CHAPTER 6

SETTLEMENT ANALYSES

This chapter provides information to use when analyzing the potential for failure due to settlement at an Ohio *waste containment facility*. It is important to account for settlement in the design of a *waste containment facility* because:

- *overall settlement* can result in changes to liquid drainage flow paths for leachate, surface water, or waste water, and can cause damage to pipes, destruction of geonets, and reduction or reversal of grades; and

- *differential settlement* can result in damage or failure of liner systems, piping, containment berms, and other engineered components.

Overall settlement and differential settlement should be analyzed for all of the following soil materials including, but not limited to: in situ soils, mine spoil, added geologic material, structural fill, recompacted soil liners, and waste materials. Differential settlement analyses should focus on areas where changes in foundation materials warrant evaluation, such as areas with high walls, separatory liner over waste, changes in *soil stratigraphy* laterally or vertically, and where significant abrupt changes in loading occur.

> Evaluating waste and foundation settlement whenever a separatory liner will be used between old and new waste is important for determining tensile strain on components. For purposes of this policy, all references to a separatory liner will include any newly constructed separatory liner system or any previously placed cap system that will be converted to a separatory liner system.

The vertical and lateral variability of settlement characteristics across a site, and the changes in the increase in vertical stress created by the geometry of the *waste containment facility* will cause each location of a facility to settle different amounts. The facility must be designed to account for the stresses and strains that result from settlement occurring in the foundation and waste mass.

REPORTING

> 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.

This section describes the information that should be submitted to demonstrate that a facility is not susceptible to damage from settlement. Ohio EPA recommends that the following information be included in its own section of a geotechnical and stability analyses report. At a minimum, the following information about an *overall settlement* and *differential settlement* analysis should be reported to Ohio EPA:

- A narrative and tabular summary of the results of the settlement analyses,
- A summary and a detailed discussion of the results of the subsurface investigation that apply to the settlement analyses and how they are used in the analyses,
- A summary of the approach, methodologies, and equations used to model settlement of the facility,
- If any of the settlement parameters were interpolated by using random generation or another method, then information must be provided to explain in detail, the equations and methodology, and how the settlement parameters were generated,
- Plan view maps showing the top of the liner system, the liquid containment and collection system, the location of the points where settlement is calculated, the expected settlement associated with each point, and the limits of the *waste containment unit(s)*.

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

- *Soil stratigraphy*,
    - Temporal high *phreatic surfaces*,
    - The range of the tested settlement parameters of each layer,
    - Depth of excavation,
    - Location of engineered components of the facility that may be adversely affected by settlement,
    - The amount of settlement calculated at each point chosen along the cross section,
- The detailed settlement calculations of the engineering components,
- Any figures, drawings, or references relied upon during the analysis marked to show how they relate to the facility, and
- The detailed tensile strain analysis.
- If vertical sump risers are included in the facility design, then include:
    - A narrative and tabular summary of the results of the bearing capacity analysis,

> Ohio EPA discourages the use of vertical sump risers in solid *waste containment units* and hazardous *waste containment units*. This is due to the inherent difficulties they present during filling operations, and the potential they create for damaging liner systems.

- A summary and a detailed discussion of the results of the subsurface investigation that apply to the bearing capacity and how they were used in the analyses,

- A summary of the approach, methodologies, and equations used to model the bearing capacity of the facility.

DESIGN CRITERIA

Ohio EPA does not specify or recommend a factor of safety to use during settlement analysis. Instead, facilities must be designed so they satisfy applicable minimum regulatory design requirements at the time they are ready to receive waste and continue to satisfy applicable minimum design requirements after settlement is complete (at least 100% of *primary settlement* plus the *secondary settlement* expected using a time-frame of 100 years or another time-frame acceptable to Ohio EPA). This also applies to any increases in weight of the facility (e.g., vertical or horizontal expansions, increases in containment berm height). Therefore, it is important for responsible parties and designers to consider the possibility for increasing the weight of the facility and account for the additional settlement during the initial design. Failure to do so is likely to result in a facility being prevented from vertically expanding because to do so would cause the *waste containment system* or the liquid removal systems to become compromised. Applicable minimum regulatory design requirements, include, but are not limited to:

- Maintaining the minimum slopes of liners and pipes,

- Maintaining the integrity of soil berms, liners, barrier layers, and other engineered components,

- Maintaining the integrity of geosynthetics,

- Ensuring that all piping will be in working order, and

- Showing that liquids in the liquid control and collection systems will be below maximum levels allowed and otherwise meet performance standards.

Ohio EPA requires that the tensile strength of geosynthetics are ignored when evaluating the slope stability of a facility design. This is because plastic materials creep under stress, and over time, the thickness of the geosynthetics will decrease under constant stress. Geosynthetics may crack under constant stress, and for geonets, constant stress may cause the collapse of the drainage pathways rendering the material useless. Tensile strain may occur in geosynthetics when placing the materials with too little slack, dragging subsequent layers of geosynthetic across previously placed layers during installation, placing materials such as soil, drainage material, waste, or waste water on top of the geosynthetics, and during settlement.

> One notable exception to the requirement for designing geosynthetic systems without accounting for tensile strength of the materials is when a slip layer of geosynthetic above an FML is purposefully included in a design (see Chapter 9 for more information).

When tensile strain is unavoidable, the facility should be designed to minimize tensile strain in geotextiles, geomembranes, geosynthetic clay liners, geocomposite drainage layers, leachate collection piping, and waste water piping. Generally, it is recommended that strain not exceed the manufacturer's recommendations for the aforementioned components. Any design that results in geosynthetics being in strain must be accompanied with documentation and test results showing that the proposed materials will maintain the integrity of the systems of which they are a part under the calculated strain. The testing will need to represent the stress history that will be caused by the loading conditions experienced by the materials at the time of installation through final loading with waste or waste water.

The above criteria to be applied during settlement analysis are appropriate if the design assumptions are conservative; site-specific, *higher quality data* are used; and the calculation methods chosen are demonstrated to be valid and appropriate for the facility. The use of a design that is more robust than regulatory requirements 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.

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 settlement analyses 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 settlement analyses 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, administrative consent agreements).

From time to time, changes to the facility design may be needed that will alter the assumptions and specifications used in the settlement 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 settlement analysis that uses assumptions and specifications appropriate for the change request or contain a justification for why a new analysis is not necessary.

