Design Considerations for Slip Interfaces on Steep-Wall Liner Systems

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ABSTRACT: This paper presents a methodology for designing side slope liner systems to accommodate downdrag due to waste settlement. Settlement and downdrag along steep-lined slopes in landfills and other waste or mining containment facilities (e.g. heap leach pads, mine tailings impoundments) will occur to varying degrees during initial construction, waste placement, and post-placement. Two key questions in this regard with respect to the design of the side slope liner system are: "how much downdrag will occur?" and "at what degree of slope inclination does downdrag become an engineering concern?" The little field monitoring and limited research that has been done on this subject indicates that at a slope inclination of perhaps 2H:1V (Horizontal:Vertical) or steeper, downdrag could be a significant concern, but it could occur on flatter slopes as well, depending on the forces and the relative interface shear resistances within the liner system. The methodology presented herein combines a slip interface above the primary geomembrane with an underlying high-strength geotextile that is anchored at the benches and side slope crest and that extends part-way down the slope to sustain tensile forces induced by downdrag. Finite difference analyses were performed that demonstrate the feasibility of this approach to meet design goals using commercially available geosynthetic material.

Keywords: Geosynthetics, containment, side slopes, downdrag, settlement

1 INTRODUCTION

Figure 1 shows a conceptual cross section of a landfill side slope, including final grades at the end of waste placement and the ultimate grades due to the settlement that occurs following the end of waste placement. Settlement at any point in the landfill will be due to a combination factors, including primary compression, waste degradation, and mechanical secondary compression. Similar settlement could occur in a heap leach pad due to primary and secondary compression and to degradation of the ore material due to leaching operations and in tailings impoundments due to primary and secondary compression. In the remainder of this paper we will only refer to the settling mass as "waste", noting here that it could equally apply to any material stored in a lined containment facility.

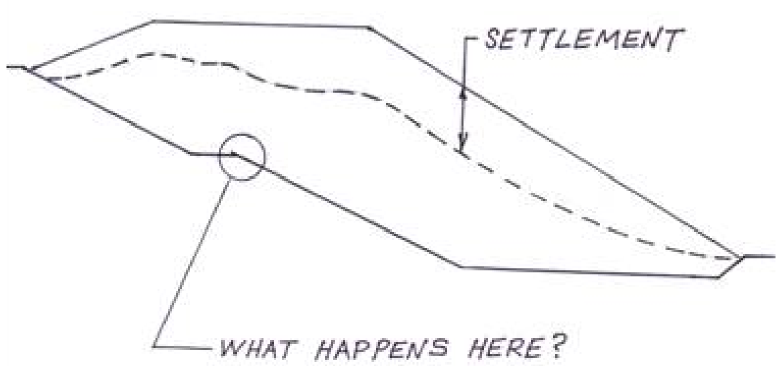

Figure 1. Landfill cross section showing side slope with bench, final grades, and post-settlement grades.

Presuming that the earthen subgrade remains relatively fixed, settlement of the waste will result in differential movement between the earthen subgrade and the settling waste body. Regardless of the reasons for settlement, the action of settlement can be expected to exert downdrag forces on the side slope liner system. Depending on the relative stiffness, shear strength, and tensile strength of the waste material, liner system materials, and material interfaces, different elements of the liner system may either simply be abraded by the settling waste or they may be dragged down with the settling waste and potentially go into tension. The case where the settling waste drags down the liner, potentially putting liner system elements into tension, is referred to herein as downdrag.

The amount of downdrag that will ultimately occur in a side slope liner system is a complex matter. Limited field measurements are available (e.g. Zamara et al. 2012). However, drawing generalizations from limited field measurements is unreliable due to the many factors that can influence the magnitude of settlement and the associated downdrag forces. Therefore, numerical modeling has been used to account for the variety of factors influencing waste settlement and downdrag. For instance, using a finite difference model, Jones and Dixon (2005) concluded that side slope "displacements in the order of meters could result from waste settlement" for a fill with lined containment side slopes. Fowmes et al. (2008) showed that the finite difference model employed by Jones and Dixon (2005) could accurately predict the stresses imposed by shear at an interface on geosynthetic liner system elements in laboratory testing.

In the design of steep-slope lining systems, the authors believe it is necessary to be able to accommodate downdrag without incurring any damage to the primary liner system. Furthermore, tension in liner system elements, and in particular in the geomembrane component of a liner system, should be minimized. Protection of a steep-slope liner against downdrag damage can be accomplished in two ways. One method is to provide one or more preferential slip surfaces above the primary liner, i.e. to provide a surface or surfaces where it is acceptable for differential movement to occur. To achieve this objective, i.e. to provide a preferential slip surface above the primary liner, the designer must provide an interface somewhere above the geomembrane with a shear strength less than any interface shear strength below the geomembrane. This preferential slip surface approach is also an effective means of minimizing tension in the geomembrane. A second alternative method is to provide a veneer-reinforcement layer above the primary liner that will have enough tensile strength to be able to resist the downdrag shear force. The two methods can also be combined to provide a redundant system, as described in this paper.

