8 Earth Pressures

All civil engineering structures eventually come into contact with the soil for their foundations. For some structures, this contact is significant, such as for retaining walls, diaphragm walls, lock chambers, culverts, open tunnel sections, and tunnels. Here, an important part of the load consists of earth pressures.

When calculating the stresses in soil, we assume that the grains in the soil form a skeleton. The *grain skeleton* can transfer forces via the contact points between the grains. Section 8.1 addresses the concept *grain pressure*.

In dry soil, the forces are transferred by means of the grain skeleton. In wet soil, the water also plays a role. The water pressure combined with the grain pressure is the *earth pressure*. Section 8.2 concerns the calculation of vertical earth pressures.

In contrast to (stationary) gases and fluids, shear stresses do occur in soil. The shear stresses are transferred by the grain skeleton. The horizontal earth pressure is therefore in general not equal to the vertical earth pressure (there is no isotropic stress state). Section 8.3 addresses the determination of horizontal earth pressures.

The active and passive grain pressure are the two extreme values between which the horizontal grain pressure can vary. These limits occur when a slide plane develops and a soil mass slides (*active grain pressure*) or is

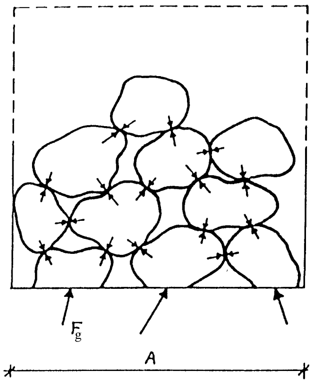

Figure 8.1 A small part of the grain skeleton in dry soil. The forces F_g are required to keep the grains on the section plane in equilibrium.

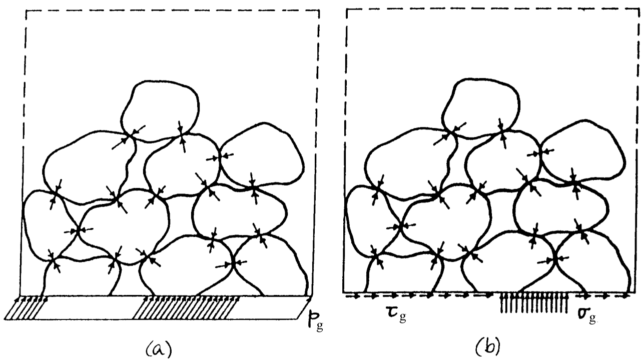

Figure 8.2 (a) The grain stress p_g is defined as the average grain force over a small area that is large compared to the grain diameter. (b) The grain stress p_g has a normal stress component σ_g that acts normal to the section plane and a shear stress component τ_g that acts along the section plane.

upset (*passive grain pressure*). This is covered in Sections 8.3.1 and 8.3.2 respectively.

An intermediate value is the *neutral grain pressure*, the horizontal grain pressure on an immovable rigid wall. The neutral grain pressure is covered in more detail in Section 8.3.3.

The explanations in this chapter remain highly elementary. Soil is a complex matter; its properties are so different from those of regular solids that soil is not part of applied mechanics, but has its own discipline: *soil mechanics*. Please therefore refer to text on soil mechanics for more detailed information.

8.1 Stresses in soil

Soil can be described as a collection of non-cohesive or mildly-cohesive, generally small particles of mineral or organic origin, in which the voids between the particles is entirely or partially filled with water or air. The solid particles are called *grains*. This definition can be taken literally for *sand*, but not too literally for *clay* or *peat* for example.

When calculating stresses in the soil, we assume that the grains in the soil form a skeleton. The *grain skeleton* can transfer forces via the contact areas between the grains. In dry soil, the forces are transferred via the grain skeleton; in wet soil, the water also plays a role.

To start with, we will look at dry soil. In Figure 8.1, part of the grain skeleton has been isolated from dry soil. The section plane, with area A cuts a number of grains. The forces F_g are required to keep the grains on the section, and thus the isolated grain skeleton in equilibrium. The *average compressive grain force* over a *small area* A, which is large compared to the grain diameter, is defined as the *grain pressure* p_g (see Figure 8.2a):

$$\vec{p}_g = \frac{\sum \vec{F}_g}{A}. \quad (1)$$

The grain pressure p_g has a normal stress component σ_g and a shear stress component τ_g. The *normal stress* σ_g acts normal to the section plane, while the *shear stress* τ_g acts in the section plane (see Figure 8.2b). For the sake of clarity, neither of the stresses have been shown in the figure along the entire length of the section.

Note that the convention from *soil mechanics* has been adopted, in which *compressive (normal) stresses* in the soil are *positive*.

The grain pressure p_g and the stress components σ_g and τ_g are a measure for the forces that are transferred via the grain skeleton.

In soil that is fully saturated with water, *water pressure* acts on the grains, in addition to the forces from the grain skeleton. If the contact surfaces between the grains are modelled as points, the water pressure acts on the entire surface of the grain. If the grains are so small that the difference between the water pressures at the top and at the base of the grain is negligible, it is said that the grain is subjected to an all-round water pressure σ_w. This load, as shown in Figure 8.3 for a single grain, forms an *equilibrium system*, regardless of the shape of the grain; see Section 7.2, Example 3 (Figure 7.14 and beyond).

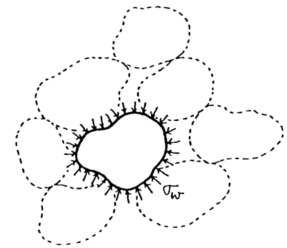

Figure 8.3 In soil saturated with water, an all-round water pressure σ_w acts on the grain. This load forms an equilibrium system, regardless of the shape of the grain.

In Figure 8.4, part of the grain skeleton has been isolated from the water-saturated soil. Here too, the section cuts a number of grains. In the figure, only the influence of the water pressure is shown. The forces in the grain skeleton that lead to grain pressure p_g have been omitted.

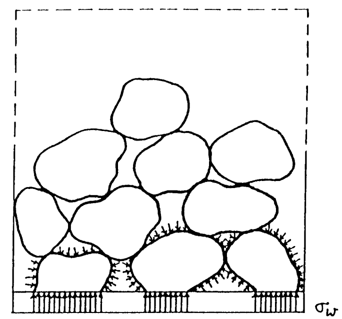

Figure 8.4 The water pressure on the grain skeleton in soil saturated with water. The cut grains on the section plane remain in equilibrium if the water pressure σ_w also acts on the grains in the section plane. Since the water is also present in the pores between the grains, there is an equal hydrostatic pressure σ_w across the entire (horizontal) section plane.

The cut grains on the horizontal section plane remain in equilibrium as long as the water pressure σ_w also acts *in the section plane on the grains*, as shown in Figure 8.4. Of course, the water pressure σ_w also acts in the (horizontal) section plane in the pores *between the grains*. If the water is stationary and all the pores are linked to one another, σ_w is the hydrostatic

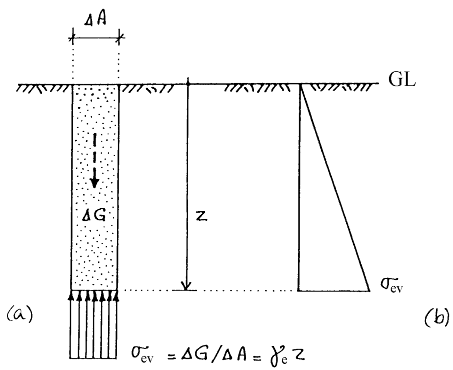

Figure 8.5 (a) The vertical earth pressure can be derived from the vertical force equilibrium of a vertical soil prism. (b) The vertical earth pressure $\sigma_{e;v}$ increases linearly with depth z.

water pressure. This leads to the following conclusion:

Due to the water, the same hydrostatic water pressure σ_w acts over the entire area of the (horizontal) section plane.

The water pressure σ_w combined with grain pressure p_g, which represents a measure for the forces in the grain skeleton, is called the *earth pressure* p_e. The earth pressure has a normal stress component σ_e and a shear stress component τ_e:

$$\sigma_e = \sigma_g + \sigma_w, \tag{2}$$

$$\tau_e = \tau_g. \tag{3}$$

Note that the shear stresses in soil are exclusively transferred by the grain skeleton!

8.2 Vertical earth pressures

In an extensive area with a horizontal ground level (GL), the vertical earth pressures and grain pressures can be deduced from the vertical equilibrium of a soil prism (see Figure 8.5a).

No shear stresses act on the vertical sides of the soil prism. This can be deduced from symmetry considerations. In an unbounded region, each vertical section is a section of mirror symmetry. Mirror symmetry implies that if the shear stress is acting upward on the left-hand side, the shear stress must at the same time be acting upward on the right-hand side, as in Figure 8.6a. According to the principle of action and reaction, the shear stresses must however be acting in opposite directions, as in Figure 8.6b. Both conditions can be met only if these shear stresses are zero.

The weight ΔG of the soil prism in Figure 8.5a, with a height z and cross-section ΔA is

$$\Delta G = \gamma_e z \Delta A. \tag{4}$$

Here, γ_e is the specific weight of the soil, including any water that may be present. For the vertical earth pressure at a depth z one finds

$$\sigma_{e;v} = \frac{\Delta G}{\Delta A} = \gamma_e z. \tag{5}$$

The vertical earth pressure increases linearly with depth z (see Figure 8.5b).

