FIGURE 1 A pond bubble can be moved manually when it is loose, and the water level is low.

Part 3

Design of exposed geomembrane-lined ponds

Controlling uplifting gas bubbles

By Richard Thiel

Part 1 of this series (Thiel 2017) demonstrated how the size, shape, pressure, and stresses and strains experienced by geomembrane bubbles inflated with gas could be analytically estimated. Part 2 of this series (Thiel 2018) evaluated the considerations for incorporating a gas-venting underdrain below the geomembrane liner. The current, and final, Part 3 of this series provides engineering and operational solutions to induce lateral movement of the bubbles to upstream side slopes, where they can be vented.

Lateral movement of gas bubbles

If the pressure in an exposed geomembrane gas bubble 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 or by using unbalanced hydrostatic forces created by a sloping bottom of the pond.

Manual inducement of lateral bubble movement

Where there is a nonexistent or nonfunctioning gas-venting underdrain, as well as inadequate bottom slope on the pond, geomembrane bubbles need to be manually pushed to the pond perimeter where they can vent up the side slopes. An example of this is described by Wallace et al. (2006). The pond in that article was lined with a single 60-mil (1.5-mm) high-density polyethylene (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 with an average depth of 2 feet (0.6 m), 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

EDITOR'S NOTE

Part 1 of "Design of Exposed Geomembrane-Lined Ponds: Controlling Uplifting Gas Bubbles" appeared in the October/November 2017 issue of *Geosynthetics*, pp. 43–49. Part 2 of this series appeared in the February/March 2018 issue of *Geosynthetics*, pp. 36–42.

Richard Thiel, P.E., is the president of Thiel Engineering in Oregon House, Calif.

All photographs and illustrations courtesy of the author.

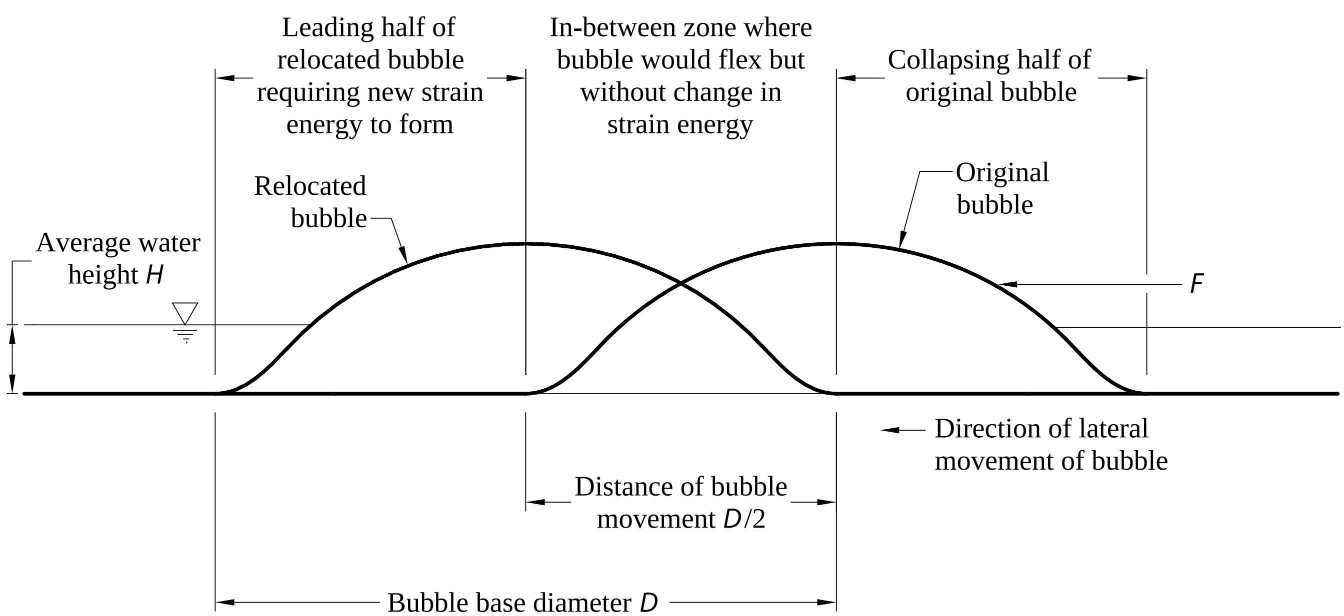
through the underdrain to the perimeter. The ultimate solution discussed in that paper was to walk the bubbles out to the perimeter slopes where they could vent out. The hypothesis given was that the air bubbles were the result of a onetime trapping of air, an event that is endemic to geomembrane installation, and that once they were vented, there was no mechanism for the air to return. 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 by wading in the water or reaching the bubble by boat, was needed to coax the bubbles to move to the perimeter slopes.

