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Improved methodology for geomembrane wind uplift design

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ABSTRACT: This paper presents a simplified methodology for the design of exposed geomembranes subjected to wind uplift, where the sizing of the anchorages is independent of the geomembrane properties. This is an improvement over the existing methodology where the sizing of the anchorages depends on the geomembrane because geomembranes with different moduli exert on the anchorage different tensions acting at different angles. The simplified methodology can be used for projects where multiple slopes are exposed to wind action and where the following special conditions are met: (1) all anchorages are identical; (2) all exposed slope sections are identical and subjected to the same wind-generated suction. These special conditions can be met, at least approximately, in landfill covers. Three other improvements over the existing methodology are also presented: a more complete equation for anchor bench design; an entirely analytical method for the analysis of the behavior of uplifted geomembranes; and a better definition of the factor of safety. Finally, a case history illustrates the use of the simplified methodology.

1 INTRODUCTION

Wind uplift is an important design consideration when geomembranes are exposed (i.e. not overlain by a protective layer or a ballasting material). This situation exists in particular when exposed geomembranes are used as covers in landfills.

1.1 *Current design methodology*

A methodology for the design of geomembranes exposed to wind uplift has been developed by Giroud *et al*. (1995, 1999) and used on a number of projects. This methodology includes two parts: (1) analysis of the behavior of the uplifted geomembrane (i.e. tension, strain, and deflection) to compare candidate geomembranes and select the most suitable one; and (2) sizing of the anchorages (e.g. anchor benches or anchor trenches). The sizing of anchorages depends on the geomembrane because, for a given wind velocity, geomembranes with different moduli exert on the anchorage different tensions acting at different angles.
The feasibility study of a project with an exposed geomembrane requires preliminary sizing of the anchorages. As mentioned above, this sizing depends on the geomembrane. Therefore, calculations need to be done for all candidate geomembranes, which requires a level of effort that is not appropriate for a feasibility study.

1.2 *Improvement of the methodology*

This paper shows that, if certain special conditions are met, the sizing of the anchorages is independent of the geomembrane behavior, which results in a simplified methodology. This remarkable result is due to the fact that, when the special conditions are met, the direction of the resultant of wind forces happens to be independent of the geomembrane deflection. As a result, it is possible to make a preliminary sizing of the anchorages without prior selection of the geomembrane, which greatly simplifies feasibility studies. It will be shown in the paper that, in most practical cases, the special conditions can be met, at least approximately, which makes it possible to perform feasibility studies with sufficient accuracy using the simplified methodology.

1.3 *Other improvements*

While the decoupling of anchorage sizing and geomembrane behavior is the main feature of this paper, two other improvements over the existing design methodology are presented herein.

The first improvement is a new equation for the sizing of anchor benches that accounts for the wind forces exerted directly on the anchor bench (whereas only the wind forces transmitted to the anchor bench through the geomembrane were accounted for in the equation used with the existing methodology). The new equation results in safer design.

The second improvement is an entirely analytical method for analyzing the behavior (tension, strain, and deflection) of the geomembrane for the cases where the geomembrane tension-strain curve can be represented by a parabolic equation, which is suitable for polyethylene (PE) geomembranes (e.g. HDPE, LLDPE). This eliminates the cumbersome step of the existing method which consists in drawing, on the same graph, the tension-strain curve of the geomembrane and the "wind-uplift curve" to determine their intersection (see Section 4.4). Thanks to this entirely analytical method for analyzing the geomembrane behavior, parametric studies can be efficiently conducted on spreadsheets.

2 DESCRIPTION AND ASSUMPTIONS

2.1 *Description of the considered case*

The side slopes of the considered landfill cover consist of multiple "exposed slope sections", where the geomembrane is exposed, separated by anchor benches (Figure 1). The geomembrane panels are welded together to provide a continuous liner that extends over the entire slope, including under the anchor benches. The methodology presented in this paper does not apply if there are less than three exposed slope sections and two anchor benches.

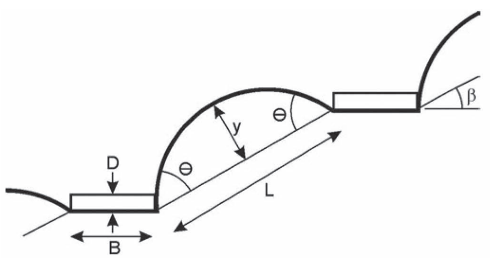

Figure 1. Cross section showing a deflected geomembrane and two anchor benches.

2.2 *General assumptions*

The following general assumptions are made:

- The thickness of each anchor bench is uniform.
- When the exposed geomembrane is uplifted by the wind, the entire weight of each anchor bench is mobilized.

