Recommendations for Design of Exposed Geomembrane-Lined Ponds to Control Uplifting Gas Pressures

R. Thiel
Thiel Engineering, USA (richard@rthiel.com)

ABSTRACT: Ponds lined with an exposed geomembrane commonly experience uplift pressure from gases. These pressures can uplift the geomembrane in the form of "bubbles" or "whales". This paper draws on results from previous studies to evaluate the transmissivity requirements for underdrains to relieve gas pressure, and presents a method to calculate the force required to move geomembrane gas bubbles laterally when underdrains are not present or functioning. A method is presented to estimate the unbalanced hydrostatic force, caused by a sloped pond bottom, which would be exerted on a geomembrane bubble. Recommendations are presented for minimum reliable pond bottom slopes to induce bubbles to move to the perimeter slope where they can be vented. The paper is concluded with a summary of practical design and operational considerations for dealing with gas pressures below exposed geomembrane pond liners.

Keywords: pond, geomembrane, uplift, underdrain, vents

1 INTRODUCTION

Using geomembranes to provide liquid containment in ponds is perhaps the oldest and first use of geomembranes, with significant use being developed in the 1950's (Kolbasuk, 2004). Koerner (1994) suggests that the term "geomembrane", first proposed by Giroud and Perfetti (1977), superseded the original term of "pond liner". There is a substantial legacy of literature devoted to the design, construction, and operation of geomembrane-lined ponds, with perhaps the best and most complete reference being 33 years old by Giroud (1983). Even with this long history there continue to be problems and failures with lined ponds. One of the problems continuing to plague the industry is that of uplifted geomembrane gas bubbles, also called "whales" or "hippos", which do not go away in ponds that have an exposed geomembrane.

Many ponds are constructed with exposed geomembranes to contain fluids. Un-ballasted geomembranes are susceptible to uplift by fluid pressures from below. The uplifting fluid pressures can be caused by either liquids (e.g. high ground water) or gases, and sometimes both. The design solutions for liquid uplift are different from, but can potentially overlap, the design solutions for gas uplift. Common design solutions for both liquid and gas uplift pressures can include the use of ballast on top of the geomembrane, and underdrains below the geomembrane. The subject of this paper is focused on gas uplift, and no further discussion of design considerations for the control of uplift pressures by liquids are included herein. The reader is referred to other literature such as Giroud (1983), Peyras and Mériaux (2009), or Firestone (2013) for liquid uplift considerations.

The subject of this paper is focused on ponds with exposed geomembranes that are not ballasted. Certainly ballast, such as a soil layer, would be an effective method to control gas uplift pressures, especially considering the relatively low pressure that is anticipated to exist in the majority of gas bubbles. That being said, there are many reasons that owners and operators often prefer not to place ballast on top of the pond liners including cost, ease of cleaning and removal of sludge, and accessibility for making repairs. The fact is, however, that there are many geomembrane-lined ponds, perhaps the majority, which are un-ballasted. As such, this paper is devoted to ponds with exposed geomembranes, and no further discussion of ballast is included herein.

The origin of gases below geomembranes can include air that is initially trapped below the geomembrane during installation, air in the soil that is moved upwards as a result of rising ground water, gases generated by decomposition of organic materials existing in the subgrade, or gases caused by chemical and organic reactions of fluids that are either pre-existing in the ground or leak from the pond through defects in the geomembrane. If the gases below the geomembrane are not able to be vented, then gas bubbles often form under the geomembrane, and have been reported as a problem in the literature for over 30 years (e.g. Giroud and Goldstein, 1982; Giroud, 1983; Koerner, 1994; EPA, 1991, Sharma & Reddy, 2004; Wallace et al. 2006; Peggs, 2006a and 2006b). Specific problems that occur due to these bubbles include a) the loss of effective pond volume above the geomembrane, b) opening up of greater areas of subgrade infiltration to leakage that may occur through defects in the geomembrane, c) increased susceptibility of the geomembrane to mechanical damage caused by raising the geomembrane closer to or above the pond liquid surface, d) poor aesthetics for decorative ponds, and e) debilitating stretching of the geomembrane due to the stresses and strains caused by the gas pressure, even to the point of bursting the geomembrane.

