Lateral Earth Pressure for Non-Geotechnical Engineers

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PDH: 2

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Introduction

Lateral earth pressure represents pressures that are “to the side” (horizontal) rather than vertical. The objective of this course is to familiarize primarily the non-geotechnical engineer such as civil engineers, structural engineers, architects and landscape architects with simple background theory and considerations.

Calculating lateral earth pressure is necessary in order to design structures such as:

- Retaining Walls
- Bridge Abutments
- Bulkheads
- Temporary Earth Support Systems Basement Walls

At the end of this course you will have learned:

- Basic method of calculating lateral earth pressure
- Other considerations when developing the total lateral force against a structure

Categories of Lateral Earth Pressure

There are three categories of lateral earth pressure and each depends upon the movement experienced by the vertical wall on which the pressure is acting. In this course, we will use the word wall to mean the vertical plane on which the earth pressure is acting. The wall could be a basement wall, retaining wall, earth support system such as sheet piling or soldier pile and lagging etc.

The three categories are:

- At rest earth pressure
- Active earth pressure
- Passive earth pressure

The at rest pressure develops when the wall experiences no lateral movement. This typically occurs when the wall is restrained from movement such as a basement wall that is supported at the bottom by a slab and at the top by a floor framing system prior to placing soil backfill against the wall.

The active pressure develops when the wall is free to move outward such as a typical retaining wall and the soil mass stretches sufficiently to mobilize its shear strength. On the other hand, if the wall moves into the soil, then the soil mass is compressed sufficiently to mobilize its shear strength and the passive pressure develops. This situation might occur along the section of wall that is below grade and on the opposite side of the wall from the higher section. Some engineers use the passive pressure that develops along this buried face as additional restraint to lateral movement.

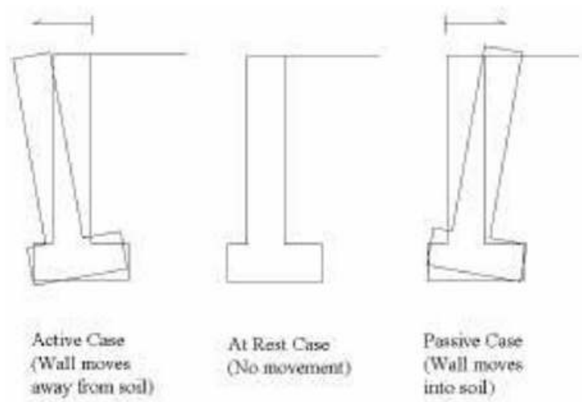


Figure 1 Wall Movement

In order to develop the full active pressure or the full passive pressure, the wall has to move. If the wall does not move a sufficient amount, then the full pressure will not develop. If the full active pressure does not develop behind a wall, then the pressure will be higher than the expected active pressure. Likewise, significant movement is necessary to mobilize the full passive pressure. This is illustrated in Figure 2. Note that the <u>at rest</u> condition is shown where the wall rotation is equal to 0, which is the condition for zero lateral strain.

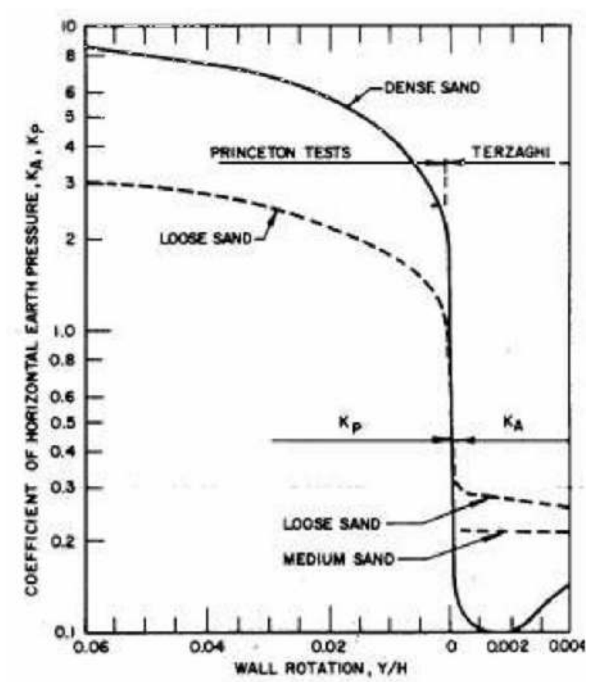


Figure 2 Effect of Wall Movement on Wall Pressure

[Ref: NAVFAC DM-7]

From this figure, it is shown that:

- As the wall moves away from the soil backfill (left side of Figure 1), the active condition develops and the lateral pressure against the wall decreases with wall movement until the minimum active earth pressure force (Pa) is reached.
- As the wall moves toward (into) the soil backfill (right side of Figure 1), the passive condition develops and the lateral pressure against the wall increases with wall movement until the maximum passive earth pressure (Pp) is reached.