SETTLEMENT ANALYSIS

A settlement analysis includes the *overall settlement* of a facility to ensure that pipes will remain intact and any liquid drainage flow paths for leachate, surface water, or waste water will satisfy design requirements after settlement is complete. Settlement analyses also include any *differential settlement* across a facility to ensure that engineered components will not be damaged, liquid drainage paths will be maintained, and the facility will satisfy design requirements, not only at the time of construction,

> In most cases, immediate settlement will not be a concern because the immediate settlement will occur during construction. However, immediate settlement must be taken into account at some facilities. This is especially true for facilities where construction is staged to build several phases. For example, one year, three berms and a liner system are constructed. Then the following year a large berm is constructed along the remaining upslope edge of the liner. In this instance, immediate settlement from the placement of the last berm may cause a portion of the liner to settle into a grade that does not meet design criteria. This could result in improper leachate flow or improper drainage of lagoons and ponds. Methods for analyzing immediate settlement can be found in most geotechnical and foundation textbooks (e.g., McCarthy, 2002; Holtz and Kovacs, 1981, etc).

but also after *differential settlement* is complete. At least two components of settlement are required to be evaluated: *primary settlement* and *secondary settlement*. The strain on engineered components created by *differential settlement* should also be calculated. Settlement is considered completed when at least 100% of *primary settlement* and the *secondary settlement* expected using a time-frame of 100 years or another time-frame acceptable to Ohio EPA is taken into account.

Due to the natural variability in soils and changes in the vertical stress across a facility, settlement characteristics and the amount of settlement are likely to be different from one point to another both vertically and laterally across a site. The variability of settlement characteristics and the changes in vertical stress due to the geometry of the *waste containment unit(s)* across a site should be discussed in detail in the summary of the subsurface investigation submitted with the settlement calculations. This discussion should describe each compressible layer found at the site, indicate if these layers exist under all or just part of the site, and discuss the extent of the variability of these layers throughout their distribution.

The vertical and lateral variability of settlement characteristics across a site and the significant damage that settlement can cause to engineered components emphasize the need for thorough and careful subsurface investigation. To facilitate a settlement analysis, it is recommended that several points be chosen along the critical cross sections of the facility and that the location of these points be spaced at a distance that would best characterize the facility depending on its size, geometry, and the variability of the soil materials at the site.

Responsible parties of *waste containment facilities* often want to expand existing facilities. This requires that a settlement analysis take into account the settlement of such things as natural foundation materials, structural fill, and waste. Estimating the settlement of structural fill, waste, and some *soil units* that are extremely variable can be difficult. This is especially true of municipal solid waste (MSW) because of the diverse mechanics occurring in the waste such as biodegradation, mechanical compression (bending, crushing, reorientation of waste caused by applied stress), and raveling (movement of fine materials into waste voids by seepage, vibration, or decomposition) (Sowers 1968, 1973). Settlement of MSW requires specialized analysis, is not well understood, and is beyond the scope of this manual. Some publications (e.g., Ling et al, 1998; Spikula, 1996; Wall and Zeiss, 1995) discuss the estimation of MSW settlement. They have been referenced at the end of this chapter.

For greenfield sites, the area within the entire footprint of each proposed *waste containment unit* must be adequately sampled (see Chapter 3). The characterization of each *compressible layer,* both vertically and laterally, is then used to calculate the expected settlement at points along any flow line or for any portion of the facility.

When a settlement analysis is being conducted for an existing *waste containment facility* where borings cannot be placed within the limits of waste placement, the variability in the soil profile of the *compressible layers* under the existing facility can be estimated by using the settlement characteristics from adjacent *borings* outside the limits of waste placement or borings performed prior to the existing waste placement.

For MSW landfills, when a separatory liner system is placed between existing waste and new waste, it must be placed at a minimum ten percent slope in all areas except along flow lines augmented by

> Many engineered components of modern *waste containment facilities* may fail if subjected to *differential settlement* which increases strain on piping and liner system components. Because of this, *responsible parties* may want to consider using additional sampling methods such as cone penetrometers or seismic refraction to gather as much detailed data as possible to accurately delineate the subsurface characteristics of each type of soil material.

leachate collection pipes or at some other slope based on a design acceptable to the director. Other types of facilities may wish to incorporate this into their designs. Nevertheless, it is recommended that all facilities with separatory liner systems not only analyze the foundation soils underlying the *waste containment facility* for settlement, but also analyze the settlement of the waste underlying the separatory liner. The analysis should verify that the leachate collection and management system portion of the separatory liner maintains drainage and the separatory liner system components maintain integrity throughout the life and post closure of the facility or longer as determined by Ohio EPA regulations.

When doing this type of analysis, the variability of the settlement parameters for the existing waste and the foundation under the waste needs to be taken into account. A method that can be used to determine settlement is to assign randomly varied values of settlement characteristics to the waste and the soil materials underlying the existing *waste containment facility*. The settlement characteristics should be varied both vertically and laterally for the waste. The variation of the *compressible layers* can be considered by varying the values of the compression index (C_c) and the initial void ratio (e_o) in a reasonable range. The range of values representing soil materials can be based on the results from the *higher quality data* retrieved from *borings* that surround the existing facility. Book values and/or *higher quality data* retrieved from waste samples or test fills can be used for the values representing waste.

Settlement should be calculated along as many cross sections as are necessary to ensure that the expected amount of *overall* and *differential settlement* that will be experienced by the engineered components of the facility has been adequately estimated. If it is discovered that *overall* and *differential settlement* along any cross section will likely cause damage to an engineered component, or cause the engineered component to be unable to meet the minimum design criteria, then the facility must be redesigned to eliminate the adverse effects of *overall* and *differential settlement* through methods such as overbuilding, surcharging, removal of the material causing the problem, or engineered reinforcement.

