 https://doi.org/10.1051/e3sconf/202456915003

Localized shear strength mobilization at geosynthetic interfaces caused by spreading soil downslope

Richard Thiel[*1], and *Jean-Pierre* Giroud[2]

[1]Thiel Engineering, Oregon House, CA, USA
[2]Consulting Engineer, Paris, France

Abstract. Localized interface shear strength failures have occurred below the tracks of a bulldozer during placement and spreading of cover soils on slopes lined with geosynthetics. The mechanisms of these types of failures are rarely considered and evaluated in design reports and calculations. A paper on this subject was recently published by Thiel and Giroud [1], but the analyses presented in that paper were limited to upslope bulldozer pushing. The present paper extends those analyses to consider downslope bulldozer pushing and deceleration forces. The paper presents straightforward equations of equilibrium that the user can easily input into a spreadsheet to model various geometries, bulldozer sizes, and shear strengths, and to determine the acceptable size of the soil pile being pushed for those conditions. The equations provided should be useful for design engineers to avoid localized slippage on slopes where bulldozers are spreading soil materials over geosynthetics, or for forensic experts who evaluate why slippage may have occurred.

1 Introduction

1.1 Localized shear stress mobilization and detrimental consequences caused by construction of thin soil layers above geosynthetic systems

The construction of geosynthetic-lined containment facilities commonly requires a relatively thin layer of soil (sometimes called a 'veneer' layer) to be spread over one or more geosynthetic layers for final cover systems and bottom liner systems of landfills, as well as liner systems of heap leach pads and reservoirs. As described in more detail by Thiel and Giroud [1], the *localized* shear stresses caused by the soil spreading operation using a bulldozer (dozer) are significantly higher than the *average* shear stresses that are assumed to be distributed over the entire slope length. The following five references, in chronological order, suggest methods to quantify the elevated localized shear stresses below the dozer tracks that could cause localized exceedance of shear strength: Paruvakat and Richardson [2], Kerkes [3], Jones et al. [4], Thiel and Narejo [5], and Thiel and Giroud [1]. Each of these

* Corresponding author: richard@rthiel.com

references either adds to, or improves upon the work presented in the other references, and, taken as a whole, they provide useful approaches to quantification of the problem, as well as suggestions for construction specifications and construction quality assurance (CQA) that can mitigate the problem.

The present paper considers only the *localized* shear stresses below the operating dozer. The method presented does not consider the stability of the entire slope taken as a whole, where the tensile strength of the geosynthetics would come into play. For those situations the 'standard' approaches presented by Richardson and Koerner [6], Koerner and Soong [7], Qian et al. [8], Drushel and Underwood [9], McKelvey [10], and USEPA [11] can be used.

The localized shear stresses that are developed, during the spreading of soil on a slope, at the base of the dozer tracks, and at the base of the soil pile being spread, are transmitted down to the geosynthetic interface(s) of the liner system. Typically the 'critical' interface, meaning the interface with the lowest peak shear strength, is one of the interfaces involving a geosynthetic, either against a soil or another geosynthetic. If the peak shear strength of any of the critical interface is exceeded by these construction-induced localized shear stresses, then the shear resistance of these interfaces will be degraded as they experience relative displacements during construction. The cumulative effect of localized shear strength degradation events over the course of construction of an entire slope can cause stretching, thinning, and tearing of the geosynthetics during construction, and can be detrimental to the slope's static and dynamic stability in the long term, potentially leading to progressive slope stability failure (Thiel [12]).

To provide some insight into this issue, testing was performed by the lead author on a textured HDPE geomembrane/geocomposite drainage layer interface, where the geocomposite surface was a nonwoven geotextile that was heat-bonded to a geonet. Two cases were checked: one for a long-term high normal stress (bottom liner) situation, and one for a long-term low-normal stress (veneer) situation. For the high-normal stress situation, this particular interface was pre-sheared at a low normal stress of 24 kPa, representative of dozer loading during construction, and then final-sheared at a higher normal stress of 192 kPa representative of a final service condition after filling of a landfill or a reservoir. The results, presented in Figure 1, indicate that the peak shear strength at the high normal stress was reduced by approximately 13% due to pre-shearing at the dozer construction stress, as compared to shearing a virgin sample at the high normal stress. For the low-normal stress situation, this particular interface was pre-sheared at a construction normal stress of 24 kPa to represent the dozer loading during construction, and then final-sheared at a lower normal stress of 10 kPa, representative of the typical long-term loading of a cover system.

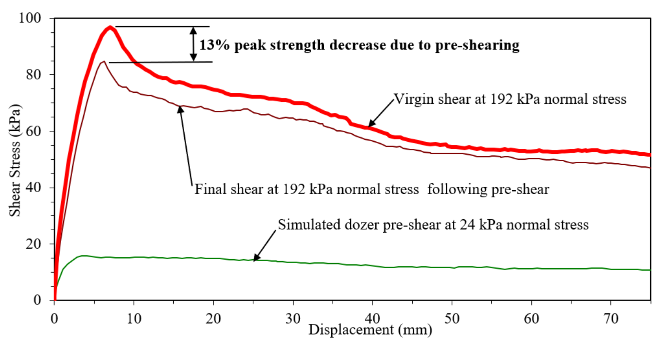

Figure 1. Test results showing effect of pre-shearing at low normal stress on the peak strength at high normal stress for an interface of a textured HDPE geomembrane against the nonwoven geotextile surface of a drainage geocomposite.

The results, presented in Figure 2, indicate that the dozer-induced pre-shearing resulted in a large-displacement shear strength reduction of approximately 42% compared to the peak strength that would typically be obtained by shearing a virgin sample at the final design load. Both of these test campaigns illustrate that localized displacements induced during construction by dozer spreading of soils could be detrimental to long-term slope stability.

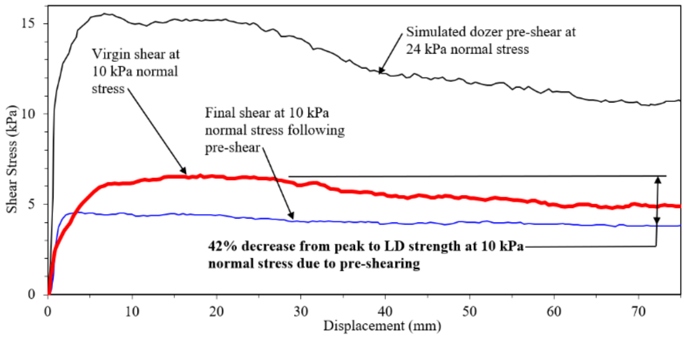

Figure 2. Test results showing effects of pre-shearing at dozer construction normal stress on the peak strength at low veneer normal stress for an interface of a textured HDPE geomembrane against the non-woven geotextile surface of a drainage geocomposite.