Thus the intensity of the active / passive horizontal pressure, which is a function of the applicable earth pressure coefficient, depends on wall movement as the movement controls the degree of shear strength mobilized in the surrounding soil.

Calculating Lateral Earth Pressure Coefficients

Lateral earth pressure is related to the vertical earth pressure by a coefficient termed the:

- At Rest Earth Pressure Coefficient (Ko)
- Active Earth Pressure Coefficient (Ka)
- Passive Earth Pressure Coefficient (Kp)

The lateral earth pressure is equal to vertical earth pressure times the appropriate earth pressure coefficient. There are published relationships, tables and charts for calculating or selecting the appropriate earth pressure coefficient.

Since soil backfill is typically granular material such as sand, silty sand, sand with gravel, this course assumes that the backfill material against the wall is coarse-grained, non-cohesive material. Thus, cohesive soil such as clay is not discussed. However, there are many textbooks and other publications where this topic is fully discussed.

At Rest Coefficient

Depending upon whether the soil is loose sand, dense sand, normally consolidated clay or over consolidated clay, there are published relationships that depend upon the soil's engineering values for calculating the at rest earth pressure coefficient. One common earth pressure coefficient for the "at rest" condition used with granular soil is:

$$Ko = 1 - \sin(\phi) \qquad (1.0)$$

Where: Ko is the "at rest" earth pressure coefficient and ϕ is the soil friction value.

Active and Passive Earth Pressure Coefficients

When discussing active and passive lateral earth pressure, there are two relatively simple classical theories (among others) that are widely used:

- Rankine Earth Pressure
- Coulomb Earth Pressure

The Rankine Theory assumes there is no adhesion or friction between the wall and soil, and:

- Lateral pressure is limited to vertical walls
- Failure (in the backfill) occurs as a sliding wedge along an assumed failure plane defined by ϕ.
- Lateral pressure varies linearly with depth and the resultant pressure is located one-third of the height (H) above the base of the wall.
- The resultant force is parallel to the backfill surface.

The Coulomb Theory is similar to Rankine except that:

- There is friction between the wall and soil and takes this into account by using a soil-wall friction angle of δ. Note that δ ranges from ϕ/2 to 2 ϕ/3 and δ = 2ϕ/3 is commonly used.
- Lateral pressure is not limited to vertical walls
- The resultant force is not necessarily parallel to the backfill surface because of the soil-wall friction value δ.

The general cases for calculating the earth pressure coefficients can also be found in published expressions, tables and charts for the various conditions such as wall friction and sloping backfill. The reader should obtain these coefficients for conditions other than those discussed herein.

The Rankine active and passive earth pressure coefficient for the condition of a horizontal backfill surface is calculated as follows:

- (Active) $K_a = (1 - \sin(\phi)) / (1 + \sin(\phi))$ (2.0)
- (Passive) $K_p = (1 + \sin(\phi)) / (1 - \sin(\phi))$ (3.0)

Some tabulated values base on Expression (2.0) and (3.0) are:

ϕ (deg)	Rankine Ka	Rankine Kp
28	.361	2.77
30	.333	3.00
32	.307	3.26

The Coulomb active and passive earth pressure coefficient is a more complicated expression that depends on the angle of the back of the wall, the soil-wall friction value and the angle of backfill. Although the expression is not shown, these values are readily obtained in textbook tables or by programmed computers and calculators. The Table below shows some examples of the Coulomb active and passive earth pressure coefficient for the specific case of a vertical back of wall angle and horizontal backfill surface.

Coulomb Active Pressure Coefficient

	δ (deg)				
ϕ (deg)	0	5	10	15	20
28	.3610	.3448	.3330	.3251	.3203
30	.3333	.3189	.3085	.3014	.2973
32	.3073	.2945	.2853	.2791	.2755

Coulomb Passive Pressure Coefficient

	δ (deg)				
ϕ (deg)	0	5	10	15	20
30	3.000	3.506	4.143	4.977	6.105
35	3.690	4.390	5.310	6.854	8.324

Some points to consider are:

- For the Coulomb case shown above with no soil-wall friction (i.e. $\delta = 0$) and a horizontal backfill surface, both the Coulomb and Rankine methods yield equal results.
- As the soil becomes stronger the friction value (ϕ) increases. The active pressure coefficient decreases, resulting in a decrease in the active force and the passive pressure coefficient increases, resulting in an increase in the passive force.
- As the soil increases in strength (i.e. friction value increases) there is less horizontal pressure on the wall in the active case.