The latter assumption implies that the anchor benches do not undergo large deformations that would result in mobilizing only a fraction of their weight. In other words, it is assumed that anchor benches act as monoliths. To achieve such behavior, the anchor benches may need to be constructed using reinforced soil or concrete.

2.3 *Special conditions*

The following special conditions lead to the simplified methodology described in Section 1.2: (1) all anchorages are identical; (2) all exposed slope sections are identical and subjected to the same wind-generated suction. In the considered case, where the anchorages are anchor benches, the special conditions are as follows:

- Anchor benches are horizontal.
- All anchor benches have the same width, B.
- The soil layer has the same thickness, D, in all anchor benches.
- All exposed slope sections have the same slope angle, β.
- All exposed slope sections have the same length measured along the slope, L.
- All exposed slope sections are subjected to the same wind-generated suction.

2.4 *Discussion of the special conditions*

The following comments can be made on the above special conditions:

- Anchor benches are generally horizontal or quasi horizontal. Therefore, the first of the special conditions is generally met.
- The width of anchor benches is often controlled by practical considerations, such as traffic of equipment. Therefore, in a given project, most anchor benches are likely to have approximately the same width. Therefore, the second of the special conditions is approximately met for most anchor benches. Calculations can be performed using an average value of the width or a small value (worst case).
- In a given landfill, all anchor benches have typically the same thickness. Therefore, the third of the special conditions is generally met.
- In a given landfill, the exposed slope sections often have various slope angles. However, most slope angles will have approximately similar values. Therefore, the fourth of the special conditions will be approximately met for most slopes in a given landfill. Calculations can be performed using an average value of the slope angle or a large value (worst case).
- In a given landfill, the exposed slope sections generally have various lengths. However, most slope sections will have lengths within a certain range. Therefore, the fifth of the special conditions will be approximately met for most slopes in a given landfill. Calculations can be performed using

an average value of the length or a large value (worst case).

- In a given landfill, the exposed slope sections located near the top of the landfill cover are subjected to greater wind-generated suction than exposed slope sections located near the toe of the landfill cover side slope because the wind-generated suction is greater near the top than near the toe of a structure exposed to wind (Giroud *et al*. 1995). For the sake of safety, and to meet the sixth of the special conditions, the calculations presented in this paper are conducted with the value of the suction at the top of the landfill cover for all slope sections (as explained in Section 2.5).

2.5 *Wind-generated suction*

The following relationship exists between the wind-generated suction and the wind velocity:

$$S = \frac{\lambda \rho V^2}{2} \tag{1}$$

where S is the wind-generated suction, λ is the wind factor defined by Giroud *et al*. (1995), ρ is the density of air, and V is the velocity of the wind. Equation 1 can be used with any set of coherent units. The basic SI units are: S (Pa), ρ (kg/m^3) and V (m/s); λ is dimensionless.

As indicated by Giroud *et al*. (1995), the wind factor, λ, varies typically from 0.55 at the toe of a structure (such as a landfill) to 0.85 at the top. As a result, in detailed design calculations, 0.55 is used for the lower exposed slope section and 0.85 for the higher exposed slope section. However, for feasibility studies or at the preliminary design stage, if one wants to use the simplified methodology presented in this paper, the same value of λ must be used for all exposed slope sections to ensure that the last of the six special conditions presented in Section 2.3 is met. Accordingly, and conservatively, $\lambda = 0.85$ is used for all exposed slope sections.

3 ANCHOR BENCH DESIGN

3.1 *Methodology*

Equations for anchor bench design have been developed by Giroud *et al*. (1999). These equations express the fact that the weight and shear strength of the anchor bench balance the forces exerted by the uplifted geomembrane on the two sides of the anchor bench. However, these equations do not include the uplifting force exerted by the wind directly on the anchor bench. This effect is included in the following equation, which is an improvement compared to the existing methodology and results in safer design.

The equation used herein (and presented in Section 3.2) is applicable only for the case where the special conditions presented in Section 2.3 and discussed in Section 2.4 are met.