1.2 Direction of dozer travel

An essential consideration is the direction of dozer pushing and decelerating on a slope, whether it be upslope, downslope, or cross-slope. It has long been recognized that pushing soil piles over geosynthetic liner systems in a downslope direction can be dangerous for the liner system. For example, Koerner and Soong [7] provided a quantitative analysis that attempted to explain why pushing or decelerating in a downslope direction can be problematic by attributing the excess driving forces in this case to the acceleration or deceleration of the dozer. Another explanation was provided by Stark at al. [13] who emphasized that the lack of a soil toe buttress when pushing downslope was highly disadvantageous compared to having a toe buttress behind the dozer when pushing upslope. The present paper addresses downslope pushing of soil piles and downslope deceleration, and provides quantitative proof that pushing or decelerating downslope is more dangerous for the condition of the geosynthetic interfaces than pushing upslope.

2 Definitions and related equations

2.1 Definition of the considered cases

The two considered situations are (1) that of a dozer pushing a soil pile downslope with the aim of spreading it to a thickness D over the geosynthetic liner system, and (2) a dozer decelerating while traveling downslope without pushing a soil pile. The slope angle is β. Figure 3 presents the case for forces acting on a geosynthetic interface *below the tracks* of the dozer when pushing a soil pile downslope. Figure 4 presents the case for forces acting on a geosynthetic interface *below the base of the soil pile* that is being pushed downslope. Figure 5 presents the case for forces acting on a geosynthetic interface below the tracks of the dozer when the dozer is decelerating in the downslope direction without pushing a soil pile. The forces have been labeled with the nomenclature described in the following sections.

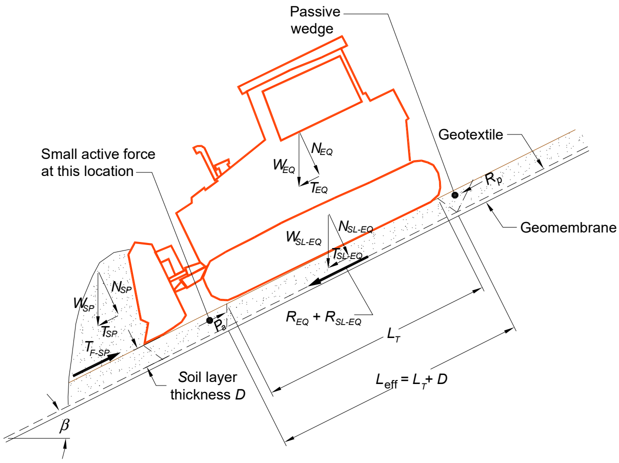

Figure 3. Forces acting on a geosynthetic interface below the tracks of a dozer pushing soil downslope.

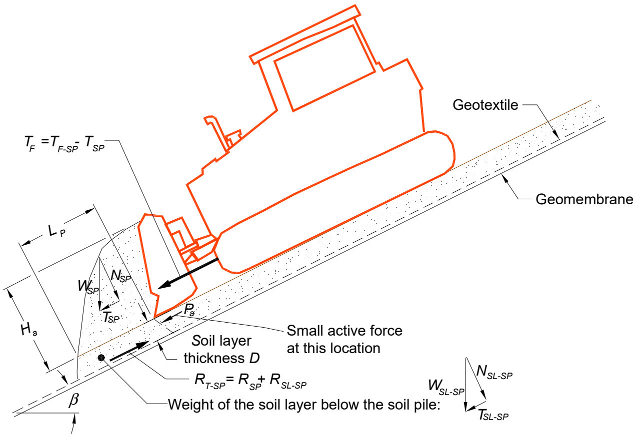

Figure 4. Forces acting on a geosynthetic interface below the soil pile being pushed downslope by a dozer.

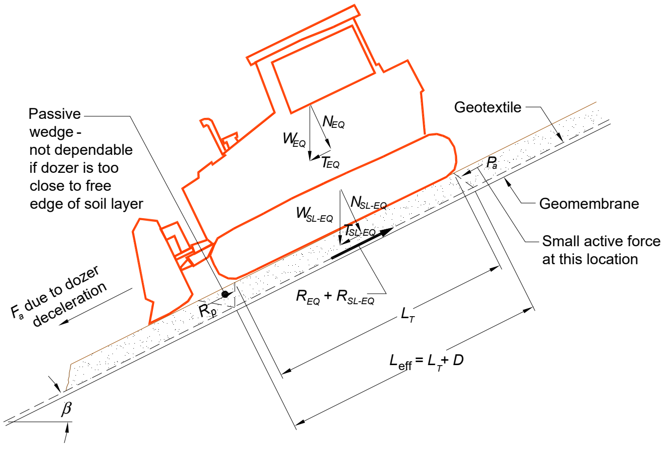

Figure 5. Forces acting on a geosynthetic interface below the tracks of the dozer when the dozer, which is not pushing a soil pile, is decelerating in a downslope direction.

2.2 Weights and geometric measurements

W is used to represent the weights as follows:

W_{EQ} is the weight of the dozer (kN).

W_{SP} is the weight of the soil pile being pushed in front of the dozer (kN):

$$W_{SP} = \gamma V_{SP} \tag{1}$$

where:

γ= unit weight of the soil in being pushed (kN/m^3);

V_{SP} = the volume of the soil pile (m^3).

$W_{SL\text{-}EQ}$ is the weight of the portion of soil layer (kN) below both of the dozer tracks (see Figure 3) acting directly on the area of the geosynthetics that are affected by the weight of the dozer:

$$W_{SL\text{-}EQ} = \gamma\ D\ \ A_{eff\text{-}EQ} \tag{2}$$

where:

D = the thickness of the soil layer between the dozer tracks and the geosynthetics measured normal to the slope (m);

$A_{eff\text{-}EQ}$ = the effective area of the geosynthetic interface affected by localized shear stresses induced by both dozer tracks (m^2).

Winterkorn and Fang [14] describe how A_{eff} can be estimated by assuming that the total load from the dozer track is distributed over an area of the same shape as the dozer track footprint, but with dimensions that are increased by an amount equal to the thickness D such that:

$$A_{eff-EQ} = 2(L_T + D)(w + D) \tag{3}$$

where:

L_T = the length of dozer track in contact with the soil (m) (see Figures 3 and 5);

w = width of a single dozer track (m).