A dramatic example of a large bubble took place in a wastewater effluent project in Southern California, in which 33 ha ponds with flat bottoms were constructed on silty fine sand well above ground water. The construction of a single HDPE geomembrane liner for these ponds resulted in significant trapped air whose pressure could not be relieved through the underlying soils that were saturated with capillary-held construction water, and were thus relatively impermeable to the passage of air. During the filling of these reservoirs the trapped air coalesced into several large bubbles (Figure 1). Because of anchor trenches in the pond bottom, which were designed to resist wind uplift when the reservoirs are empty, there was no possibility of "walking" the bubbles to the slopes for venting. The bubbles had to be pierced and vented with specially designed vents. Once vented, though, the bubbles never returned.

There are many instances (both published and unpublished) of gas being trapped below liners in wastewater ponds as a result of biologically-active liquid that gets between the geomembrane and the underlying subgrade, usually via leaks in the geomembrane. This is discussed in the references by Peggs (2006).

Another potential mechanism for air collection below liners that is discussed in references going back to the early 1980's (e.g., Giroud and Goldstein 1982) is the cyclic rise and fall of ground water. This mechanism, however, is difficult to prove, but conservative project-specific estimates could be calculated.

While most of the literature references cited above recognize the problem with gas bubbles under geomembranes, the design solutions proposed in the references all have one or more of the following deficiencies: lacking specificity; lacking quantified design approach that could support a design basis; incomplete recognition of other circumstances that may defeat the design goal; or containing errors in assumptions or concept.

The subject of the remainder of this paper provides: guidelines and references for the design of underdrain venting to control uplift from gases in ponds with exposed geomembranes; equations to calculate the force required to move bubbles laterally when underdrains are either not present or do not function; and equations and guidance to specify the minimum pond bottom slope needed to create the unbalanced hydrostatic forces required to induce bubbles to move to the perimeter slope where they can be vented.

Figure 1: Example of large geomembrane gas bubble (note people in photo for scale).

2 UNDERDRAIN DESIGN FOR GAS VENTING

2.1 *Terminology regarding "underdrain"*

The term "underdrain" is used in many non-consistent ways in the literature. In this paper "underdrain" denotes a transmissive layer below a geomembrane. Because this paper is focused on the technical aspects of relief of gas pressures below a geomembrane, the functional term "underdrain" is used for any drainage layer below a pond geomembrane regardless of whether it is a primary or secondary drainage layer in a single- or double-lined pond. It is left to the designer to understand the mechanics of the design, and then adopt design-specific nomenclature for their project.

2.2 *Pressure range of geomembrane gas bubbles*

The magnitude of the stresses and strains experienced by geomembranes bubbles inflated with gas is not intuitively apparent, and is lower than often presumed. The first attempt to analytically estimate the internal pressure of geomembrane bubbles was presented by Thiel (2016). Starting with an observed diameter of a bubble at the water surface and an assumed state of stress-and-strain in the geomembrane, Thiel (2016) derived equations to estimate the depth of water surrounding the bubble that would exert hydrostatic pressures on the outside of the bubble to balance the calculated internal bubble pressure needed to develop the assumed stress-strain state in the bubble. The method also predicts the bell-shaped profile of the entire bubble shape, illustrated in Figure 2. Using an iterative calculation technique, Thiel (2016) developed the following examples of bubble diameters and water depths that would be associated with the requisite bubble pressure, stress, and strain states for 1.5 mm HDPE geomembrane:

- For an "allowable" state of 3.7% strain and 6,500 kPa tensile stress in the geomembrane (these and other stress-strain combinations used in this paper are slow-strain multiaxial-test values taken from Norbert, 1993), apparent bubble diameters at the water surface (dimension *B* in Figure 2b) ranging from 3.9 to 33 m would occur due to a water depth, *H*, ranging from 0.83 to 0.50 m, respectively. The base bubble footprint diameters, equal to the dimension *D* in Figure 2b, for these cases ranged from 8.5 to 36 m, and had internal pressures ranging from 4.2 to 0.53 kPa, respectively.

- For an "ultimate" state, which could imply imminent bursting of the geomembrane, of 12.4% strain and 10,000 kPa tensile stress in the geomembrane, apparent bubble diameters, *B*, at the water surface ranging from 0.88 to 33 m would occur due to a water depth, *H*, ranging from 2.2 to 1.1 m, respectively. The base bubble footprint diameters, *D*, for these cases ranged from 8.9 to 36 m, and had internal pressures ranging from 13 to 1.4 kPa, respectively. Note that "ultimate state" stress-and-strain combination is for the free-field geomembrane. Stress concentrations caused by complicated seam geometries, or weak seams, may result in bursting at even lower strains.