2 DESIGN APPROACH TO MANAGE DOWNDRAG FORCES

It is generally recognized that by making the interface shear strength on top of the primary liner surface lower (weaker) than the strength of any of the interfaces below the primary liner, downdrag settlement is accommodated by slipping along that low interface strength surface without inducing tension in the primary geomembrane (e.g. Cowland et al. 2008). For example, a slip surface consisting of a single-sided geocomposite could be deployed over a geomembrane on a steep slope. The description of the side slope liner system at the City of Los Angeles Lopez Canyon landfill by Snow et al. (1994), illustrated in Figure 2, is perhaps the first published example of this design approach. The interface between the bare geonet and the geomembrane in the Lopez Canyon side slope liner system is much more slippery (i.e., has a lower shear resistance) than any other interface in the lining system and will therefore slip when there is downslope movement above the primary liner due to waste settlement and downdrag.

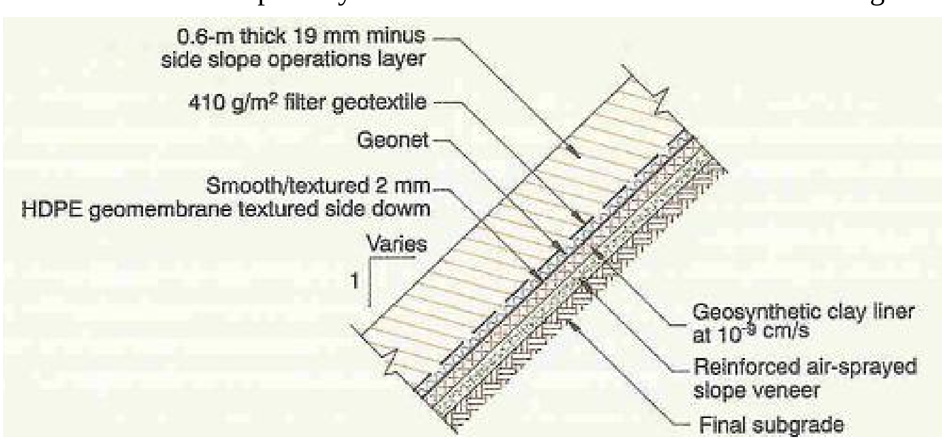

Figure 2. Lopez Canyon landfill side slope liner system (Snow et al, 1994)

From a design point of view, it is the tensile strains (or forces) induced in the side slope liner system elements by downdrag that are of concern because many geosynthetic liner system elements are not designed to carry sustained tensile loads. Furthermore, even if they are designed to carry tension excessive tensile strain might eventually lead to tearing of the liner system element. In general, the greatest amount of tensile strain induced in a liner system by downdrag will be experienced either at the crest of the side slope or at the crest of an intermediate bench, as identified in Figure 1. Conversely, compressive strains will generally be experienced near the toes of slope and the heel of an intermediate bench. Thus, the critical locations for risk of tearing are at the crests of slope segments. For the conceptual example shown in Figure 1, the tension and potential for tearing at the crest of the intermediate bench is of more concern than tearing at the perimeter crest of the landfill because the intermediate bench is buried deep within the waste, thus tearing may not be detected and would be difficult to repair if detected. Tension at the perimeter crest can be mitigated simply by not rigidly anchoring the geomembrane at the top of the slope or by releasing it from its anchor after the waste has reached the crest.

Tensile failure of a geosynthetic element in a side slope liner system is a concern not only with respect to the geomembrane barrier layer but also with respect to the geosynthetic layers overlying the geomembrane. If the slip-interface material tears, it could potentially expose the barrier layer below that material to shear forces and abrasion by the continued action of the overlying waste settlement. In the Lopez Canyon liner system shown in Figure 2, if the geocomposite (which has a relatively low tensile strength) ripped at the crest due to excessive tensile strains the underlying geomembrane would be exposed to the overlying soil and/or waste materials. If those materials continued to settle, they could potentially cause undesirable strains (and thereby undesirable tensile forces) and abrasions in the primary geomembrane. Furthermore, the side-slope operations layer soil could intrude and clog the geocomposite drainage layer.