$W_{SL\text{-}SP}$ is the weight of the portion of soil layer (kN) below the soil pile (see Figure 4) acting directly on the area of the geosynthetics that are affected by the weight of the soil pile:

$$W_{SL\text{-}SP} = \gamma\ D\ \ A_{eff\text{-}SP} \tag{4}$$

where:

$A_{eff\text{-}SP}$ = the effective area of the geosynthetic interface affected by the localized shear stresses induced by the soil pile (m^2).

In the same manner as described previously, $A_{eff\text{-}SP}$ can be estimated by assuming that the total load from the soil pile is distributed over an area of the same shape as the soil pile footprint, but with dimensions that are increased by an amount equal to the depth D such that:

$$A_{eff-SP} = (L_P + D)(B + D) \tag{5}$$

where:

L_P = the length of the soil pile in front of the dozer blade (m) (see Figure 4);
B = the width of the dozer blade, which is assumed to be the same as the width of the soil pile being pushed (m).

For purposes of calculating the pile volume and the dimensions of the pile base, the following simplified relationship for volumetric push capacity, V_S, of a standard straight dozer blade can be used as given by SAE Standard J1265 [15]:

$$V_S = 0.8\ B\ H^2 \tag{6}$$

where:

H = the height of the dozer blade (m).

The volume, V_{SP}, of the soil pile being pushed is assumed to be related to the height of the pile, H_a, being pushed measured normal to the slope using the following equation, which is similar to Equation 6:

$$V_{SP} = 0.8\ B\ (H_a)^2 \tag{7}$$

The volume of the soil pile can also be calculated as follows, assuming that the soil pile has a triangular cross section:

$$V_{SP} = 0.5\ B\ L_P\ H_a \tag{8}$$

Combining Equations (7) and (8) results in the following value for the length of the soil pile in front of the dozer blade:

$$L_P = 1.6\ H_a \tag{9}$$

The 1.6 ratio between L_P and H_a matches some field observations. However, design engineers are encouraged to adjust the estimate of V_{SP} to suit the conditions appropriate to the project-specific soils, slope, and dozer type in a manner that is representative for the project being designed.

2.3 Force components normal to the slope

N is used to represent the weight vector components that are normal to the slope. Thus, N_{EQ}, $N_{SL\text{-}EQ}$, N_{SP}, and $N_{SL\text{-}SP}$ are the symbols for the components normal to the slope due to the weights of: dozer, portion of soil layer below the tracks, soil pile, and portion of soil layer below the pile, respectively. From the force diagrams shown in Figures 3, 4 and 5, the following generic relationship is applicable to any of these normal forces N:

$$N_{xx} = W_{xx} \cos(\beta) \tag{10}$$

where the subscript xx could represent *EQ, SL-EQ, SP, or SL-SP.*

2.4 Force components tangential to the slope and factor of safety

2.4.1 Categories of forces tangential to the slope and factor of safety

There are two categories of forces tangential to the slope: driving and resisting. Driving forces are those that potentially cause slippage at the critical geosynthetic interface and are collectively labelled S_T. Resisting forces are those that resist slippage at the critical geosynthetic interface and are collectively labelled R_T. To prevent slippage at the critical geosynthetic interface during construction would require that the following condition is met:

$$R_T > S_T \tag{11}$$

Since this calculation is only for a very short-term condition during construction, there is not a requirement for a factor of safety (*FS*) to be significantly greater than 1.0, provided that the parameters for the calculation are assumed conservatively and the construction is controlled. However, there are other reasons that justify *FS* to be greater than unity. As pointed out by Thiel [12], there are often unavoidable low-shear-strength zones that can exist at geosynthetic interfaces due to manufacturing and installation variability. Examples of manufacturing variability include variation in the asperity height of textured geomembranes, and zones of low adhesion between geotextiles and geonets heat-bonded together to create geocomposite drainage layers. Examples of installation variability occur at the seams of textured geomembranes that have smooth edges to facilitate seaming, and at the edges of geocomposite drainage layers that are intentionally manufactured with a significant unbonded edge width along each side of the rolls in the machine direction to allow overlapped edge seams. For a single interface between a textured geomembrane and a geocomposite drainage layer, Thiel [12] has shown that 15-30% of the area could have an interface friction angle of 10° or less in the direction of the geonet ribs due to these factors, with the actual value dependent on the project-specific materials and installation.

If a calculated value for the factor of safety, *FS*, is desired, it can be defined as follows:

$$FS = R_T / S_T \tag{12}$$

2.4.2 Driving forces

T is used to represent the driving force vector components that are tangential to the slope. Thus, T_{EQ} , $T_{SL\text{-}EQ}$, T_{SP}, and $T_{SL\text{-}SP}$ are the symbols for the tangential driving force components due to the weights of: dozer, portion of soil layer below the tracks, soil pile, and portion of soil layer below the pile, respectively. To obtain a positive value for the factor of safety, the tangential forces that are in the direction of potential sliding along the critical geosynthetic interface are considered positive. Thus, the positive direction for the tangential driving forces is upslope for the case presented in Figure 3, and downslope for the cases presented in Figures 4 and 5. From the force diagrams shown in Figures 3-5, the following generic relationship is applicable to any of these tangential forces *T*:

$$T_{xx} = W_{xx} \sin(\beta) \tag{13}$$

where the subscript *xx* could represent *EQ, SL-EQ, SP, or SL-SP.*

Another tangential force vector is the reaction force of the dozer blade, T_F, against the soil pile as it is pushing the soil pile (see Figure 4). This force can be decomposed into two component forces: (1) T_{SP}, which is the tangential component of the soil pile weight that acts in the same direction that the dozer is pushing, and (2) $T_{F\text{-}SP}$, which is the force required to overcome the friction at the base of the soil pile to allow the pile to be spread downslope.

When the forces acting below the tracks of a dozer pushing downslope are of interest, the force T_F is internal to the free body diagram shown in Figure 3 and does not appear. When the forces acting on the soil pile are of interest, the force T_F is an external force to the soil pile and is considered as shown on the free-body diagram in Figure 4. The magnitude of T_F can be calculated as:

$$T_F = T_{F\text{-}SP} - T_{SP} \tag{14}$$

The tangential frictional force $T_{F\text{-}SP}$ that is delivered by the dozer blade is manifested at the base of the soil pile as it is being pushed and spread into the desired layer thickness, D. The following classical equation from soil mechanics can be used to estimate this force:

$$T_{F\text{-}SP} = N_{SP} \tan(\phi) \tag{15}$$

where:
ϕ = internal friction angle of the soil being spread (degrees).

