CHAPTER 7

HYDROSTATIC UPLIFT ANALYSIS

This chapter provides information to use when analyzing the hydrostatic uplift potential at a *waste containment facility* in Ohio. Hydrostatic uplift may affect the subbase or engineered components of a *waste containment facility* anytime ground water exists at a facility. When an excavation or a portion of a *waste containment facility* will be constructed at a depth where a *phreatic surface* of ground water is present or piezometric pressures are present, the potential adverse effects upon the *waste containment facility* will need to be taken into account.

> When the ground water head is sufficiently high, pressure may cause soil layers affected by the pressure to lose strength and fail. It is widely accepted that the effective stress created by a soil mass is the main factor that determines the engineering behavior of that soil. According to Terzaghi et al, 1996, total stress in soil is a sum of an effective stress (or intergranular stress as a result of particle-to-particle contact pressure) and a neutral stress (pore water pressure). At the instance of failure, total stress in the soil is equal to the pore water pressure, and the effective stress is equal to zero. In other words, when particle-to-particle contact disappears, so does the soil's strength.

The discussion in this chapter assumes that hydrostatic uplift occurs when enough water pressure builds to simply lift a soil layer or flexible membrane liner (FML). Although this may be a common case, other possible mechanisms of soil disruption exist under hydrostatic uplift forces. Some of them are roofing, boiling, or even a uniform heave throughout the soil mass without formation of a large blister. The mechanism that develops is controlled mainly by soil characteristics and construction practices. Details on these mechanisms are given in literature and are beyond the scope of this policy.

REPORTING

This section describes the information that should be submitted to demonstrate that a facility is not susceptible to hydrostatic uplift. Ohio EPA recommends that the following information be included in its own section of a geotechnical and stability analyses report:

> Any drawings or cross sections referred to in this policy that are already present in another part of the geotechnical and stability analyses report can be referenced rather than duplicated in each section. It is helpful if the *responsible* party ensures the referenced items are easy to locate and marked to show the appropriate information.

- A narrative and tabular summary of the results of the hydrostatic uplift analysis,

- A summary and discussion of the results of the subsurface investigation that apply to hydrostatic uplift analysis and how they were used in the analysis,

- A summary of the worst-case scenarios used to analyze the hydrostatic uplift potential of the facility,

- Isopach maps comparing the excavation and construction grades, depicting the temporal high *phreatic* and *piezometric surfaces* and showing the limits of the *waste containment unit(s)*,

Figure 7-1 Hydrostatic pressure can cause in situ materials to fracture and allow the passage of the underlying ground water into an excavation, causing flooding of the excavation and weakening the in situ materials. Note the two delta formations in the above picture that are obvious evidence of flow through the in situ materials, which at this Ohio landfill, are over 20 feet thick.

- Drawings showing the cross sections analyzed. The cross sections should include:

  1. the engineered components and excavation limits of the facility

  2. the *soil stratigraphy*,

  3. the temporal high *phreatic* and *piezometric surfaces*, and

  4. the field densities of each layer.

- The detailed hydrostatic uplift calculations, and

- Any figures, drawings, or references relied upon during the analysis marked to show how they relate to the facility.

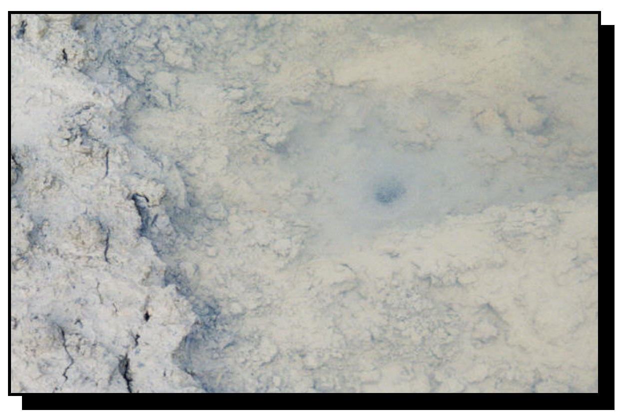

Figure 7-2 Hydrostatic pressures are causing ground water to pipe into an excavation of an Ohio landfill. This may have been caused by fracturing of the in situ materials, piping, or from an improperly abandoned *boring*.

FACTOR OF SAFETY

The following factor of safety should be used, unless superseded by rule, when demonstrating that a facility will resist hydrostatic uplift.

Hydrostatic Uplift Analysis: FS $\geq$ 1.40

> The number of digits after the decimal point indicates that rounding can only occur to establish the last digit. For example, 1.579 can be rounded to 1.58, but not 1.6.