Calculating the Vertical Effective Overburden Pressure

The vertical effective overburden pressure is the effective weight of soil above the point under consideration. The term "effective" means that the submerged unit weight of soil is used when calculating the pressure below the groundwater level. For instance, assume that a soil has a total unit weight (γ) of 120 pcf and the groundwater level is 5 feet below the ground surface. The vertical effective overburden pressure ($\sigma v'$) at a depth of 10 feet below the ground surface (i.e. 5 feet below the groundwater depth) is:

$$\sigma v' = 5(\gamma) + 5(\gamma')$$

Where γ is the total unit weight of the soil and γ' is the effective (or submerged) unit weight of the soil which equals the total unit weight of soil minus the unit weight of water (i.e. 62.4 pcf). Thus:

$$\sigma v' = 5(120) + 5(120\text{-}62.4) = 888 \text{ psf}$$

Calculating the Lateral Earth Pressure

There is a relationship between the vertical effective overburden pressure and the lateral earth pressure. The lateral earth pressure (σ) is:

- $\sigma a = Ka\ (\sigma v')$ Active lateral earth pressure (4.0)
- $\sigma p = Kp\ (\sigma v')$ Passive lateral earth pressure (5.0)

Where ($\sigma v'$) is the vertical effective overburden pressure.

If water pressure is allowed to build up behind a retaining wall, then the total pressure and the resulting total force along the back of the wall is increased considerably. Therefore, it is common for walls to be designed with adequate drainage to prevent water from accumulating behind the wall. Thus, weepholes, lateral drains or blanket drains along with granular soil (freely draining backfill) are commonly used behind retaining walls. In the case of a drained condition, the total unit weight of soil (γ) is used behind the full height of the wall and there is no water pressure contribution.

An example of an earth pressure calculation using the Rankine active earth pressure coefficient is shown later in the *Example* section of this course. A similar calculation can be performed for the Coulomb case by using the Coulomb earth pressure coefficient applicable to the case at hand.

Calculating the Total Lateral Earth Pressure Force

The total lateral force is the area of the pressure diagram. In the simple example shown later in this course, the area of the earth pressure diagram is the earth pressure at the bottom of the wall (K$a\gamma$H) times the height of the wall (H) times one-half (1/2) since the pressure distribution increases linearly with depth creating a triangular shape. Thus the total active earth pressure force (Pa) acting along the back of the wall is the area of the pressure diagram expressed as:

$$Pa = ½\ Ka\ \gamma\ H^2 \quad (6.1)$$

The total passive earth pressure force is:

$$Pp = 1/2\ Kp\gamma H^2 \qquad (6.2)$$

The total force acts along the back of the wall at a height of H/3 from the base of the wall.

In more complicated cases, the earth pressure distribution diagram is drawn and the total force is calculated by determining the area of the pressure diagram. The location of the resultant force is also determined.

Other Forces Acting on the Wall

Aside from the earth pressure force acting on wall, other forces might also act on the wall. These forces include:

- Surcharge load
- Earthquake load
- Water Pressure

<u>Surcharge Load</u>

A surcharge load results from forces that are applied along the surface of the backfill behind the wall. These forces apply an additional lateral force on the back of the wall. Surcharge pressures result from loads such as a line load, strip load, embankment load, traffic (such as a parking lot), floor loads and temporary loads such as construction traffic. Generally, elastic theory is used to determine the lateral pressure due to the surcharge and these methods have been extensively published.

In the case of a uniform surcharge pressure (q) taken over a wide area behind the wall, the lateral pressure due to the uniform surcharge:

$$K_0q \qquad (7.0)$$

Where K_0 is the applicable at rest, active or passive pressure coefficient. The pressure diagram behind the wall for a uniform surcharge is rectangular and acts at a height of H/2 above the base of the wall. Thus, the additional lateral force (Ps) acting behind the wall resulting from a uniform surcharge is the area of the rectangle, or:

$$Ps = K_0qH \qquad (8.0)$$

Whether the total surcharge load is calculated from elastic theory or as shown in Expression (8.0), the force (pressure) is superimposed onto the calculated lateral earth pressure.

Earthquake Force

Additional lateral loads resulting from an earthquake are also superimposed onto the lateral earth pressure where required. Publications such as AASHTO Standard Specifications for Highway Bridges and other textbooks provide methods for calculating the earthquake force.