Another tangential driving force vector is P_a, which is a small active lateral earth pressure within the soil layer that could act at the lower end of the dozer tracks when the dozer is pushing a large pile downslope (Figure 3), the upper end of the soil pile that is being pushed (Figure 4), or the upper end of the dozer tracks when the dozer is decelerating (Figure 5). Thiel and Giroud [1] describe approaches used by others to estimate this relatively small force and concluded that it is justified to simplify the estimate of the active lateral force at this location by assuming that it is parallel to the slope. Assuming the soil to be cohesionless with an internal friction angle ϕ, and assuming that the width of the active soil block in front of the dozer track is approximately equivalent to the width of the dozer track, w, acting through a vertical soil depth equal to $D/(\cos\beta)$, then the following expression (which is classical in soil mechanics) can be used:

$$P_a = \frac{1}{2} K_a \, \gamma \, \left(\frac{D}{\cos\beta}\right)^2 (b) \tag{16}$$

where b is equal to $2w$ for the two dozer tracks in the cases shown in Figures 3 and 5, or b is equal to B for the width of the soil pile in the case shown in Figure 4; and where K_a is the active lateral earth pressure coefficient for the soil, which can be estimated as follows using a classical soil mechanics relationship:

$$K_\alpha = \tan^2\left(45 - \frac{\phi}{2}\right) \tag{17}$$

where ϕ is in degrees.

It should be noted that Eqn 16 is for the case where there is no surcharge on the soil surface. This is appropriate because the locations where the active lateral earth pressure is effective are not directly under the dozer or the soil pile.

The deceleration force, F_a, shown in Figure 5 occurs when the dozer is travelling downslope without pushing soil and needs to stop. Note that this situation can occur at the end of a downslope push, or when backing up to reset the dozer for a new upslope push. Additionally, the same type of force can occur as acceleration, rather than deceleration, when the dozer, initially moving upslope, reverses direction to start moving upslope, but as mentioned by Qian et al. [8] the sharp braking action at the end of a downslope movement is typically the more severe condition. The deceleration/acceleration force F_a can be estimated as:

$$F_a = W_{EQ} \times a/g \tag{18}$$

where a is the deceleration/acceleration of the dozer and g is the acceleration due to gravity.

The magnitude of dozer deceleration is not well documented in the literature. Qian et al. [8] imply a typical range of from 0.05g to 0.3g for dozer acceleration/deceleration. The upper end of this range can be justified considering a dozer traveling at a pedestrian walking speed of 5 km/h (1.39 m/s) and attempting to stop within a distance of 0.32 m, resulting in a deceleration $a > 0.3g$ (see end of Calculation No. 3). As implied in this example, this magnitude of deceleration is commonly experienced by anyone who abruptly interrupts an average walking pace. This is corroborated by AASHTO [16] which suggests that a deceleration of 0.35g is a 'comfortable deceleration rate for most drivers' [of automobiles].

The sum of the forces potentially causing slippage in the upslope direction at the critical geosynthetic interface below the dozer tracks when pushing a soil pile downslope (Figure 3), collectively called the 'dozer driving forces', is $S_{T\text{-}EQ}$, given by the following equation:

$$S_{T\text{-}EQ} = (T_{F\text{-}SP} - T_{SP}) - T_{EQ} - T_{SL\text{-}EQ} + P_a \tag{19}$$

The sum of the forces potentially causing slippage in the downslope direction at the critical geosynthetic interface below the soil pile that is being pushed downslope (Figure 4), collectively called the 'soil pile driving forces', is $S_{T\text{-}SP}$, given by the following equation, which has been simplified using Eqn 14:

$$S_{T\text{-}SP} = T_F + T_{SP} + T_{SL\text{-}SP} + P_a = T_{F\text{-}SP} + T_{SL\text{-}SP} + P_a \tag{20}$$

The sum of the forces potentially causing slippage in the downslope direction at the critical geosynthetic interface below the dozer tracks when decelerating downslope (Figure 5), collectively called the 'dozer deceleration driving forces', is $S_{T\text{-}EQ\text{-}a}$, given by the following equation:

$$S_{T\text{-}EQ\text{-}a} = T_{EQ} + T_{SL\text{-}EQ} + P_a + F_a \tag{21}$$

2.4.3 Resisting forces

R is used to represent the force components tangential to the slope that resist slippage at the critical geosynthetic interface, either below the dozer or below the soil pile. Thus, R_{EQ} , $R_{SL\text{-}EQ}$, R_{SP}, and $R_{SL\text{-}SP}$ are the tangential resisting force components due to the normal forces (defined in Section 2.3) due to the weights of the dozer, the portion of soil layer below the tracks, the soil pile, and the portion of the soil layer below the soil pile, respectively. The following classical relationship applies to these forces:

$$R_{xx} = N_{xx} \tan(\delta) \tag{22}$$

where the subscript *xx* could represent *EQ, SL-EQ, SP* or *SL-SP,* and δ is the peak critical geosynthetic interface friction angle.

R_p is the passive lateral soil resistance engaged in the soil layer that could act at the upper end of the dozer tracks when the dozer is pushing a large pile downslope (Figure 3), or potentially at the lower end of the dozer tracks when the dozer is decelerating (Figure 5). Note that the reliability of R_p to act is reduced as the dozer approaches a free edge of the soil layer being spread. For the case shown in Figure 5, it is recommended to assume R_p = zero if the dozer, that is spreading soil downslope, nears the edge of the layer being spread.

A precise computation of the passive lateral force, R_p, and its vector direction is complex. Using similar arguments as were discussed previously for the active lateral force, P_a, a simplified conservative approximation of the passive lateral resistance is proposed using a reduced passive lateral earth coefficient, K'_p, with the calculated force vector, R_P, acting in the direction tangential to the slope.

A reduced passive lateral earth pressure coefficient, K'_p, for the soil can be estimated as

$$K'_p = 0.3 \tan^2\left(45 + \frac{\phi}{2}\right) \tag{23}$$

where ϕ is in degrees.

The coefficient 0.3 is included in the formulation of K'_p with the intent to limit the passive resistance to small strain conditions that would be compatible with the small deformations (e.g. < 12 mm) that would be allowable at the base of the central block to maintain peak strength conditions.

It should be noted that Eqn 23 is for the case where there is no surcharge on the soil surface. This is appropriate because the locations where the passive lateral earth pressure is effective are not directly under the dozer or the soil pile.

Based on the above discussion, a conservative estimate of R_p can be calculated as follows:

$$R_p = \frac{1}{2} K'_p \, \gamma \, D^2 \, (2w) \tag{24}$$

The multiplier '2' in front of the term '*w*' accounts for the two dozer tracks.