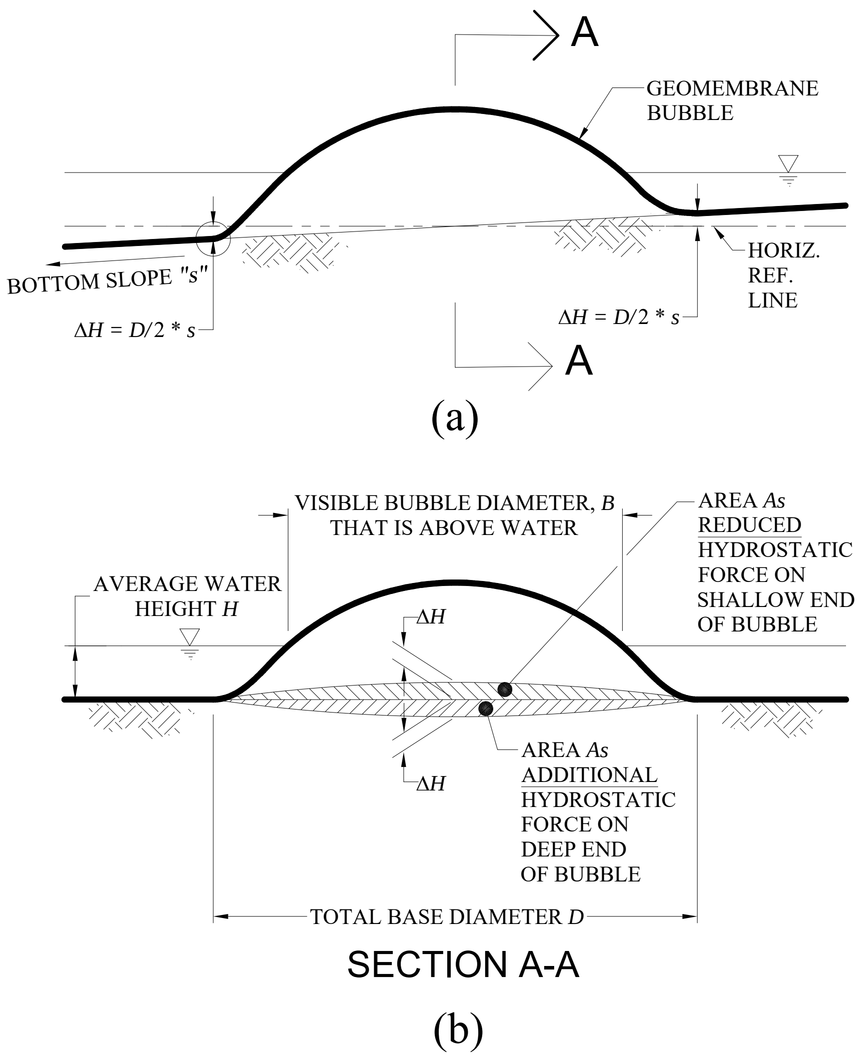

Figure 2: Bubble geometry adapted from Thiel (2016). (a) Section of bubble along longitudinal sloping axis of pond. (b) Lateral section of bubble illustrating average height of water, bubble dimensions, and areas of unbalanced hydrostatic forces caused by a sloped pond bottom.

2.3 *Requirement for unsaturated state of any gas underdrain gas system*

If it is desired to remove excess gas pressure from below the geomembrane by means of an underdrain, then the underdrain must be transmissive to gas. While this statement sounds obvious, what it implies is that the underdrain must be unsaturated because gas will not flow through water from a practical point of view. Examples are given in the preceding section showing that even for significant bubbles of concern the internal pressures in the bubble may be as low as 0.5 kPa, which corresponds to only 50 mm of water depth. Nuisance bubbles, which may be quite large and voluminous, but not yet creating any significant tension in the geomembrane, may have substantially less pressure. Thus, even a few millimeters of excess water head in the underdrain, defined here as the amount of head that is greater than the 'unconfined' flow capacity of the underdrain layer, might be enough to prevent deflation of unwanted bubbles. Only 140 mm of excess water head in the underdrain could block gas flow and allow gas pressures to build up to the point that could start to compromise the integrity of the geomembrane. Saturation of underdrains can occur due to several reasons including: elevated ground water, infiltration of storm water through the perimeter dikes, and localized saturation due to leakage from above through defects in the geomembrane. If the pond design is dependent on deflation of gas bubbles via an underdrain, it is essential that a robust liquid underdrain system is provided that will maintain subsurface liquid levels below the level of the gas underdrain system.

