K-Réa v4

# D. TUTORIAL MANUAL

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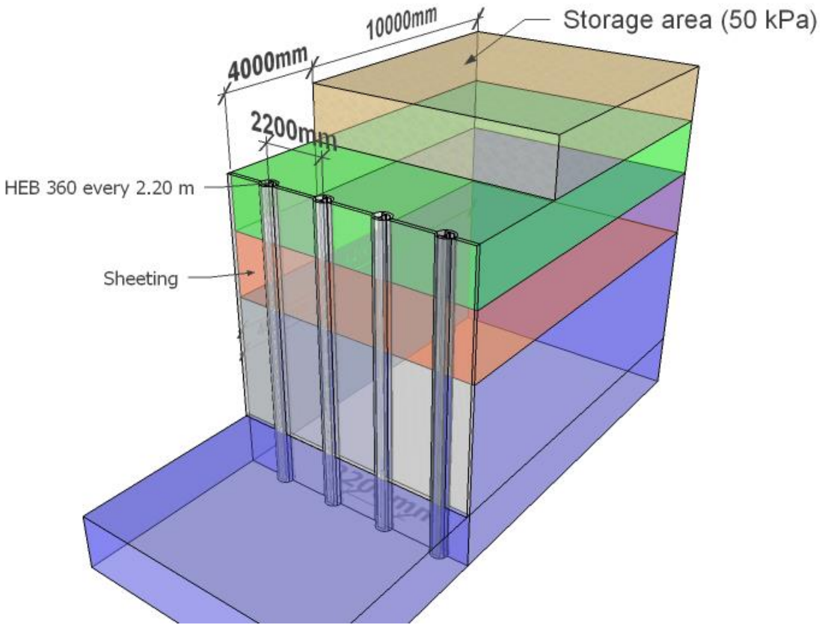
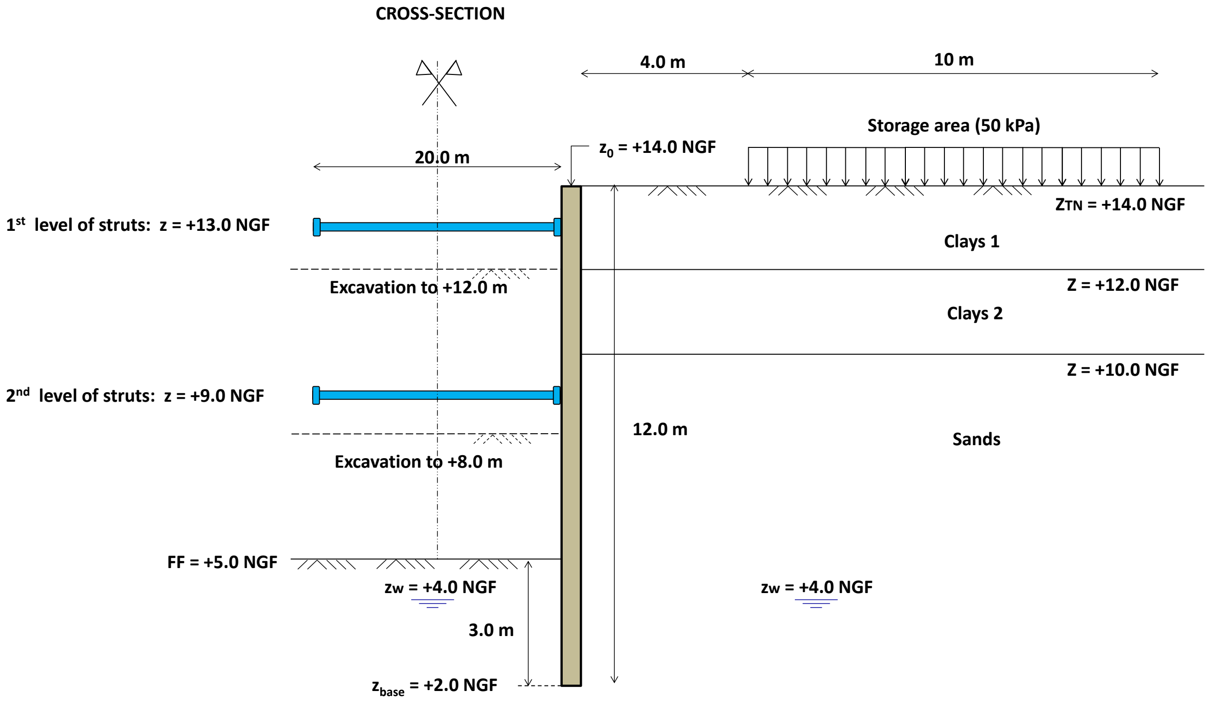
# D.1. Tutorial 1: Soldier pile wall with struts

We will be studying a composite wall of the soldier-pile type. The stability of the wall will be guaranteed by two layers of struts.