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* (see **Figure 2**). 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 unstrained state. The zone in between, which 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.

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. Thus, the work, *W*, will be estimated as the strain energy,

FIGURE 2 Schematic of force moving a geomembrane bubble a distance *D*/2



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

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

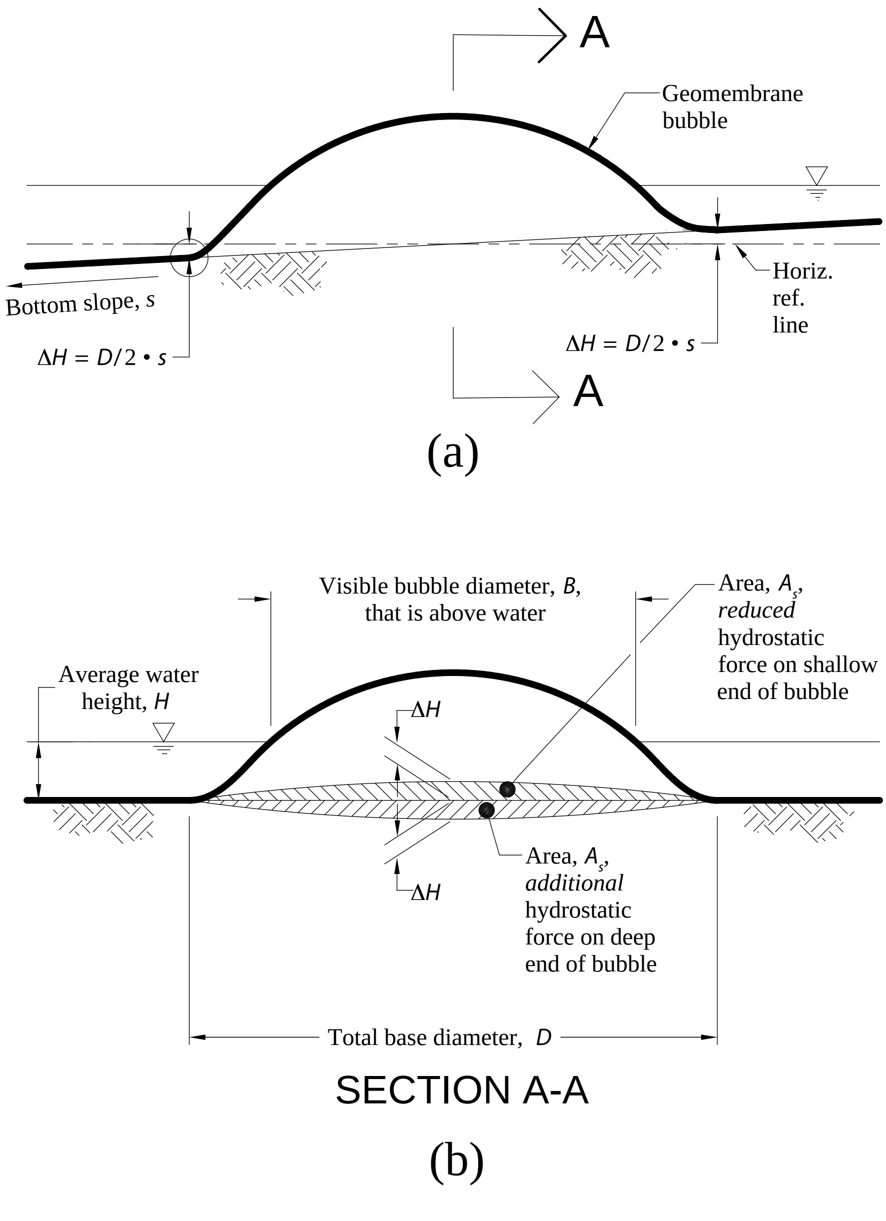
where V = half of the volume of the original geomembrane material comprising the bubble = $\frac{1}{2} \cdot \pi \cdot (D^2/4) \cdot t$, t = thickness of the geomembrane, σ = average stress in geomembrane material and ε = average strain in geomembrane material.