If the soil is *entirely dry*, the weight is carried entirely by the grain skeleton, and the vertical grain pressure is equal to the vertical earth pressure:

$$\sigma_{g;v} = \sigma_{e;v}. \tag{6}$$

If the soil is *entirely saturated with water* up to the ground level, the vertical grain pressure is no longer equal to the vertical earth pressure:

$$\sigma_{g;v} \neq \sigma_{e;v}. \tag{7}$$

In that case, the vertical grain pressure $\sigma_{g;v}$ is deduced from the vertical earth pressure $\sigma_{e;v}$ by reducing it by the water pressure σ_w:

$$\sigma_{g;v} = \sigma_{e;v} - \sigma_w.$$

If the water is stationary and all the pores are linked to one another, the water pressure increases hydrostatically from zero at ground level to $\gamma_w z$ at a depth z:

$$\sigma_w = \gamma_w z$$

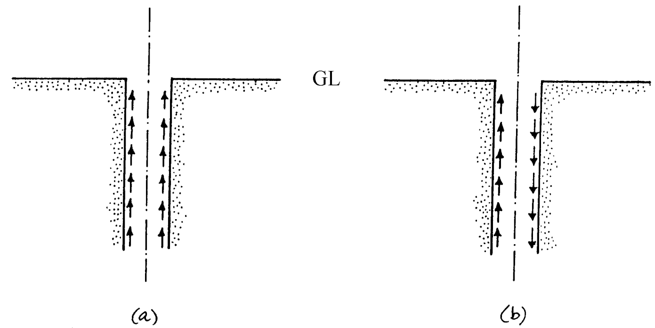

Figure 8.6 There are no shear stresses acting in the vertical planes of the soil prism. This can be deduced from the condition of mirror symmetry in combination with the principle of action and reaction. (a) Mirror symmetry means that if the shear stress is acting upwards on the left-hand side of a vertical section, it must also act in an upward direction on the right-hand side. (b) On the basis of the principle of action and reaction, the shear stresses on the left-hand and right-hand sides must have opposite directions. Both conditions can be met concurrently only if these shear stresses are zero.

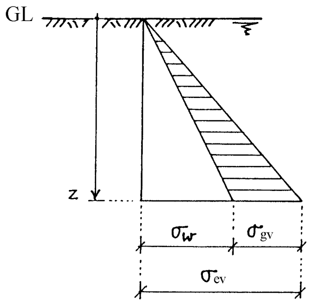

Figure 8.7 In fully saturated soil, the vertical grain pressure $\sigma_{g;v}$ is found from the vertical earth pressure $\sigma_{e;v}$ by subtracting it by the water pressure σ_w. The vertical grain pressure is shown by means of a hatching.

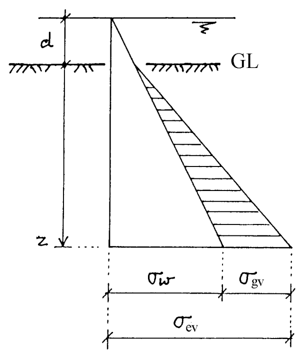

Figure 8.8 If in fully saturated soil the water level is increased to above ground level, this influences the vertical earth pressure $\sigma_{e;v}$ but not the vertical grain pressure $\sigma_{g;v}$.

so that

$$\sigma_{g;v} = \sigma_{e;v} - \sigma_w = \gamma_e z - \gamma_w z = (\gamma_e - \gamma_w)z. \tag{8}$$

In Figure 8.7, the contribution of the vertical grain pressure $\sigma_{g;v}$ in the vertical earth pressure is shown by means of a hatching.

If, with fully saturated soil, the water level is raised to above the ground level, this influences the vertical earth pressures, but not the vertical grain pressures (see Figure 8.8):

$$\begin{aligned} \sigma_{e;v} &= \gamma_w d + \gamma_e z, \\ \sigma_{g;v} &= \sigma_{e;v} - \sigma_w = \gamma_w d + \gamma_e z - \gamma_w(d+z) = (\gamma_e - \gamma_w)z. \end{aligned} \tag{9}$$

An extensive, uniformly distributed load p on the ground level increases both the vertical earth pressure and the vertical grain pressure by an amount p. The water pressure does not change (see Figure 8.9):

$$\begin{aligned} \sigma_{e;v} &= p + \gamma_e z, \\ \sigma_{g;v} &= \sigma_{e;v} - \sigma_w = p + (\gamma_e - \gamma_w)z. \end{aligned} \tag{10}$$

Example
Figure 8.10a shows a package with three soil layers. In the figure, the specific weight of the soil is given for each layer. The water level is 3 metres below ground level. A uniformly distributed load of 15 kN/m^2 is acting on the ground level.

Question:
Determine the distribution of the vertical earth pressure and grain pressure.

Solution (units in kN and m):
First the vertical earth pressure $\sigma_{e;v} = p + \gamma_e z$ is determined. Second, we determine the water pressure $\sigma_w = \gamma_w z$. The vertical grain pressure is found by subtracting the water pressure from the earth vertical pressure.

Table 8.1

z (m)	$\sigma_{e;v}$ (kN/m^2)	σ_w (kN/m^2)	$\sigma_{g;v} = \sigma_{e;v} - \sigma_w$ (kN/m^2)
0	15	0	15
3	$15 + 16 \times 3 = 63$	0	63
8	$63 + 20 \times 5 = 163$	$10 \times 5 = 50$	113
10	$163 + 18 \times 2 = 199$	$10 \times 7 = 70$	129

The calculation is shown in Table 8.1.

Figure 8.10b shows the distribution of the vertical earth pressure, split according to grain pressure (hatched) and water pressure (not hatched). If one is only interested in the distribution of the vertical grain pressure, one can also use the expression (10) given above:

$$\sigma_{g;v} = p + (\gamma_e - \gamma_w)z.$$

The calculation is summarised in Table 8.2.

Table 8.2

z (m)	$\gamma_e - \gamma_w$ (kN/m^3)	$\sigma_{g;v}$ (kN/m^2)
0	–	$p = 15$
3	$16 - 0 = 16$	$15 + 16 \times 3 = 63$
8	$20 - 10 = 10$	$63 + 10 \times 5 = 113$
10	$18 - 10 = 8$	$113 + 8 \times 2 = 129$

Figure 8.10c shows the distribution of the vertical grain pressure separately.

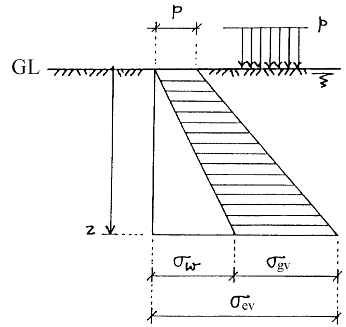

Figure 8.9 An extensive, uniformly distributed terrain load p on the ground level increases both the vertical earth pressure and the vertical grain pressure by an amount p. The water pressure does not change.

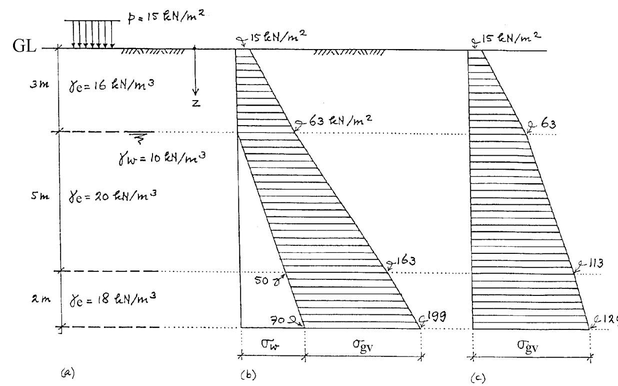

Figure 8.10 (a) The specific weight of the soil is given for three soil layers. The water level is 3 m below ground level. A uniformly distributed load of 15 kN/m^2 is acting on the ground level. (b) The distribution of the vertical earth pressure, split into grain pressure (hatched) and water pressure (not hatched). (c) The distribution of the vertical grain pressure shown separately.

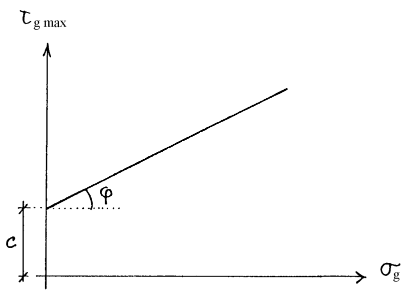

Figure 8.11 The maximum shear stress $\tau_{g;max}$ that the grain skeleton can transfer in a section is dependent on the normal stress σ_g in that section according to $\tau_{g;max} = c + \sigma_g \tan\varphi$. Here c is the cohesion and φ is the angle of internal friction.

Comment: In this section, the following were not taken into account:

- Deviation in the hydrostatic distribution of the water pressure due to the presence of poorly-permeable layers;
- The influence of groundwater currents;
- The influence of time on a range of phenomena (time effects).

For these issues, please refer to the specialist field of soil mechanics.

8.3 Horizontal earth pressures

In contrast to (stationary) gases and fluids, shear stresses can occur in soil. The shear stresses are transferred by the grain skeleton. The horizontal earth pressure is therefore in general not equal to the vertical earth pressure (there is no isotropic state of stress). To simplify the problem, we will for the moment consider only *dry soil*. The grain pressures then remain equal to the earth pressures.

It is often not easy to calculate the horizontal grain pressure. It is possible, however, to indicate the limits to which it is bound. These limits are determined by the maximum shear stress that the grain skeleton can transfer. The *maximum shear stress* $\tau_{g;max}$ in a section depends on the normal stress σ_g in that section:

$$\tau_{g;max} = c + \sigma_g \tan\varphi.$$

Here c is the *cohesion*[1] and φ is the *angle of internal friction*. This relationship is shown in Figure 8.11.

[1] Cohesion is the resistance to sliding resulting from a certain bond between the soil particles because of sticking and tangling, the influence of capillary water, and/or the hooking of particles with an irregular shape (hook resistance).

To keep matters simple, we will consider only grainy matter, such as sand, for which cohesion c is practically zero, so that

$$\tau_{g;max} = \sigma_g \tan\varphi.$$

In order to find the extreme values of the horizontal grain pressure, a triangular slice OPQ is isolated from the soil (see Figure 8.12).

No shear stresses are acting on the vertical boundaries (section OP and the front and back of the slice). This was shown by means of symmetry in Section 8.2.

Suppose grain stresses σ_g and τ_g are acting on the oblique section PQ, and horizontal grain pressure $\sigma_{g;h}$ is acting in the vertical section OP. Vertical grain pressure $\sigma_{g;v}$ is acting on the horizontal section OQ. From the moment equilibrium in the plane of the drawing, about the middle of PQ, it follows that no shear stresses can be acting in the horizontal section OQ. Check it!

If shear stress τ_g on the oblique section PQ has reached its maximum $\tau_{g;max}$, the soil mass will *slide*. Here one can distinguish two situations, depending on the direction in which the soil slides, and therefore the direction of the shear stress $\tau_{g;max}$. Figure 8.13 shows both cases; the situation after sliding is shown by a dashed line.