3.2 *Equation*

Failure of an anchor bench can be due to uplifting or sliding of the anchor bench. Depending on various parameters, sliding can occur in the upslope direction or, more likely, in the downslope direction. As shown by Giroud *et al*. (1999), sliding is more critical than uplifting, and sliding is more critical in the downslope than in the upslope direction. Therefore, only sliding in the downslope direction is considered herein. The required anchor bench thickness, for the case of sliding in the downslope direction, is given by the following equation (in the case where the special conditions presented in Section 2.3 are met):

$$D_{\text{req}} = \frac{S}{\gamma}\left[1 + \left(\frac{L}{B}\right)\frac{\sin(\beta + \delta)}{\sin \delta}\right] \tag{2}$$

where D_{req} is the required thickness of the anchor bench, S is the wind-generated suction given by Equation 1, γ is the unit weight of the anchor bench material, L is the length of exposed geomembrane measured along the slope, B is the anchor bench width, β is the slope angle, and δ is the interface friction angle along the potential slip surface located below the geomembrane at the anchor bench (e.g. between the geomembrane and the underlying geocomposite, or between the geocomposite and the underlying soil). Equation 2 can be used with any set of coherent units. The basic SI units are: D_{req} (m), S (Pa), γ (N/m^3), L (m), B (m), β (°), and δ (°).

It is interesting to note that the required thickness of the anchor bench depends on the L/B ratio, not on the length of exposed geomembrane, L.

3.3 *Discussion of the equation*

Inspection of Equation 2 shows that the influence of parameters is as follows:

- The required anchor bench thickness is a function of the ratio of the length over which the geomembrane is exposed, L, and the width of the anchor bench, B. (The fact that the parameter is a ratio facilitates parametric studies.) The required anchor bench thickness increases as the L/B ratio increases.
- The required anchor bench thickness is proportional to the square of the wind velocity.
- The required anchor bench thickness increases with increasing values of the slope angle, β. This is because the risk of sliding of the anchor bench increases if the slope angle increases.
- The required anchor bench thickness increases with decreasing values of the interface friction angle, δ. This is because the risk of sliding of the anchor bench increases if the interface friction angle decreases.

4 GEOMEMBRANE BEHAVIOR

The methodology for evaluating geomembrane tension, strain and deflection for an uplifted geomembrane has been developed by Giroud *et al.* (1995). The wind-generated suction is normal to the deflected geomembrane. As a result, the shape of the geomembrane (two-dimensional problem) is circular.

4.1 *Geomembrane tension*

The tension of a deflected geomembrane (Figure 1) is given by:

$$T = \frac{SL}{2 \sin \theta} \tag{3}$$

where θ is the angle between the deflected geomembrane and the plane on which the geomembrane was resting initially (Figure 1). Equation 3 can be used with any set of coherent units. The basic SI units are: T (N/m), S (Pa), L (m), and θ (°).

4.2 *Geomembrane strain*

The strain of a deflected geomembrane is given by:

$$\varepsilon = \frac{\theta}{\sin \theta} - 1 \tag{4}$$

Combining Equations 3 and 4 gives:

$$\varepsilon = \frac{\sin^{-1}\left(\dfrac{SL}{2T}\right)}{\dfrac{SL}{2T}} - 1 \tag{5}$$

For given values of S and L, Equation 5 can be represented by a curve of the strain, ε, as a function of the geomembrane tension, T (Curve (W) in Figure 2). This curve is called the “wind-uplift curve”.

4.3 *Geomembrane deflection*

It is not necessary to calculate the geomembrane deflection, y, to determine the geomembrane tension. However, it may be desirable to calculate the geomembrane deflection.

The geomembrane deflection is given by:

$$y = \frac{1 - \cos \theta}{2 \sin \theta} L \tag{6}$$

The following relationship exists between the geomembrane strain and deflection:

$$\varepsilon = \frac{\sin^{-1}\left(\dfrac{2}{\dfrac{2y}{L} + \dfrac{L}{2y}}\right)}{\left(\dfrac{2}{\dfrac{2}{L} + \dfrac{L}{2y}}\right)} - 1 \tag{7}$$

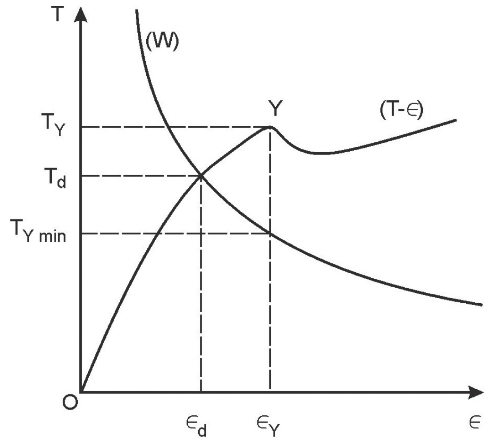

Figure 2. Determination of exposed geomembrane tension and strain at the intersection of the geomembrane tension-strain curve (Curve T-ε) and the “wind-uplift curve” (Curve W). (Note: Y is the yield point of the tension-strain curve.)