*3D view of retaining structure project*




Calculation cross-section

The retaining structure is situated 4 metres from an existing storage area, which can be compared to a constant load of 50 kPa over a length of 10 metres.
The modelling of the wall shall consider an **initial phase** to take account of this load that exists prior to the construction.

The retaining structure consists of two circular concrete piles reinforced by a metal section inside each pile. We consider that the metal beams alone take up the wall internal loads.

The characteristics of the piles are as follows:

- Diameter = **0.62 m**
- Spacing = **2.20 m** (axis-to-axis)
- Metal section: **HEB 360**

In the initial phase we will apply the active/passive earth pressure reduction coefficients to take account of the composite nature of the wall.

The phasing then comprises **3 excavation phases** with gradual installation of sheeting and **2 levels of struts**: **HEB 320 spaced 4.40 m apart**.

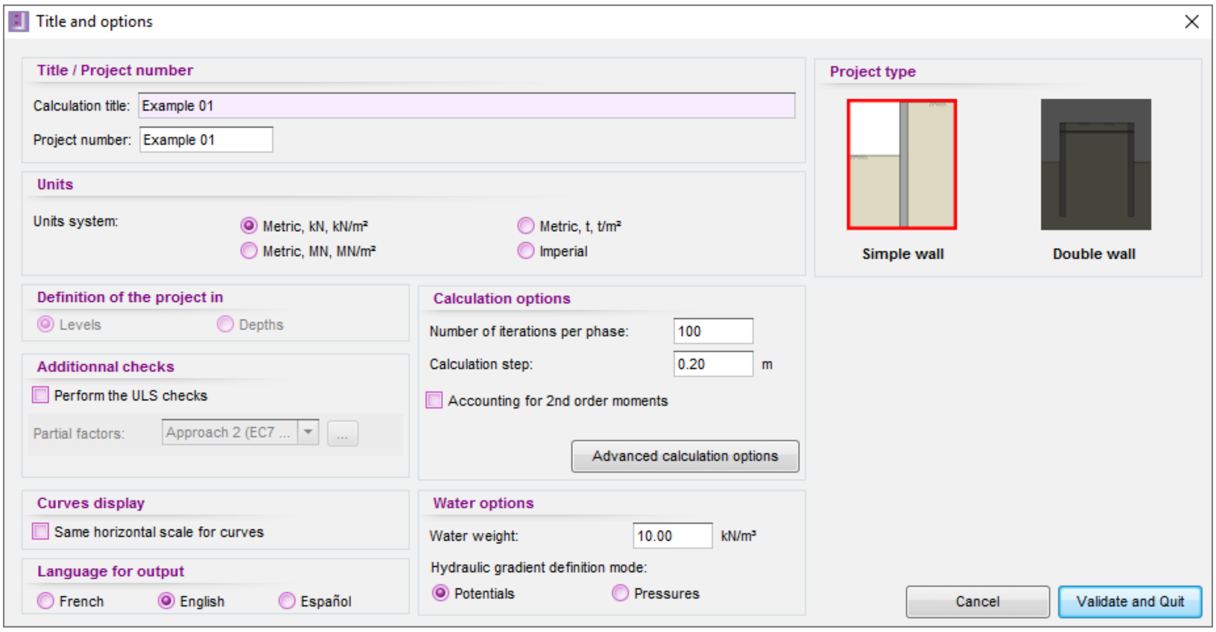
The soil cross-section comprises three soil layers. The characteristics of the layers are given further on in the exercise. We will be carrying out a study without ULS checks using a MISS calculation without weighting factors. The ULS checks will be dealt with in other examples.

## D.1.1. Step 1: Data input

To start K-Réa:

- Double-click the **K-Réa** icon.
- Choose the appropriate protection mode, select the appropriate language and click **OK.**
- Choose **New project** to access the **Title and Options** form.

### D.1.1.1. Title and options




- In the **Project type** frame (right), select “Simple wall”.
- In the **Title/Project number** frame, input the title and the project number of your choice.
- In the **Units** frame, choose the units system for your project, by ticking “Metric, kN, kN/m$^2$”.
- Choose **Definition of the project in** ”Levels”, which enables the vertical axis to be directed **upwards**.
- **Additional checks**: leave the “Perform the ULS checks” box unticked for this example.
- In the **Curves display** frame, tick the “Same horizontal scale for curves” box.
- Choose the **Language for output**.
- In the **Calculation options** frame, keep the default settings: 100 iterations per calculation phase and calculation step of 0.2m for the wall.
- In the **Water options** frame, leave the water weight setting of 10.00 kN/m³.
- Click on the Validate and Quit button.
- K-Réa then asks you to save the new project: define the appropriate name and directory.