The soil element in Figure 8.13a is *sliding* (moving downwards); the shear stress in the *slide plane* PQ is acting upwards. In Figure 8.13b, the soil element is *upset* (moving upwards) and the shear stress in the *slide plane* PQ is directed downwards. For both cases with given $\sigma_{g;v}$ we can look for the angle α for which the horizontal grain pressure $\sigma_{g;h}$ is extreme.

It is conventional to express the horizontal grain pressure in the vertical grain pressure using a coefficient K:

$$\sigma_{g;h} = K\sigma_{g;v}.$$

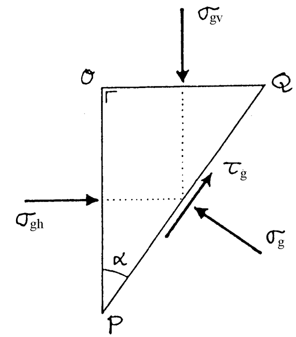

Figure 8.12 The grain stresses on a triangular soil element.

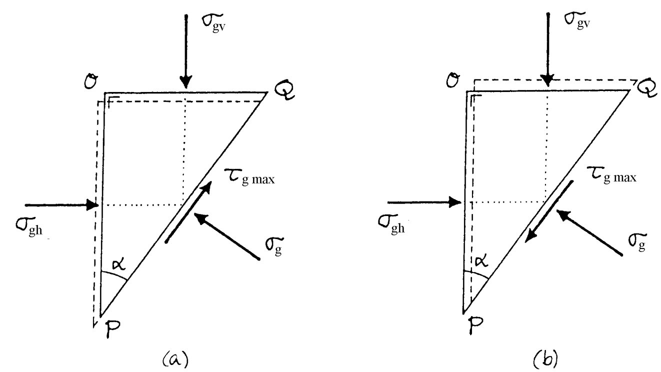

Figure 8.13 The maximum shear stress $\tau_{g;max}$ is reached when the soil slides. One can distinguish two cases: (a) the soil element slides (moves downwards) and the shear stress in the slide plane PQ works upwards, and (b) the soil element is upset (moves upwards) and the shear stress in the slide plane PQ is directed downwards. The condition after sliding or upsetting is shown with a dashed line.

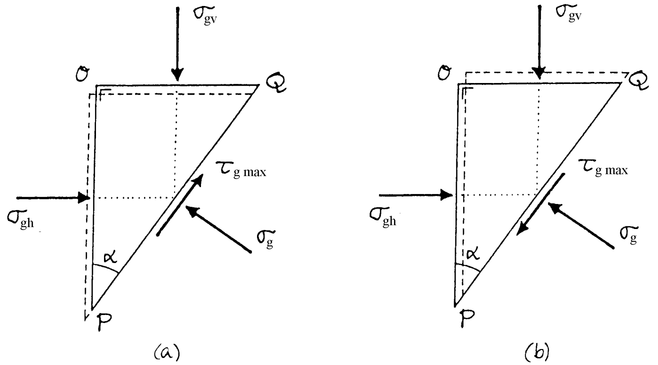

Figure 8.13 The maximum shear stress $\tau_{g;max}$ is reached when the soil slides. One can distinguish two cases: (a) the soil element slides (moves downwards) and the shear stress in the slide plane PQ works upwards, and (b) the soil element is upset (moves upwards) and the shear stress in the slide plane PQ is directed downwards. The condition after sliding or upsetting is shown with a dashed line.

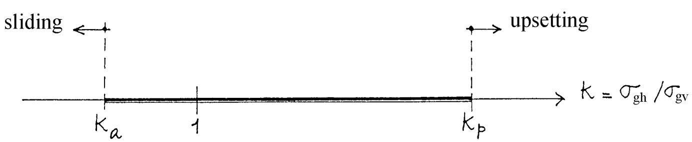

Figure 8.14 The coefficient K_a and K_p for the active and passive soil pressure respectively, shown on a number line.

The *slide* in Figure 8.13a leads to the so-called *active earth pressure*:

$$\sigma_{g;h} = K_a \sigma_{g;v}.$$

The active earth pressure is the largest horizontal pressure for which the soil yields sideways (with smaller pressures the soil will certainly yield).

The *upset* in Figure 8.13b leads to the so-called *passive earth pressure*:

$$\sigma_{g;h} = K_p \sigma_{g;v}.$$

The passive earth pressure is the smallest horizontal pressures for which the soil is upset (with larger pressure, the soil will certainly be upset).

The distinction between *active* and *passive* is derived from the way in which the soil mass acts on its surroundings: active when (part of) a structure yields under the influence of earth pressure, and passive when the soil offers resistance to the displacement of (part of) a structure.

The *active earth pressure* on a wall has the same direction as the one in which the wall yields; the *passive earth pressure* acts opposite to the direction in which the wall moves.

Passive earth pressure can be expected to be greater than active earth pressure. It will always require greater effort (pressure) to upset the soil (passive earth pressure) than to resist sliding (active earth pressure). Figure 8.14 contains the coefficients for active and passive earth pressures on a number line.

With the coefficients K_a and K_p for the active and passive earth pressures respectively, we have determined the *extreme limits for the horizontal earth pressure* (in dry soil). These limits occur when a *slide plane* can develop. If this is not the case, the horizontal earth pressure lies somewhere between both limits. One of the intermediate values is the *neutral earth pressure*. This is the horizontal earth pressure on an entirely rigid wall, which does not move. This may include heavy retaining walls, lock walls, or tunnel walls. One assumes that (in dry soil) the neutral earth pressure is also in proportion to the vertical earth pressure, and refers to the associated coefficient as K_0.

The coefficients mentioned here for active, passive and neutral earth pressure relate to the normal stresses in *dry soil*, or in other words, the normal stresses in the grain skeleton (grain pressures). The earth pressure in *soil saturated with water* is found by superposing the water pressure on the normal stress in the grain skeleton.

The following sections address the magnitude of the coefficients for active, passive, and neutral earth pressure.

8.3.1 Active earth pressure

The coefficient K_a for active earth pressure is derived using the triangular slice of soil in Figure 8.15a.

If the area of side PQ is equal to ΔA, then the area of side OP is equal to $\Delta A \cos\alpha$ and that of side OQ is equal to $\Delta A \sin\alpha$. The forces on the three sides of the soil element are therefore

OP: $\sigma_{g;h}(\Delta A \cos\alpha)$,

OQ: $\sigma_{g;v}(\Delta A \sin\alpha)$,

PQ: $\sigma_g \Delta A$ and $\tau_{g;max}\Delta A$.

The equations for the force equilibrium in the plane of the drawing are easy to derive from the closed force polygon in Figure 8.15b.

Force equilibrium normal to PQ:

$$\sigma_g \Delta A - \sigma_{g;h}(\Delta A \cos\alpha)\cos\alpha - \sigma_{g;v}(\Delta A \sin\alpha)\sin\alpha = 0.$$

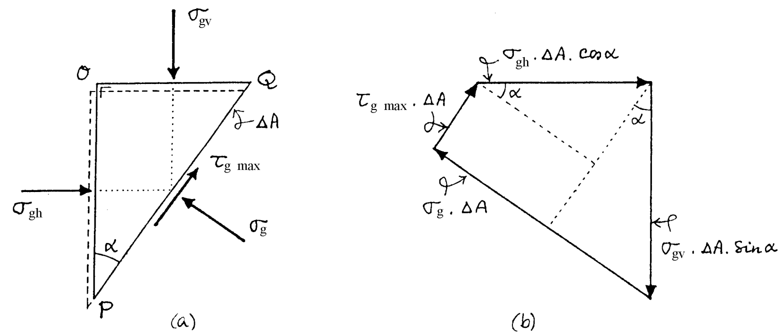

Figure 8.15 (a) The grain stresses on a triangular soil element that is sliding (moving downwards). (b) The equations for the force equilibrium in the plane of the drawing can be derived easily from the fact that the force polygon is closed.

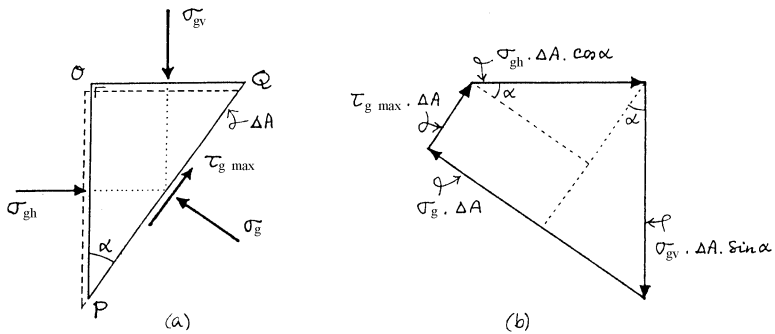

Figure 8.15 (a) The grain stresses on a triangular soil element that is sliding (moving downwards). (b) The equations for the force equilibrium in the plane of the drawing can be derived easily from the fact that the force polygon is closed.

Force equilibrium parallel to PQ:

$$\tau_{g;\max}\Delta A + \sigma_{g;h}(\Delta A\cos\alpha)\sin\alpha - \sigma_{g;v}(\Delta A\sin\alpha)\cos\alpha = 0.$$

From the two equations above, one can find the stresses in the slide plane PQ:

$$\sigma_g = +\sigma_{g;h}\cos^2\alpha + \sigma_{g;v}\sin^2\alpha,$$

$$\tau_{g;\max} = -\sigma_{g;h}\sin\alpha\cos\alpha + \sigma_{g;v}\sin\alpha\cos\alpha.$$

Since the shear stress has its maximum, also

$$\tau_{g;\max} = \sigma_g\tan\varphi.$$

In this expression, substitute those found before for σ_g and $\tau_{g;\max}$:

$$-\sigma_{g;h}\sin\alpha\cos\alpha + \sigma_{g;v}\sin\alpha\cos\alpha = (+\sigma_{g;h}\cos^2\alpha + \sigma_{g;v}\sin^2\alpha)\tan\varphi.$$

This gives the coefficient for the active earth pressure[1]:

$$K_a = \frac{\sigma_{g;h}}{\sigma_{g;v}} = 1 - \frac{2\sin\varphi}{\sin(2\alpha+\varphi)+\sin\varphi}.$$

We are looking for the largest horizontal earth pressure for which the soil *slides*. In other words, for which value of α does K_a have its maximum?