Thus, we have

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

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 W as a force acting over a distance:

$$W = F \cdot \frac{D}{2} \qquad (3)$$



FIGURES 3a and 3b Bubble geometry adapted from Thiel (2017). (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.

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

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

- **Example 1**: Calculate the force needed to move a gas bubble trapped below a 60-mil (1.5-mm) HDPE geomembrane that would be at the limit for allowable operating strain where D = 28 feet (8.5 m), σ = 943 psi (6500 kPa) and ε = 3.7%. (Note that the water depth, H, for this condition is estimated from Part 1 of this series as 2.7 feet [0.83 m], which will be used in **Example 3**.)

$$F = \left(\frac{\pi \cdot 8.5}{8}\right) \cdot 0.0015 \cdot 6500 \cdot 0.037 = 270\ pounds\ (1.2\ kN) \qquad (5)$$

- **Example 2**: Calculate the force needed to move a gas bubble trapped below a 60-mil (1.5-mm) HDPE geomembrane at an ultimate state that could lead to bursting where D = 29 feet (8.9 m), σ = 1450 psi (10,000 kPa) and ε = 12.4%. (Note that H for this condition is estimated from Part 1 of this series as 7.3 feet [2.2 m], which will be used in **Example 4**.)

$$F = 1460\ pounds\ (6.5\ kN) \qquad (6)$$

One of the implications of this calculation is that nuisance bubbles should be moved as soon as they are observed to be stuck in place. 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 example described by Wallace et al. (2006). Bubbles can be moved with relative ease by laborers in waders when the water level is low, and the bubbles are loose (see **Figure 1** on pp. 10–11). 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 more difficult to move at this 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 (as shown in a field case in **Figure 5** of Part 1 of this series [Thiel 2017]).

Unbalanced hydrostatic forces caused by a 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. Considering the relatively poor footing and traction conditions in a flat-bottomed pond partly filled with water, it might require five or more people to move the bubble described in **Example 1**, and 30 or more people to move the bubble described in **Example 2**. To help with this situation, calculations are presented herein to 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 presented in Part 1 of this series, and illustrated in **Figures 3a** and **3b** in this article. The average height of the water on the middle side of the bubble is *H* (**Figure 3b**). As illustrated in **Figure 3a**, 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

$$\Delta H = \left(\frac{D}{2}\right) \cdot s \tag{7}$$

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 3b** illustrates the average cross section of the bubble with a straight horizontal base along the subgrade at

>> For more, search **Bubbles** at www.GeosyntheticsMagazine.com.

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 3b**, together making an eye-shaped area. The net lateral unbalanced F_{hs} 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 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 D, and the chord offset equal to ΔH. The area of each circular segment, A_s, with D and ΔH, is given by a standard equation for the geometry of circles as

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

The unbalanced F_{hs} would then be calculated as

$$F_{hs} = \cdot \gamma_w H \cdot 2A_s \qquad (9)$$

- **Example 3**: Consider the same problem as **Example 1** in the previous section. What would be the minimum required pond bottom slope to move the bubble where D = 28 feet (8.5 m), H = 2.7 feet (0.83 m) and the required force F = 270 pounds (1.2 kN)? The solution, A_s, is shown in **Equation 10**:

$$A_s = \frac{1.2}{(2 \cdot 9.8 \cdot 0.83)} = 0.79 \text{ square feet } (0.0738 \text{ m}^2) \qquad (10)$$

Use **Equation 8** and a spreadsheet to iteratively solve for ΔH knowing D and A_s to find that ΔH = 0.04274 feet (0.01303 m). Finally, s can be solved using **Equation 7** as $s = 2 \cdot 0.01303/8.5 = 0.0031$.

- **Example 4**: Consider the same problem as **Example 2** in the previous section. What would be the minimum required pond bottom slope to move the bubble where D = 29 feet (8.9 m), H = 7.3 feet (2.21 m) and F = 1460 pounds (6.5 kN)?

$$A_s = 1.6 \text{ square feet } (0.15 \text{ m}^2); \quad s = 0.0057 \qquad (11)$$

The examples presented 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. Additional resistance might occur due to sandbags, sludge, stiff wrinkles and welds. Thus, it appears that a pond bottom with an effective slope of 0.75% should be adequate to overcome most foreseeable resistances to bubble movement. 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 occurs: construction grading tolerances and elevated underliner liquids in the bubbles.