Overall Settlement Analysis

When calculating the overall settlement for a facility, points of settlement should be located along the length of critical liquid drainage flow paths and especially at points where increased settlement may occur. Points chosen along the pathways should be evaluated for each compressible layer below the bottom of the facility and the vertical stress being applied above these points. One approach may be to select a range for each settlement parameter for each compressible layer using the sampling and testing procedures outlined in Chapters 3 and 4. The range of the parameters should then be utilized in such a manner as to create the worst-case scenario for primary and secondary settlement of the chosen flow path. Less settlement occurs at a point when the values for C_c, C_r (recompressive index), and C_a (secondary compression index) are at the lowest end of their respective ranges and σ_p' and e_o are at the highest end. The opposite is true of the reverse, and a combination will yield a value between these two extremes. These aspects of the calculations should be considered when determining the settlement along the flow path. The input parameters used in these calculations should be conservative and based on site specific concerns. Once the expected settlement is determined for each point, the slope between the points on the flow paths can be determined. The resulting slopes must meet any regulatory minimums for drainage slopes and/or maintain drainage in the proper direction.

It is important to clearly understand the assumptions and limits of any given method for determining the increase in vertical stress and expected settlement because many methods will not be applicable to *waste containment facilities*. For example, according to Civil Engineering Reference Manual by Lindeburg, Boussinesq's equation applies only to small footings compared to the depth of interest.

Differential Settlement Analysis

Differential settlement can occur due to many factors. Typically, *differential settlement* is a result of variable materials underlying the facility, such as areas of highly compressible material adjacent to less compressible material. These transitional areas should be thoroughly investigated and sampled during the geologic investigation (see Chapter 3 for more information). Then, a critical cross section should be determined across the transition of the two materials. *Differential settlement* may also occur where abrupt changes in loading have been applied to the facility. Cross sections should be analyzed across the loading transition. *Differential settlement* also occurs at locations of mine highwalls or where vertical risers have been incorporated into the liquids management system design. It is recommended in the area of mine highwalls that the settlement analysis incorporate two-dimensional stress distribution theory to verify that the waste containment facility and liquid drainage pathways will not be compromised by the differential settlement. In the case of vertical risers, a bearing capacity analysis is the appropriate calculation to be performed.

Strain

After *overall* and *differential settlement* analyses have been performed, the engineered components of the *waste containment facility*, such as geotextiles, geomembranes, geosynthetic clay liners, geocomposite drainage layers, leachate collection piping, and waste water piping, should be analyzed for tensile strain. The analysis should verify that the engineering components can maintain their integrity when subjected to the induced strain due to the settlement determined in the *overall* and *differential settlement* analyses. The analysis should also include a discussion of the predicted strain compared to the manufacturers' specifications for allowable strain in the products proposed for use at the facility.

Determining Settlement and Strain

The first step of calculating expected settlement (*overall* and *differential*) is to calculate the initial effective vertical stress (σ_o' = total vertical stress - pore water pressure) and the change in the effective vertical stress ($\Delta\sigma_o'$) caused by the facility on a point of interest in the underlying materials. The values added together are the effective vertical stress ($\sigma_o' + \Delta\sigma_o'$) exerted upon the materials that will cause settlement. When calculating effective vertical stress in situations where no differential settlement will occur, a one-dimensional approximation of the settlement may be used. This can be accomplished by calculating the weight of the material directly above the point of interest. When calculating the effective vertical stress where strain may be developed due to differential settlement, a two-dimensional stress distribution theory should be used. Once σ_o' and $\Delta\sigma_o'$ have been calculated, a typical settlement analysis would be performed using the following:

Primary Settlement (Sc)

Primary settlement, also known as *primary consolidation* settlement (Sc), is the reduction in volume of a soil mass caused by the application of a sustained load to the mass and due principally to a squeezing out of water from the void spaces of the mass and accompanied by a transfer of the load from the soil water to the soil solids (ASTM D 653). The rate of settlement is controlled by the permeability of the soil. As a result, in higher permeability cohesionless soils, the settlement occurs rapidly, and in lower permeability cohesive soils, the process is gradual.

The following equation is used to estimate the *primary settlement* in normally consolidated clays or loose granular materials:

$$S_c = \left(\frac{C_c}{1+e_0}\right)\cdot H \cdot \log\left(\frac{\sigma_0' + \Delta\sigma_0'}{\sigma_0'}\right) \qquad (6.1)$$

where H = thickness of the layer after excavation to be evaluated,

C_c = primary compression index,

e_o = initial void ratio,

σ_o' = effective vertical stress at the middle of the layer after excavation, but before loading, and

$\Delta\sigma_o'$ = increase or change in effective vertical stress due to loading.

The following equation is used to estimate the consolidation settlement in overconsolidated clays. Dense cohesionless materials do not settle significantly and thus, do not have to be evaluated using this equation.

$$S_c = \left(\frac{C_r}{1+e_0}\right)\cdot H \cdot \log\left(\frac{\sigma_0' + \Delta\sigma_0'}{\sigma_0'}\right) \qquad (6.2)$$

where C_r = recompressive index.

If the increase in vertical stress at the middle of the consolidation layer is such that ($\sigma_o' + \Delta\sigma_o'$) exceeds the preconsolidation pressure (σ_p') of the consolidating layer, the following equation should be used:

$$S_c = \left[\left(\frac{C_r}{1+e_0}\right)\cdot H \cdot \log\left(\frac{\sigma_p'}{\sigma_0'}\right)\right] + \left[\left(\frac{C_c}{1+e_0}\right)\cdot H \cdot \log\left(\frac{\sigma_0' + \Delta\sigma_0'}{\sigma_p'}\right)\right] \qquad (6.3)$$

The increase in vertical stress is caused by the application of a surcharge to the consolidating layer. Usually the engineered components and waste of a facility will be the surcharge. The entire vertical stress that will be induced at the middle of each consolidating layer should be used in the calculations. This vertical stress typically corresponds to the maximum weight of the facility (e.g., when a solid waste facility is at its maximum waste height, or a waste water lagoon is operating at minimum freeboard).

Ohio EPA stresses the use of laboratory data to determine the various inputs for the settlement equations. ASTM D 2435-03 describes methods to determine σ_p' and e_o from laboratory data. Although not directly indicated in the standard, C_c can also be obtained from the same diagram that σ_p' is obtained. C_c is the slope of the virgin compression curve (i.e., the line that ends with "F" from Fig. 4 of the ASTM standard). C_r is obtained from a diagram for overconsolidated soils, where C_r is the slope of the recompression curve (see **Figure 6-1** on page 6-9).