### D.1.1.2. Definition of soil layers

The characteristics of the 3 layers of soil in the project must now be defined.

- Fill out the characteristics of the first soil layer. By default, the first line of the summary table is selected.
- Click the input box corresponding to **Phreatic level** and enter $z_w$ = +4 m.
- Input the "**Name**" of the first soil layer: Clays 1.
- Give the **Level of top of layer** z = +14 m.
- Repeat this operation to input **γ, $\gamma_d$, φ, c**, **$\delta_a$/φ**, **$\delta_p$/φ** and **$p_{max}$** the values of which are given in the following summary table:

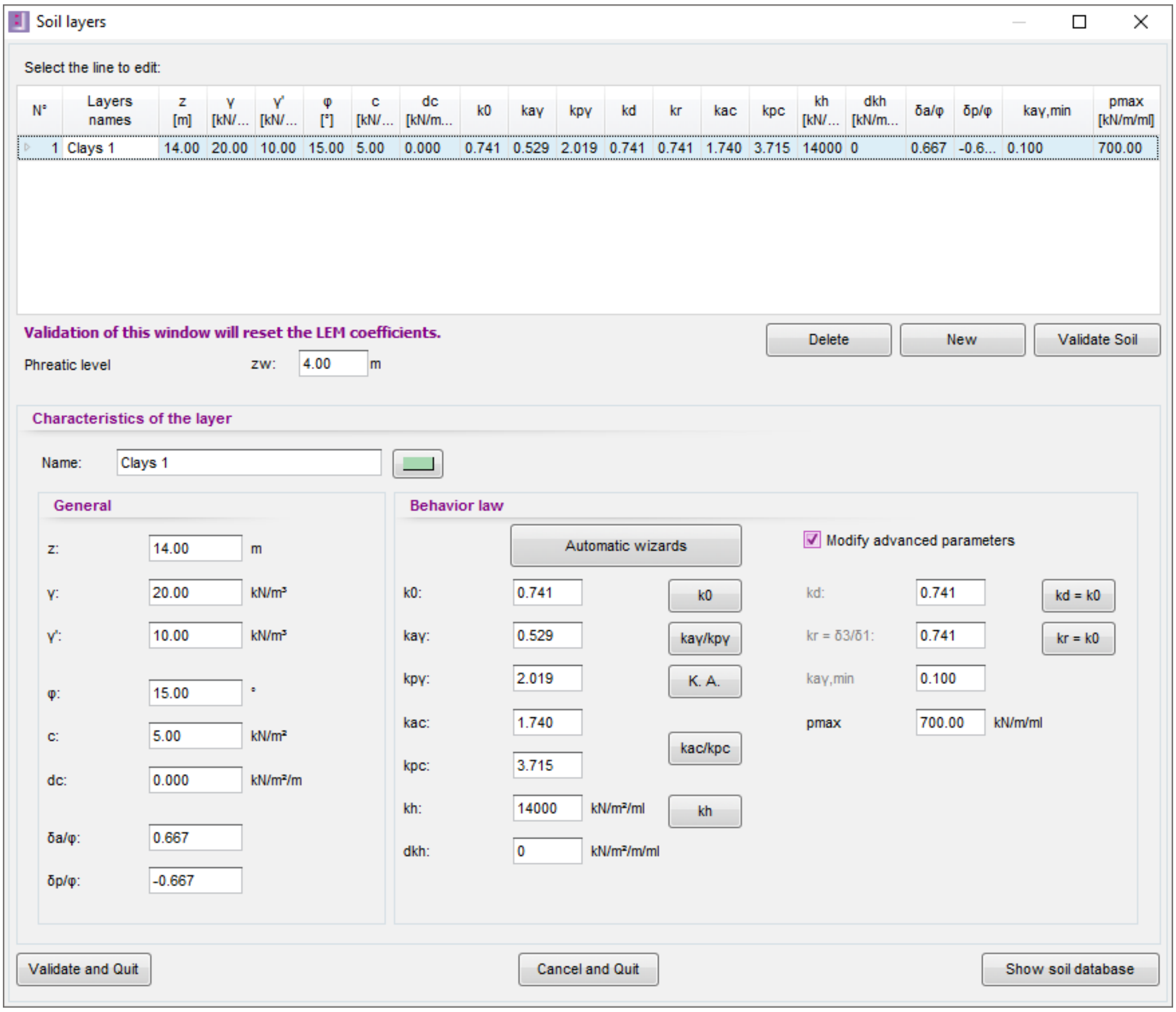
| Layer name | z (m) | γ (kN/m$^3$) | γ' (kN/m$^3$) | φ (°) | c (kN/m²) | dc (kN/m²/m) | $\delta_a$/φ (-) | $\delta_p$/φ (-) | $p_{max}$ (kN/m/ml) |
|---|---|---|---|---|---|---|---|---|---|
| **Clays 1** | 14 | 20 | 10 | 15 | 5 | 0 | +0.667 | -0.667 | 700 |

The values of δa/φ and δp/φ correspond to:

- An inclination of +2/3 φ of the active earth pressure (downwards)
- An inclination of -2/3 φ of the passive earth pressure (upwards)

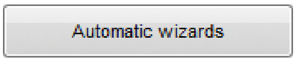
The value of dc corresponds to the increase in cohesion with depth.
In this example, we consider that cohesion is constant over the height of the layer (dc = 0).