2.4 *Evaluation of required underdrain transmissivity for gas flow*

The approach for quantitatively designing the required transmissivity of a gas underdrain layer, including the spacing of piping and vents, is provided by Thiel (1998). While Thiel (1998) was developed to address gas relief below landfill covers, the methodology for gas relief below a pond liner would be identical. Due to space limitations, design examples are not presented herein. What is clear from that reference, and worthy of discussion in this paper, is that the unknown variable of greatest significance, as related to our topic, is the amount of gas flux that must be managed.

If the influx of gas to the underdrain is relatively consistent and can be estimated, then a project-specific maximum allowable pressure could be assigned to the problem, the required transmissivity of the underdrain layer could be calculated, and the required size and spacing of vents around the perimeter of the pond slope crest could be determined. While Thiel (1998) provides a starting point for the gas influx at the base of final landfill covers, no such general literature-based estimates are available for pond subgrades, and a site-specific determination would need to be made. Since gas flux estimates below pond liners are very difficult to establish, design practitioners have developed "rules of thumb" practices. An example of such a practice that the author has seen more than once is that of providing underdrain "strips", typically fabricated by cutting 0.6 m wide pieces from a geocomposite roll, on a spacing of 15 m below the geomembrane, connected to vents at the same spacing around the crest of the pond perimeter. An early example of a similar design is described by Giroud and Bonaparte (1984). While this rule of thumb may often prove satisfactory, Thiel (2016) provides calculations indicating that the smallest bubble for a 1.5 mm HDPE geomembrane material that might result in an "ultimate" condition of imminent rupture would have a base diameter on the order of 8.9 m. Thus, to be safe for 1.5 mm HDPE it might be recommended to have strip drains at half the spacing given by the rule of thumb, which would be at 7.5 m instead of 15 m, based on calculations.

If only a one-time gas deflation is necessary (e.g. initial air trapped under the geomembrane during deployment), and no new gas generation is anticipated, or gas generation is extremely slow (e.g. slow degradation of cellulose matter in subgrade), or gas generation is intermittent and of low-magnitude (e.g. due to modest seasonal ground water fluctuations), then a relatively low transmissivity material may be acceptable for the gas underdrain layer.

Thiel (1998) evaluated various materials for venting landfill gas below final covers. Laboratory testing of drained samples having moisture at field capacity indicated that standard nonwoven-needlepunched (NWNP) geotextiles with a mass/area of 540 g/m^2 would have a gas transmissivity of approximately 6E-07 m^2/s, which was about 30% lower than for a dry geotextile. Bouazza (2004) found similar low values of gas transmissivity for a standard NWNP geotextile with a mass/area of 513 g/m^2 having a gas transmissivity of approximately 3E-07 m^2/s when dry, and approximately 40% lower when wet. These values would typically be too low for applications below a landfill cover, but could potentially function as a slow relief for one-time gas bubbles below a pond geomembrane. Thiel (1998) also tested a special coarse-fiber (15 denier) NWNP geotextile with a mass/area of 680 g/m^2, which is not generally available but was manufactured specially for the project, that had a higher "wet" gas transmissivity of approximately 2E-06 m^2/s. The laboratory testing results were even less favorable for a fine sand material. Even though the sand material exhibited a saturated hydraulic conductivity of more than 1E-05 m/s, and even though it would normally be approved by the State of New York (2016) landfill regulations for a "gas venting layer" below a final landfill cover, the amount of capillary-held water in a "moist-drained" condition resulted in a gas transmissivity of only about 2E-07 m^2/s for a 0.3 m thick layer. Thiel (1998) concluded that granular materials containing significant fine sands are generally not appropriate for gas transmissivity because of their tendency to have plugged pore spaces due to capillary water. For relief of a consistent influx of gas, robust transmissive underdrain materials such as medium- to coarse-grained sands, gravels, or geocomposites are generally required in this capacity.