Secondary Settlement (S_s)

Secondary settlement can be calculated using the following equation:

$$S_s = \frac{C_a}{1+e_p} \cdot H \cdot \log\left(\frac{t_s}{t_{pf}}\right) \qquad (6.4)$$

where C_a = *secondary compression* index of the *compressible layer*,
H = thickness of the layer to be evaluated after excavation, but before loading
t_s = time over which *secondary compression* is to be calculated (use 100 years plus the maximum time it will take to complete *primary consolidation* under the facility unless some other time frame is acceptable to Ohio EPA for a specific facility), and
t_{pf} = time to complete *primary consolidation* in the consolidating layer in the field, and
e_p = the void ratio at the time of complete *primary consolidation* in the test specimen of the *compressible layer*.

Secondary settlement, also known as creep, is the reduction in volume of a soil mass caused by the application of a sustained load to the mass and due principally to the adjustment of the internal structure of the soil mass after most of the load has been transferred from the soil water to the soil solids (ASTM D 653). Due to the absence of pore water pressure, the solid particles are being rearranged and further compressed as point-to-point contact is experienced.

Both t_s and t_{pf} must be expressed in the same units (e.g., days, months, years).

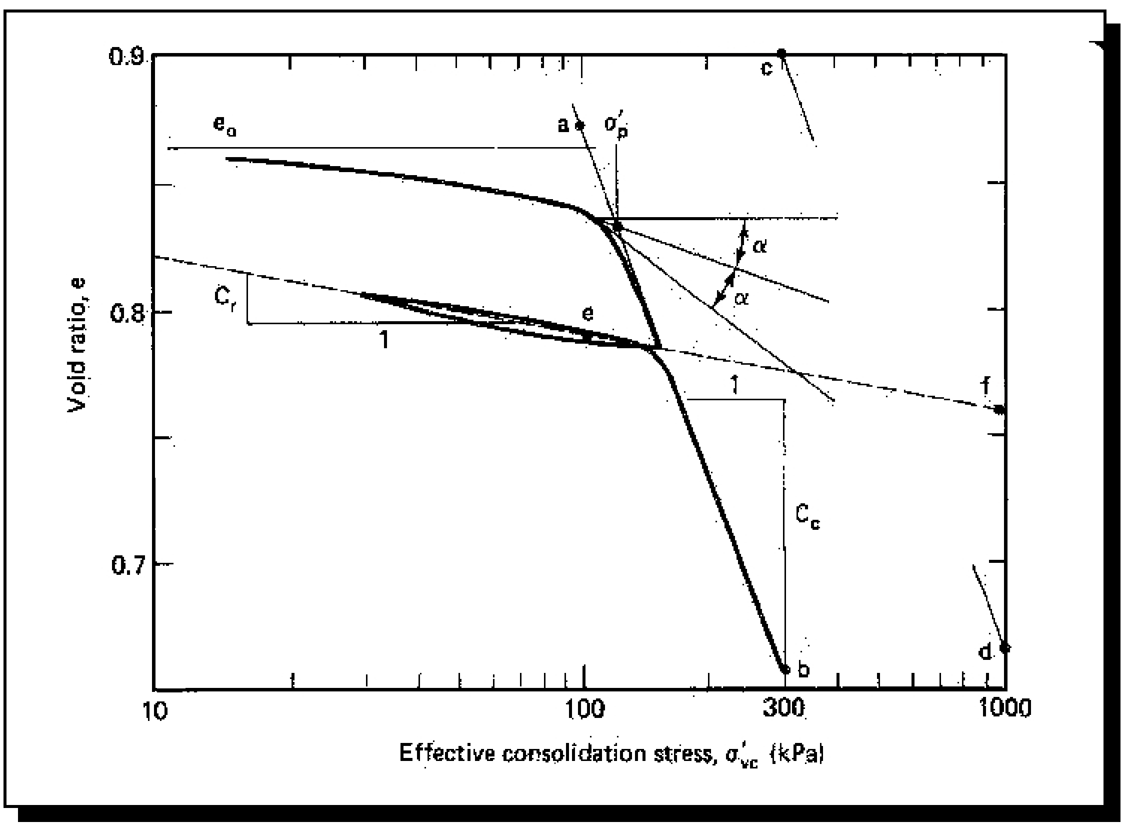

Figure 6-1 Overconsolidated stress diagram. From Ex. Figure 8.9, Holts and Kovacs, pp. 316

The values for e_p and C_a are determined graphically, such as from a void ratio - log time curve as shown in **Figure 6-2**. The value of C_a is the slope of the plot exceeding 100 percent primary consolidation or t_p in **Figure 6-2**.

The value for t_p shown in **Figure 6-2** is the time to complete primary consolidation for the *specimen.* The value of t_p which is needed in equation 6.4, is the field value for t_p. Therefore, t_p (referred to as t_{pf}) should be determined from the following equation to best represent a field value for t_p.

$$t_{pf} = \frac{T_v \cdot H_t^2}{C_v} \qquad (6.5)$$

where H_t = maximum length of drainage in the consolidating layer so that H_t is the full thickness of the consolidating layer if it is drained on one side (top or bottom), and H_t is one-half of the thickness of the consolidating layer if it is drained on both sides (top and bottom),

t_{pf} = time to complete *primary consolidation* in the consolidating layer in the field (years),

C_v = coefficient of consolidation (converted to ft^2/year or m^2/year as appropriate), and

T_v = a dimensionless time factor associated with the time it takes for primary settlement to be completed (see discussion below for more information).

C_v can be determined from one of the methods described in ASTM D 2435-03.