The sum of the forces resisting slippage at the critical geosynthetic interface below the dozer tracks (Figures 3, where slippage would occur in the upslope direction, and Figure 5, where slippage would occur in the downslope direction), collectively called the 'dozer resisting forces', is $R_{T\text{-}EQ}$:

$$R_{T\text{-}EQ} = R_P + R_{EQ} + R_{SL\text{-}EQ} \tag{25}$$

The sum of the forces resisting slippage in the downslope direction at the critical geosynthetic interface below the soil pile (Figure 4), collectively called the 'soil pile resisting forces', is $R_{T\text{-}SP}$:

$$R_{T\text{-}SP} = R_{SP} + R_{SL\text{-}SP} \tag{26}$$

3 Example analyses of downslope pushing

The example problems presented below use the same dozer, soil, interface, and slope parameters presented in the companion paper by Thiel and Giroud [1] for upslope pushing.

3.1 Example problem parameters

A contractor proposes to use a Caterpillar D6D LGP dozer to spread a layer of angular drainage gravel to a thickness, D, of 0.305 m over a geosynthetic liner system, consisting of a geomembrane overlain by a geotextile cushion, on a 3(H):1(V) ($\beta = 18.4°$) slope. The gravel will be delivered to the leading edge of the layer being constructed using tracked dump haul vehicles that travel very slowly on the slope without changing direction. The dumped piles will then be spread by the dozer by pushing in the downslope direction. What is the largest volume (V_{SP}) of the gravel pile that should be allowed to be pushed downslope to not exceed the peak shear strength of the critical geosynthetic interface below the dozer tracks (Calculation No. 1) or below the soil pile (Calculation No. 2)? What is the maximum rate of dozer deceleration, a_{max}, when traveling downslope without pushing a soil pile that could be tolerated to avoid exceeding the peak interface shear strength of the critical geosynthetic interface, and what would be the minimum stopping distance, d, and time, t, from the point that the deceleration commenced assuming an initial dozer velocity, v_0, of 5 km/h (Calculation No. 3)?

The following data are used for this problem:

- The weight of the dozer: $W_{EQ} = 201$ kN
- The track length of the dozer: $L_T = 3.24$ m
- The track width of the dozer: $w = 0.991$ m
- The width of the dozer blade, $B = 3.66$ m
- The unit weight of the gravel: $\gamma = 15.7$ kN/m^3
- The internal friction angle of the gravel at the normal loads experienced during construction: $\phi = 60°$ (this is a common value for angular gravels at low normal loads; see, for example, FHWA [17])
- The peak interface friction angle between the textured geomembrane and protective geotextile cushion measured in the laboratory at the normal loads experienced during construction: $\delta = 29.2°$. It is assumed that the critical geosynthetic interface is between the geotextile and the geomembrane.

3.2 Calculation No. 1: shear stresses below the dozer tracks when pushing soil pile downslope (Figure 3)

The purpose of this Calculation No. 1 is to determine the maximum soil pile size to limit shear stresses below the dozer tracks.

Areas and weights:

$A_{eff\text{-}EQ} = 2(3.24 + 0.305)(0.991 + 0.305) = 9.19 \text{ m}^2$ (Eqn 3)

$W_{SL\text{-}EQ} = 15.7(0.305)(9.19) = 44.0$ kN (Eqn 2)

$W_{SP} = 15.7 \times V_{SP}$ kN (Eqn 1)

Normal components:

$N_{EQ} = 201 \cos(18.4) = 190$ kN (Eqn 10)

$N_{SL\text{-}EQ} = 44.0 \cos(18.4) = 41.8$ kN (Eqn 10)

$N_{SP} = (15.7\ V_{SP}) \cos(18.4) = 14.9\ V_{SP}$ kN (Eqn 10)

Driving forces:

T_{EQ} = 201 sin(18.4) = 63.4 kN (Eqn 13)

$T_{SL\text{-}EQ}$ = 44.0 sin(18.4) = 13.9 kN (Eqn 13)

T_{SP} = 15.7 V_{SP} sin(18.4) = 4.96 V_{SP} kN (Eqn 13)

$T_{F\text{-}SP}$ = 14.9 V_{SP} tan(60) = 25.8 V_{SP} kN (Eqn 15)

Active lateral earth pressure:

$K_a = \tan^2(45 - 60/2) = 0.072$ (Eqn 17)

$P_a = (0.5)(0.072)(15.7)(0.305/\cos(18.4))^2(2)(0.991) = 0.12$ kN (Eqn 16)

Sum of driving forces

$S_{T\text{-}EQ} = (25.8V_{SP} - 4.96\,V_{SP}) - 63.4 - 13.9 + 0.12 = 20.84\,V_{SP} - 77.2$ (Eqn 19)

Resisting forces:

$K'_p = (0.3)\tan^2(45 + 60/2) = 4.18$ (Eqn 23)

$R_p = (0.5)(4.18)(15.7)(0.305)^2(2)(0.991) = 6.05$ kN (Eqn 24)

$R_{EQ} = (190)\tan(29.2) = 106$ kN (Eqn 22)

$R_{SL\text{-}EQ} = (41.8)\tan(29.2) = 23.4$ kN (Eqn 22)

Sum of resisting forces

$R_{T\text{-}EQ} = 6.05 + 106 + 23.4 = 135.4$ kN (Eqn 25)

To determine the maximum allowable soil pile size that can be pushed downslope without causing slippage below the dozer tracks, set the sum of resisting forces to be greater than or equal to the sum of driving forces, and solve for V_{SP} as follows:

$135.4 \geq 20.84\,V_{SP}$ (Eqns 11, 19 and 25)

Hence $20.84\,V_{SP} \leq 212.6$, hence $V_{SP} \leq 10.2$ m^3

This result indicates that 10.2 m^3 is the maximum soil pile volume that can be attempted to be pushed with a factor of safety of 1.0 against slippage in the upslope direction below the dozer tracks, which is a volume in excess of the capacity of any dozer that would be working on a slope above a geomembrane. Interestingly, the factor of safety for this particular example is 'infinity' when the soil pile size is approximately 3.70 m^3, which is the point at which the sum of driving forces, S_T, are balanced at zero. For soil piles smaller than 3.70 m^3 the factor of safety becomes negative with a decreasing absolute value as the pile size gets smaller. The negative value can be interpreted as the absolute value of the factor of safety for sliding of the dozer in the downslope direction. The limiting condition for this situation is when there is no soil pile, and there is only the dozer, for which the calculation yields the same factor of safety (FS = 1.68) as the situation shown in Figure 5 when P_a, R_p, and F_a are set to zero, and is representative of the 'infinite slope' equation $FS = \tan(\delta) / \tan(\beta)$.

In conclusion, the potential for shear stresses to cause localized slippage below the dozer tracks when pushing in the downslope direction is not a critical condition. However, pushing a soil pile downslope *is a very critical condition* for the shear stresses that would occur below the soil pile, as illustrated in the following example.

