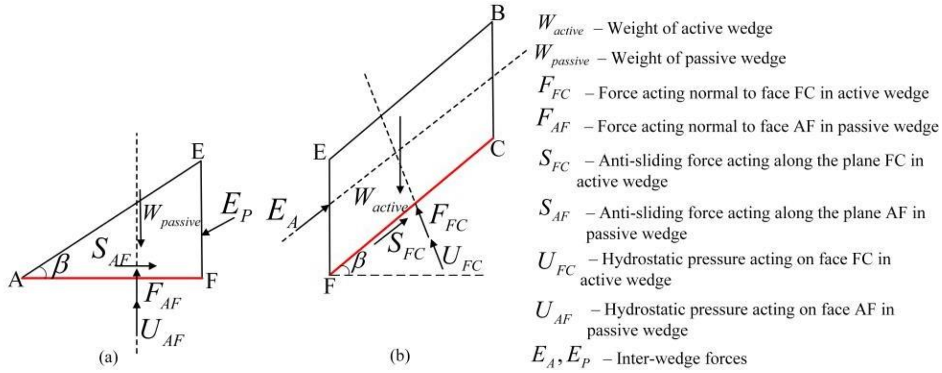

Fig. 4. Force body diagrams (a) Passive wedge, (b) Active wedge

5 Direct sliding (*ds*) failure in the absence of internal seeper

The approach used in the analysis of internal seeper is applied to the case where internal seeper is absent. The saturated unit weight (γ_{sat}) is replaced by the total unit weight (γ_t) in the equations (4) and (9) due to the absence of an internal seeper. The hydro- static forces, U_{AF}, and U_{FC} in equations (5), (8), (10), and (13) would remain zero.

6 Results and discussions

The maximum permissible thickness of cover soil layer (h) for a target value of factor of safety (FS_{ds}) against direct sliding failure is computed. The range of design parameters considered in the study are as follows: slope angle of cover soil (β) = 10^o to 60^o, internal friction angle of cover soil (ϕ) = 20^o, 25^o, and 30^o, interface friction angle between cover soil and the drainage layer (δ) = $\phi/2$ and ϕ, length of the cover soil slope, (L) = 5 to 80 m, height of the landfill (H) = 5 to 70 m, the thickness of cover soil layer (h) = 0.1 to 1.5 m, stability number ($c/\gamma H$) = 0.02, 0.04, and 0.06, and immersion ratio (I_r) = 0, 0.1 to 0.7. The variation of a factor of safety (FS_{ds}) with the increase of *h/H* values is shown in **Fig. 5.** It is noted from **Fig. 5** that the factor of safety (FS_{ds}) decreases significantly with the increase in values of *h/H* and immersion ratio (I_r). An increase of cover soil thickness (h) increases the weight of the active wedge, resulting in the requirement of more anti-sliding forces from the passive wedge. This tends to the reduction of a factor of safety (FS_{ds}) with the increase of *h/H* values. When the immersion ratio (I_r) increases, there is a considerable reduction in the effective stress of the cover soil, leading to the reduction of FS_{ds}. The effect of presence of internal seeper can be clearly observed from **Fig. 5**, as FS_{ds} values reduce significantly when I_r increases from 0 to 0.1. It is noted from **Fig. 5** that for a typical value of h/H = 0.12, FS_{ds} reduces by 9.2%, 10.6%, 12.0%, 13.4%, 14.8%, 16.2%, and 17.6% when I_r increases from 0 to 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7 respectively. **Figs. 6, 7,** and **8** are the developed design charts for $c/\gamma H$ = 0.02, 0.04, and 0.06 respectively for different values of friction angle (ϕ) and δ/ϕ ratio under different immersion ratio (I_r) conditions.