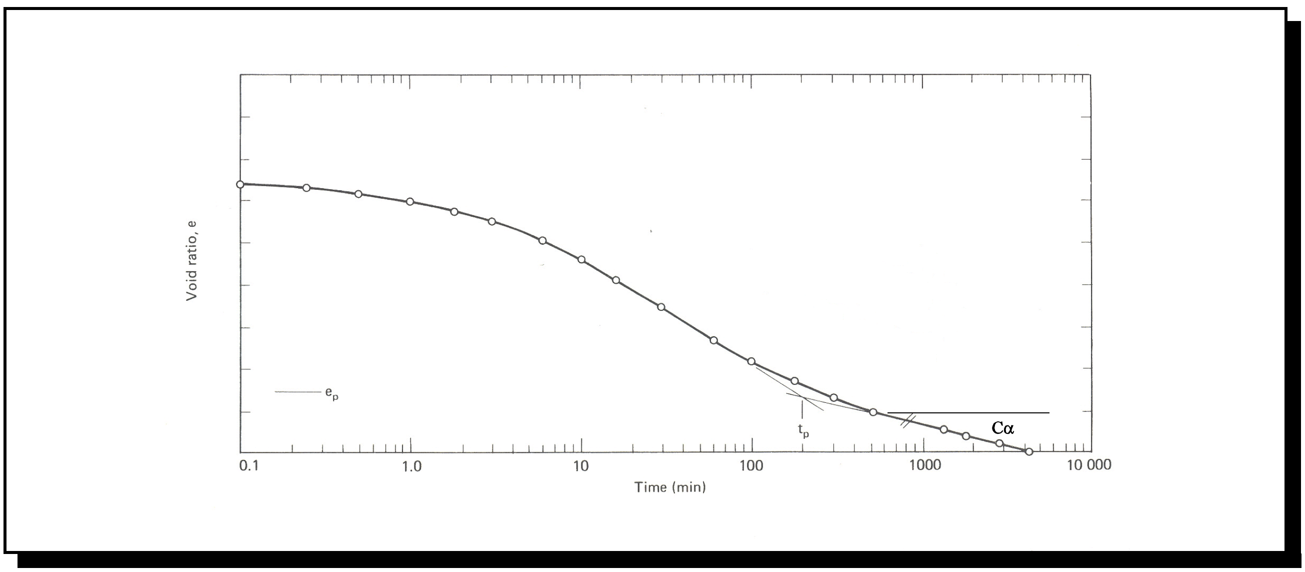

Figure 6-2 Graphical determination of e_p and Cα. Adapted from Figure Ex. 9.10b, Holtz and Kovacs, pp 412.

The dimensionless time factor (T_v) has a theoretical relationship with the percent of primary consolidation (U%) that can be expressed by the following two equations:

For U<60% $$T_v = \frac{p}{4}\left(\frac{U\%}{100}\right)^2 \qquad (6.6)$$

For U>60% $$T_v = 1.781 - 0.933\log(100 - U\%) \qquad (6.7)$$

Plotting these two equations produces the chart solution of Terzaghi's theory of consolidation. Because the equation produces an asymptotic line, Ohio EPA recommends deriving Tv using U% = 99.999 for most facilities. This results in a Tv = 4.58.

Although Ohio EPA recommends a laboratory determination of the above inputs, many can be derived from various charts found in engineering textbooks and manuals used across the country such as the U.S. Army Corps of Engineers manual 1110-1-1904 (September 30, 1990). Some of these charts use a correlation between other inputs or field/lab data, such as blow counts and liquid limits. If charts are used in the settlement analysis, their applicability should be validated with correlations to laboratory data, and the analysis should include a description of how the use of the information from the charts is appropriate with respect to the material represented.

Strain

Once settlement has been calculated for each settlement point, the strain that will occur between each adjacent point can be calculated. The strain can be estimated by using the following equation:

$$E_T(\%) = \frac{L_f - L_0}{L_0} \bullet 100 \qquad (6.8)$$

where E_T = tensile strain,
L_0 = original distance separating two location points, and
L_f = the final distance separating the same two points after settlement is complete.

Primary Consolidation - Example Calculations

An example of calculating the primary settlement for clay is illustrated using a landfill that has a maximum excavation of 30 ft and a maximum waste depth of 210 feet over a 50-foot thick overconsolidated clay layer underlain by a 40-foot thick dense gravel layer. The settlement of the dense gravel layer would not be calculated because significant settlement is not likely due to its density. To be conservative, all the clay is assumed to be saturated. Any amount of immediate settlement is likely to be compensated for during construction. Oedometer tests on undisturbed specimens from three borings provided the following range of values: preconsolidation pressure (σ_p') = 3,900 psf - 4,000 psf, C_c = 0.152 - 0.158, C_r = 0.023 - 0.026, e_0 = 0.4797 - 0.4832, C_v = 0.0240 - 0.0250, $C\alpha$ = 0.0129 - 0.0134, and e_p = 0.0866 - 0.0867. The field saturated unit weight of the clay is typically 135 pcf. Because this clay layer will be recompacted for bottom liner, we will assume that the liner will have the same settlement parameters. Six of the points of concern for settlement in this example are shown in **Figure 6-3**:

For this example, settlement will be analyzed for only points #1 through #6. The average initial effective overburden pressure at the center of the clay layer σ_o'=3,375 psf. Because σ_p' > σ_o', the in-situ clay is overconsolidated. Since σo' + $\Delta\sigma_o$' > σ_p', equation 6.3 will be used. The increase in vertical stress ($\Delta\sigma_0$') at points #1 through #6 will be determined using a one-dimensional stress distribution analysis.