The following screenshot illustrates that of K-Réa following these operations:




Tick the "**Modify advanced parameters**" box.

To complete coefficients $k_0$, $k_{a\gamma}$, $k_{p\gamma}$, $k_{ac}$, $k_{pc}$, $k_d$, $k_r$, we will use the automatic wizards:

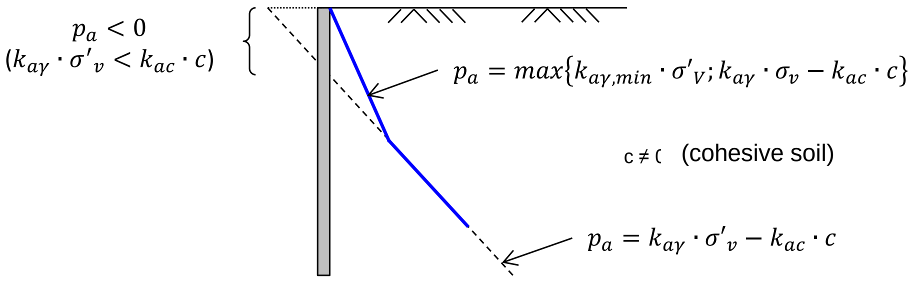
- Click the: 

button

  These various values are then filled out in accordance with the following principles:

  - $\mathbf{k_0}$ is calculated using the Jaky formula, with Roc = 1, $\beta = 0$ and taking account of the characteristics already input above.
  - $\mathbf{k_{a\gamma}}$ is calculated via the "Kérisel and Absi tables" wizard – Active earth pressure, weighted cohesionless soil, without overload, with $\lambda = 0$ and $\beta/\varphi = 0$ (horizontal ground) and taking account of the characteristics already input above.
  - $\mathbf{k_{p\gamma}}$ is calculated via the "Kérisel and Absi tables" wizard – Passive earth pressure, weighted cohesionless soil, without overload, with $\lambda = 0$ and $\beta/\varphi = 0$ and taking account of the characteristics already input above.
  - $\mathbf{k_d} = \mathbf{k_r} = \mathbf{k_0}$.
  - $\mathbf{k_{ac}}$ and $\mathbf{k_{pc}}$ (coefficients applied to the cohesion value) are obtained with the corresponding wizard.

- **$k_{a\gamma,min}$** corresponds to the minimum active earth pressure coefficient required by the French Standard P 94-282. By default, the value is equal to 0.1 to take account of a horizontal active thrust stress of at least 10% of the effective vertical stress. This enables a minimum active earth pressure to be considered in the case of cohesive soils (our case).




- **$p_{max}$** represents the maximum allowable soil pressure value. In this example, it plays an important role. Its value will be the bound of the allowable soil passive earth pressure limit in accordance with standard NF P 94-282 Appendix B.3.6. It corresponds to the creep pressure ($p_f$) or the limit pressure ($p_l$) depending on the type of calculation (SLS or ULS respectively).

- In this example, leave value **dc** = 0.

- One now needs to simply define the value of **$k_h$** and its increment. To do this, enter the value of 14 000 kN/m²/ml for **$k_h$** (this value was not determined here by a wizard but it is assumed that it is known in the context of this exercise). Then click the **$dk_h$** box to input the value 0 ($k_h$ constant with depth).
- In order to display the summary of the characteristics of this soil layer, click the summary table.

  Note: in this dialogue box, the fact of clicking [Validate and Quit] will validate your inputs, but if you quit this dialogue box in any other way, your inputs will be cancelled.
- In the same way, input the other two soil layers by clicking the [New] button and referring to the following summary table:

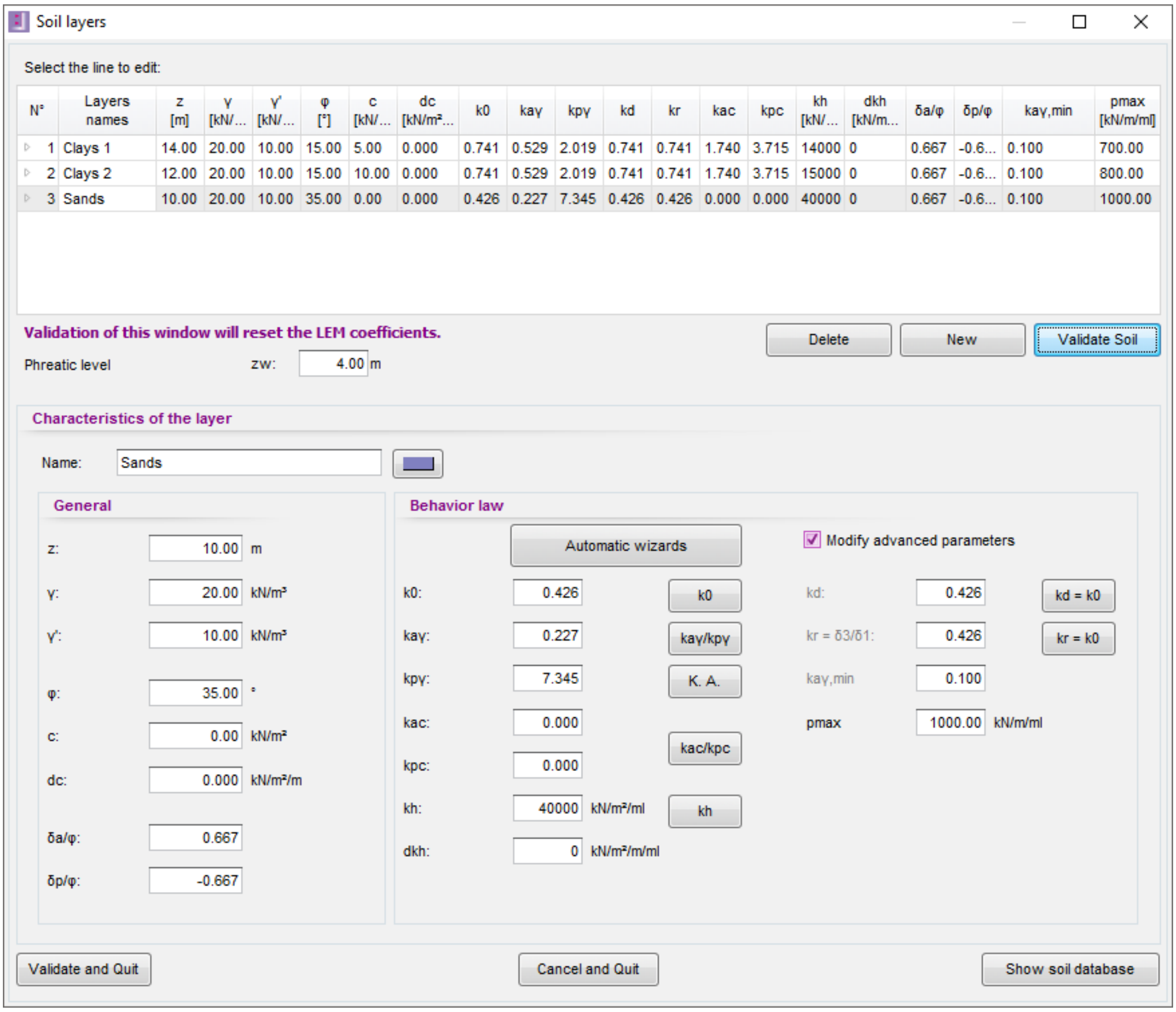
| Layer | z (m) | γ (kN/m³) | γ' (kN/m³) | φ (°) | c (kN/m²) | dc (kN/m²/m) | $\delta_a/\varphi$ (-) | $\delta_p/\varphi$ (-) | $p_{max}$ (kN/m/ml) |
|---|---|---|---|---|---|---|---|---|---|
| **Clays 1** | 14 | 20 | 10 | 15 | 5 | 0 | +0.667 | -0.667 | 700 |
| **Clays 2** | 12 | 20 | 10 | 15 | 10 | 0 | +0.667 | -0.667 | 800 |
| **Sands** | 10 | 20 | 10 | 35 | 0 | 0 | +0.667 | -0.667 | 1 000 |

Then use the K-Réa wizards to calculate the parameters used to constitute the behaviour law for each layer.

The following parameters are to be obtained using the wizards.

| Layer | $k_0$ (-) | $k_{ay}$ (-) | $k_{py}$ (-) | $k_{ac}$ (-) | $k_{pc}$ (-) | $k_h$ (kN/m²/ml) | $dk_h$ (kN/m³/ml) | $k_d$ | $k_r$ | $k_{ay,min}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| **Clays 1** | 0.741 | 0.529 | 2.019 | 1.740 | 3.715 | 14 000 | 0 | 0.741 | 0.741 | 0.100 |
| **Clays 2** | 0.741 | 0.529 | 2.019 | 1.740 | 3.715 | 15 000 | 0 | 0.741 | 0.741 | 0.100 |
| **Sands** | 0.426 | 0.227 | 7.345 | 0 | 0 | 40 000 | 0 | 0.426 | 0.426 | 0.100 |

The following screen is then obtained:




Click [Validate and Quit].