3.3 Calculation No. 2: shear stresses below the soil pile when pushing soil pile downslope (Figure 4)

For this calculation, the same parameters are used as for Calculation No. 1, but the purpose of this Calculation No. 2 is to determine the maximum soil pile size to limit shear stresses below the soil pile that is being pushed (whereas Calculation No.1 addressed shear stresses below the dozer tracks).

Areas and weights:

$A_{eff\text{-}SP}$ = $[1.6\times V_{SP}{}^{0.5}/(0.8\times 3.66)^{0.5} + 0.305]\,(3.66 + 0.305) = 3.71\ V_{SP}{}^{0.5} + 1.21$ m^2 (Eqns 5, 7 and 9)

$W_{SL\text{-}SP} = 15.7(0.305)(3.71\ V_{SP}{}^{0.5} + 1.21) = 17.8\ V_{SP}{}^{0.5} + 5.79$ kN (Eqn 4)

$W_{SP} = 15.7\ V_{SP}$ kN (Eqn 1)

Normal components:

$N_{SL\text{-}SP} = (17.8\ V_{SP}{}^{0.5} + 5.79)\cos(18.4) = 16.9\ V_{SP}{}^{0.5} + 5.49$ kN (Eqn 10)

$N_{SP} = (15.7\ V_{SP})\cos(18.4) = 14.9\ V_{SP}$ kN (Eqn 10)

Driving forces:

$T_{SL\text{-}SP} = (17.8\ V_{SP}{}^{0.5} + 5.79)\sin(18.4) = 5.62\ V_{SP}{}^{0.5} + 1.83$ kN (Eqn 13)

$T_{F\text{-}SP} = 14.9\ V_{SP}\tan(60) = 25.8\ V_{SP}$ kN (Eqn 15)

Active lateral earth pressure:

$K_a = \tan^2(45 - 60/2) = 0.072$ (Eqn 17)

$P_a = (0.5)(0.072)(15.7)(0.305/\cos(18.4))^2(3.66) = 0.214$ kN (Eqn 16)

Sum of driving forces

$S_{T\text{-}SP} = 25.8V_{SP} + (5.62\ V_{SP}{}^{0.5} + 1.83) + 0.214$

$= 25.8V_{SP} + 5.62\ V_{SP}{}^{0.5} + 2.044$ (Eqn 20)

Resisting forces:

$R_{SP} = (14.9\ V_{SP})\tan(29.2) = 8.33\ V_{SP}$ (Eqn 22)

$R_{SL\text{-}SP} = (16.9\ V_{SP}{}^{0.5} + 5.49)\tan(29.2) = 9.45\ V_{SP}{}^{0.5} + 3.07$ (Eqn 22)

Sum of resisting forces

$R_{T\text{-}SP} = 8.33\ V_{SP} + 9.45\ V_{SP}{}^{0.5} + 3.07$ kN (Eqn 26)

To determine the maximum allowable soil pile size that can be pushed without causing slippage, set the sum of resisting forces greater than or equal to the sum of driving forces, and solve for V_{SP} as follows:

$8.33\ V_{SP} + 9.45\ V_{SP}{}^{0.5} + 3.07 \geq 25.8V_{SP} + 5.62\ V_{SP}{}^{0.5} + 2.04$ (Eqns 11, 20 and 26)

hence $17.47\ V_{SP} - 1.03 \leq 3.83\ V_{SP}{}^{0.5}$

hence $305\ V_{SP}{}^2 - 36\ V_{SP} + 1.06 \leq 14.7\ V_{SP}$

hence $305\ V_{SP}{}^2 - 50.7\ V_{SP} + 1.06 \leq 0$;

solve the quadratic equation to find:

$V_{SP} \leq 0.141$ m^3

This result indicates that 0.141 m^3 is the maximum soil pile volume that should be attempted to be pushed to prevent slippage below the gravel pile, which an extremely small quantity for construction production, and is much less than the 10.2 m^3 limitation calculated for slippage beneath the dozer. This low value for the allowable pile size suggests that, for the parameters assumed for this particular example, downslope pushing would be highly discouraged.

The equations described in this example can be set up in a spreadsheet to easily perform a comparison of results and sensitivity analyses. Using such a spreadsheet can avoid having to use the quadratic equation that was used in Calculation No 2, because the factor of safety can easily be calculated for many assumed soil pile volumes with the results easily graphed for project-specific conditions, as shown in Figure 6.

Figure 6 presents a graph of the cover soil internal friction angle, ϕ, versus the maximum allowable soil pile sizes, V_{SP}, that would result in FS = 1.0 for slippage at the critical geosynthetic interface for two assumed interface friction angles, δ, of 29.2° and 25°. Two sets of curves are presented for two scenarios, both of which are based on the project parameters used in the design examples presented herein and in Thiel and Giroud [1]. One set of curves with the solid lines represents downslope pushing as presented in this section (Calculation No. 2) for potential slippage below the soil pile when pushing downslope. The other set of curves with the dashed lines is for potential slippage below the dozer tracks when pushing upslope using the method of Thiel and Giroud [1]. It should be noted that the comparison is made between slippage below the soil pile in the case of the dozer pushing soil downslope and slippage below the dozer tracks in the case of the dozer pushing soil upslope. This is because it was shown in Thiel and Giroud [1] that, when soil is pushed upslope, potential slippage is more critical below the dozer tracks than below the soil pile if the interface friction angle is lower than 56º for the assumed parameters of the example problem. Two patterns are noted from the graphs: (1) the allowable size of the soil pile to be pushed either downslope or upslope is significantly affected by the critical geosynthetic interface shear strength, and (2) there is a significant decrease in the allowable pile size for downslope pushing with increasing values of the internal friction of the soil (which happens when coarser soils are used). For example, for the case where $\delta = 29.2°$ the results indicate that for $\phi > 38°$ the maximum pile size for downslope pushing is less than 50% of that allowed for upslope pushing, decreasing to about 7% at $\phi = 60°$. There is a cross-over when $\phi \leq 35°$ where the allowable pile size for downslope pushing is greater than for upslope pushing. In general, when the internal shear strength of the soil is less than the critical geosynthetic interface shear strength, then pushing downslope is safe for any pile size provided that there is no deceleration force.

