Repairs on exposed geomembrane liners

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ABSTRACT: The default position for high quality geomembrane liner installations is to not allow large patches on exposed HDPE geomembrane lined slopes. The concern is around stress cracking over time due to liner degradation and potential high loads from wind uplift and thermal movement of the liner. The potential rejection of slope panels can have serious program and cost implications on projects. This paper presents on some 3D strain and stress modelling conducted on a geomembrane lined slopes which considers the geometric details of the panel welds of large patches on the slope. The conclusion of the modelling show that under certain conditions the conventional approach to repairs on slopes may be modified.

Keywords: geomembrane, slopes, repairs, deformation, strains

1 INTRODUCTION

Geomembranes are low permeability materials used in solid waste, liquid and gas containment. Geomembranes may be constructed from a variety of polymers, including high density polyethylene (HDPE) and linear low density polyethylene (LLDPE) to name two.

HDPE is a commonly used polymer for waste and liquid containment due to its high chemical and UV resistance and is often used in exposed applications on slopes such as pond embankments, landfill side liners and tailings storage facilities. However, the semi-crystalline micro structure of the material which results in the chemical resistance of the material also means that HDPE geomembrane liner is susceptible to stress cracking. Additionally, the manufacturing process and density of HDPE means that large prefabricated panels are generally not feasible to form and therefore substantial lengths of field welding is required.

During installation and welding of high quality HDPE geomembrane liner, the default position is to not allow large repair patches on exposed lined slopes. The concern is around stress cracking over time due to liner degradation and potentially high loads from wind uplift and thermal movement of the liner. However, unforeseeable circumstances during and after installation of HDPE geomembrane liner can result in damage to installed geomembrane panels on slopes. Replacing the complete panels can have significant program and cost implications on projects.

The results of large strain finite element analyses using the computer modelling software Plaxis 3D are presented in this paper. This program was adopted based on its capacity for three-dimensional analysis with large strain deformation. The analysis considers the geometric details of the welds of large patches installed on exposed geomembrane lined slopes.

HDPE has been selected for this assessment based on the products popularity due to its mechanical properties and relatively low cost, compared to other geomembrane liners.

2 STRAIN AND STRESS CRACKING

Yield is the point where a material begins plastic deformation under an applied load. This is an important parameter for HDPE geomembrane liner as it typically represents the practical limit of use, as opposed to the ultimate break point. Yield properties of geomembrane liner depend on the polymer crystallinity as well as the polymer morphology. HDPE geomembrane liner exhibits a distinct yield point in its uniaxial tensile stress/strain curve typically at around 12 % strain. Up to this point HDPE behaves elastically without damage to the polymer's micro-structure for short term loading.

Stress cracking in geomembrane is caused when a stress is applied to the crystalline structure of the HDPE material, allowing the microstructure to separate. This separation means the material can break suddenly (i.e. crack) without yielding or elongation. Most commercial forms of HDPE used for the manufacture of geomembrane exhibit stress cracking at strains below the yield point of the material. Initiation of stress cracking may be influenced by the presence of welds, where scratches or heat affected zones may have degraded the liner. Some HDPE geomembrane resins are now manufactured to have comparatively good stress crack resistance properties.

To reduce the risk of stress cracking, design with medium to long term life should consider limiting the geomembrane strain to less than the yield strain and selecting materials with high stress crack resistance.

The following table has been reproduced from Peggs et al. (2005), and provides a guide to the general industry for suggested strain limits for different geomembrane liners.

Table 1. Typical maximum allowable geomembrane strains (Peggs et al. 2005.)