The design approach suggested in this paper to safely mitigate the potential for undesirable shearing and tension of the primary geomembrane, illustrated in Figure 3, is to introduce a slip element (e.g., a single-sided geocomposite) underlain by a high-strength geotextile that would be anchored on the intermediate benches (and crest, if so desired) of the side slope and extend part way down the slope. If the high-strength geotextile is anchored on the bench directly beneath the geocomposite, then if the geocomposite tears and is dragged down-slope, it is the high-strength geotextile that will be exposed to the overlying soil that is engaging the downdrag forces. This situation is illustrated in Figure 3. The high-strength geotextile in this situation provides two functions: (1) it protects the underlying primary geomembrane from being directly exposed to the overlying soil materials, and (2) it carries the downdrag load without tearing, assuming it is strong enough. Using this design approach, the design engineer still has to assess 1) whether or not the tensile load induced by downdrag would exceed the tensile strength of the high-strength geotextile and 2) whether the downdrag displacement would exceed the point at which the high strength geotextile was terminated on the slope. If it was deemed possible that the downdrag movement would continue past the termination point for the high strength geotextile, then the high-strength geotextile could be extended further down the slope. If it is deemed possible that the tensile strength of the high-strength geotextile would be exceeded, then either a stronger geotextile could be employed or a second high-strength geotextile could be installed below the first layer, thus allowing another sequence of downdrag movement before this layer, in its turn, has its tensile strength challenged.

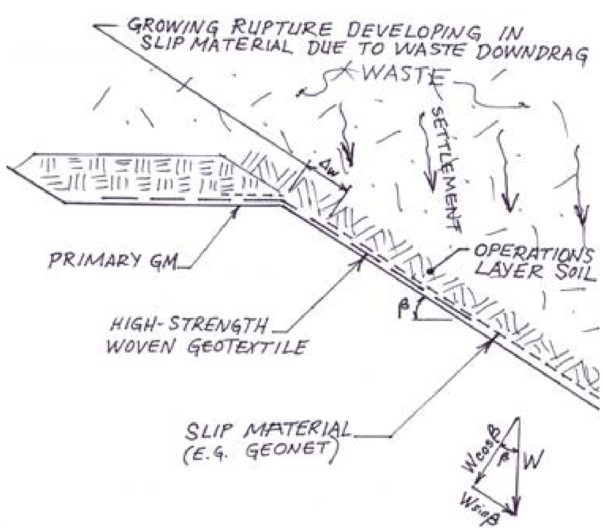

Figure 3. High-strength geotextile protecting primary geomembrane after slip element ruptures due to downdrag.

3 EXAMPLE OF DESIGN CALCULATIONS TO MITIGATE DOWNDRAG IMPACTS ON A SIDE SLOPE LINER

The magnitude of downdrag displacement that will ultimately occur against the landfill side slope and the magnitude of the tensile force induced in liner system elements are difficult to estimate. Rough estimates of the magnitude of downdrag displacement were proposed by EPA (1987) but are not considered by the authors to be particularly reliable and do not provide a basis for estimating the induced tensile force. However, finite difference and finite element numerical modeling, such as the finite difference model developed by Jones and Dixon (2005) and Fowmes et al. (2008), provide a basis for evaluating both the magnitude of displacement and the tensile force induced by downdrag.

Following the methodology used by Jones and Dixon (2008) and Fowmes et al. (2008), a finite difference model of a geosynthetics-lined landfill was developed using the computer program FLAC (ITASCA 2011) to estimate the stresses and displacements that would be induced in a side slope liner system by waste settlement. FLAC is a large-strain finite difference program with beam elements that can be used to model geosynthetic materials and interface elements that allow for relative displacement (slip) at the interface. The landfill configuration that was employed in the finite difference analysis, illustrated in Figure 4, was a transverse cross section of a canyon landfill. Each side of the cross section consisted of three 12.3 m-high (vertical) side slope segments separated by two 4-m wide benches. The slope inclination between benches was 1H:1V on the left side slope and 2H:1V on the right side slope. The above grade portion of the landfill also consisted of three 12.3 m-high segments separated by two 4 m-wide benches. The inclination of the final landfill grades above the ground surface was 3H:1V on the left side of the waste fill and 4H:1V on the right side of the waste fill.