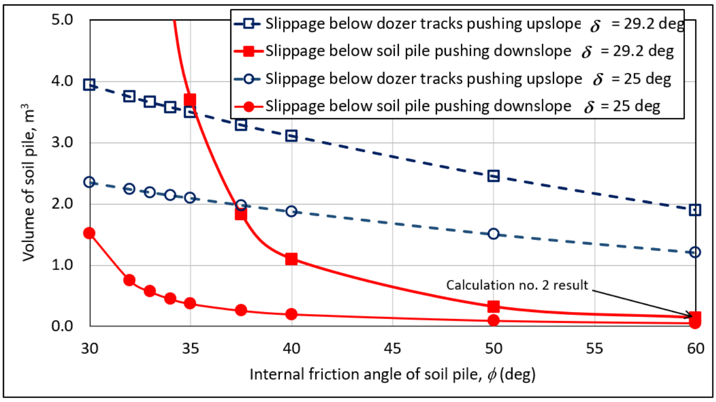

Figure 6. Soil pile internal friction angle versus maximum allowable soil pile size for two assumed interface friction angles that would result in $FS = 1.0$ for slippage at the critical geosynthetic interface for assumed parameters of the example problem. The two solid curves are for the scenario presented in Calculation No. 2 for potential slippage below the soil pile when pushing downslope. The two dashed curves are for the scenario of potential slippage below the dozer tracks when pushing upslope based on Thiel and Giroud [1].

When downslope pushing is performed, it is recommended that the parameters described in this paper be carefully checked by the engineer, and it is recommended that close construction monitoring be performed to minimize the occurrence of localized shear displacements that cause reduced shear strengths and potential thinning and tearing of the upper geosynthetic layer(s).

As mentioned above, the curves in Figure 6 show that the factor of safety decreases for increasing values of the internal friction angle of the soil being pushed. Therefore, to perform a conservative design, the design engineer should consider overestimating the internal friction angle of the soil being pushed. This is an important recommendation, because design engineers who want to do a conservative design, for example for bearing capacity or slope stability, rightfully underestimate the internal friction angle of the soil. Clearly, for the consideration of downslope pushing with a dozer, design engineers should not follow their usual tendency. It is important to note that this comment is not applicable to forensic analyses. If a forensic expert investigates why slippage occurred when a dozed pushed, or as a result of a dozer having pushed a soil pile, the exact internal friction angle should be used or the internal friction angle of the soil should be slightly underestimated for a slightly conservative investigation.

3.4 Calculation No. 3: shear stresses below the dozer tracks when coming to a stop (decelerating) with no soil pile (Figure 5)

For this calculation, the same parameters are used as for Calculation No. 1 but with no soil pile. The purpose of this Calculation No. 3 is to determine the effects of deceleration when a dozer comes to a stop in the downslope direction. As noted previously, this analysis would also apply for the acceleration forces when a dozer restarts movement in an upslope direction, but the sharp braking action at the end of a downslope movement is typically the more severe condition.

Areas and weights:
$A_{eff\text{-}EQ}$ = 2(3.24 + 0.305)(0.991 + 0.305) = 9.19 m^2 (Eqn 3)
$W_{SL\text{-}EQ}$ = 15.7(0.305)(9.19) = 44.0 kN (Eqn 2)
Normal components:
N_{EQ} = 201 cos(18.4) = 190 kN (Eqn 10)
$N_{SL\text{-}EQ}$ = 44.0 cos(18.4) = 41.8 kN (Eqn 10)
Driving forces:
T_{EQ} = 201 sin(18.4) = 63.4 kN (Eqn 13)
$T_{SL\text{-}EQ}$ = 44.0 sin(18.4) = 13.9 kN (Eqn 13)
Active lateral earth pressure:
$K_a = \tan^2(45 - 60/2) = 0.072$ (Eqn 17)
$P_a = (0.5)(0.072)(15.7)(0.305/\cos(18.4))^2(2)(0.991) = 0.12$ kN (Eqn 16)
Resisting forces:
$K'_p = (0.3)\tan^2(45 + 60/2) = 4.18$ (Eqn 23)
$R_p = (0.5)(4.18)(15.7)(0.305)^2(2)(0.991) = 6.05$ kN (Eqn 24)
R_{EQ} = (190) tan(29.2) = 106 kN (Eqn 22)
$R_{SL\text{-}EQ}$ = (41.8) tan(29.2) = 23.4 kN (Eqn 22)
Deceleration force:
$F_a = 201 \times a/g$ (Eqn 18)

To determine the maximum allowable rate of deceleration, a_{max}, that will not cause slippage, set the sum of resisting forces greater than or equal to the sum of driving forces, and solve for a_{max} as follows:

$S_{T\text{-}EQ\text{-}a} = 63.4 + 13.9 + 0.12 + 201(a_{max}/g) = 77.4 + 201(a_{max})$ kN (Eqn 21)
$R_{T\text{-}EQ} = 6.05 + 106 + 23.4 = 135.4$ kN (Eqn 25)
$135.4 \geq 77.4 + 201(a_{max}/g)$ (Eqn 11)
Hence $a_{max} \leq 0.29g$

The stopping distance, d, given an initial velocity, v_0, and constant rate of deceleration, a_{max}, is calculated by the following formula:

$$d = v_0{}^2/(2a_{max}) \tag{27}$$

and the time to stop, t, is calculated as:

$$t = v_0 / a_{max} \tag{28}$$

For the example problem, the initial velocity is assumed to be a walking speed of 5 km/h = 1.39 m/s. For the calculated maximum deceleration value, a_{max}, of 0.29g, the stopping distance can be calculated as:

$$d = \frac{1.39^2}{2\times 0.29\times 9.81} = 0.34 \text{ m}$$

and the stopping time can be calculated as:

$$t = \frac{1.39}{0.29\times 9.81} = 0.49 \text{ s}$$

This result indicates that 0.29g is the maximum deceleration rate that should occur for the example problem, and is specific to the slope inclination, interface shear strength, soil layer thickness, and dozer size modeled. For the example of a dozer traveling downslope at a pedestrian walking speed of 5 km/h, the stopping distance and time should be greater than approximately 0.35 m and 0.5 s, respectively, to satisfy this condition.

If the decelerating dozer approaches a free edge of the soil layer then the passive lateral force R_P would not be reliable and should be set to zero. In that case the calculated maximum deceleration value for the example problem would decrease by 10% to a_{max} = 0.26g.

Figure 7 presents a graphical sensitivity analysis of the scenario described in Calculation No. 3 where dozer deceleration/acceleration is plotted versus the factor of safety against slippage. The graph presents the results for a range of different geosynthetic interface friction angles.