It is also worth considering that for very low gas-transmissivity materials, such as a NWNP geotextile, the local transmissivity could easily be overcome by leakage through a defect in the geomembrane, causing the geotextile material to be saturated and/or clogged by the sludge-laden water. Gas trapped in this area would not be able to vent through the saturated or clogged low-transmissivity material, and may allow a slight bubble to form locally under the geomembrane. A slight bubble might serve to increase the orifice flow through the geomembrane defect because it would locally raise the geomembrane away from the subgrade. More leakage might elevate the liner even higher, causing saturation and/or clogging of the underdrain for a further radius, and attract more gas to increase the size of the bubble at this location, and thus this situation could potentially feed on itself. In most ponds of significance, leakage detection and management is important, and for this reason Thiel and Giroud (2011) suggest that all important exposed-geomembrane ponds be designed with a double-liner system containing a high-transmissivity leakage collection layer between the liners. Again, it is mandatory that the design ensure that the gas underdrain is maintained in an unsaturated state, and is protected from potential saturation due to rising ground water, storm water intrusion, or leakage from above.

3 LATERAL MOVEMENT OF GAS BUBBLES

If the bubble pressure is not allowed to vent via an underdrain, there are two mechanisms by which force can be applied to a bubble to cause it to move laterally to the perimeter slopes: manually, and with unbalanced hydrostatic forces created by a sloping pond bottom.

3.1 *Manual inducement of lateral bubble movement*

Where there is a non-functioning gas underdrain and inadequate bottom slope on the pond, geomembrane bubbles need to be manually pushed to the pond perimeter where they can vent up the sideslopes. An excellent example of this is described by Wallace et al. (2006). The pond described in that article had top dimensions of 196 m by 126 m, and a maximum depth of 4 m. The pond was lined with a single 1.5 mm HDPE geomembrane and was underlain with a geocomposite underdrain layer. The bottom longitudinal slope was nominally 0.75%

and contained side-slope vents at the crest. Upon filling, when the pond contained effluent whose average depth was approximately 0.6 m deep, 15-20 bubbles appeared spread out over the bottom of the pond area. Some of the bubbles coalesced and floated the geomembrane, but did not freely dissipate through the underdrain to the perimeter. The ultimate solution discussed in that paper was to simply “walk” the bubbles out to the perimeter slopes. Once at the steeper perimeter slope the excess gas pressure escaped through the crest vents. The hypothesis given in the paper was that the air bubbles were the result of a one-time trapping of air, an event that is endemic to geomembrane installation, and that once they were vented, there was no mechanism for the air to return. This approach proved successful on that project. It is noteworthy that the underdrain blanket layer did not perform its intended function of venting the air, nor did the bottom slope of the pond cause the bubbles to migrate to the high end. Rather, a slight mechanical “nudge”, in the form of human effort, either wading in the water or from boats, was needed to coax the bubbles to move to the perimeter slopes where they could be vented. The explanation of why neither the geocomposite underdrain, nor the assumed bottom slope, did not work to relieve the bubbles was not definitively explained in the paper, although it was suggested that areas of the pond subgrade may have been saturated with high ground water.

3.2 *Estimation of force required to move bubbles laterally*

To approach the development of an equation to calculate the force required to move a geomembrane bubble laterally, consider moving a bubble a distance equal to one half of its base diameter, *D*, as illustrated in Figure 3. In the course of this movement, the front half of the relocated bubble will have expanded and strained new virgin geomembrane material, while the back half of the original bubble will have collapsed to its original un-strained state. The zone in-between, which would have started as the front half of the original bubble, and ended up as the back half of the relocated bubble, will have flexed but is assumed to have maintained the same strain level throughout the movement.