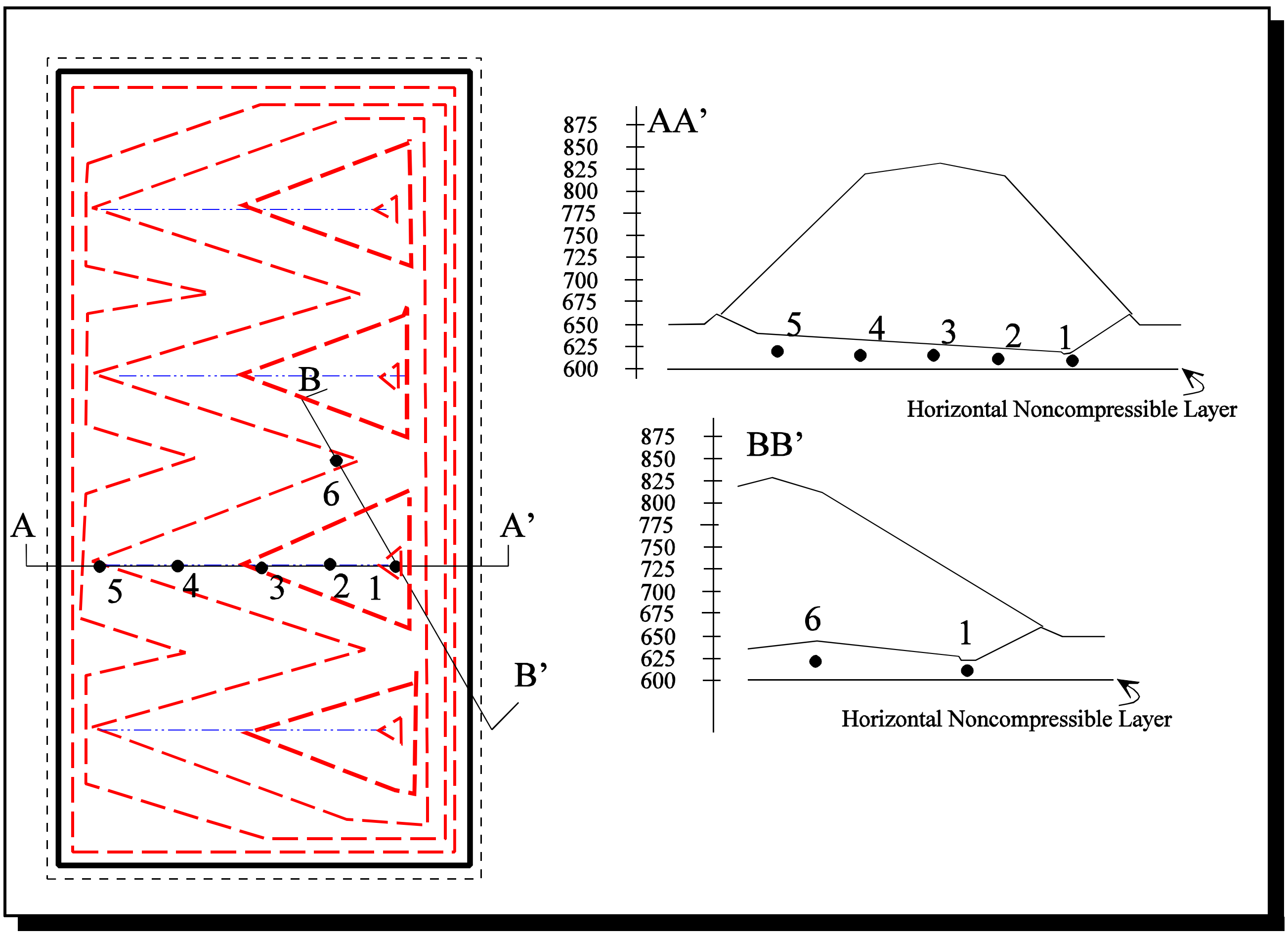

Figure 6-3 Example plan view and cross sections showing some of the locations selected for settlement analysis.

Primary Consolidation - Example Calculations (cont.)

$$S_c = \left[\left(\frac{C_r}{1+e_0}\right)\cdot H\cdot\log\left(\frac{s_p'}{s_0'}\right)\right] + \left[\left(\frac{C_c}{1+e_0}\right)\cdot H\cdot\log\left(\frac{s_0' + \Delta s_0'}{s_p'}\right)\right]$$

Point	Top of Gravel	Top of Liner	Top of LDF	H (ft)	σ_o' (psf)	Load Height (ft)	$\Delta\sigma_o'$	C_c	C_r	e_o	σ_p'	S_c (ft)
1	600	619	732	19	1283	113	8475	0.152	0.023	0.4832	4000	0.8996
2	600	624	820	24	1620	196	14700	0.158	0.026	0.4797	3900	1.7540
3	600	629	830	29	1958	201	15075	0.158	0.026	0.4797	3900	2.1350
4	600	635	820	35	2363	185	13875	0.158	0.026	0.4797	3900	2.4489
5	600	640	725	40	2700	85	6375	0.158	0.026	0.4797	3900	1.6788
6	600	641	820	41	2768	179	13425	0.158	0.026	0.4797	3900	2.8140

$$t_{pf} = \frac{T_v \cdot H_t^2}{C_v} \qquad S_s = \frac{C_a}{1+e_p}\cdot H\cdot\log\left(\frac{t_s}{t_{pf}}\right)$$

Point	H_t (ft)	t_s (yr)	C_v @T_{90} (in^2/min)	t_{pl} (yr)	e_p	C_α	S_s (ft)
1	19	559.3	0.0250	459.2722	0.0867	0.0129	0.019
2	24	863.3	0.0240	763.3333	0.0866	0.0134	0.016
3	29	1215.0	0.0240	1114.5197	0.0866	0.0134	0.013
4	35	1723.0	0.0240	1623.4086	0.0866	0.0134	0.011
5	40	2220.4	0.0240	2120.3704	0.0866	0.0134	0.010
6	41	2328.0	0.0240	2227.7141	0.0866	0.0134	0.010

Primary Consolidation - Example Calculations (cont.)

	Top of Liner	Primary Settlement S_c (ft)	Secondary Settlement S_s (ft)	Top of Liner after Settlement	Length (ft)	Initial Slope (%)	Final Slope (%)
1	619	0.8996357	0.019296	618.08107			
					500	1.0%	0.8%
2	624	1.7498684	0.015824	622.23431			
					500	1.0%	0.9%
3	629	2.1350133	0.013346	626.85164			
					600	1.0%	0.9%
4	635	2.4489316	0.011205	632.53986			
					500	1.0%	1.2%
5	640	1.6788209	0.00987	638.31131			
1	619	0.8996357	0.019296	618.08107	1000	2.2%	2.0%
6	641	2.813968	0.00964	638.17639			

The resulting strain between the points can be estimated using Equation 6.8.

$$E_T(\%) = \frac{L_f - L_0}{L_0} \bullet 100$$

Point	Top of Liner	X Coordinate	Top of Liner after Settlement	Original Length (ft)	Length after Settlement	E_T (%)
1	619	0	618.1			
				500.025	500.017	0.00%
2	624	500	622.2			
				600.0208	600.018	0.00%
3	629	1000	626.9			
				500.036	500.032	0.00%
4	635	1600	632.5			
				500.025	500.033	0.00%
5	640	2100	638.3			
1	619	0	618.1	1000.242	1000.202	0.00%
6	641	950	638.2			

Considerations for Mine Spoil

Although this section is specifically tailored to address mine spoil, the techniques described herein may be applicable to other types of foundation materials susceptible to *differential settlement*.