4.4 *Determination of tension and strain*

The tension in the deflected geomembrane, T_d, must be determined graphically unless the equation of the geomembrane tension-strain curve is known.

The graphical solution is as follows: (1) draw the tension-strain curve (obtained from tensile tests) of the considered geomembrane in the usual axes (T vertical versus ε horizontal) (Curve (T-ε) in Figure 2); (2) use Equation 5 to draw the “wind-uplift curve”, i.e. the curve of strain, ε, as a function of tension for a generic deflected geomembrane in axes of T versus ε for the considered values of S and L (Curve (W) in Figure 2); and (3) determine the tension in the deflected geomembrane, T_d, and the strain in the deflected geomembrane, ε_d, at the intersection of the two curves.

The graphical method described above, can be implemented analytically if the equation of the geomembrane tension-strain curve is known. The case of parabolic tension-strain curves is addressed in Section 4.5.

4.5 *Parabolic tension-strain curve*

As shown by Giroud (1994) the portion of the tension-strain curve of an HDPE geomembrane between the origin of axes and the yield point (Y in Figure 2) may be represented by a parabolic equation of the Nth degree:

$$\frac{T}{T_Y} = 1 - \left(1 - \frac{\varepsilon}{\varepsilon_Y}\right)^N \tag{8}$$

where T_Y is the tension at yield and ε_Y is the strain at yield of the HDPE geomembrane.

Equation 8 is the equation of the geomembrane tension-strain curve, with axes of T versus ε. The geomembrane tension-strain curve and the "wind-uplift curve" (the curve of ε as a function of T given by Equation 5) are drawn on the same graph. The intersection of these two curves gives the tension in the deflected geomembrane, T_d, as illustrated in Figure 2. Analytically, this is achieved by combining Equations 5 and 8 with $T = T_d$, hence:

$$\frac{T_d}{T_Y} = 1 - \left\{1 - \left(\frac{1}{\varepsilon_Y}\right)\left[\frac{\sin^{-1}\left(\frac{SL}{2T_d}\right)}{\frac{SL}{2T_d}} - 1\right]\right\}^N \tag{9}$$

The tension in the deflected geomembrane, T_d, is obtained by solving Equation 9 iteratively. The strain in the deflected geomembrane, ε_d, is then derived from the tension, T_d, using Equation 8 with $T = T_d$.

Equation 9 can also be written as a function of the angle θ_d, which provides an elegant way of solving the problem. Combining Equations 3 (with $\theta = \theta_d$) and 9 gives the following equation:

$$\frac{SL}{2T_Y \sin\theta_d} = 1 - \left[1 - \left(\frac{1}{\varepsilon_Y}\right)\left(\frac{\theta_d}{\sin\theta_d} - 1\right)\right]^N \tag{10}$$

where θ_d is the value of the angle θ that corresponds to the tension T_d and S is given by Equation 1.

The angle θ_d is obtained by solving Equation 10 iteratively. Then, the tension of the deflected geomembrane, T_d, is derived from θ_d using Equation 3, the strain of the deflected geomembrane, ε_d, is derived from θ_d using Equation 4, and the relative deflection, y/L, is derived from θ_d using Equation 6.

In conclusion, the problem can be solved by using either Equation 9 or Equation 10. In both cases the solution is obtained iteratively.

It should be noted that Equations 9 and 10 cannot be solved for values of the geomembrane tension, T_d, greater than T_Y (or values of the strain greater than ε_Y, which is equivalent). The reason is the following. The left side of any of these two equations is equal to T_d/T_Y while the right side is smaller than 1. Graphically, this means the equation cannot be solved if Curves (1) and (2) of Figure 2 do not meet (or meet for values of the strain greater than ε_Y, which is irrelevant).

4.6 *Factor of safety*

The geomembrane factor of safety can be calculated using the following equation:

$$FS = \frac{T_Y}{T_{Y\min}} \tag{11}$$

where $T_{Y\min}$ is the geomembrane tension at yield that would give a factor of safety of one, assuming that the geomembrane strain at yield, ε_Y, is the same for the actual geomembrane (i.e. the geomembrane having a tension at yield equal to T_Y) and the fictitious geomembrane having a tension at yield equal to $T_{Y\min}$ (Figure 2). Using Equation 5 with $\varepsilon = \varepsilon_Y$ and Equation 11 it is possible to demonstrate that the factor of safety defined by Equation 11 is equivalent to a factor of safety on suction.