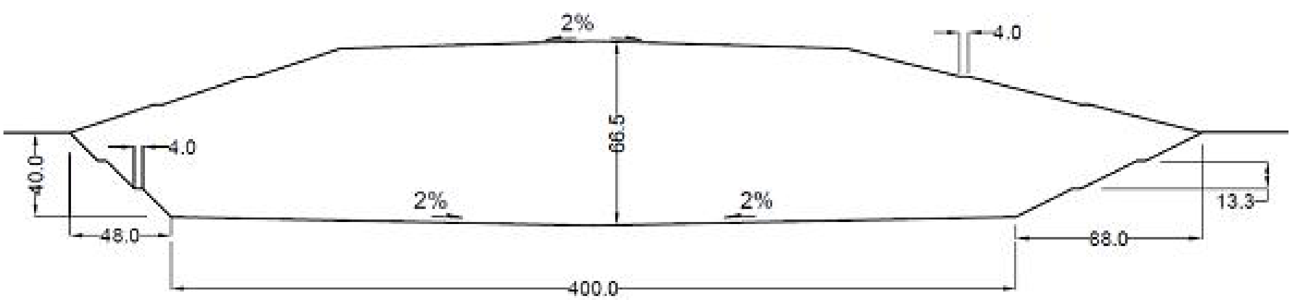

Figure 4. Prototype landfill geometry following post-placement (waste degradation) settlement (all dimensions in meters)

Following the approach used by Jones and Dixon (2005) and Fowmes et al. (2008), the geosynthetic materials were modeled in the finite difference analysis as beam elements with zero moment of inertia and with interface elements on both sides. The Cam-Clay constitutive model was employed to model the waste material. Waste was placed in lifts and allowed to compress under its own weight to evaluate downdrag due to primary compression. Settlement due to waste degradation and mechanical secondary compression following the end of waste placement settlement was modeled by changing the compressibility of the waste after it reached the designated final placement grades. The initial Cam-Clay properties of the waste material were developed by Arab (2011) from the results of field and laboratory tests on solid waste conducted as part of the pre-design geotechnical investigation for the OII landfill Superfund site (Kavazanjian et al. 2013). The initial total unit weight of the waste (the total unit weight of the first lift of waste following placement and compaction) was approximately 10.5 kN/m^3 and the waste was assigned a primary compressibility ratio (equal to the volumetric strain per log cycle increase in overburden stress) of 0.20. The model assumed waste was placed in twelve lifts that totaled 88 m in initial thickness but resulted in only 80.5 m of waste in the center of the landfill at the end of waste placement due to self-weight primary compression. After reaching the final grade, the compressibility of the waste was reduced to induce 14 m of post-placement settlement in the center of the landfill (equal to 17% of end of placement thickness of 80.5 m). The landfill geometry shown in Figure 4 is the geometry following the 14 m of post-placement settlement.

To calculate the maximum anticipated displacement along the side slope, the geosynthetic element on the side slope was assigned an upper interface friction angle of zero. As expected, displacement progressively increased from zero at the toe of each slope segment (there is no waste to settle at the toe) to a maximum value at the crest of each slope segment. Table 1 summarizes the vertical and downslope displacements at the crest of each side slope segment, calculated from the time when waste first reached the designated point. Note that the displacements are significantly greater along the 1H:1V slope than the 2H:1V.

Table 1 Vertical settlement and relative slope displacement at the crest of each slope segment for frictionless side slopes

	1H:1V Slope			2H:1V Slope		
	Lower Slope	Middle Slope	Upper Slope	Lower Slope	Middle Slope	Upper Slope
Vertical settlement	2.00 m	1.78 m	0.65 m	1.20 m	0.40 m	0.21 m
Slope displacement	2.83 m	2.52 m	0.92 m	2.68 m	0.89 m	0.47 m

A second finite difference analysis was conducted to calculate the tensile force the high strength geotextile would be subjected to. In order to reduce the complexity of the finite difference grid and save computational effort, only a single geosynthetic element was modeled when calculating the induced tension in the high strength geotextile. Based upon the calculated maximum vertical displacement of 2 m (for the crest of the lower slope segment of the 1H:1V slope) the high strength geotextile was assumed to extend to a vertical depth of 4 m below the crest of each segment (to provide a factor of safety of 2) and the side slope geotextile was assigned properties representative of the high strength reinforcing fabric to this depth. An axial stiffness of 4200 kN/m was assigned to this segment of the reinforcing fabric based upon manufacturer recommendations for a typical woven polyester high strength fabric. Below this depth the beam element representing the side slope geotextile was assigned a stiffness that was two orders of magnitude less than that of the high strength fabric (to prevent it from restraining side slope displacement as it went into compression). An interface friction angle of 30 degrees was used on the top of the side slope geotextile, representative of operations layer soil against a woven polyester fabric, and an interface friction angle of 10 degrees was assigned to the bottom of the high strength geotextile, representative of geotextile/geotextile or geonet/geomembrane interface shear resistance.