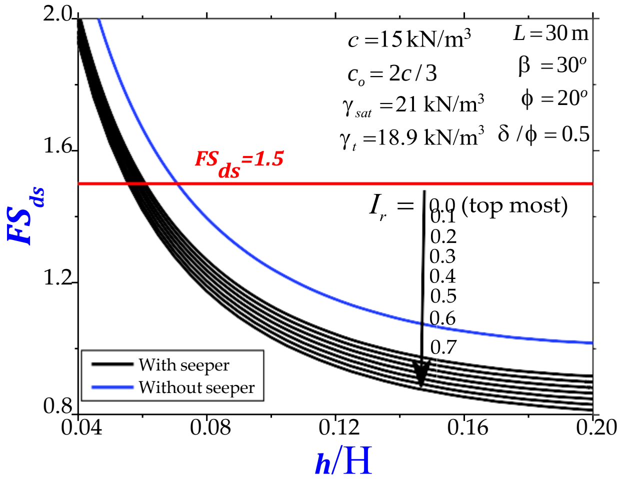

Fig. 5. Effect of *h/H* ratio on FS_{ds}

6.1 Influence of immersion ratio (I_r)

It can be noted from **Figs. 6, 7,** and **8** that the maximum required cover soil thickness (*h*) decreases as the immersion ratio (I_r) increases. This is due to the reduction of a factor of safety (FS_{ds}) with the increase of *h/H* values as shown in **Fig. 5**. From **Fig. 6(a)**, for a constant value of *L/H* = 4, the maximum permissible thickness (*h*) required reduced by 8.65%, 13.45%, 17.68%, 21.47%, 24.90%, 27.99%, and 30.81% when I_r increases from 0 to 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7 respectively.

6.2 Influence of ϕ, δ/ϕ, and $c/\gamma H$

Figs. 6, 7, and **8** show that the cover soil thickness (*h*) needs to be increased with the increase in values of ϕ, δ/ϕ, and $c/\gamma H$. This is because the factor of safety (FS_{ds}) reduces with the increase in *h/H* value as can be noted from **Fig. 5**. It indicates that the veneer cover thickness (*h*) needs to be increased with the increase in parameters, ϕ, δ/ϕ, and $c/\gamma H$ to attain the targeted value of factor of safety (FS_{ds}) of 1.50. It is

noted from **Figs. 6, 7,** and **8** that the thickness of cover soil layer (*h*) computed from these design charts provides the maximum allowable thickness after meeting the targeted value of factor of safety of 1.50.

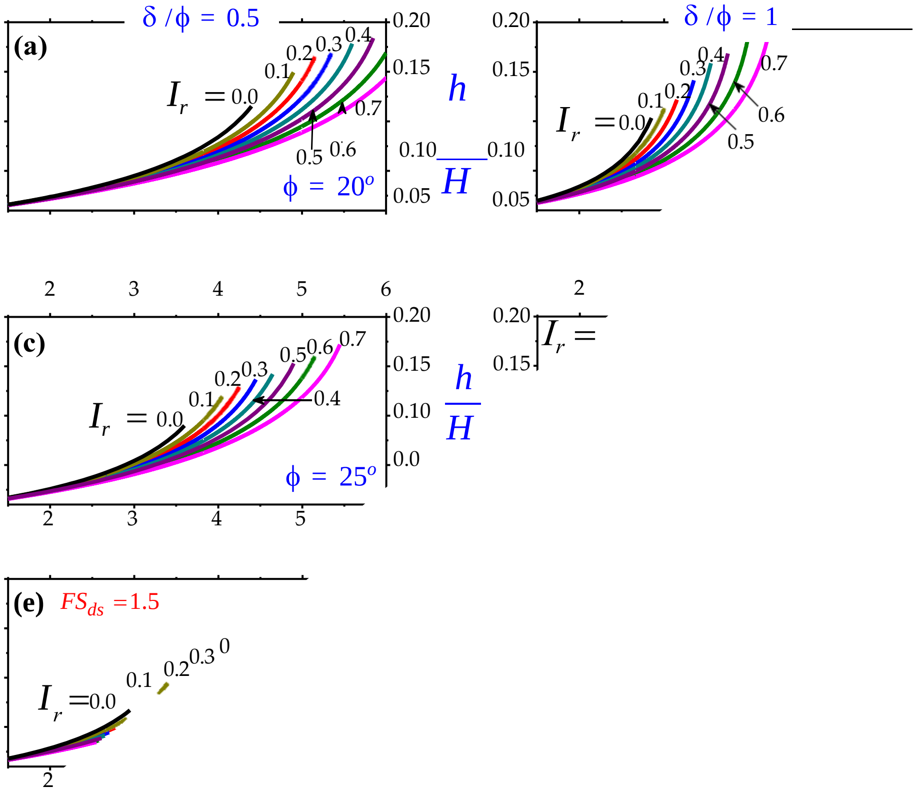

Fig. 6. Maximum allowable thickness of cover soil layer (*h/H*) ratio for $c/\gamma H$ = 0.02, $c_0/\gamma H$ = 0.013 for different values of immersion ratio (I_r)