Geomembrane Type	Maximum allowable strain (%)
HDPE smooth (SCR*< 1500 hr)	6
HDPE smooth (SCR > 1500 hr)	8
HDPE randomly textured	4
LLDPE, density <0.935 g/cm3	12
LLDPE, density >0.935 g/cm3	10

* SCR – stress crack resistance

3 STRAIN CONCENTRATIONS AT WELDS

The effects of stress cracking and liner degradation are particularly relevant at welds of repair patches. The procedure of welding can cause liner degradation from scratching during preparation and/or heating during the welding process. Stresses acting on geomembrane welds have been previously assessed by others including Zhang et al. (2017), Giroud et al. (1995a) and subsequently by Kavazanjian et al. (2017). Zhang et al. noted that overheating associated with wedge welding can lead to accelerated consumption of antioxidant reserves within the geomembrane, which can increase the risk of stress cracking at the location of the seam. As documented by Giroud et al. (1995a) the change in geometry at the location of a weld can result in localized increased strains adjacent to the weld. Hence, welds are generally considered regions of high stress concentration and are often the weakest points of an installed geomembrane liner.

Giroud et al. (1995a) demonstrated that two geomembrane panels of constant thickness and loaded in tension, bend at the weld to remain co-planar. This bending results in additional incremental tensile strains adjacent to the weld. Giroud et al. (1995a) developed equations for estimating these average tensile strains adjacent to the welds.

Through digital image correlation (DIC) on weld specimens tested in a wide-width tensile testing apparatus, Kavazanjian et al. (2017) showed the average tensile strain concentrations adjacent to a weld loaded uniaxially were reasonably close to the average strain concentrations estimated by Giroud et al (1995a). Due to variation in the weld process, Kavazanjian et al. (2017) also showed the maximum localised strains adjacent to the welds were significantly greater than predicted using the Giroud et al. (1995) equations. The methods adopted by both Giroud et al. (1995a) and Kavazanjian et al. (2017) are based on tensile stresses applied to the weld in a uniaxial direction. In assessing the maximum localised strains adjacent to the welds, Kavazanjian et al. (2017) developed factors for application to the average stresses, to reflect the peak stresses. In particular, Kavazanjian et al. (2017) developed strain concentration factors which represent the ratio of maximum strain adjacent to the seam measured using DIC to the theoretical strain adjacent to the seam calculated using Giroud et al. (1995) equations. Based on the DIC image test results for laboratory welded samples by Kavazanjian et al. (2017), a strain concentration factor of 1.6 was applied to fusion welds and a strain concentration factor of 2.0 was applied to extrusion welds.

To assess whether installing repair patches on geomembrane slopes induces unacceptably high strains at the welds, a large strain finite element analysis was conducted for two different types of large patches on a slope. The theoretical equations by Giroud et al. (1995a) and strain concentration factors developed by Kavazanjian et al. (2017) were then applied to the strain outputs of the finite element analysis.

4 WIND LOADING

Geomembrane uplift by wind is often observed on exposed geomembrane liners and is the main loading condition considered in this paper. Note, only wind uplift by suction has been considered, as opposed to wind uplift from beneath the geomembrane liner.

Using the methods presented by Giroud et al. (1995b) the pressure variation, or suction on an exposed geomembrane liner can be estimated with the following equation:

$$Se = -\Delta\rho R = 0.05\lambda * V^2 e^{-(1.252x10^{-4})z} - 9.81\mu_{GM}\, g \tag{1}$$

Where S_e = suction, $\Delta_{\rho R}$= reference pressure variation (Pa), λ = suction factor, v = wind velocity (m/s), z = altitude above sea level (m), μ_{GM} = mass per unit area of the geomembrane liner (kg/m^2), g = acceleration due to gravity (m/s^2).

As shown, suction is dependent on the site elevation, wind velocity and the weight of the geomembrane liner. Small increases in velocity can result in large increases in suction. The effects of wind suction are the greatest at the crest of a slope.

For suction to occur on geomembrane liner, sustained wind loads are required and therefore slower wind velocities may be adopted compared to designing against wind gusts. For the purpose of this assessment a design wind velocity of 65 km/hr has been adopted. This is based on a long term exposure period in a relatively temperate climate not subject to tropical cyclones or high wind events. The selection of the design wind speed must be assessed based on the site location, climate and the level of risk willing to be accepted in terms of geomembrane movement due to wind uplift. Using the methods described by Giroud et al. (1995b), a design wind velocity of 65 km/hr results in net suction pressure on the geomembrane liner of approximately 130 Pascals (Pa), for a 2 mm thick HDPE geomembrane liner with a density of 0.94 g/cm^3.