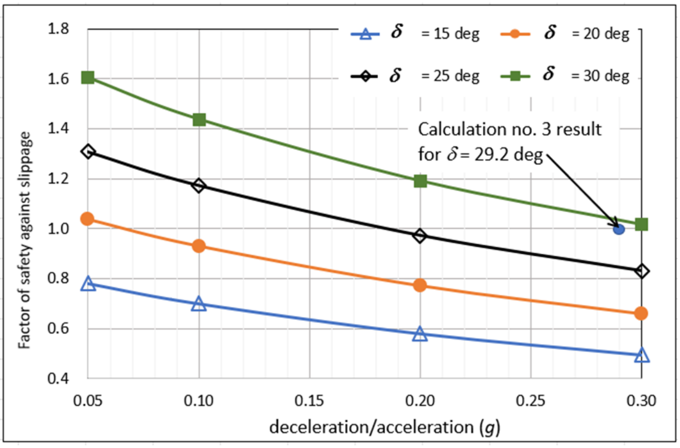

Figure 7. Rate of dozer deceleration/acceleration vs. factor of safety on 3(H):1(V) slope for various interface friction angles. All other parameters are the same as used in Calculation No. 3.

4 Conclusions

Localized interface shear strength failures have occurred during placement and spreading of cover soils on top of geosynthetic layers on slopes. If a design engineer evaluating slope stability assumes that the peak shear strength of geosynthetic interfaces will exist after spreading soil layers above geosynthetics on slopes, then project specific calculations should be performed to determine the allowable size of dozer, maximum size of soil piles that can be pushed for upslope and downslope pushing, and maximum allowable deceleration/acceleration to prevent shear strength degradation at the critical geosynthetic interface. Factors that affect these calculations include the slope angle, the internal shear strength of the soils being spread, the interface shear strength of the critical geosynthetic interface, the thickness of the soil layer being spread over the geosynthetics, the characteristics of the dozer such as its weight and the contact area of its tracks, the direction of pushing, and the rate of dozer acceleration/deceleration.

Previous literature references on this subject were evaluated and found to be either overly conservative to the point of affecting project construction economics, or numerically complex and prone to errors. Furthermore, some of these references provide only a few examples based on numerical simulations for limited conditions that could not be extrapolated to situations other than those modelled. The present paper focused on downslope pushing and decelerations, and complements a previous paper by Thiel and Giroud [1] for upslope pushing. These papers are based on easily understood principles of statics and contain simplifying assumptions for lateral soil forces that have relatively little impact on the results and that often result in complex solutions. The equations provided in these papers are easy to program on a spreadsheet for any project-specific situation.

The following specific conclusions can be made based on the results presented in this paper:

- The allowable soil pile sizes that can be pushed downslope to achieve an appropriate *FS* against localized slippage during construction are highly dependent on several project-specific factors including the critical geosynthetic interface shear strength. The reduction in long-term in-service shear strength that could occur due to localized slippage during construction can be evaluated by shear testing of the project specific materials at the appropriate normal loads.
- The results of the examples evaluated in the present paper indicate that downslope pushing of soil piles consisting of granular (high friction) materials should generally be avoided if localized interface slippage is to be prevented. Deceleration rates of dozers moving downslope should be controlled so that they do not exceed the threshold decelerations that would cause interface slippage for the project specific parameters. This can be predicted through material testing and calculations described in this paper, and verified in the field by close observation during construction, and perhaps aided by accelerometers mounted on the dozer.
- Variabilities in geosynthetics manufacturing and installation that affect interface shear strength along the critical surface should be taken into account when selecting an appropriate factor of safety against localized slippage during construction.

References

1. R. Thiel and J.P. Giroud, *Localized shear strength mobilization at geosynthetic interfaces caused by* spreading *soil upslope*, Presented at GeoAfrica23, 4th African Regional Conference on Geosynthetics, February 20th – 23rd, 2023, Cairo, Egypt, published in *E3S Web of Conferences* Vol. 368, p. 02002 (2023).
2. N. Paruvakat and G. Richardson, *Landfill Cover Failure Prompts Standards Upgrade,* GFR Magazine, **17,** No 7, IFAI (1999)
3. D.J. Kerkes, *Analysis of Equipment Loads on Geocomposite Liner Systems,* Proc. of Geosynthetics '99 held April 28-30, 1999 in Boston, MA. IFAI, pp. 1043-1054. (1999)
4. D.R.V. Jones, N. Dixon, and A. Connell, *Effect of Landfill Construction Activities on Mobilized Interface Shear Strength,* Proc. EuroGeo 2000, Bologna, Italy, pp. 581-586 (2000)
5. R. Thiel and D. Narejo, *Lamination strength requirements for geonet drainage geocomposite*, Proceedings of the 18th Annual GRI Conference/ASCE Geofrontiers Conference, Austin, TX (2005)
6. G. Richardson and R.M. Koerner, Geosynthetic Design Guidance for Hazardous Waste Landfill Cells and Surface Impoundments., EPA-600/2-87-097. USEPA, (1987)
7. R.M. Koerner and T.Y. Soong, *Analysis and Design of Veneer Cover Soils,* Proc. of 6th Int'l Conf. on Geosynthetics, 25-29 March 1998, Atlanta, GA, IFAI, (1998)
8. X. Qian, R.M. Koerner, and D. Gray, Geotechnical Aspects of Landfill Design and Construction, Pearson (publ), 1st Ed. (2001)
9. S.J. Drushel and E.R. Underwood, *Design of Lining and Cover System Side Slopes*, Proc. of Geosynthetics '93, Vancouver B.C. IFAI, pp. 1341-1355 (1993)
10. J.A. McKelvey, *Consideration of Equipment Loadings in Geosynthetic Lined Slope Designs,* Computer Methods and Advances in Geomechanics, Siriwardane and Zaman (Eds.) Balkema, Rotterdam, pp. 1371-1377 (1994)
11. USEPA, *EPA (Draft) Technical Guidance For RCRA/CERCLA Final Covers*, Office of Solid Waste and Emergency Response, EPA 540-R-04-007, OSWER 9283.1-26, (2004)
12. R. Thiel, *Selection of long-term shear strength parameters for strain softening geosynthetic interfaces*, 12th International Conference on Geosynthetics – "Geosynthetics: leading the way to a resilient planet", Biondi et al. (eds) – Roma (Italy) September 17-21 (2023)
13. T.D. Stark, H. Choi, C. Lee, and B. Queen, *Compacted Soil Liner Interface Strength Importance*, ASCE JGGE, **138** N4, pp. 544-550 (2012)
14. H.F. Winterkorn and H.Y. Fang, Foundation Engineering Handbook, Van Nostrand Reinhold, New York (1975)
15. SAE, Standard J1265, Capacity Rating – Dozer Blades. (2003)
16. AASHTO, A Policy on Geometric Design of Highways and Streets, 6th Edition, American Association of State Highway and Transportation Officials, Washington, D.C. (2011)
17. FHWA, *Friction Angles of Open-Graded Aggregates from Large Scale Direct Shear Testing,* Techbrief FHWA-HRT-13-068, Federal Highway Administration, (2013)