Figure 5 shows the tensile forces induced in the high strength geotextile due to waste downdrag as calculated in the finite difference analysis. Again, note the significant influence of slope angle: tensile forces induced in geotextile on the 2H:1V slope are on the order of 20 to 25 percent of the forces induced in the geotextile on the 1H:1V slope. High strength woven polyester geotextiles capable of sustaining these tensile forces are commercially available, indicating the viability of this design concept.

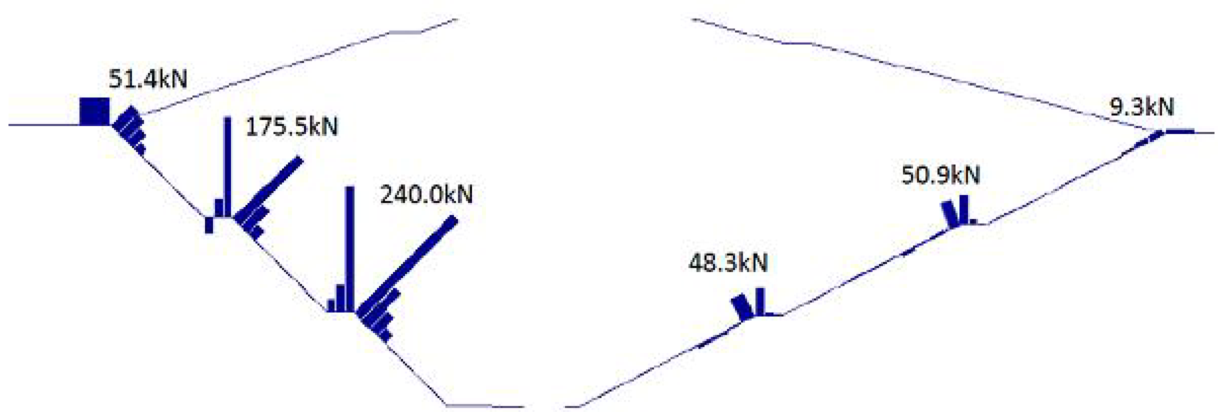

Figure 5. Tensile forces (per meter) induced in the high strength geotextile by downdrag

4 SUMMARY AND CONCLUSIONS

A methodology for designing side slope liner systems to accommodate downdrag due to waste settlement has been developed. This methodology combines a slip interface above the primary geomembrane with an underlying high-strength geotextile that is anchored at the benches and side slope crest and that extends part-way down the slope to sustain tensile forces induced by downdrag. The methodology is applied to a prototype municipal solid waste canyon-type landfill with 40-m tall lined side slopes. The lined side slopes on each side of the fill have two intermediate benches, splitting each side slope up into three

12.3-m (vertical) segments with an inclination of 1H:1V on one side and 2H:1V on the other side. The waste is subject to average volumetric strains in the center of the waste fill on the order of 10 percent of the waste thickness due to self weight consolidation during waste placement, resulting in a waste thickness of 80.5 m at the end of waste placement, and an additional 17 percent following the end of waste placement due to waste degradation and secondary compression, resulting in a final waste thickness of 66.5 m.

Finite difference analyses using frictionless side slopes result in a maximum vertical displacement due to waste settlement at the crest of the lowest slope segment of 2 m along the 1H:1V side slope and of 1.2 m along the 2H:1V side slope . A second finite difference analysis using manufacturer-recommended stiffness properties for a typical high strength woven polyester geotextile, an interface friction angle of 30 degrees on top of the side slope geotextile, and an interface friction angle of 10 degrees on the bottom of the side slope geotextile yielded a maximum tensile force of 240 kN/m in the high strength geotextile due to downdrag. The value of the induced tension (i.e. 240 kN/m) is below the creep-reduced strength and long-term design strength cited by the manufacturer for the woven polyester geotextile employed n the analyses.

Results of the analyses show that the design concept of using a slip interface in conjunction with a high strength geotextile to accommodate downdrag is a feasible design methodology. The downdrag displacement along the length of the slope of up to nearly 3 m predicted by the analysis for a prototype landfill configuration is consistent with displacement values from previous analyses and field measurements (Jones and Dixon 2005; Zamara et al. 2012). Predicted tensile forces induced by downdrag in the high strength geotextile are within the strength limits of commercially available geotextiles. The tensile forces were significantly less on the 2H:1V slopes than on the 1H:1V slopes. Although sensitivity studies of bench spacing were not performed, logic suggests that having more frequent benches and shorter side-slope distances will also result in less downdrag demand on the liner system. Additional work is necessary to develop a simplified design methodology that can facilitate selection of an appropriate reinforcing geotextile and dimensioning of the system without a finite difference numerical analysis.

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