This estimated suction was used in the finite element analysis model to assess the tensile forces and strains acting on the geomembrane liner. Note, the tensile forces are directly related to the slope length of the exposed liner and are therefore specific to the adopted slope geometry in this paper.

5 MODEL SET-UP

Fusion and extrusion welds are the two welding processes typically employed to join two HDPE geomembrane panels in the field. Fusion welds connect the two geomembrane panels using heat and pressure to fuse the two panels together. Extrusion welds include grinding the surface and the application of extrudate material to join the two panels together. This paper considers dual wedge fusion welds and extrusion fillet welds as they are the two most commonly used weld types in the installation of HDPE geomembrane liners.

Fusion welding is the preferred welding method of the two, based on consistency and weld strength. The quality of an extrusion fillet weld depends on surface preparation, heating consistency, extrudate thickness, and equipment placement, which are all dependent on the weld operator. Additionally, as noted by Scheirs (2009) the extrusion fillet welding method creates a large heat affected zone adjacent to the weld when compared with wedge welding. These factors contribute to the potential for strain concentrations and/or liner degradation adjacent to the welds.

The finite element analysis model was used to assess the tensile forces in geomembrane slope panels subject to wind loading. The slope was modelled as 40 m in length with a batter grade of 1V:3H. The model set-up also included two large repair patches installed on a slope. Patch A is the larger of the two and was modelled as 35 m in length and 5.0 m in width, and was located across a cut out fusion weld between two panels. Patch B was modelled as 25 m in length and 2.0 m in width, located in the middle of a slope panel. The model set-up is shown on the graphic output in Figure 1.

The finite element analysis model was set-up with 200 mm overlaps at the panel or patch edges comprising two layers of geomembrane liner with no thickness reduction. Therefore a 2 mm sheet was modelled as 4 mm thick at the location of the overlap. This represents the overlap zone required to form the weld and not the dimensions of the welds themselves.

As noted by Giroud et al. (1995a) and Kavazanjian et al. (2017), strain concentrations adjacent to a weld are localised and depend on the weld type and thickness. Therefore, the outputs from the finite element analysis were then used to assess the strains adjacent to the patch welds using the equations and factors presented by Giroud et al. (1995a) and Kavazanjian et al. (2017). As the intent of this paper is to assess the effect of installing patches on exposed geomembrane slopes, the effects of weld variability has not been assessed. Therefore, for consistency the same weld dimensions for fusion seams and extrusion seams, respectively have been adopted in the analysis of maximum strains adjacent to the seam when using the Giroud et al. (1995a) equations.

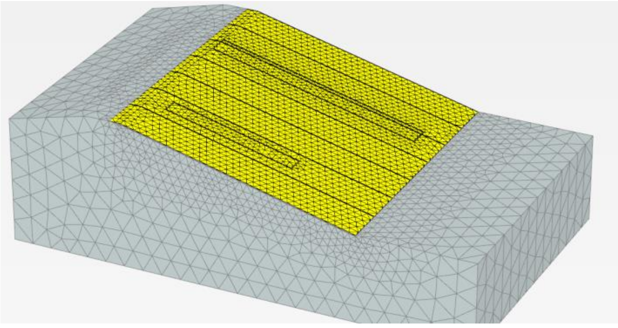

Figure 1: Finite element analysis model set-up for a slope geomembrane with two large patches

6 RESULTS OF FINITE ANALYSIS MODELLING

The analysis was undertaken for three scenarios, as listed:

- Scenario A - a single geomembrane panel with no patches. Panel width 7.0 m and panel length (i.e. length of slope) is 40 m.
  This scenario was modelled to gain an understanding of the forces acting on a slope panel installed with no patches.
- Scenario B – Patch A installed over the weld of two adjoining geomembrane panels.
  The top of the patch terminates at 0.5m from the crest of the slope. The weld between the two panels under the patch is removed in the model, as per best practice in the field.
- Scenario C – Patch B installed within the sheet of the original panel. The top of the patch terminates at 5.0 m from the crest of the slope.