To edit or modify the soil layers subsequently, click **Data Menu,** then **Soil layers**.

### D.1.1.3. Definition of the wall

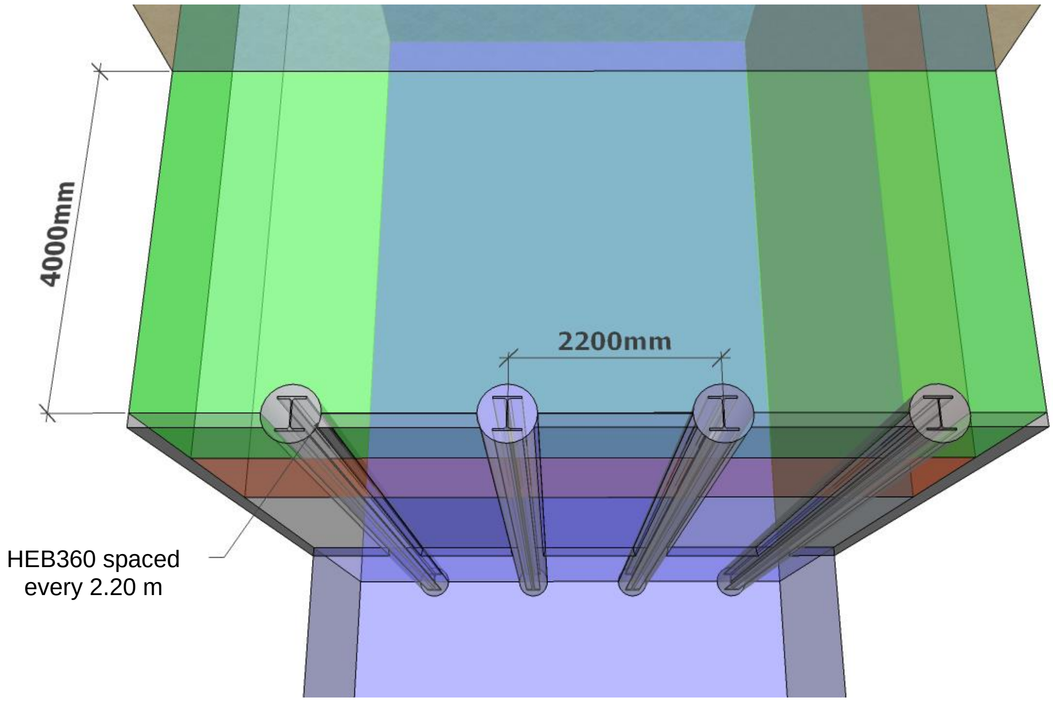
- Wall levels:

The upper level of the wall is at elevation GL, that is $z_0$ = +14.0 m.
The lower level of the wall is at elevation $z_{base}$ = +2.0 m.

- Product of inertia of wall (EI):

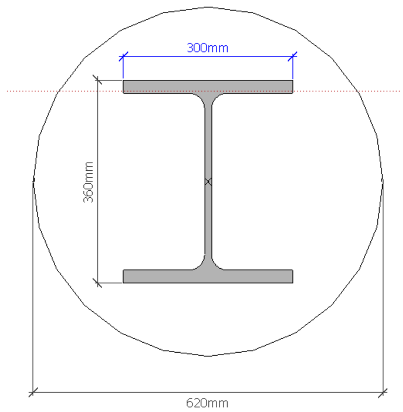
The product of inertia corresponds to that of the HEB 360 metal sections spaced every 2.20 m, because we will consider that they alone take up the wall internal forces.

The sections are spaced at intervals of 2.20 m (axis-to-axis).