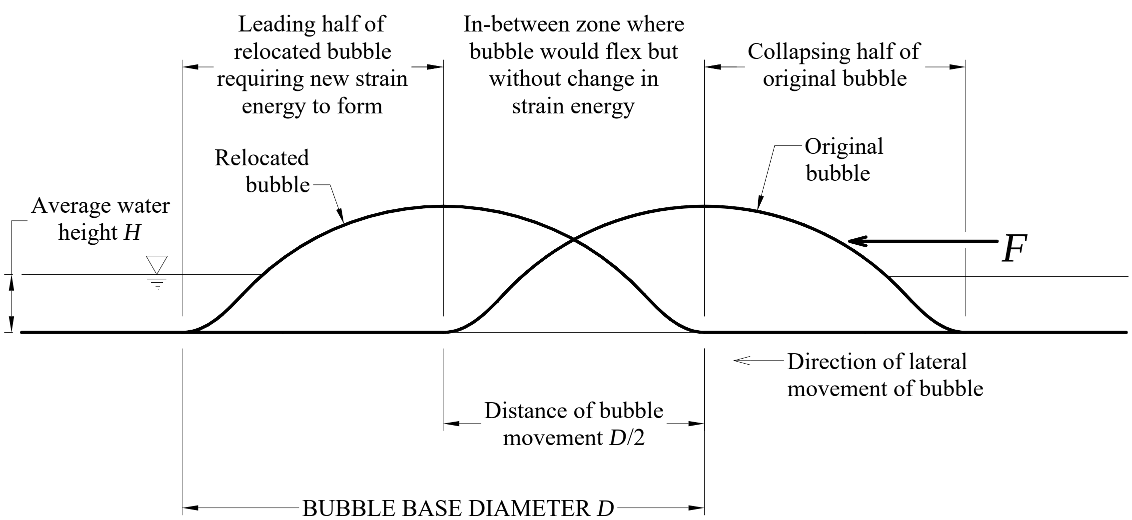

Figure 3: Schematic of force moving a geomembrane bubble a distance D/2.

For this calculation, if we ignore any work recovery due to contraction of the back side of the original bubble, and we only consider work required to expand the leading side of the relocated bubble, then it is probably conservative to ignore any work required for flexing the in-between zone. Conservative, in this sense, means that the calculation will probably be an over-estimate of the work required to move the bubble. Thus, the work, *W*, in this case will be estimated as the strain energy, *U*, stored in the half of the bubble surface that is being newly created. Linear-elastic strain energy is defined by classical physics as one-half the volume of the material times the stress times the strain, or

$$U = \left(\frac{1}{2}\right) \cdot V * \sigma * \varepsilon \tag{1}$$

where V = half of the volume of the original geomembrane material comprising the bubble = $\frac{1}{2} * \pi * (D^2/4) * t$; t = thickness of geomembrane; σ = average stress in geomembrane material; and ε = average strain in geomembrane material. Thus in our case we have:

$$W = U = \left(\frac{\pi D^2}{16}\right) * t * \sigma * \varepsilon \tag{2}$$

If we consider that the cause, or inducement, of the bubble to move laterally by the assumed distance of $D/2$ is an effective lateral force, F, then we can write a second equation for the work, W, as a force acting over a distance:

$$W = F * \frac{D}{2} \tag{3}$$

Setting these two equations for W equal to each other we obtain an expression for the force, F, as:

$$F = \left(\frac{\pi D}{8}\right) * t * \sigma * \varepsilon \tag{4}$$

Example 1: Calculate the force needed to move a gas bubble trapped below a 1.5 mm HDPE geomembrane that would be at the limit for “allowable operating strain” where D = 8.5 m, σ = 6,500 kPa, and ε = 3.7%. (Note that the water height, H, for this condition is estimated as 0.83 m, which will be used in Example 3.)

$$F = \left(\frac{\pi \cdot 8.5}{8}\right) * 0.0015 * 6{,}500 * 0.037 = 1.2\,\text{kN}$$

Example 2: Calculate the force needed to move a gas bubble trapped below a 1.5 mm HDPE geomembrane at an “ultimate” state that could lead to bursting where D = 8.9 m, σ = 10,000 kPa, and ε = 12.4%. (Note that the water height, H, for this condition is estimated as 2.21 m, which will be used in Example 4.) Result: F = 6.5 kN

The estimated bubble dimensions, water height, and associated stresses and strains in the above examples are taken from calculations presented in Thiel (2016), which are based on a 3-dimensional pressurized-sphere-type of geometry. We note that this formulation for the force needed to move a geomembrane bubble does not account for other forms of resistance that may need to be overcome such as stiff wrinkles and welds, left over sand bags, settled sludge, or other things in the path of the moving bubble.