The three scenarios were assessed with two different material thicknesses, 1.5 mm and 2.0 mm. The material thicknesses were selected as they are commonly selected material thicknesses in exposed geomembrane liner applications.

In Scenario A, the 2.0 mm thick geomembrane liner was assessed to lift off the subgrade surface by approximately 4.2 m when subjected to wind loading. This resulted in a maximum tensile principal stress in the geomembrane liner of 10.3 kN/m. This distribution of stresses is shown on the graphic output of Figure 2. Assuming a geomembrane liner of 31 N/mm tensile strength at 12 % strain, this is equivalent to a short term maximum average strain of approximately 4.0 %. As noted in Section 2.0, a strain limit between 4 % and 6 % may be applicable for contemporary smooth and textured HDPE geomembrane.

As shown in Figure 2, the maximum tensile stress occurs in the slope geomembrane liner at the crest of the slope where there is a change in slope geometry. This also coincides with the section on the slope where the effects of wind suction are the greatest. When assessing the stresses in the geomembrane liner across the remaining portion of the panel (i.e. excluding the effects of the crest and toe) the average principal stress is closer to 4.0 kN/m.

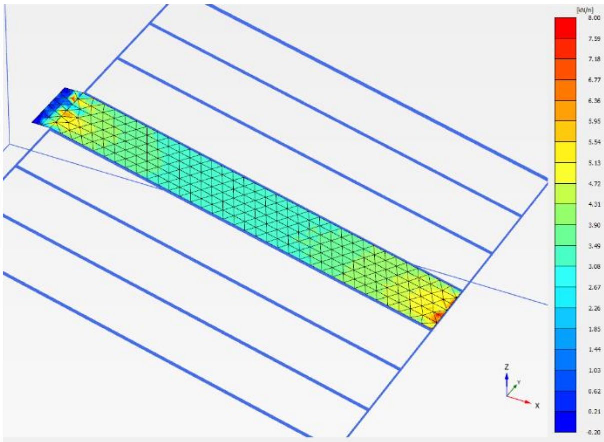

Figure 2: Graphic output of tension forces for typical slope geomembrane panel subjected to wind loading

The outputs from the finite element analysis indicate varying distribution of tensile loads acting on the respective patches. Red indicates a higher tensile load and blue is a lower tensile load.

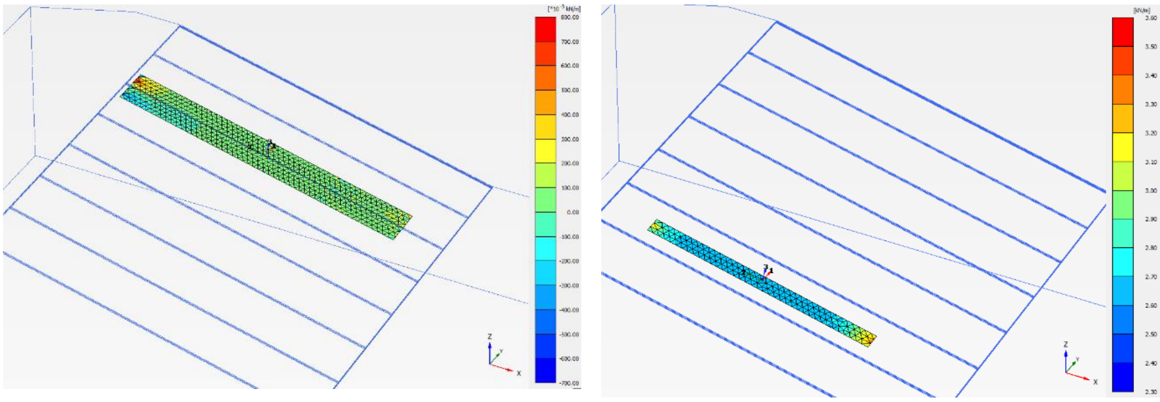

Figure 3: Graphic output for distribution of tensile loads at Patch A and Patch B, respectively

Based on the results presented in Figure 3, the finite element analysis indicates the following:

1. The tensile loads at the ends of Patch A include significant shear and lateral loads due to the re-distribution of loads and strains related to the higher stiffness of the welds relative to the sheet and patch. The maximum localised principal tensile strain during design wind events adjacent to the weld may be up to 2.0 %, assuming 2.0 mm thick geomembrane liner.
   Between its ends, the patch is at a strain of approximately 1.2 %, which is approximately equivalent to a geomembrane panel without patches.
2. The maximum localised principal tensile strain during design wind events at the ends of Patch B may be up to 1.4 %. This indicates the loads and strains in the smaller patch located within a panel are less than the loads and strains in the larger patch located across two panels.
   Between the ends of the patch the patch is at a strain of approximately 1.1 %, which is slightly less than both the larger patch installed across two panels and a geomembrane panel without patches.

Large patches installed across two panels on slope geomembrane liner result in changed local loads in the geomembrane panels compared to panels without patches. The location of the patches effects the resulting strains, as shown in Figure 3. In particular, the cross weld of Patch A results in significantly increased stresses at the intersection with the fusion weld of the two panels.

The estimated tensile forces and corresponding principal tensile strains are summarised in Table 2 for the different patch sizes.

Table 2:Typical strains assessed using finite element analysis (2 mm thick geomembrane liner)

No.	Item	Principal Tensile Load (kN/m)	Strain (%)
1	Panel (at the crest) 2 mm	10.3	4.0
1a	Panel (along the slope) 2 mm	4.0	1.6
2	Patch A, 2 mm	5.1	2.0
3	Patch B, 2 mm	3.6	1.4

As shown in Table 2, the maximum tensile load in the geomembrane liner is estimated to be approximately 10 kN/m for a typical geomembrane panel installed on a slope. This high load is associated with the crest and therefore the average tensile load across the panel itself is closer to 4.0 kN/m. The associated strains are approximately 4.0 % and 1.6 % respectively. For Patch A, the maximum tensile load is 5.1 kN/m with an associated strain of 2.0 %. The tensile strength of the assessed geomembrane liner is 31 kN/m. Therefore, the estimated tensile loads represent geomembrane liner stressing between 11 % and 30 % of the yield strength.

The geomembrane liner of 1.5 mm thickness returned similar results to the 2.0 m thick geomembrane liner and is due to the marginal difference in material thickness. The difference strains between Patch A and Patch B is considered to be a result of the patch geometries, as Patch A is likely pulled in multiple directions where the end of the patch intersects with the previously installed fusion weld of the two underlying panels. The increased thickness of geomembrane liner at this location is estimated to attract approximately double the load.

7 ANALYSIS

As noted in Section 2.0, published data indicates strains are locally higher adjacent to welds than in the geomembrane sheet itself.

Based on the assessed strains in the repair patches, the equations by Giroud et al. (1995a) were applied to assess the potential average strain concentrations adjacent to welds for fusion and extrusion fillet welds.

For a 2.0 mm thick panel of geomembrane liner with an estimated strain of 1.6 % perpendicular to the weld, the theoretical strains estimated by Giroud et al. (1995a) indicate a strain concentration adjacent to the weld of approximately 3.1 % for a fusion weld and 3.8 % for an extrusion fillet weld. Applying the same principles to Patch A and Patch B of different material thicknesses, the maximum localised strain concentration was assessed to occur adjacent to an extrusion weld on Patch A of 2 mm thickness, with an estimated strain of 4.6 %. A summary of the estimated localised strains adjacent to the welds for different weld types is provided in Table 3.

Table 3: Estimated strains at welds due to bending using Giroud et al. Equations

No.	Item	Estimated maximum tensile (%)	Estimated strain concentration at fusion weld (%)	Estimated strain concentration at extrusion weld (%)
1	Panel*	1.6	3.1	3.8
2	Large Patch	2.0	3.8	4.6
3	Small Patch	1.4	2.8	3.4

*assessed within the panel along the slope and not at the crest or toe line

The maximum localised strain concentrations adjacent to a weld were also estimated using the adopted factors provided by Kavazanjian et al. (2017) and as summarised in Section 3.0. With these factors, localised maximum strain concentrations as high as approximately 9 %for the patch welds were estimated. This is particularly important for the ends of the patches, where the welds are perpendicular to the applied wind load and the patches are finished with an extrusion weld.