K_a has its maximum if the function

$$f = \sin(2\alpha+\varphi)$$

---

[1] See Appendix 8.1 at the end of this chapter.

is a maximum, therefore, $2\alpha + \varphi = \frac{\pi}{2}$. For the angle α that the slide plane PQ makes with the vertical, one finds

$$\alpha = \frac{\pi}{4} - \frac{\varphi}{2}.$$

For this value of α

$$f = \sin(2\alpha + \varphi) = \sin(\pi/2) = 1$$

which is a maximum. This also means that K_a and therefore the horizontal earth pressure $\sigma_{g;h}$ reaches a maximum for this value of α.

By substituting the value of α found in the derived expression for K_a, one can immediately determine the value of the coefficient for the active earth pressure:

$$K_a = \frac{1 - \sin\varphi}{1 + \sin\varphi}.$$

For sand, for example, with $\varphi = 30°$, one finds

$$K_a = \frac{1 - \sin 30°}{1 + \sin 30°} = \frac{1}{3}.$$

In this case, the angle that the associated slide plane PQ makes with the vertical is

$$\alpha = 45° - \frac{30°}{2} = 30°.$$

Example
A sheet piling is located in an impermeable layer of clay 4.5 metres below ground level (see Figure 8.16). The specific weight of the dry soil behind

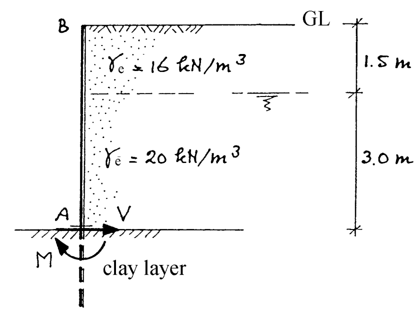

Figure 8.16 A sheet-pile wall is located in a relatively impermeable layer of clay 4.5 m below ground level. The groundwater level behind the sheet piling is 1.5 m below ground level. The specific weight γ_e of the soil (dry and wet) behind the wall is given in the figure.

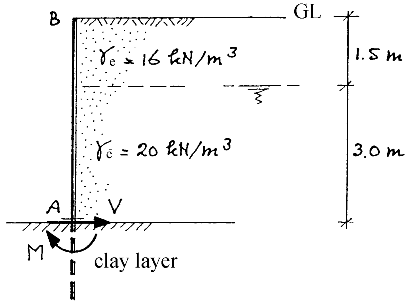

Figure 8.16 A sheet-pile wall is located in a relatively impermeable layer of clay 4.5 m below ground level. The groundwater level behind the sheet piling is 1.5 m below ground level. The specific weight γ_e of the soil (dry and wet) behind the wall is given in the figure.

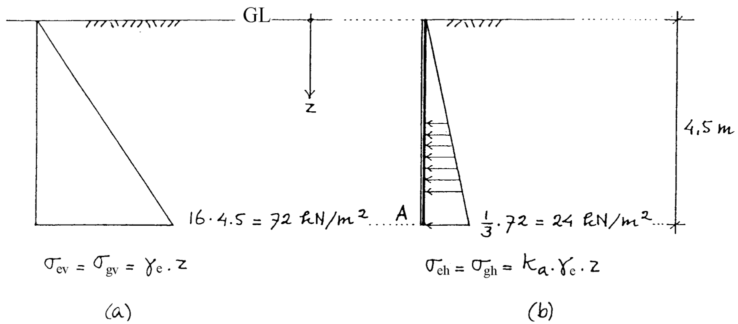

Figure 8.17 The distribution of (a) the vertical earth pressure and (b) the horizontal earth pressure on the sheet piling when the earth behind the sheet piling is entirely dry.

the sheet-pile wall is 16 kN/m^3. The same soil, fully saturated with water, has a specific weight of 20 kN/m^3. The angle of internal friction is $\varphi = 30°$. There is no cohesion.

Question:
Determine the "shear force" V and the "bending moment" M acting in cross-section A on a 1-metre wide vertical strip AB from the sheet piling. The following two cases must be distinguished:

a. The soil behind the sheet piling (not as shown in Figure 8.16) is entirely dry.
b. The groundwater level behind the sheet piling is 1.5 metres below the ground level.

Solution:
a. Due to the deformation of the sheet piling caused by the earth pressure, it will move slightly, and the soil may slide. The active earth pressure is then acting on the dam wall. With $\varphi = 30°$, the coefficient for active earth pressure is

$$K_a = \frac{1 - \sin 30°}{1 + \sin 30°} = \tfrac{1}{3}.$$

If the soil behind the sheet piling is entirely dry, the earth pressures are equal to the grain pressures. The horizontal earth pressure is 1/3 of the vertical earth pressure, so that

$$\sigma_{e;v} = \sigma_{g;v} = \gamma_e z,$$

$$\sigma_{e;h} = \sigma_{g;h} = K_a \gamma_e z = \tfrac{1}{3}\gamma_e z.$$

Figure 8.17a shows the distribution of the vertical earth pressure, and Figure 8.17b shows the distribution of the horizontal earth pressure. The horizontal earth pressure on the sheet piling increases linearly from 0 at the ground level to $\frac{1}{3} \times (16 \text{ kN/m}^3)(4.5 \text{ m}) = 24 \text{ kN/m}^2$ at A.

Now isolate a vertical strip with a width of 1 metre from the sheet pile, and model it as a line element. The horizontal load on the line element is equal to the horizontal earth pressure multiplied by the width of 1 metre, and therefore increases linearly from 0 at ground level to

$$(24\ \text{kN/m}^2)(1\ \text{m}) = 24\ \text{kN/m}$$

at A (see Figure 8.18).

The resultant R of the load is

$$R = \tfrac{1}{2} \times (4.5\ \text{m})(24\ \text{kN/m}) = 54\ \text{kN}.$$

In cross-section A, there must be acting a shear force V and a (bending) moment M. From the equilibrium of part AB cut from the wall, with the directions as shown in Figure 8.18 we find

$$V = R = 54\ \text{kN},$$

$$M = (54\ \text{kN})(1.5\ \text{m}) = 81\ \text{kNm}.$$

These are the requested forces at A that act on the 1-metre wide vertical strip AB isolated from the sheet piling.

b. If there is water behind the wall, the earth pressure is composed of a water pressure and a grain pressure. Figure 8.19a shows the distribution of the vertical earth pressure $\sigma_{e;v}$, including the contribution of the water pressure σ_w. If the water pressure is subtracted from the vertical earth pressure, it gives the vertical grain pressure $\sigma_{g;v}$ (see Figure 8.19b). The horizontal (active) grain pressure $\sigma_{g;h}$ is equal to the vertical grain pressure $\sigma_{g;v}$ multiplied by $K_a = 1/3$ (see Figure 8.19c).

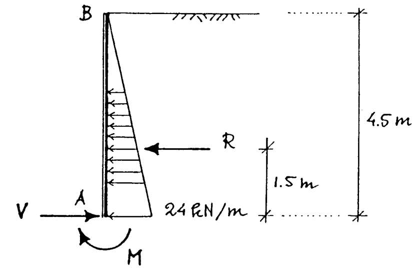

Figure 8.18 The horizontal load on a vertical strip of sheet piling that is 1-metre wide modelled as a line element for when the soil behind the sheet piling is entirely dry. Shear force V and the bending moment M in cross-section A are also shown.

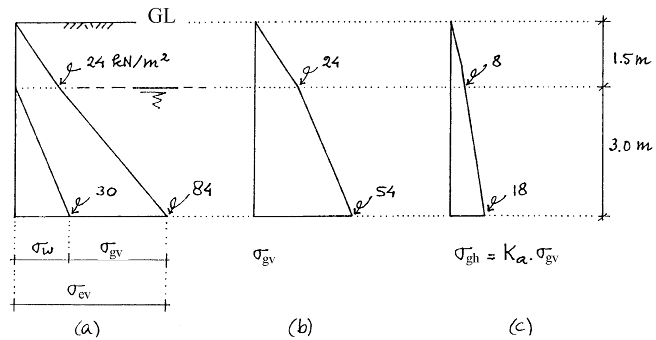

Figure 8.19 If there is water behind the sheet piling, the soil pressure is composed of a water pressure and a grain pressure. (a) The distribution of the vertical earth pressure $\sigma_{e;v}$, including the contribution of the water pressure σ_w. (b) If the water pressure is subtracted from the vertical earth pressure, one finds the vertical grain pressure $\sigma_{g;v}$. (c) The horizontal (active) grain pressure $\sigma_{g;h}$ is equal to the vertical grain pressure $\sigma_{g;v}$ multiplied by $K_a = 1/3$.

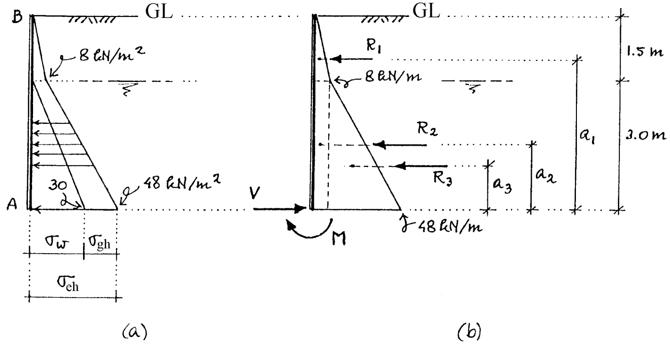

Figure 8.20 (a) The horizontal earth pressure $\sigma_{e;h}$ on the sheet piling, composed of the horizontal water pressure σ_w and the horizontal grain pressure $\sigma_{g;h}$. (b) The horizontal load on a 1-metre wide strip of sheet piling modelled as a line element, together with the shear force V and the bending moment M at A.

The sheet piling is subjected not only to the horizontal grain pressure, but also to water pressure. Figure 8.20a shows the distribution of the horizontal earth pressure $\sigma_{e;h}$, composed of the horizontal water pressure σ_w and the horizontal grain pressure $\sigma_{g;h}$.