Influence of construction grading tolerances

In standard earthwork construction over large areas, a common tolerance for the elevation at any particular point is ± 1.2 inches (30 mm). 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 postconstruction 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 1.2 inches (30 mm) on each end of a 33-foot (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 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.

Influence of elevated underliner liquids in the bubbles

As the liquid level under the pond liner, either due to elevated groundwater or leakage, increases above the pond bottom, hydrostatic forces on the interior of the bubble wall will tend to offset the unbalanced hydrostatic forces exerted on the outside of the bubble. At the extreme, high groundwater or leakage levels would tend to remove the benefit of a pond subgrade slope.

Summary and recommendations

A summary of and recommendations on the practical implications for managing underliner gas and bubbles in exposed geomembrane-lined ponds from the articles in this series are presented in the following list for design practitioners and pond operators:

1. The presence of gas bubbles in exposed geomembrane ponds is relatively common, if for no other reason than the frequent occurrence of initial trapped air below newly deployed geomembranes. Several other potential reasons for gas accumulation exist.
2. A method exists to estimate the size, shape, pressure, stresses and strains in a gas bubble for a specified geomembrane material in a given depth of liquid.
3. The pressure within geomembrane gas bubbles is surprisingly low. As such, the ability to vent the pressurized gases is sensitive to small pressure blockages caused by shallow subgrade flooding.
4. Shallow subgrade flooding can be the result of high groundwater, perimeter surface water intrusion or leakage through the geomembrane.
5. There are two mechanisms for the relief of excess gas pressure below a geomembrane: dissipation through a gas-transmissive underdrain venting layer and forced lateral movement of bubbles to the pond perimeter where they can escape up the perimeter slope to the vents.
6. If an underdrain venting layer is incorporated to manage gas pressures, it must be maintained in an unsaturated condition, and it needs to have adequate gas transmissivity to serve its function. Single nonwoven-needlepunched geotextiles and fine sands will have weak performance in part because they hold capillary water. Coarse sands, gravels and geocomposite drainage layers will be more robust. Methods are available to calculate the required gas transmissivity if the gas flux can be estimated.
7. If the underliner zone is flooded, then any gas underdrain will be rendered ineffective, in which case bubbles must be forced to move laterally.
8. There are two means by which lateral movement of a bubble can be

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.

induced: manual pushing and by employing a bottom slope in the pond to create unbalanced hydrostatic pressures that cause the bubble to move upslope.

9. If there is elevated liquid in a gas bubble below the geomembrane, either because of elevated groundwater or because of leakage occurring into a given bubble, then not only will a venting layer be rendered ineffective, but the interior hydrostatic forces on the bubble will tend to offset the unbalanced hydrostatic forces exerted on the outside. This condition will reduce the effectiveness of the pond bottom slope. At the extreme, the benefit of a pond bottom slope would be nullified. Bubbles in these situations will need additional applied lateral force to move them to the perimeter.
10. If a pond bottom slope is incorporated in a design to manage gas bubbles, it must have adequate slope to overcome construction tolerances within localized areas, in addition to a minimum slope to cause adequate forces on bubbles and to overcome other elements of resistance such as stiff wrinkles. A minimum dependable slope range of 0.75% to 2.0% is recommended. The lower end of the range may be adequate where the subgrade conditions are firm with no tire ruts, where no differential settlement is expected and where good quality control on final grading is performed. The upper end of the range is recommended where the subgrade conditions exhibit deflection under wheel loads, where tire ruts may occur, where some differential settlement may occur and where construction tolerances are rough. The average of the range, 1.4%, is a reliable recommendation for a pond bottom slope that would remove geomembrane gas bubbles as long as the underliner is not flooded with elevated groundwater or leakage, and good earthworks construction practices are followed.
11. 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.

References

Thiel, R. (2017). "Design of exposed geomembrane-lined ponds: Controlling uplifting gas pressures–Part 1." *Geosynthetics*, 35(5), 42–49.

Thiel, R. (2018). "Design of exposed geomembrane-lined ponds: Controlling uplifting gas pressures–Part 2." *Geosynthetics*, 36(1), 36–42.

Wallace, R., Giroud, J. P., and Shanks, M. (2006). "Impacts of construction practices and reservoir filling on geomembrane uplift." *Geosynthetics: Proc, 8th Int. Conf. on Geosynthetics (8ICG)*, Junichi Koseki, ed., Vol. 2, Millpress, Rotterdam, The Netherlands, 615–618.