The potential damage caused by settlement of engineered components by constructing across an existing highwall/mine spoil interface (see **Figure 6-4**) or a buried valley can be considerable. A highwall is the edge of the quarry and the transition point from existing *bedrock* to the mine spoil used to fill the quarry area. This transition point presents a sharp contrast between the compressible mine spoil and rigid highwall that can result in severe tensile stress from *differential settlement*. The increase in tensile stress in the engineered components installed across the highwall/mine spoil interface is determined by estimating the mine spoil settlement and assuming that the highwall will not settle. This creates a conservative estimate of the *differential settlement* across the highwall/mine spoil interface that can then be used to determine the strain on engineered components.

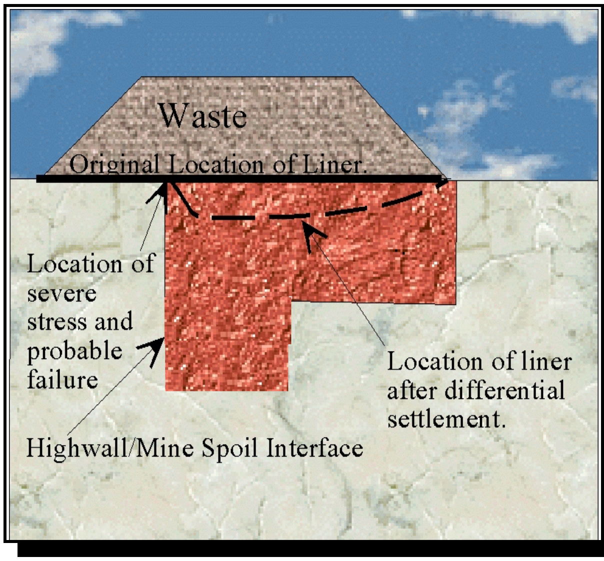

Figure 6-4 Example of failure point at a highwall/mine spoil interface.

Several alternatives can be considered to reduce the tensile stress created by *differential settlement* upon engineered components at the highwall/mine spoil interface. One alternative is cutting back the highwall to increase the length over which the *differential settlement* will occur. This will reduce the tensile strain because the *differential settlement* is occurring over a longer length rather than at the vertical highwall/mine spoil interface. This could involve excavating the *bedrock* of the highwall to create a grade sloping away from the mine spoil and placing fill in the excavation to reduce the effects of the difference in compressibility of the two materials.

A second alternative is to surcharge the mine spoil to cause a large portion of the settlement of the mine spoil to occur before constructing any engineered components across the high tensile stress area. The surcharge should be applied using a significant percentage of the proposed weight to be placed over the highwall. Thus, when the surcharge is removed, less settlement will occur when the facility is constructed, which should reduce the tensile strains in the engineered components. This alternative can be undertaken in conjunction with cutting back the highwall.

A third alternative, tensile reinforcement using geogrids or geotextiles, might be suitable in some rare cases for bridging the highwall/mine spoil transition. However, the use of tensile reinforcements will require sufficient anchorage on both ends to generate the tensile forces necessary to resist settlement.

Whenever an engineered solution is proposed for use to eliminate or mitigate *differential settlement*, detailed calculations and a design proposal must be submitted to Ohio EPA for approval. This usually occurs as part of a permit application or other request for authorization. The submittal must demonstrate the long-term effectiveness of the engineered solution and include a proposed plan for monitoring the effectiveness of the solution or provide a justification that long-term monitoring is not warranted.

The orientation of engineered components (e.g., geomembrane seams) should also be considered. Engineered components in the mine spoil area should be oriented so that the tensile strain that develops because of *differential settlement* will be directed away from stress sensitive engineered components. For example, the seams of geosynthetics should be installed perpendicular to a mine spoil/highwall interface, rather than parallel to it.

BEARING CAPACITY

Although the design of a *waste containment facility* is governed mostly by the results of the slope stability and settlement analyses, bearing capacity should be addressed. The analyses of bearing capacity and settlement are interrelated because they rely upon the same subsurface investigation data, use similar calculations for determining the increase in vertical stress created upon the foundation materials by the facility, and are similarly affected by the geometry of the facility. Designing a facility to account for induced settlements usually addresses all concerns except when the entire *waste containment facility* is underlain by a nonrigid foundation such as soft clays; has vertical leachate sump risers in the design; or contains stabilized waste. After a successful settlement analysis of the facility has been performed, a bearing capacity analysis of the facility over the nonrigid foundation; vertical riser; or stabilized waste relative to equipment travel during operations and after closure should be conducted.

> Stabilized waste is defined as any waste, such as sludge or pickle liquors, that must be blended with another material to generate the strength necessary to bear the weight of objects or other materials. *Responsible parties* may need to stabilize the waste and/or contaminated soils being disposed to provide support for a cap and equipment. It is recommended that the unconfined compressive strength of the stabilized waste and/or contaminated soil be at least 15 psi. If this amount of compressive strength cannot be made available at the time of construction, it is important that the *responsible party* ensure that the waste will increase in strength over time and has adequate strength to support construction and maintenance activities. For the short-term, the waste should be capable of supporting the combined weight of the cap with a heaviest piece of construction equipment. This can be demonstrated by having a factor of safety against bearing capacity failure of at least 2.0 or greater using the heaviest piece of construction equipment. For the long term, the waste should be able to support the weight of the cap and the heaviest piece of maintenance equipment once construction is complete. This can be demonstrated by having a factor of safety against bearing capacity failure of at least 3.0 using the heaviest piece of maintenance equipment.

Reporting of the bearing capacity analysis would include the same elements as the settlement analysis with the addition of a description of any downdrag forces and the assumptions associated with those forces used in the bearing capacity analysis.

Three modes of bearing capacity failures exist that may occur under any foundation. They are general shear, punching shear, and local shear (see **Figure 6-5** on Page 6-17). Designers should evaluate all potential bearing failure types for applicability to their facility design, especially if vertical sump risers are included in the design. Ohio EPA discourages the use of vertical sump risers in solid waste and hazardous *waste containment units* due to the inherent difficulties they present during filling operations, and the potential they create for damaging underlying liner system. They also pose a risk to the integrity of the *waste containment system* if they are not designed properly. The size and stiffness of the foundation slab are critical. If the slab is not large enough in area, and is not stiff enough to prevent deflection under the expected load, then excessive settlement or a bearing capacity failure could occur. This would likely breach the *waste containment system* at one of its most critical points. Also, it is not recommended that geosynthetic clay liners be installed beneath vertical sump risers due to the likelihood of the bentonite squeezing out from beneath the foundation slab.