One of implications of this calculation is that nuisance bubbles should be moved as soon as they are observed to be ‘stuck’. If a pond is designed with a weak underdrain or a weak bottom slope, and bubbles that are coalescing do not appear to be disappearing or migrating to the side slopes, it would behoove the operator to stop filling the pond immediately and implement measures to work the bubbles to the perimeter, such as in the excellent example described by Wallace et al. (2006). If the bubbles are ignored and filling continues, then the internal pressures of the bubbles, and the geomembrane stresses and strains, will climb. Not only will the bubbles be much more difficult to move at this more extreme condition, as indicated by the calculations above, but they will also approach a critical state that could lead to geomembrane rupture as has occurred on some projects.

3.3 *Unbalanced hydrostatic forces caused by sloping pond bottom*

The required amount of force to move a gas bubble as calculated in the examples presented in the previous section could be difficult for one or more persons to exert either from a boat, or while wading in the water. The Canadian Occupational Health and Safety guidelines, for example, suggest that manual work situations should not require more than about 0.23 kN of horizontal pushing force for a person standing on the ground, and perhaps up to 0.68 kN of horizontal pushing force if there is a good reactionary structure against which the laborer can support his body or feet. Considering the relatively poor footing and traction conditions in a flat-bottomed pond partly filled with water, it might require 5 or more people to move the bubble described in Example 1, and 30 people to move the bubble described in Example 2. The calculations presented in this section demonstrate that the required forces to move bubbles are fairly easy to generate using the unbalanced hydrostatic forces caused by a mildly-sloped pond bottom.

Consider a bubble of base diameter D in a pond with a bottom having a slope s. The bubble is bell-shaped in accordance with the derivation by Thiel (2016) and illustrated in Figure 2. The average height of the water on the middle side of the bubble is H (Figure 2b). As illustrated in Figure 2a, the deep end of the bubble will have an increased water height by an amount of ΔH, and the shallow end of the bubble will have a decreased water height by the same amount ΔH, where

$$\Delta H = (D/2*s) \tag{5}$$

A net unbalanced hydrostatic force, F_{hs}, would result from the difference in water pressures acting on the vertical projections between the opposing deep and shallow ends of the bubble. Figure 2b illustrates the average cross section of the bubble with a straight horizontal base along the subgrade at the middle of the bubble. The "additional" and "reduced" areas of vertical projection, for the deep and shallow ends of the bubble, respectively, are superimposed on this cross section in Figure 2b, together making an eye-shaped area. The net lateral unbalanced hydrostatic force would be calculated as the water pressure acting on the centroid of this eye-shaped area times the vertically-projected area. The average pressure for this area would be calculated using the water depth H at the middle of the bubble multiplied by the unit weight of water, γ_w. To calculate the area of the eye shape, the lower and upper projected outlines were assumed to be circular arcs, with chord length equal to the bubble diameter, D, and chord offset equal to ΔH. The area of each circular segment, A_s, with chord length D and chord offset ΔH, is given by a standard equation for the geometry of circles as:

$$A_s = \left[\frac{D^2}{8\Delta H} + \frac{\Delta H}{2}\right]^2 \cdot \arccos\left[\frac{\left(D^2 - 4\Delta H^2\right)}{\left(D^2 + 4\Delta H^2\right)}\right] - \frac{D^3}{16\Delta H} + \frac{D\Delta H}{4} \tag{6}$$

The unbalanced hydrostatic force, F_{hs}, would then be calculated as

$$F_{hs} = \gamma_w H * 2A_s \tag{7}$$

Example 3: Consider the same problem as Example 1 in the previous section. What would be the minimum required pond bottom slope required to move the bubble where $D = 8.5$ m, $H = 0.83$ m, and the required force $F = 1.2$ kN?

Solution: Solve Eqn (7) for A_s:

$$A_s = 1.2 / (2\times9.8\times0.83) = 0.0738 \text{ m}^2$$

Use Eqn (6) and a spreadsheet to iteratively solve for ΔH knowing D and A_s to find that $\Delta H = 0.01303$ m. Finally the slope s can be solved using Eqn (5) as

$$s = 2\times0.01303 / 8.5 = 0.0031$$

Example 4: Consider the same problem as Example 2 in the previous section. What would be the minimum required pond bottom slope required to move the bubble where D = 8.9 m, H = 2.21 m, and the required force F = 6.5 kN? Results: A_s = 0.15 m^2; s = 0.0057

The examples presented above represent extreme bubble conditions, and indicate that a pond bottom slope between 0.3% and 0.6% should be adequate to cause a gas bubble to move to the perimeter. Assuming numerous sandbags, having a buoyant vertical force of 1 kN, occur in the path of the moving bubble, they would add a sliding resistance of less than 0.5 kN. This would increase the required bottom slope for the two examples to approximately 0.44% and 0.62%, respectively. Additional resistance due to stiff wrinkles and welds might add an additional fraction of a percent to the required bottom slope. At the upper end it appears that a pond bottom with an effective slope of 0.75% should be adequate to overcome most foreseeable resistances to bubble movement even at extreme bubble conditions.