6.3 Influence of *L/H* ratio

It can be observed from **Figs. 6, 7,** and **8** that the maximum cover soil thickness (*h*) increases with an increase in *L/H* ratio for all the immersion ratios (I_r). This can be attributed to the increase in weight of the active wedge due to an increase in slope length (*L*). An increase in *L/H* ratio also increases the anti-sliding forces along the sliding surface. Hence, an increase in cover soil thickness (*h*) provides the required anti-sliding forces for the cover system to achieve stability against direct sliding failure. Besides, **Figs. 6, 7,** and **8** provide the maximum allowable slope length of cover soil (*L*) for a given value of *h/H* ratios.

Design example. Assume an MSW landfill of height (*H*) of 10 m with a slope angle (β) of 20°. The design parameters considered for the final veneer cover system are as follows: unit weight (γ) = 19 kN/m^3, cohesion =7.6 kPa, Stability number ($c/\gamma H$) = 0.04, internal friction angle of cover soil (ϕ) = 25° with the ratio of δ/ϕ = 0.5. The drainage layer of the landfill cover system is assumed to be clogged with an internal seeper of immersion ratio (I_r) = 0.4. For the specifications mentioned above, the maximum allowable cover soil thickness (*h*) required to resist direct sliding failure for the factor of safety (FS_{ds}) of 1.50 can be calculated as follows: For the given design conditions of the veneer cover system, plot (c) of **Fig. 7** needs to be used to calculate the value of *h*. The calculated slope length (*L*) = $H/\sin\beta$ is 29.24 m and hence the *L/H* ratio becomes 2.92. The corresponding *h/H* ratio of 0.1 is obtained for I_r = 0.4 and *L/H* = 2.92 from plot (c) of **Fig. 7**. Therefore, the maximum allowable cover soil thickness (*h*) is obtained as 1.0 m using the relation, *h* = (*h/H*) **H*.

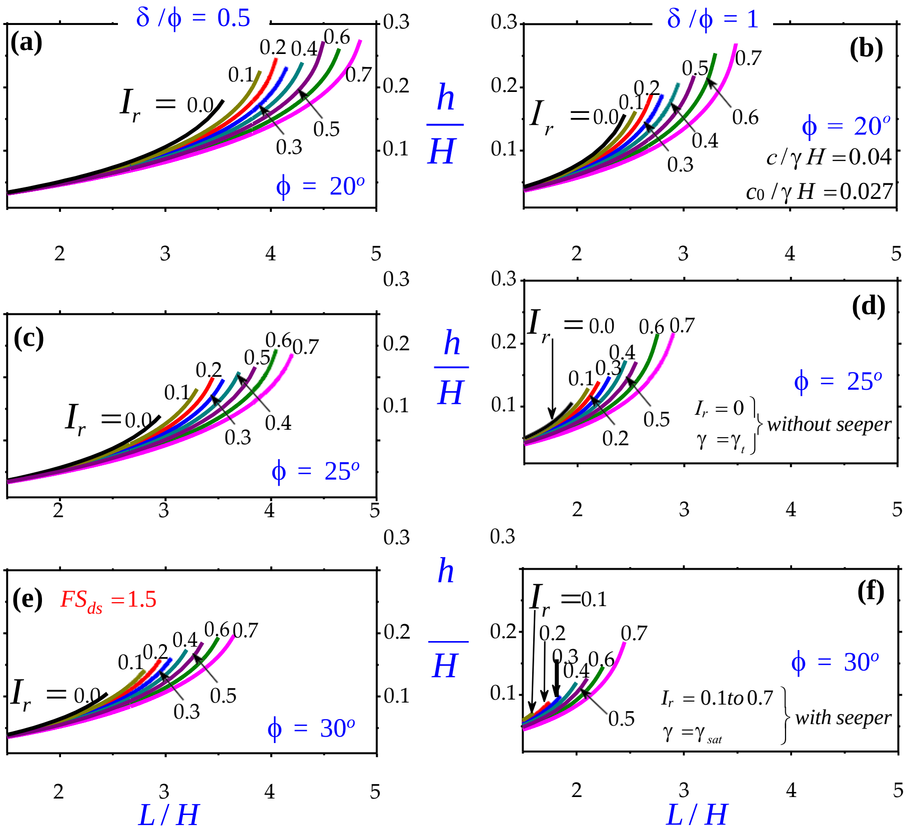

Fig. 7. Maximum allowable thickness of cover soil layer (*h/H*) ratio for $c/\gamma H$ = 0.04, $c_0/\gamma H$ = 0.027 for different values of immersion ratio (I_r)