The following factor of safety should be used, unless superseded by rule, when demonstrating that a facility is designed to be safe against bearing capacity failures.

Bearing Capacity Analysis: FS $\geq$ 3.0

> The number of digits after the decimal point indicates that rounding can only occur to establish the last digit. For example, 1.57 can be rounded to 1.6, but not 2.0.

Using a factor of safety less than 3.0 against bearing capacity failure for long-term loading situations is not considered a sound engineering practice in most circumstances. This is due to the many large uncertainties involved when calculating bearing capacity. The factor of safety is also high, because any failure of the *waste containment facility* due to a bearing capacity failure is likely to increase the potential for harm to human health and the environment. If a vertical sump riser has a factor of safety against bearing capacity failure less than 3.0, the following alternatives can be considered: elimination of the vertical sump riser in favor of a side slope sump riser, removal of soil layers susceptible to a bearing capacity failure, or redesigning the vertical sump riser to be within the bearing capacity of the soils. In the case of stabilized waste, if the factor of safety is less than 3.0, the waste must be reprocessed to meet the stability requirement. If a bearing capacity analysis of a facility over soft clays is less than 3.0, then the facility will need to be redesigned or the soil layers susceptible to a bearing capacity failure removed.

> 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.

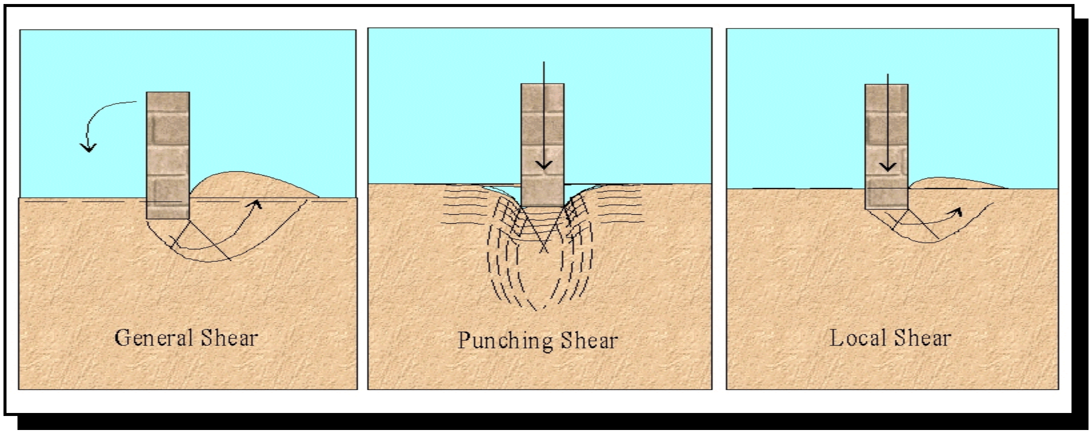

Figure 6-5 The three modes of bearing failures.

State and local building departments require permits before constructing and using any structure, such as storage tanks, scale houses, or office buildings. The building departments require bearing capacity analysis and settlement analysis as part of the permit process for these types of structures. Ohio EPA expects that the *responsible party* will comply with all building and occupancy requirements for these types of peripheral structures. Therefore, although these types of structures are often defined as being a part of a *waste containment facility*, Ohio EPA will not review the bearing capacity or settlement calculations for these types of structures.

The factor of safety against bearing capacity failure is calculated as follows:

$$FS_b = \frac{q_{ult}}{p_{total}} \geq 3.0 \qquad (6.9)$$

where FS_b = factor of safety against bearing failure,
q_{ult} = ultimate bearing capacity of the foundation soils, and
p_{total} = the total pressure applied to the base of a foundation by an overlying mass.

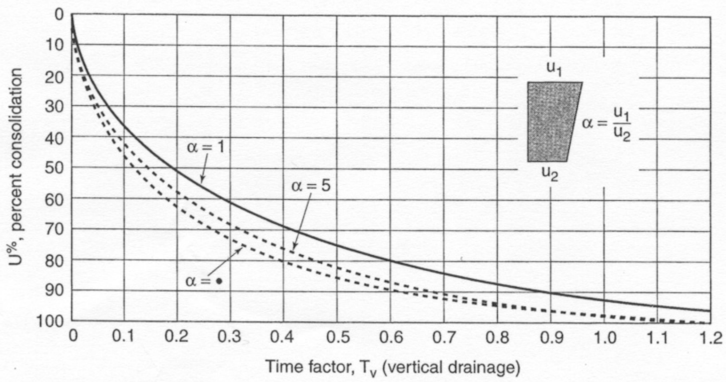

Figure 10-23 Variation of time factor T_v with percentage of consolidation U.

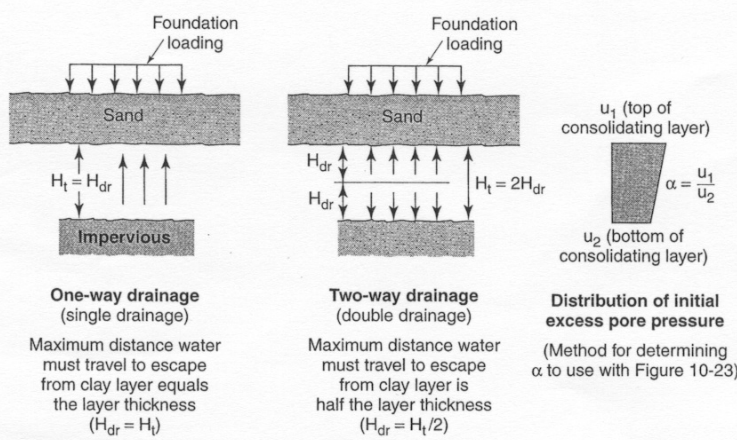

Figure 10-24 Vertical drainage conditions in consolidation theory.

Figure 6-6 This set of figures and the chart can be used for determining the time factor (T_v) for settlement and identifying the drainage path length (H_{dr}). Determining T_v for U%>95 can be calculated using: T_v=1.781-0.933log(100-U%)   Source: McCarthy, 2002, Page 383.

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