3.4 *Factors affecting the 'effective' pond bottom slope to cause lateral forces on geomembrane gas bubbles*

The previous section indicated that a conservative pond bottom slope that should be able to confidently propel geomembrane gas bubbles towards the perimeter slope at the high end of the pond would be on the order of 0.75%. Likely even less slope than this would be required if the bubble was not allowed to become large and stiff. It has been observed, however, that ponds with assumed adequate bottom slopes sometimes result in 'stuck' bubbles that do not move without additional assistance, such as in the case presented by Wallace et al. (2006). There are at least two possible explanations for why this could occur: construction grading tolerances, and elevated underliner liquids in the bubbles.

3.5 *Influence of construction grade tolerances*

In standard earthwork construction over large areas, such as that required for creating a pond subgrade, a common tolerance for the elevation at any particular point is $\pm$ 30 mm. Firm foundations created with great care can achieve tighter tolerances, while softer foundation soils graded with less care may have looser tolerances. It is generally recognized that having dependable drainage on ditches and flat surfaces with few "bird baths" is very difficult at 0.5%, and much more realistic at 1% design slope. Even with 1% slope some "bird baths" will still show after a light rain on a completed surface. This implies that even though the overall average grade of the slope may be very close to the design, there will still be localized low, high, and flat spots. Tire ruts and post-construction settlement will also contribute to localized slope anomalies. Thus the "effective" local slope could substantially vary from the assumed nominal slope of a pond bottom. As a bubble traverses a pond bottom, it might get 'stuck' at a localized flat or high spot. If we apply an assumed maximum construction tolerance of 30 mm on each end of a 10 m distance, an adverse grade of 0.060/10 = 0.006 could result. This means that if our original goal was to have a minimum slope of 0.75% at all locations, we may actually need to specify an average bottom slope of 0.75+0.6 = 1.35%, or even more if the subgrade was subjected to tire ruts or differential settlement, to have a high degree of reliability at all locations that the minimum of 0.75% would be achieved.

3.6 *Influence of leakage and high ground water on effective bottom slope*

As the liquid level under the pond liner, either due to elevated ground water or leakage, increases above the pond bottom, unbalanced hydrostatic forces will be exerted on the inside of a trapped gas bubble. These interior hydrostatic forces will tend to offset the unbalanced hydrostatic forces exerted on the outside of the bubble that would normally be counted upon to cause the bubble to move. At the extreme, hydrostatic uplift of the geomembrane over a large area, which would occur when the piezometric ground water, or leakage, level was at or above the pond fill level, would tend to totally remove the benefit of a pond subgrade slope.

Bubbles in these situations may need additional assistance (applied lateral force) to get them to move to the perimeter. Note that in such a case underdrains would be of no value in relieving the gas bubble because of their flooded state.

4 CONCLUSIONS

Gas pressure relief below exposed geomembranes in ponds and reservoirs is often desireable to avoid the formation of unwanted gas bubbles. When an adequate venting layer is not present, or does not perfom properly due to clogging or flooding, then gas bubbles may become trapped. Using recently-developed methods to estimate the size, shape, and pressures within trapped bubbles, a method to calculate the amount of lateral force required to move trapped bubbles to the pond perimeter has been proposed. The calculations indicate that an average pond bottom slope of 1.4% might be adequate in most cases to generate the necessary unbalanced lateral hydrostatic force required to automatically move bubbles to the pond perimeter, with more or less bottom slope required depending on the reliability and precision of the constructed pond bottom slope.

If the formation of bubbles is noticed during pond filling, the evolution of the bubbles should be closely watched. If they do not appear to be migrating upslope as filling proceeds, then filling should stop and actions should be taken to manually push the bubbles to the perimeter slopes. Continued filling around 'stuck' bubbles risks making the bubbles more difficult to move, as well as creating a critical state that could lead to geomembrane rupture.

4.1 *References*

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