HEB 360 every 2.20 m

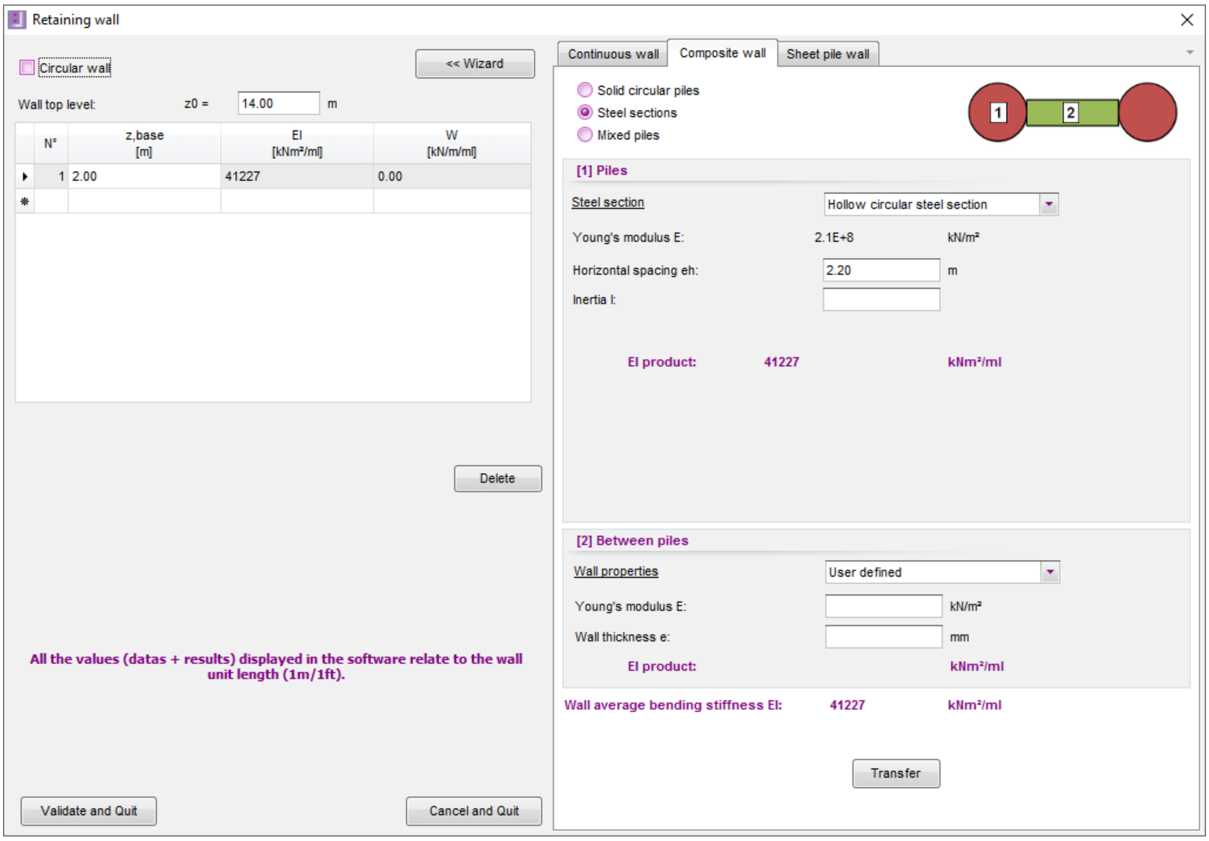
*Plan view of retaining structure from excavation side*




*Plan view of a 620 mm pile reinforced with an HEB360 section*

## Definition of wall with K-Réa:

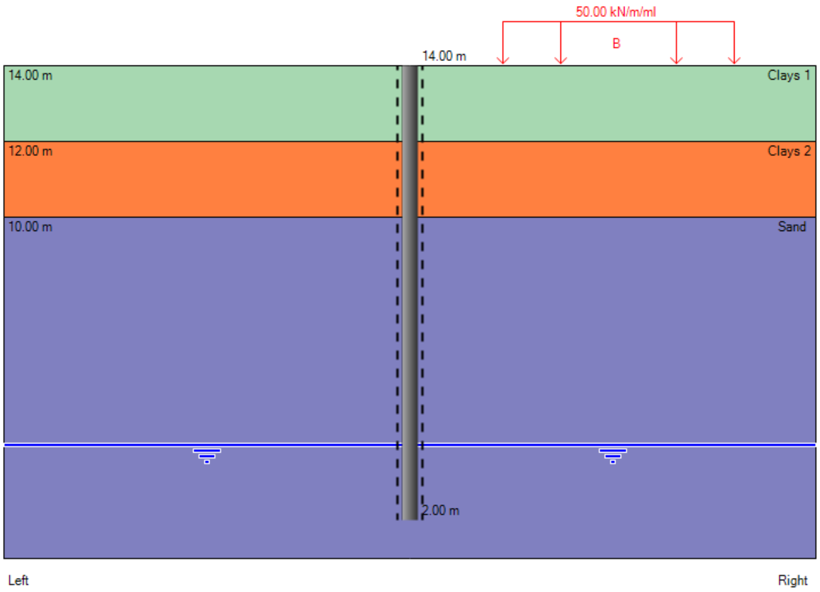
- Input the wall upper level $z_0$ = +14.0 m.
- Click the first line of the table (corresponding to the first wall section to be defined, which in this particular example will be the only one), in the first column input the base of the section, here elevation $z_{base}$ = +2.0 m.
- Then click the [Wizard >>] button to determine the EI product of the steel sections:
  - Choose the Composite wall tab, then select "Steel sections".
  - From the drop-down list of sections, choose HE 360 B.
  - Then input the horizontal spacing (axis-to-axis) of the sections at 2.20 m.
  - We will not take account of the inertia contributed by the sheeting between the steel sections and will thus leave the corresponding input zones empty.
- Click [Transfer] then quit the wizard.