Figure 8.20b shows the horizontal load acting on a 1-metre strip isolated from the sheet piling and modelled as a line element. The load diagram can be split into a rectangle and two triangles, of which the resultants R and their distances a to A are easy to calculate:

$$R_1 = 0.5 \times (1.5\text{ m})(8\text{ kN/m}) = 6\text{ kN}, \quad a_1 = 3.5\text{ m},$$
$$R_2 = (3\text{ m})(8\text{ kN/m}) = 24\text{ kN}, \quad a_2 = 1.5\text{ m},$$
$$R_3 = 0.5 \times (3\text{ m})(40\text{ kN/m}) = 60\text{ kN}, \quad a_1 = 1.0\text{ m}.$$

From the equilibrium of part AB of the sheet piling strip, we find with the directions of V and M as shown in Figure 8.20b:

$$V = R_1 + R_2 + R_3 = (6 + 24 + 60)\text{ kN} = 90\text{ kN},$$
$$M = R_1 a_1 + R_2 a_2 + R_3 a_3$$
$$= (6\text{ kN})(3.5\text{ m}) + (24\text{ kN})(1.5\text{ m}) + (60\text{ kN})(1\text{ m}) = 117\text{ kNm}.$$

These are the requested forces acting in A on the 1-metre wide vertical strip AB from the sheet piling.

In practice, one often uses a method developed by *Coulomb*[1] based on *flat slide planes*. Here, one assumes that the pressure on the wall is caused by a

[1] Charles Auguste de Coulomb (1736–1806), French scientist, known for his experiments in friction and electrostatic forces.

triangular piece of soil that slides along a flat slide plane (see Figure 8.21). One can deduce that the most dangerous slide plane (in the active case of a yielding wall) makes an angle

$$\alpha = \frac{\pi}{4} - \frac{\varphi}{2}$$

with the vertical. This turns out to be precisely the angle of the planes, as derived earlier, in which the shear stress is a maximum. The magnitude of the earth pressure according to Coulomb's method also agrees with the result above.

The agreement can best be understood by means of the sliding wedge of soil in Figure 8.21, assuming that there are no shear stresses in the horizontal and vertical planes (there is therefore also no wall friction). For simplicity, we will again assume that the soil is entirely dry.

One can recognise the triangular soil element we dealt with earlier on the edge of the slide plane, with stresses σ_g and $\tau_{g;max}$ on the oblique side. The weight of the vertical soil column determines the vertical grain pressure $\sigma_{g;v}$. The horizontal strip of soil transfers the horizontal grain pressure $\sigma_{g;h}$ to the wall.

The method with slide planes has the advantage that it is relatively easy to see that a terrain load on ground level increases the horizontal earth pressure on the wall only if it acts on the sliding soil wedge.

Comment: For the influence of wall friction, oblique walls, or oblique ground levels, as well as the necessary nuances in the examples shown here, please refer to a text book on the field of soil mechanics.

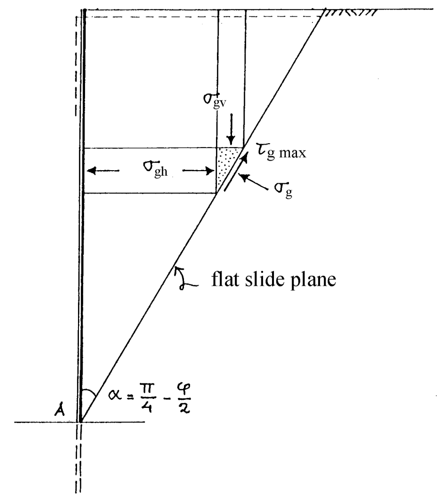

Figure 8.21 In practice, one often uses a method developed by Coulomb based on flat slide planes. Here one assumes that the pressure on the wall is caused by a triangular piece of soil that slides along a flat slide plane. One can recognise the triangular soil element from Figure 8.15a on the edge of the slide plane.

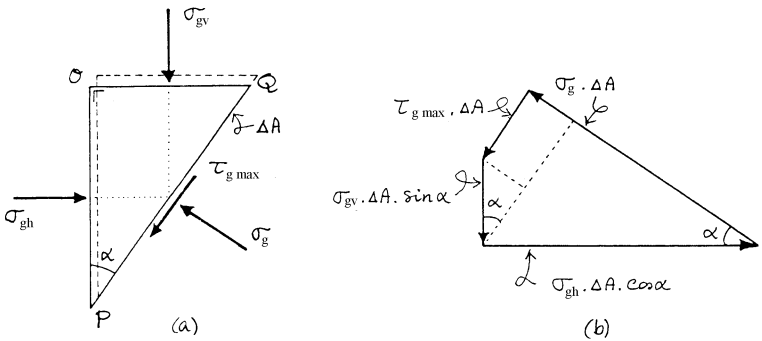

Figure 8.22 (a) The grain stresses on a triangular soil element that is upset (moving upwards). (b) The equations for the force equilibrium in the plane of the drawing can easily be derived from the fact that the force polygon is closed.

8.3.2 Passive earth pressure

The coefficient K_p for *passive earth pressure* can be derived using the triangular wedge of soil in Figure 8.22a, in the same way as the coefficient for active earth pressure in Section 8.3.1.

The equations for the force equilibrium in the plane of the drawing can be found from the closed force polygon in Figure 8.22b.

Force equilibrium perpendicular and parallel to PQ:

$$\sigma_g \Delta A - \sigma_{g;h}(\Delta A \cos\alpha)\cos\alpha - \sigma_{g;v}(\Delta A \sin\alpha)\sin\alpha = 0,$$

$$\tau_{g;\max}\Delta A - \sigma_{g;h}(\Delta A \cos\alpha)\sin\alpha + \sigma_{g;v}(\Delta A \sin\alpha)\cos\alpha = 0$$

so that

$$\sigma_g = +\sigma_{g;h}\cos^2\alpha + \sigma_{g;v}\sin^2\alpha,$$

$$\tau_{g;\max} = +\sigma_{g;h}\sin\alpha\cos\alpha - \sigma_{g;h}\sin\alpha\cos\alpha.$$

The shear stress is a maximum, therefore

$$\tau_{g;\max} = \sigma_g \tan\varphi.$$

In this expression substitute the expressions found for σ_g and $\tau_{g;\max}$:

$$+\sigma_{g;h}\sin\alpha\cos\alpha - \sigma_{g;v}\sin\alpha\cos\alpha = (+\sigma_{g;h}\cos^2\alpha + \sigma_{g;v}\sin^2\alpha)\tan\varphi.$$

This gives the coefficient for passive earth pressure[1]:

$$K_p = \frac{\sigma_{g;h}}{\sigma_{g;v}} = 1 + \frac{2\sin\varphi}{\sin(2\alpha - \varphi) - \sin\varphi}.$$

We are trying to find the smallest horizontal earth pressure for which the soil is *upset*. In other words, for which value of α is K_p a minimum?

K_p is a minimum if the function

$$f = \sin(2\alpha - \varphi)$$

is a maximum, therefore $2\alpha - \varphi = \frac{\pi}{2}$. For the angle α that the slide plane PQ makes with the vertical one finds

$$\alpha = \frac{\pi}{4} + \frac{\varphi}{2}.$$

For this value of α

$$f = \sin(2\alpha - \varphi) = \sin(\pi/2) = 1$$

and f indeed is a maximum. This means that K_p and therefore the horizontal grain pressure $\sigma_{g;h}$ has a minimum for this value of α.

The value of the coefficient K_p for passive earth pressure is found directly by substituting the value found for α in the expression derived for K_p:

$$K_p = \frac{1 + \sin\varphi}{1 - \sin\varphi}.$$

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[1] See Appendix 8.2 at the end of this chapter.

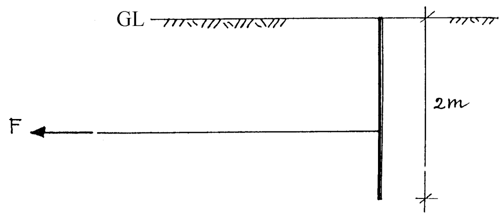


Figure 8.23 A square anchor plate in dry soil.

With sand, for instance, with $\varphi = 30°$, one finds

$$K_p = \frac{1 + \sin 30°}{1 - \sin 30°} = 3.$$

In this case the coefficient K_p for passive earth pressure is 9 times larger than the coefficient K_a for active earth pressure! The angle α that the associated slide plane PQ makes with the vertical is

$$\alpha = 45° + \frac{30°}{2} = 60°.$$

Note that:

- The angle α that the slide plane makes with the vertical in the *active* case (when the wall yields) is always *smaller* than 45° and in the *passive* case (if the wall is upset) is always *larger* than 45°.
- There is a relationship between the coefficients for active and passive earth pressure, namely

$$K_a K_p = 1.$$

Example

A square anchor plate is located in entirely dry soil (see Figure 8.23). The specific weight of the soil is 18 kN/m^3. The angle of internal friction is 24°. There is no cohesion.

Questions:

a. Determine the maximum anchor force that the plate can provide.
b. Determine the influence of a vertical terrain load of 20 kN/m^2 on the magnitude of the maximum anchor force.

Solution:

a. Due to the anchor force, the plate will tend to move to the left. An area of passive earth pressure develops in front of the plate, and an area of active earth pressure develops behind the plate. The coefficients K_p and

K_a, respectively for the active and passive earth pressure, are

$$K_p = \frac{1 + \sin 24°}{1 - \sin 24°} = 2.37,$$

$$K_a = \frac{1 - \sin 24°}{1 + \sin 24°} = 0.42.$$

Figure 8.24a shows the distribution of the vertical earth pressure. Derived from the vertical earth pressure, Figure 8.24b shows the distribution of the (horizontal) passive and active earth pressure on the plate. Taking into account the width of 2 metres of the plate, the resultants R_p and R_a of respectively the passive and active earth pressure are

$$R_p = (2\text{ m}) \times 0.5 \times (85.32\text{ kN/m}^2)(2\text{ m}) = 170.64\text{ kN},$$

$$R_a = (2\text{ m}) \times 0.5 \times (15.12\text{ kN/m}^2)(2\text{ m}) = 30.24\text{ kN}.$$

The maximum anchor force F that the plate can provide is

$$F = R_p - R_a = (170.64\text{ kN}) - (30.24\text{ kN}) = 140.4\text{ kN}.$$

b. Any *terrain load p* increases the vertical grain pressure in the soil and therefore also increases the active earth pressure (resultant R_a) and the passive earth pressure (resultant R_p).