The use of a higher factor of safety against hydrostatic uplift may be warranted whenever:

- A failure would have a catastrophic effect upon human health or the environment,
- Uncertainty exists regarding the accuracy, consistency, or validity of data, and no opportunity exists to conduct additional testing to improve or verify the quality of the data,
- Large uncertainty exists about the effects that changes to the site conditions over time may have on the *phreatic* or *piezometric surfaces*, and no engineered controls can be implemented that will significantly reduce the uncertainty.

> Designers may want to consider increasing the required factor of safety if repairing a facility after a failure would create a hardship for the *responsible parties* or the waste disposal customers.

A facility must be designed to prevent failures due to hydrostatic uplift. A factor of safety against hydrostatic uplift lower than 1.40 is not considered a sound engineering practice in most circumstances. This is due to the uncertainties in calculating a factor of safety against hydrostatic uplift, and any failure of the *waste containment facility* due to hydrostatic uplift is likely to increase the potential for harm to human health and the environment. If a facility has a factor of safety against hydrostatic uplift less than 1.40, mitigation of the hydrostatic uplift pressures, redesigning the facility to achieve the required factor of safety, or using another site not at risk of a failure due to hydrostatic uplift will be necessary.

> The factors of safety specified in this policy are based on the assumptions contained in this policy. Those assumptions include, but are not limited to, the use of conservative, site-specific, *higher quality data*; proper selection of worst-case geometry; and the use of calculation methods that are demonstrated to be valid and appropriate for the facility. If different assumptions are used, these factors of safety may not be appropriately protective of human health and the environment.

However, if unusual circumstances exist at a facility, such as the geometry of the worst-case location for hydraulic uplift is unique to one phase, it is a small portion of the phase, pumping of water out of the *saturated soil unit* or *bedrock* can be done to alleviate hydrostatic uplift pressure, and the area can be excavated, constructed and buried by sufficient waste or fill material during the same construction season so that failure of the engineered components will be prevented, then the *responsible party* may propose (this does not imply approval will be granted) to use a lower factor of safety against hydrostatic uplift in the range of 1.4 to 1.2. The proposal should include any pertinent information necessary for demonstrating the appropriateness of the lower factor of safety to the facility.

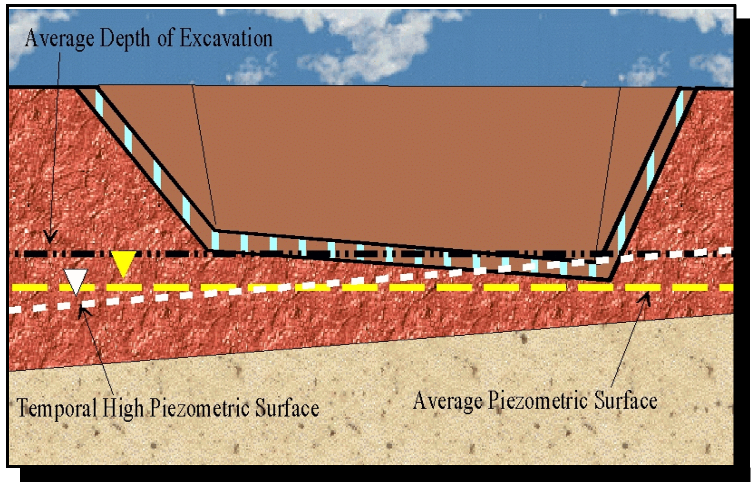

Figure 7-3 Example of how using the average depth of excavation (double-dot dashed line) and the average elevation of the *piezometric surface* (large dashed line) result in the conclusion that hydrostatic uplift will not occur, which is incorrect. Note that the temporal high *piezometric surface* (small dashed line) does intersect the liner system (hashed area) creating the potential for hydrostatic uplift that must be analyzed.

The *responsible party* should ensure that the design and specifications in all authorizing documents and the QA/QC plans clearly require that the assumptions and specifications used in the hydrostatic uplift analysis for the facility will be followed during construction, operations, and closure. If the *responsible party* does not do this, it is likely that Ohio EPA will require the assumptions and specifications from the hydrostatic uplift analysis to be used during construction, operations, and closure of a facility through such means as are appropriate (e.g., regulatory compliance requirements, approval conditions, orders, settlement agreements).

From time to time, changes to the facility design may be needed that will alter the assumptions and specifications used in the hydrostatic uplift analysis. If this occurs, a request to change the facility design is required to be submitted for Ohio EPA approval in accordance with applicable rules. The request to change the facility design must include a new hydrostatic uplift analysis that uses assumptions and specifications appropriate for the change request.