5 CASE HISTORY

5.1 *Description of the case*

The methodology presented above was used for the first time to design a landfill cover to be constructed in a South Pacific island subjected to high-velocity winds. The design example presented below is based on the design of this project. The geomembrane considered for this project is an HDPE geomembrane, selected in part for its proven durability. This geomembrane will be covered with a geogrid to foster the growth of climbing plants that will protect the geomembrane from direct exposure to sunlight.

5.2 *Numerical values of parameters*

The following numerical values are used:

$\rho = 1.293$ kg/m^3 (air density at sea level and 0°C).
$\gamma = 18$ kN/m^3 (soil unit weight in anchor bench)
$V = 76$ m/s = 273.6 km/h = 170 miles/hour
$L = 10$ m $B = 6$ m
$\beta = \tan^{-1}(0.5) = 26.57°$ $\delta = 20°$

5.3 *Geomembrane properties*

The geomembrane considered herein is an HDPE geomembrane with a thickness of 2 mm. Based on test data for several geomembranes, the following average tensile characteristics were considered in the machine direction under plane strain biaxial conditions: tension at yield, $T_Y = 29$ kN/m, and strain at yield, $\varepsilon_Y = 18\%$, at a temperature of 50°C.

The temperature of 50°C is used because this is the expected temperature of the geomembrane protected by vegetation. Thermal expansion of the geomembrane is conservatively neglected, as it would decrease the geomembrane tension. Geomembrane properties at other temperatures were also used in the design, including 0°C as an attempt to simulate the geomembrane behavior under the action of gusts of wind, since thermoplastic polymers become stiffer under low temperatures as they do under rapid loading.

As indicated in Section 4.5, the tension-strain curve of an HDPE geomembrane can be represented by an N-order parabola. An analysis of tension-strain curves of HDPE candidate geomembranes showed that an adequate value of the exponent for these geomembranes is approximately $N = 3.5$.

5.4 *Results*

The following results were obtained using the equations presented in this paper:

$S = 3174$ Pa $\quad D_{req} = 0.80$ m
$\theta_d = 38.7°$ $\quad y = 1.76$ m
$T_d = 25.4$ kN/m $\quad \varepsilon_d = 0.080 = 8\%$
$T_{Y\min} = 19.1$ kN/m $\quad FS = 1.52$

This is only an example of the many similar calculations that were performed for the design of this project. Thanks to the simplicity of the methodology described in this paper, it was possible to perform systematic calculations covering a wide range of parameter values.

5.5 *Discussion*

The uplifting of the geomembrane is likely to disturb the vegetation growing along the geogrid located on top of the geomembrane. Also, repeated uplifting may cause fatigue of the geomembrane and its anchors. Therefore, it is preferable not to allow the geomembrane to be uplifted every time the wind blows.

Stabilization of the geomembrane up to a certain wind velocity can result from the suction exerted under the geomembrane by landfill gas extraction. The gas extraction system in the considered landfill has been designed to apply a vacuum of at least 51 water-mm (500 Pa) below the geomembrane. Based on Equation 1, this suction should prevent geomembrane uplifting by wind having velocities up to 30 m/s (approximately 110 km/h). In the case of wind exceeding 110 km/h the geomembrane can be expected to be uplifted. Furthermore, it can be assumed that, during periods of high-velocity winds (e.g. major storms such as typhoons), electric power supply may be disrupted and the gas extraction system may not function.

Based on the wind data in the island available to the design engineers (January 1997-March 2005), wind gusts exceeding 110 km/h have been measured only in 1997 (4 days), 2000 (1 day) and 2002 (5 days), hence 10 days over 3012 days. Therefore, the anchor benches designed as explained in this paper are expected to be needed only on a limited number of days during the service life of the landfill cover.

The geogrid strength is not taken into account for the sake of conservatism, and because adjacent geogrid panels are not laterally connected, which limits their ability to restrain the geomembrane.

6 CONCLUSIONS

The design of anchor benches for geomembranes exposed to wind uplift depends on the geomembrane behavior, which is not convenient for feasibility studies or preliminary design, i.e. at a stage when several candidate geomembranes are still being considered. If the special conditions presented in Section 2.3 are met, a simplified methodology can be used where the anchor bench design is independent of the geomembrane behavior. The special conditions are likely to be met in the case of landfill covers that consist of multiple exposed slope sections separated by anchor benches.

With the simplified methodology, it is easy to conduct parametric studies to determine for which range of parameters (L, B, D, β) it is possible to find a viable solution (i.e. a solution such that the anchor bench thickness is not excessive and a commercially available geomembrane can withstand the calculated tension). Thus, the simplified methodology presented in this paper is a suitable tool for preliminary design and feasibility studies.

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