Maximum anchor force means the anchor force that the plate can offer is *guaranteed*. In fact, we are therefore looking for the smallest value of

$$F = R_p - R_a.$$

The least favourable condition occurs when R_p is a minimum (no terrain load in the passive area) and R_a is a maximum (terrain load in the active area).

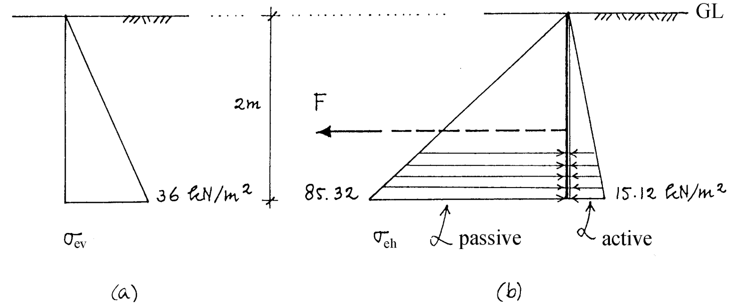


Figure 8.24 (a) The distribution of the vertical earth pressure and (b) the distribution of the passive and active (horizontal) earth pressure on the anchor plate.

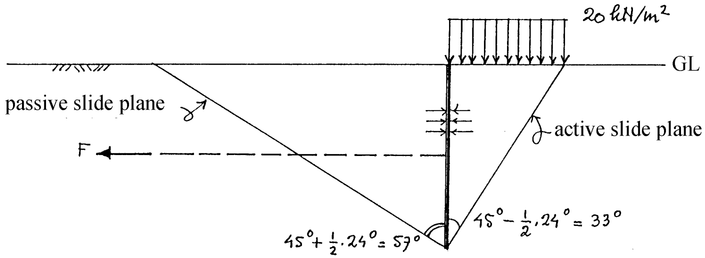


Figure 8.25 Using slide planes according to Coulomb's method, we quickly realise that a terrain load in the active area decreases the anchor force: the passive earth pressure remains unchanged while the active earth pressure increases across the entire plate.

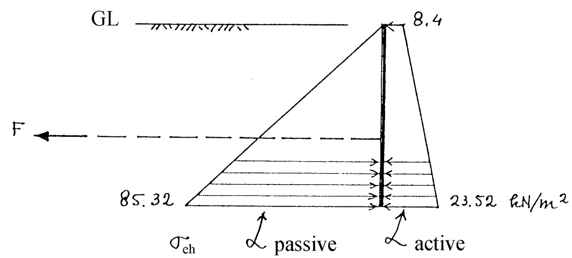


Figure 8.26 The distribution of the passive and active earth pressure on the anchor plate.

This unfavourable condition is shown in Figure 8.25, as well as the slide planes according to Coulomb's method. The associated distribution of the passive and active earth pressure is shown in Figure 8.26. The passive earth pressure remains unchanged, but the active earth pressure increases across the entire plate by

$$K_a p = 0.42 \times (20\ \text{kN/m}^2) = 8.4\ \text{kN/m}^2.$$

The resultant R_a of the active earth pressure is now

$$R_a = (30.24\ \text{kN}) + (2\ \text{m})(2\ \text{m})(8.4\ \text{kN/m}^2) = 63.84\ \text{kN}$$

so that the maximum anchor force is

$$F = R_p - R_a = (170.64\ \text{kN}) - (63.84\ \text{kN}) = 106.8\ \text{kN}.$$

The terrain load of 20 kN/m^2 in the area where the active earth pressures develop decreases the force that the plate can take by 33.6 kN, from 140.4 kN to 106.8 kN.

Note: When calculating the anchor force, we assume that the soil is upset over a width of 2 m (the width of the anchor plate). In reality, the width of the soil that is upset will be greater. For this and other discrepancies between the model and reality, please refer to a textbook on the field of soil mechanics.

8.3.3 Neutral earth pressure

With the coefficients K_a and K_p for the active and passive earth pressure respectively, we have defined the *extreme limits of the horizontal earth pressure*. These limits occur when a *slide plane* can develop. If this is not possible, the horizontal earth pressure is between these values.

One of these intermediate values is the *neutral earth pressure*. This is the horizontal earth pressure on an immovable wall, which may include heavy retaining walls, lock walls, or tunnel walls.

One assumes that the neutral earth pressure is also proportional to the vertical earth pressure $\sigma_{\mathrm{g;v}}$ and we call the associated coefficient K_0:

$$\sigma_{\mathrm{g;h}} = K_0 \sigma_{\mathrm{g;v}}.$$

The value of K_0 will be between $K = K_\mathrm{a}$ and $K = 1$ (when there are no shear stresses). One often *poses* that:

$$K_0 = 1 - \sin\varphi.$$

Figure 8.27 shows the coefficients K_a, K_p and K_0 on a number line. The numerical values included relate to soil with an angle of internal friction $\varphi = 30°$, such as sand, for instance.

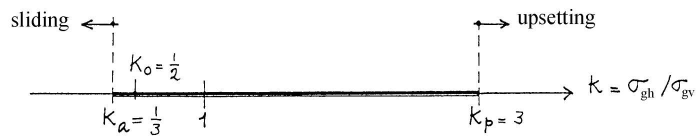


Figure 8.27 The coefficients K_a, K_p and K_0 for the active, passive, and neutral earth pressure respectively, depicted on a number line. The numerical values relate to soil with an angle of internal friction $\varphi = 30°$, like sand, for instance.

Appendix 8.1

Determining the coefficient K_a for active earth pressure:

$$\begin{aligned} K_\mathrm{a} &= \frac{\sin\alpha\cos\alpha - \sin^2\alpha\tan\varphi}{\sin\alpha\cos\alpha + \cos^2\alpha\tan\varphi} = 1 - \frac{\cos\alpha^2\tan\varphi + \sin^2\alpha\tan\varphi}{\sin\alpha\cos\alpha + \cos^2\alpha\tan\varphi} \\ &= 1 - \frac{\sin\varphi}{\cos\alpha(\sin\alpha\cos\varphi + \cos\alpha\sin\varphi)} = 1 - \frac{\sin\varphi}{\cos\alpha\sin(\alpha+\varphi)} \\ &= 1 - \frac{2\sin\varphi}{\sin(2\alpha+\varphi) + \sin\varphi}. \end{aligned}$$

To determine the coefficient, we used the two trigoniometric equations shown below:

$$\sin(\alpha + \beta) = \sin\alpha\cos\beta + \cos\alpha\sin\beta,$$

$$2\sin\alpha\cos\beta = \sin(\alpha + \beta) + \sin(\alpha - \beta).$$

Appendix 8.2

Determining coefficient K_p for passive earth pressure:

$$K_\mathrm{p} = \frac{\sin\alpha\cos\alpha + \sin^2\alpha\tan\varphi}{\sin\alpha\cos\alpha - \cos^2\alpha\tan\varphi} = 1 + \frac{\cos\alpha^2\tan\varphi + \sin^2\alpha\tan\varphi}{\sin\alpha\cos\alpha - \cos^2\alpha\tan\varphi}$$

$$= 1 + \frac{\sin\varphi}{\cos\alpha(\sin\alpha\cos\varphi - \cos\alpha\sin\varphi)} = 1 + \frac{\sin\varphi}{\cos\alpha\sin(\alpha - \varphi)}$$

$$= 1 + \frac{2\sin\varphi}{\sin(2\alpha - \varphi) - \sin\varphi}.$$

To determine the coefficient, we used the two trigoniometric equations shown below:

$$\sin(\alpha - \beta) = \sin\alpha\cos\beta - \cos\alpha\sin\beta,$$

$$2\cos\alpha\sin\beta = \sin(\alpha + \beta) - \sin(\alpha - \beta).$$

8.4 Problems

Unless indicated otherwise, the following apply for all questions:

- Specific weight of water: $\gamma_{\text{water}} = 10\ \text{kN/m}^3$.
- Coefficient for active earth pressure: $K_a = 1/3$.
- Coefficient for passive earth pressure: $K_p = 3$.
- The soil has no cohesion.
- All levels are given in metres with respect to sea level (SL).

Vertical earth pressures (Section 8.2)

8.1 In an area with sandy soil, the groundwater is 1 m below ground level. The specific weight of dry sand is 15 kN/m^3. The pore volume of sand is 40%.

Questions:

a. Determine the specific weight of wet sand.
   Draw the distribution to 3 m under the ground level of:
b. the vertical earth pressure.
c. the vertical grain pressure.
d. the water pressure.
e. How do the vertical earth pressure, grain pressure and water pressure change if the groundwater rises by 0.5 m?
f. How do the vertical earth pressure, grain pressure and water pressure change if the groundwater drops by 0.8 m?

8.2 As problem 8.1, but now with a terrain load of 5 kN/m^2.

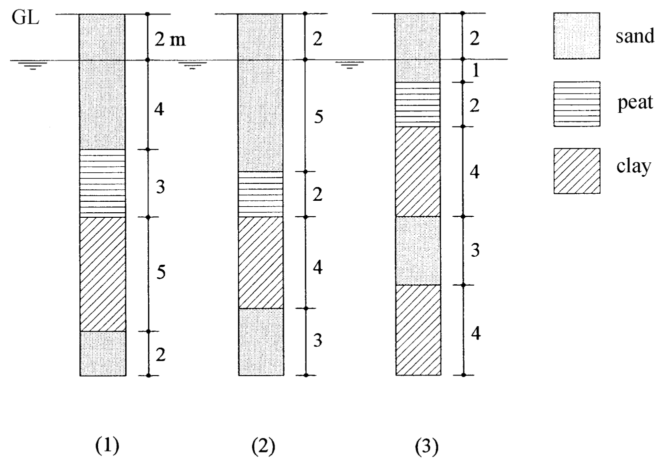
8.3 In an area with sandy soil, the groundwater is 1.2 m below ground level. Specific weight of the wet sand is 18 kN/m^3. The pore volume of the sand is 35%.

Questions:

a. Determine the specific weight of dry sand.
   Draw the distribution to 3 m under the ground level of:
b. the vertical earth pressure.
c. the vertical grain pressure.
d. the water pressure.
e. How do the vertical earth pressure, grain pressure and water pressure change if the groundwater rises by 0.6 m?
f. How do the vertical earth pressure, grain pressure and water pressure change if the groundwater drops by 0.8 m?