ANALYSIS

When selecting the scenarios for analysis of hydrostatic uplift, it must be ensured that the worst-case interactions of the excavation and of the construction grades with the *phreatic* and *piezometric surfaces* are selected. Temporal changes in *phreatic* and *piezometric surfaces* must be taken into account. The highest temporal *phreatic* and *piezometric surfaces* must be used in the analysis. Using average depth of excavation or average elevation for the *phreatic* and *piezometric surfaces* is not acceptable (see **Figure 7-3**). The purpose of the analysis is to find all areas of the facility, if any, that have a factor of safety less than 1.40 for hydrostatic uplift.

Figure 7-4 This is another example of hydrostatic pressures at an Ohio landfill creating flow through more than 20 feet of heavy in situ clay materials causing flooding of the excavation.

Figure 7-5 illustrates a situation where a clay liner (or another soil layer) is constructed above a *saturated* layer. The piezometric head (H_P) is applying upward pressure on the liner.

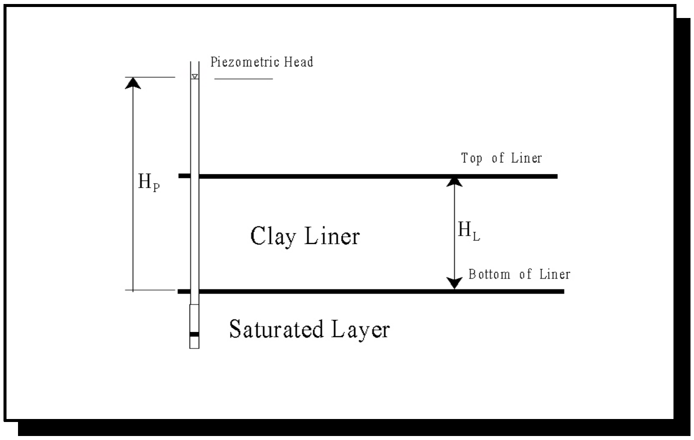

Figure 7-5 An example of piezometric head from ground water exceeding the top of an engineered component or soil layer creating a potential for hydrostatic uplift .

If γ_L = field density of clay liner,
γ_W = density of water,
H_L = clay liner thickness, and
H_P = piezometric level (head),

then, at some depth (for instance at the interface between the liner and the *saturated* layer)

$\gamma_L \cdot H_L$ would represent the total stress (*s*), and
$\gamma_W \cdot H_P$ would represent the pore water pressure (u).

An unstable (or point of failure) situation could then be described as: $\sigma = u$

$$\text{i.e., } \gamma_L \cdot H_L = \gamma_W \cdot H_P \tag{7.1}$$

or as a stress ratio:

$$\frac{\gamma_L \cdot H_L}{\gamma_W \cdot H_P} = 1 \tag{7.2}$$

Conversely, the total stress required to achieve a factor of safety of 1.4 is:

$$\gamma_L \cdot H_L > 1.4(\gamma_W \cdot H_P) \tag{7.3}$$

An unstable condition caused by hydrostatic uplift may develop when the hydrostatic uplift force overcomes the downward force created by the weight of the soil layer(s). If an area acted upon by the hydrostatic force is sufficiently great, excess water pressure may cause overlying soil to rise, creating a failure known as “heave.” Although heave can take place in any soil, it will most likely occur at an interface between a relatively impervious layer (such as a clay liner) and a *saturated*, relatively pervious base.

Water percolation through a soil layer affects hydrostatic uplift force. As a result, considering seepage may theoretically be a more accurate approach. The shear resistance of the soil could also be theoretically taken into account. However, for practical purposes, a conservative evaluation of the resistance created by a soil layer against hydrostatic uplift can be accomplished by calculating a maximum uplift force based on a maximum measured piezometric head and comparing it to the normal stress created by the overlying soil layers. This is especially true when checking an interface between a subbase and a clay (or plastic) liner, where any significant seepage through the liner material is not anticipated nor wanted.

Rather than assigning specific values, the terms "relatively impervious" and "relatively pervious" are used here only to indicate a difference in permeabilities between the two respective layers. In simple terms, the bigger this difference is, the higher the uplift force on the "relatively impervious" layer will be.

Figure 7-6 This is another example of hydrostatic pressures at an Ohio landfill causing flow through more than 20 feet of heavy in situ clay materials resulting in flooding of the excavation. Note that in this case, the presence of water cannot be taken into account due to precipitation. The flow of uplift water is evidenced only by a cloudy disturbance in the flooded excavation.

Hydrostatic Uplift - Example Methodology

A factor of safety is commonly calculated as a ratio between a resisting (available or stabilizing) force and a driving (attacking or destabilizing) force. The factor of safety against hydrostatic uplift can be expressed as:

$$FS = \frac{F_{GL}}{F_{HW}} \geq 1.40 \qquad (7.4)$$

where F_{GL} = downward force resulting from the weight of soil,
F_{HW} = hydrostatic uplift force, and
FS = factor of safety against hydrostatic uplift.