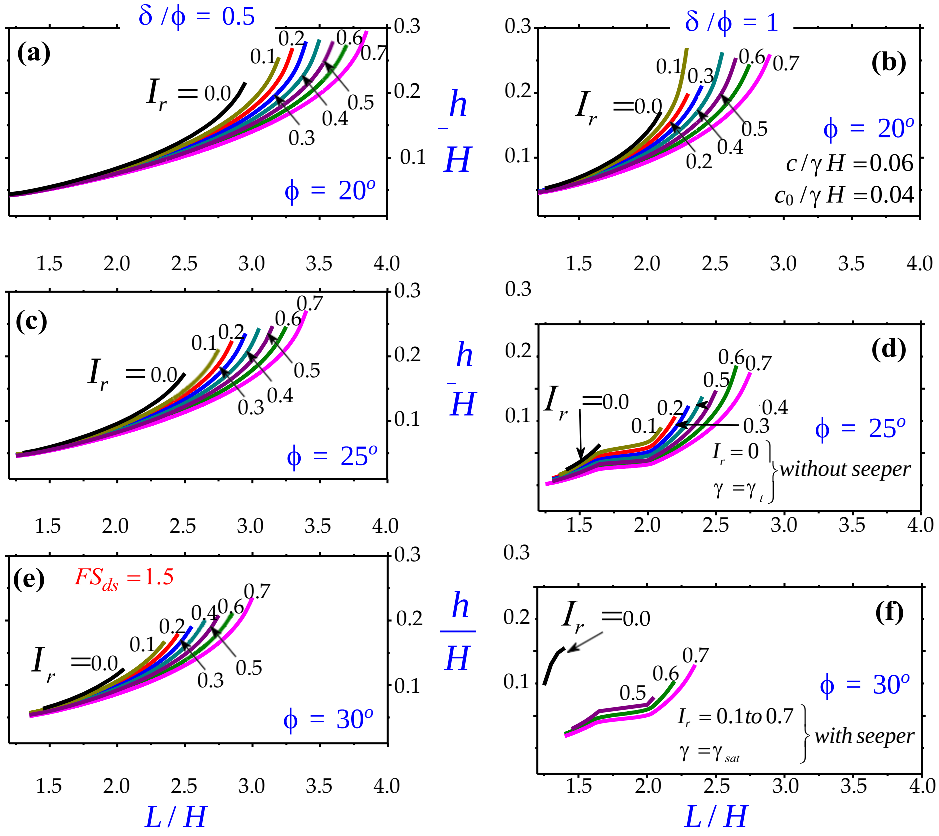

Fig. 8. Maximum allowable thickness of cover soil layer (*h/H*) ratio for $c/\gamma H$ = 0.06, $c_0/\gamma H$ = 0.04 for different values of immersion ratio (I_r)

7 Conclusions

The present study recommends the maximum allowable veneer cover thickness (*h*) to resist the direct sliding failure (*ds*) of the veneer cover system for MSW landfill. The two-wedge failure mechanism in conjunction with the limit equilibrium approach is used to obtain the expression of a factor of safety (FS_{ds}) against direct sliding failure. The study targets the factor of safety against direct sliding failure (FS_{ds}) of 1.50 for the successful performance of the veneer cover system. The following conclusions are drawn from the study.

- The immersion ratio (I_r), friction angle of cover soil (ϕ), interface friction angle between cover soil and the drainage layer (δ/ϕ), and stability number of cover soil ($c/\gamma H$) greatly influences the maximum allowable veneer cover thickness (*h*).
- Cover soil thickness (*h*) obtained from the design charts is the maximum permissible thickness required for the target value of factor of safety, FS_{ds} = 1.50.
- Cover soil thickness (*h*) needs to be reduced with the increase of immersion ratio (I_r).

- Cover soil thickness (*h*) needs to be increased with the increase in values of ϕ , δ/ϕ , and $c/\gamma H$ to achieve the target value of factor of safety (FS_{ds}) of 1.50.

- The maximum permissible cover soil thickness (*h*) increases with the increase in value of *L/H* for the given values of I_r, ϕ , and δ/ϕ .

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