Water Pressure

Walls are typically designed to prevent hydrostatic pressure from developing behind the wall. Therefore the loads applied to most walls will not include water pressure. In cases where water pressure might develop behind an undrained wall, the additional force resulting from the water pressure must be superimposed onto the lateral earth pressure. Since water pressure is equal in all directions (i.e. coefficient (K) = 1), the water pressure distribution increases linearly with depth at a rate of $\gamma_w z$ where γ_w is the unit weight of water (62.4 pcf) and z is the depth below the groundwater level. If the surface of water behind a 10-foot high wall (H) were located 5-feet (d) below the backfill surface, then the superimposed total lateral force resulting from groundwater pressure would be:

- $W = ½ (\gamma_w)(H\text{-}d)^2 = 780$ pounds, which is the area of the linearly increasing pressure distribution.
- W acts at a height of (H-d)/3 (or 1.67-ft) above the base of the wall.
- Note that the earth pressure would be calculated using the submerged unit weight of soil γ' below the groundwater level.

If seepage occurs, then the water pressure must be derived from seepage analysis, which is outside the scope of this course.

Compaction

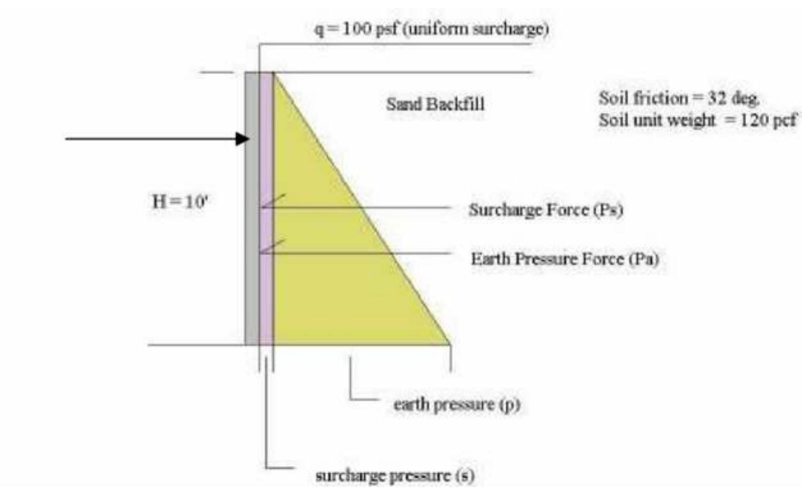
If heavy rollers are used to compact soil adjacent to walls, then high residual pressures can develop against the wall. Although a reasonable amount of backfill compaction is necessary, excess compaction should be avoided.

Building Codes

Building codes might also provide information related to earth pressure and calculating lateral soil load. The topic "Lateral Soil Loads" is included in The BOCA National Building Code.

Example

Use the Rankine method to calculate the total **active** lateral force and location of the forces behind a 10-foot high vertical wall. Assume that the soil has a total unit weight of 120 pcf and a friction value of 32 degrees. Assume that there is a uniform surcharged of 100 psf located along the surface behind the wall. Groundwater is well below the depth of the foundation so that groundwater pressure does not develop behind the wall.



Ka = 1 – sin (32) / 1 + sin (32) = 0.307 is the Active Earth pressure Coefficient At

bottom of wall (surcharge pressure) s = Ka (q) = 0.307(100) = 30.7 psf

At bottom of wall (active lateral earth pressure) p_a = Ka () H = 0.307(120)(10) = 368.4 psf

Total Surcharge Force: Ps = Ka(q)H = 307 pounds and acts at a height of H/2 from the base of the wall.

Total Earth Pressure Force: Pa = ½ Ka (γ) H^2= 1/2 (0.307) (120) $(10)^2$ = 1842 pounds and act at a height of H/3 from the base of the wall.

Total Active Force = 1842 + 307 = 2149 pounds

Important Points

The purpose of this course is to present basic subject matter to a diverse audience in order to convey the general concepts used when calculating lateral pressures against a wall. The reader should understand the following:

- Lateral earth pressure acts to the side and is a function of the vertical effective soil overburden pressure and the applicable earth pressure coefficient.
- There are three categories of earth pressure, each dependent upon magnitude and direction of wall movement. These categories are: At Rest, Active and Passive.
- Two classical earth pressure theories in common use are: Rankine and Coulomb.
- In addition to earth pressure, other common superimposed lateral pressures result from: surcharge, earthquake, and water.
- The total lateral force equals the area of the pressure distribution along the back of the wall.

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