Table 4: Estimated strains at Welds using Kavazanjian et al. factors

No.	Item	Estimated maximum tensile (%)	Estimated peak local strain adjacent to fusion weld (%)	Estimated peak local strain adjacent to extrusion weld (%)
1	Panel	1.6	5.0	7.6
2	Patch A	1.9	6.0	9.0
3	Patch B	1.4	4.4	6.8

The results in Table 3 and Table 4 indicate a maximum strain adjacent to an extrusion weld of 9.0 % for Patch A and 6.8 % for Patch B. The maximum strain reported for the slope panel (i.e. not at the crest) is 7.6 %. However, extrusion welding on a typically installed panel may not be required and therefore a maximum strain adjacent to a fusion weld of 5.0 % may be more realistic. Therefore, installing patches on slope geomembrane liner may result in reduced strains as the increased material thickness at the longitudinal fusion welds distributes the loads across the welds, as shown with the results of Patch B. However, the strains have been assessed for the sides of the panels, where the welds were modelled as two layers of geomembrane liner. The strains are estimated to be higher for Patch B, at the junction between the patch welds and the fusion weld of the two underlying panels where the tensile forces act in multiple directions. For Patch A, this may also occur near the crest, where the effects of wind suction are the greatest.

The assessment also indicates that average localised strains adjacent to the weld subject to wind loading are less than the yield strain of geomembrane liners, using the Giroud et al. (1995a) equations. The localised maximum strains, as assessed by Kavazanjian et al. (2017), are considered to be high and approaching the tensile yield strain of HPDE geomembrane liners.

These results will be different for different slope and patch layouts, or wind velocities.

8 ALTERNATIVE GEOMEGRANE MATERIALS

Based on the results of the finite element analysis model assessment, strains adjacent to welds on exposed geomembrane lined slopes can be high. In these applications, consideration may be given to alternative geomembrane liners, which are less susceptible to stress cracking.

In the case of water containment facilities, where strong chemical resistance is not required, linear low density polyethylene (LLDE) geomembrane liner may be a more suitable material. Note, the UV resistance of LLDPE is generally less than HDPE and therefore if exposed, may have a shorter design life.

9 CONCLUSION

The results of finite element analysis modelling indicate installing patches on exposed slope geomembrane liner may result in both lower and higher local strains compared to unpatched slope liner. The lower strains are considered to be the result of additional longitudinal welds on the slopes, from the patches, where the thickness of the geomembrane may approach double the geomembrane panels. These thicker portions of the liner carry a higher portion of the load.

The estimated maximum principal strains are considered to be at the upper end of suggested limits for sustained wind loads on the geomembrane liner, but may be acceptable for smooth geomembrane liner under short term loading. This is strongly linked to the quality of the geomembrane material, and welding of seams and patches.

As extrusion welds result in higher stress concentration when compared to fusion welds, large patches should be installed with the fusion welding method to the extent practical. It is noted the ends of larges patches are generally finished off with some unavoidable extrusion welding. As the stresses are the highest at the crest of the slope, terminating patches at the crest line should be avoided.

The effects of wind loading on slope geomembrane liner for an unpatched panel are considered to be relatively similar for a large patch installed on a slope. However, the effects of wind loading are considered to be critical where there is an intersection in welds. This coincides with the location of extrusion welds at the end of the patch and a large heat affected zone. The heat affected geomembrane liner in this zone is more susceptible to loading, so its permissible strain may need to be reduced when compared to the typical values provided by Peggs et al. (2005) and summarised in Table 1. Based on current knowledge the strain limits suggested by Peggs et al. (2005) are applied to welded portions of geomembrane liner.

If large patches are proposed to be installed on exposed geomembrane slopes, consideration should also be given to the length of the slope, the effects of wind loading and the type of weld selected. In many situations the installation of large patches on exposed geomembrane lined slopes can be accepted.

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