8.4 As problem 8.3, but now with a terrain load of 4 kN/m^2.

8.5: 1–3 An area consists of various soil layers. The groundwater is 2 m below ground level (GL).

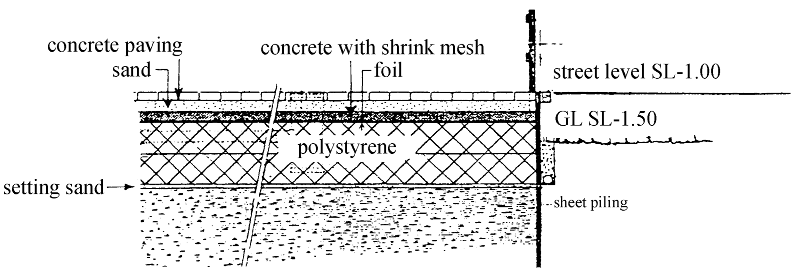


Material	Specific weight (kN/m^3)
dry sand	16
wet sand	20
wet peat	12
wet clay	18

Question:
Draw the distribution to 15 m under ground level of:
a. the vertical earth pressure.
b. the vertical grain pressure.
c. the water pressure.
e. How do the vertical earth pressure, grain pressure and water pressure change if the groundwater rises by 1.0 m?
f. How do the vertical earth pressure, grain pressure and water pressure change if the groundwater drops by 1.0 m?

8.6: 1–3 As problem 8.5, but now with a terrain load of 6 kN/m^2.

8.7 Soil mechanical research showed that with traditional preparation of a site for building works, one has to take into account a settlement of 2.0 m after 17.5 years. For this reason, a settlement-free raise was selected, using polystyrene.

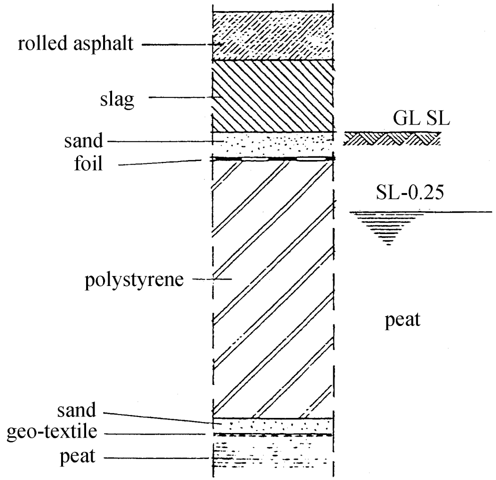


Existing situation	Level SL (m)	Material	Specific weight (kN/m^3)
ground level	–1.50	peat/dry	12
groundwater level	–2.10		

New situation	Specific weight (kN/m^3)
Street level SL–1.00 m	–
0.05 m concrete paving	23
0.15 m dry sand	14
foil	–
0.10 m concrete with shrink mesh	24
??? m polystyrene	0.2
0.05 m wet setting sand	17.5

Question:
How thick does the layer of polystyrene have to be if the earth pressure under the raise is the same as in the original situation?

8.8 Polystyrene is to be used for the construction of an access road in a peat area. The road structure is as follows (see the table below):
The weight of foil and geo-textile are negligible. Assume that polystyrene does not absorb water.
The ground level is at SL. The base of the slag layer is at the same height as the ground level. The average groundwater level is SL–0.25. The terrain load on the road is 6 kN/m^2.



Construction	m
rolled asphalt	0.17
slag	0.25
sand	0.10
foil	–
polystyrene	???
sand	0.10
geo-textile	–
peat	–

Material	Specific weight (kN/m^3)
rolled asphalt	24
slag	17
dry sand	15
wet sand	19
dry peat	13
wet peat	15
polystyrene	0.2

Questions:

a. How thick, with the average water level, does the layer of polystyrene have to be so that, for the road with the terrain load, the earth pressure under the geo-textile is equal to the earth pressure in the original situation?
b. To which height can the groundwater level rise so that the road (without terrain load) does not rise up?

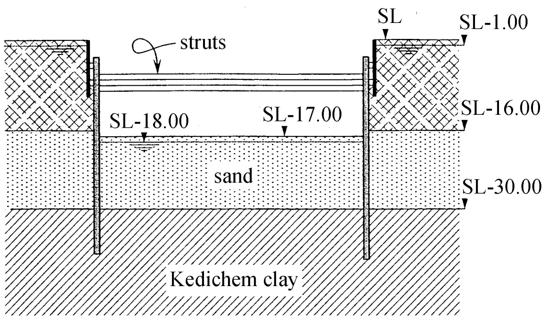
8.9 Two tubes of a tunnel for slow traffic under a river have been drilled using a special drilling machine. The external diameter of the concrete tunnel tube is 8.3 m, the walls are 0.3 m thick. In the river, the tunnel has a ground cover of 8.3 m. The riverbed consists of a layer of clay 1.5 m thick on sand. From the ground level, the south bank has a 2.0 m thick layer of clay on peat/sand. The groundwater level is 1.5 m under ground level. As vertical load, only the soil directly above the tube is taken into account.

Material	Specific weight (kN/m^3)
dry clay	14
wet clay	17
wet peat/sand	15
wet sand	18
concrete	24

Questions:

a. Determine the upward and downward forces on an empty tunnel tube under the riverbed, in kN/m (force per m length of the tunnel).
Check whether the tunnel will float.
b. How deep must the tunnel be built under the ground level of the south bank so that the difference between the upward and downward forces is 87.5 kN/m?

8.10 Concrete diaphragm walls have been used to build an underground railroad. The walls were poured into the clay. The clay layer is located under a layer of sand from SL–16.00 to SL–30.00. The building pit is dug to SL–17.00 and drained to SL–18.00. The groundwater is at SL–1.00.



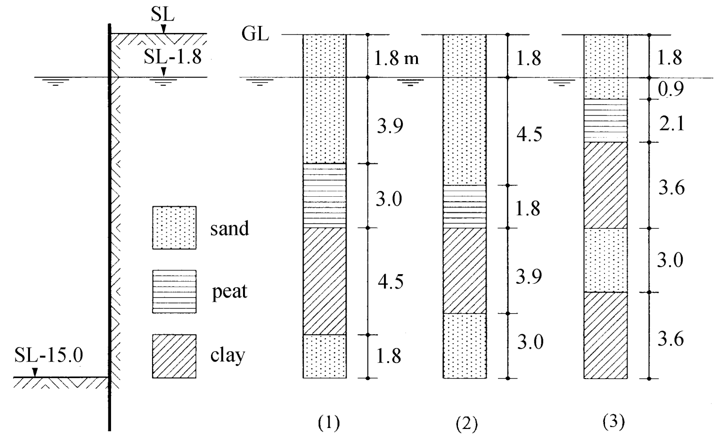
Material	Specific weight (kN/m^3)
dry sand	14
wet sand	18
wet clay	17

Questions:

a. How thick must the clay layer be so that after digging and draining in the building pit there is a grain pressure of 5 kN/m^2 at the base of the clay layer?
   Hint: clay is highly impermeable.
b. At which thickness of the clay will the building pit burst?

Horizontal earth pressures (Section 8.3)

8.11: 1–3 You are given a sheet-pile wall alongside a quay. There are three different soil profiles.



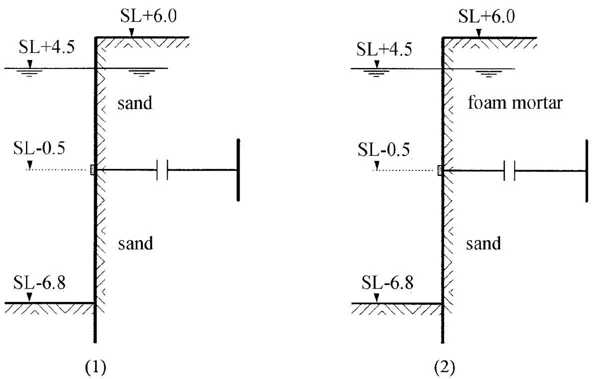
Material	Specific weight (kN/m^3)
dry sand	16
wet sand	20
wet peat	12
wet clay	18

Questions:

a. Up to SL–15.00, draw the distribution of the horizontal water pressure to the left and the earth pressure to the right of the sheet pile. Split the earth pressure up into grain pressure and water pressure.
b. Draw the distribution of the resulting pressure on the sheet-pile wall.
c. Determine the resultant of the horizontal load on a 1-metre wide vertical strip of the wall in kN/m.
d. Also answer questions a to c with a terrain load of 12 kN/m^2.

8.12: 1–3 As problem 8.11, but now the water level to the left of the sheet piling is 1.5 m below the groundwater level to the right.

8.13: 1–2 Sand is located under the anchor bars of an anchored sheet piling in a port. The soil is filled up to ground level. To fill the site, there is a choice between sand and a (far more expensive) foam mortar. The terrain load is 20 kN/m^2.

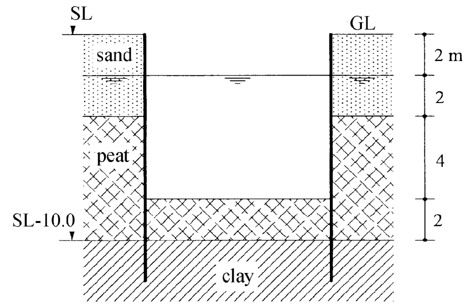


Material	Specific weight (kN/m^3)
dry sand	15
wet sand	18
dry foam mortar	2
wet foam mortar	6

Questions:

a. To SL–6.8, draw the distribution of the horizontal pressures to the left and to the right of the sheet piling.
b. Draw the distribution of the resulting horizontal pressure on the sheet piling.
c. Determine the resultant of the horizontal load on a 1-metre wide vertical strip of sheet piling in kN/m.
d. How does the horizontal load change if there is no terrain load?

8.14 A building pit is surrounded by a steel sheet piling and is still full of water. The soil profile is shown in the figure.