The forces in Equation 7.4 can be defined as:

$$F_{GL} = \gamma_L \cdot H_L \cdot A$$

and

$$F_{HW} = \gamma_w \cdot H_p \cdot A$$

where A = unit area.

When the forces in Equation 7.4 are substituted with above definitions, unit areas cancel. The expression now takes the form of Terzaghi's equation (Equation 7.2), with exception that number 1, previously indicating an unstable condition, is replaced with a FS:

$$FS = \frac{\gamma_L \cdot H_L}{\gamma_W \cdot H_P} \geq 1.40 \qquad (7.5)$$

For example, if γ_L= 112 pcf and γ_W= 62.4 pcf then the critical piezometric level can be calculated by using Equation 7.5 as follows:

$$H_P \leq \frac{\gamma_L \cdot H_L}{\gamma_W \cdot FS} \leq \frac{112 \cdot H_L}{62.4 \cdot 1.4} \leq 1.282 \cdot H_L \quad (\approx 1.3 \cdot H_L)$$

The piezometric level in the *saturated* layer can be measured with piezometers, water levels in *borings*, or other techniques, and compared to $1.3 \cdot H_L$ to very roughly assess the likelihood of hydrostatic uplift. However, for permit applications or other authorization requests submitted to Ohio EPA, accurate calculations using facility specific values must be included.

A rough rule of thumb can be drawn from this example, such that potential for heaving of a soil layer exists whenever a piezometric level (head) extends to an elevation more than 1.3 times the thickness of the layer that is above the plane of potential failure (usually the contact plane between two layers with different permeabilities).

Hydrostatic Uplift - Example Calculation

If a sump (or another hole) is being excavated in a soil layer subjected to hydrostatic pressure (H_P, see **Figure 7-7**), the maximum depth of the sump can be calculated that would still allow for the required factor of safety. This can be determined by substituting H_L in Equation 7.5 with H_{Lsump} and calculating its value.

For example, determine if a three-foot deep sump can be constructed under the following conditions (see **Figure 7-7**):

H_L = 5 ft,
H_P = 8 ft,
γ_L = 112 pcf,
γ_w = 62.4 pcf, and
D_{SB} = depth from top of liner to sump bottom (8 ft).

Using Equation 7.5 the factor of safety is: $FS = \frac{g_L \cdot H_L}{g_W \cdot H_P} = \frac{112 \cdot 5}{62.4 \cdot 8} = 1.12$, which is unacceptable.

As a result, a thicker liner will be needed in the sump. The thickness of liner in the sump necessary to provide a factor of safety of 1.40 can be calculated as follows:

$$H_{L\,sump} = \frac{FS \cdot g_W \cdot H_P}{g_L} = \frac{1.4 \cdot 62.4 \cdot 8}{112} = 6.24\ ft$$

Therefore, the maximum depth of the sump should not exceed:

$$\mathrm{H_{sump} = D_{SB} - H_{L\,sump} = 8\,ft - 6.24\,ft = 1.76\,ft}$$

To avoid water infiltrating into the excavation and damaging the liner, some form of reduction to the piezometric head (e.g., using dewatering wells) will be necessary during excavation and construction of the liner system and sump used in this example.

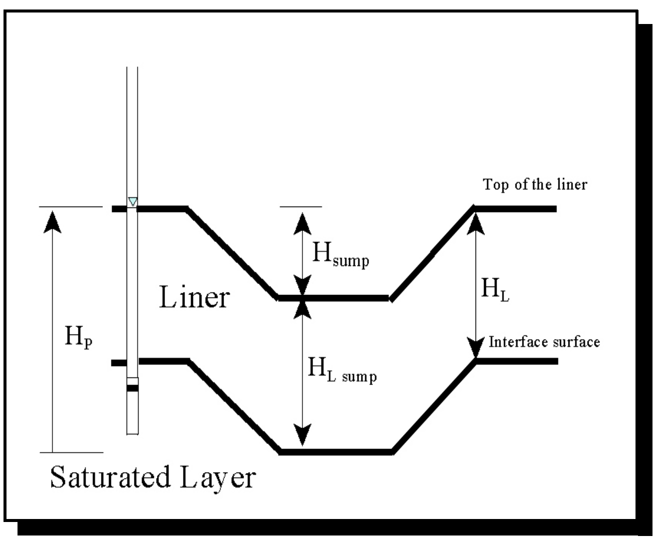

Figure 7-7 An example of piezometric head on a soil liner with a sump.

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