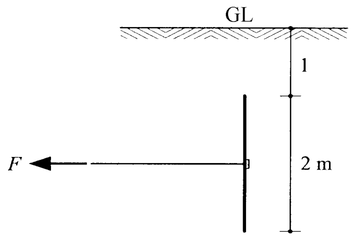


Material	Specific weight (kN/m^3)
dry sand	15
wet sand	18
wet peat	12

Questions:

a. Up to the clay layer, draw the distribution of the horizontal pressure on the outside of the sheet piling, split into grain pressure and water pressure.
b. Up to the clay layer, draw the distribution of the horizontal pressure on the inside of the sheet piling, split into grain pressure and water pressure.
c. Draw the distribution of the resulting horizontal load on the sheet piling.
d. Determine the resultant of the horizontal load on a 1-metre wide vertical strip of sheet piling in kN/m.
e. How does the resultant of the horizontal load on the sheet piling (in kN/m) change if the water level in the building pit is lowered to SL–8.0?

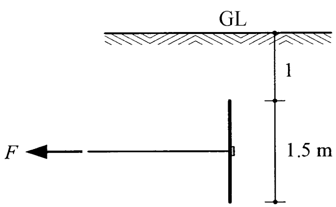
8.15 An anchor plate is located in dry soil, 1 m below ground level. The plate is 2 m high and 1.5 m wide. It can be assumed here that the anchor plate runs up to ground level. The specific weight of the soil is 15 kN/m^3.



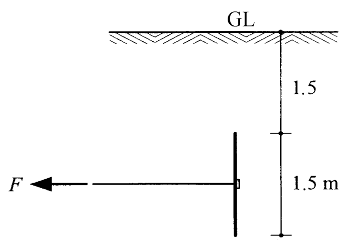
Questions:

a. Determine the maximum anchor force that the plate can provide.
b. Determine the influence of an terrain load of 18 kN/m on the magnitude of the anchor force.

8.16: 1–2 As 8.15, but now with an anchor plate that is 1.5 m high and 2 m wide, with the plate 1 m, respectively 1.5 m under ground level.

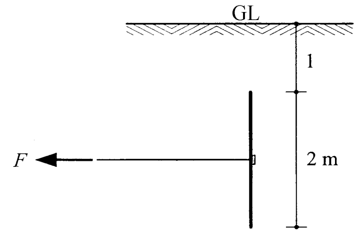


(1)



(2)

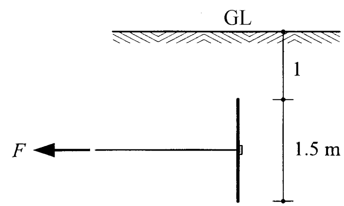
8.17 An anchor plate is located in dry soil, 1 m below ground level, and is 2 m high and 1.5 m wide. It can be assumed here that the anchor plate runs up to ground level. The specific weight of the soil is 15 kN/m^3. The angle of internal friction is 20°.



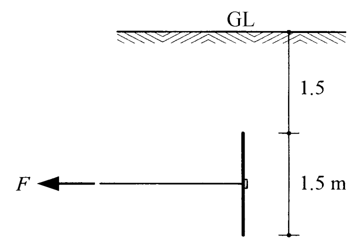
Questions:

a. Determine the coefficient for active earth pressure.
b. Determine the coefficient for passive earth pressure.
c. Determine the maximum anchor force that the plate can provide.
d. Determine the influence of an terrain load of 18 kN/m on the magnitude of the anchor force.

8.18: 1–2 As 8.17, but now with an anchor plate that is 1.5 m high and 2 m wide, with the anchor plate 1 m, respectively 1.5 m under ground level.



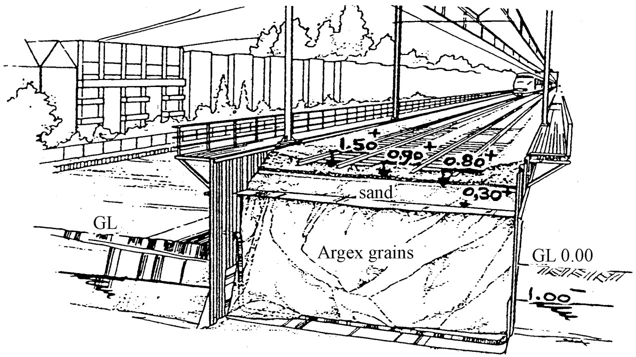
(1)



(2)

Various questions

8.19 During the construction of a railway, part of the existing railway was moved to make room for the building pit of the new railway. In order to prevent settlement, it was decided to introduce a raise with light argex grains. The grains are sealed from the groundwater by means of a waterproof membrane and are kept dry by means of drainage.



Construction in the railway:	Level SL (m)	Material	Specific weight (kN/m^3)
topside ballast bed	+1.50	ballast	18
topside gravel layer	+0.90	gravel	17.5
topside sand layer	+0.80	sand/dry	15
topside argex grains	+0.30	argex/dry	6.5

Next to the railway:	Level SL (m)	Material	Specific weight (kN/m^3)
ground level	0.00	soil/dry	14
groundwater level	–1.00	soil/wet	17

Questions:

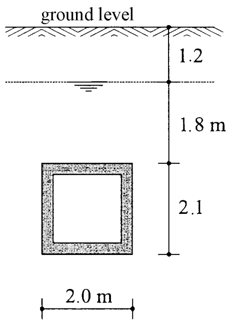
a. Up to 3 m below ground level, draw the distribution of the vertical earth pressure outside the sheet-pile walls. In the diagram, indicate which part of the earth pressure is caused by the grain pressure and which is caused by the water pressure.

b. How deep must the waterproof membrane be with respect to SL, so that the vertical earth pressure directly under the membrane is equal to the earth pressure outside the sheet-pile walls?

c. Draw the distribution of the vertical earth pressure within the sheet-pile walls, to 3 m below ground level. In the diagram, indicate which part of the earth pressures is caused by the grain pressure and which is caused by the water pressure.

d. Up to 3 m below ground level, draw the distribution of the horizontal earth pressure on the outside of the sheet piling. In the diagram, indicate which part of the earth pressures is caused by the grain pressure and which is caused by the water pressure.

8.20 A concrete culvert with rectangular cross-section 2 m wide and 2.1 m high and the same wall thickness everywhere of 0.25 m, is located with its top side 3.0 m under ground level. The groundwater is located 1.2 m under ground level.



The specific weights are

$$\gamma_{\text{earth;dry}} = 17.5 \text{ kN/m}^3;$$

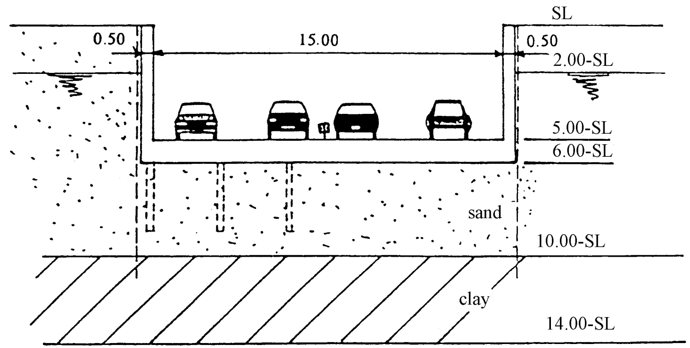
$$\gamma_{\text{earth;wet}} = 20 \text{ kN/m}^3;$$

$$\gamma_{\text{concrete}} = 24 \text{ kN/m}^3.$$

Question:
Determine the distribution of the earth pressure, split up into grain pressure and water pressure, on

a. the top side of the culvert.
b. the sides of the culvert.
c. the base of the culvert.

8.21 At a crossroad with unequal levels, one of the roads passes under the other in a trough structure. Sheet-pile walls are driven into the clay layer. Subsequently, the pit is dug down until SL–6.00 and the water in the pit is drained to SL–7.00. Once the trough structure is completed, the sheet-pile walls are removed.



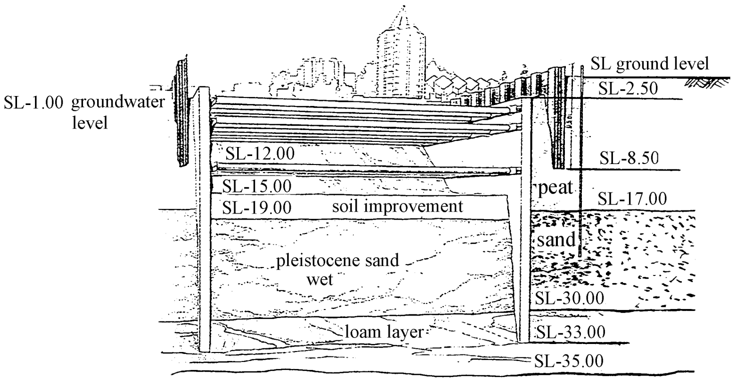
Material	Specific weight (kN/m^3)
dry sand	15
wet sand	20
wet clay	18
concrete	24

Questions:

a. To SL–14.00, draw the distribution of the vertical earth pressure. In the diagram, indicate which part of the earth pressure is caused by the grain pressure and which is caused by the water pressure.
b. Is the building pit safe from bursting once it has been dug out but prior to the placement of the concrete trough structure?
c. Show that, if there are no tension piles, the concrete trough will rise once the sheet-pile walls have been removed.
d. Draw the horizontal earth pressure on the wall of the trough structure. In the diagram, indicate which part of the earth pressure is caused by the grain pressure and which is caused by the water pressure.

8.22 Diaphragm walls have been used to build a tunnel. The diaphragm walls run to SL–33.00. The building pit has been dug out to SL–19.00, after which a soil improvement of 4 m was used to SL–1500. The lower struts are at SL–12.00. Ground level is at SL. The groundwater is at SL–1.00. The soil profile is as follows:

- 17 m peat: from SL to SL–17.00
- 13 m (Pleistocene) sand: from SL–17.00 to SL–30.00
- 5 m loam: from SL–30.00 to SL–35.00
- sand: from SL–35.00



Material	Specific weight (kN/m^3)
dry peat	13
wet peat	15
pleistoc. sand wet	19
loam	18
soil improvement	16

Questions:

a. To SL–35.00, draw the distribution of the vertical earth pressure adjacent to the building pit, split up into grain pressure and water pressure.

b. After applying the soil improvement in the building pit, how large is the grain pressure directly under the loam layer? The water in the building pit is at SL–19 .00

c. From SL–12.00 to SL–20.00, draw the distribution of the horizontal earth pressure on the outside of the diaphragm wall, split into grain pressure and water pressure.