Finally, click [Validate and Quit] to take account of the values input and the data will appear on the graphic representation of the project initial data. To modify the characteristics of the wall subsequently, click the **Data** menu, then **Wall Definition**.

### D.1.2. Step 2: Phasing definition

The K-Réa main window now shows the project's initial phase with a representation of the soil layers and wall.




The actions to be considered in each construction phase should now be defined.

These actions are summarised in the following table on the basis of the chosen phasing:

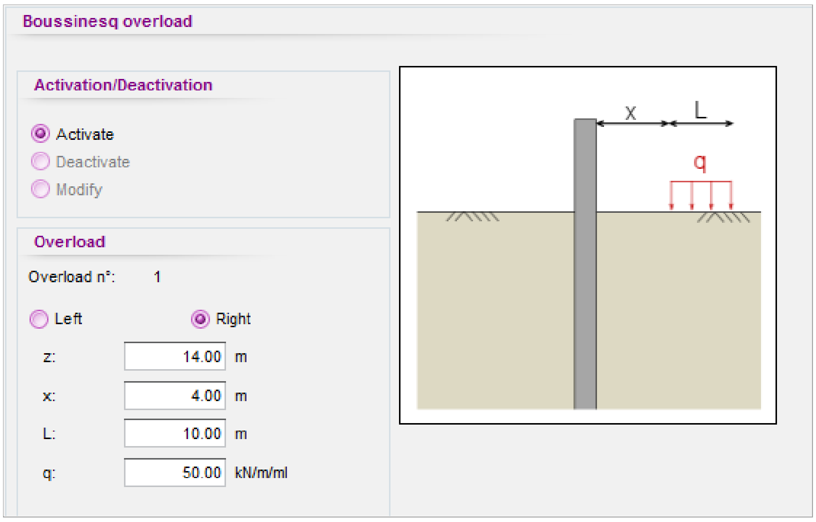
| PHASE | ACTIONS |
|---|---|
| **Initial**<br>*Before works* | • Boussinesq overload of 50 kN/m/ml at 4 metres behind the wall over a width of 10 metres.<br>• Reduced active and passive earth pressure over entire height of wall. |
| **1**<br>*Excavation* | • Intermediate excavation with installation of sheeting at +12.0 m. |
| **2**<br>*1st layer struts + Excavation* | • Installation of layer of horizontal struts (HEB 320 every 4.40 m axis-to-axis distance) at +13.0 m, or $K_{layer\ struts}$ = 76 984 kN/m/ml (work only authorised in compression, no preload)<br>• Intermediate excavation with installation of sheeting down to +8.0 m. |
| **3**<br>*2nd layer struts + Excavation to bottom of excavation* | • Installation of a strut layer at +9.0 m (same mechanical and geometrical properties as previous layer of struts).<br>• Excavation to bottom of excavation with installation of sheeting down to +5.0 m. |

### D.1.2.1. Initial phase

In the initial phase, the first action to be defined is a **Boussinesq overload** to take account of the existence of the storage area behind the wall, before it is built.

We define a Boussinesq overload as follows:

1. In the “List of available actions” frame, “Loads – Forces - Moments” category, the drop-down list can be used to select the “Boussinesq overload” action. Clicking the “Transfer” button will call it up in the list of actions for the initial phase, in the right-hand part of the window.
2. Set the overload to “Right”.
3. Input the following values:
    - z = + 14.0 m
    - x = 4 m (behind the wall)
    - L = 10 m (overload application width)
    - q = 50 kN/m/ml



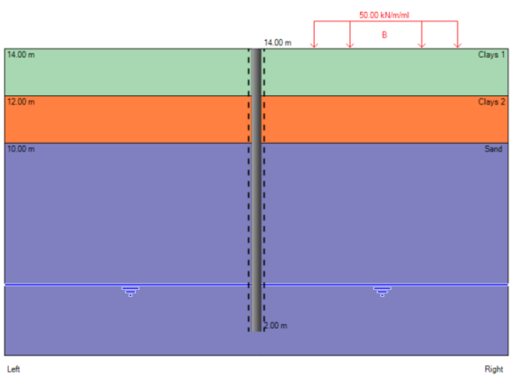
The **Reduced active earth pressure** action must then be defined, so that the reduced active and passive earth pressure stresses can be taken into account for the wall, owing to the fact that it is composite.

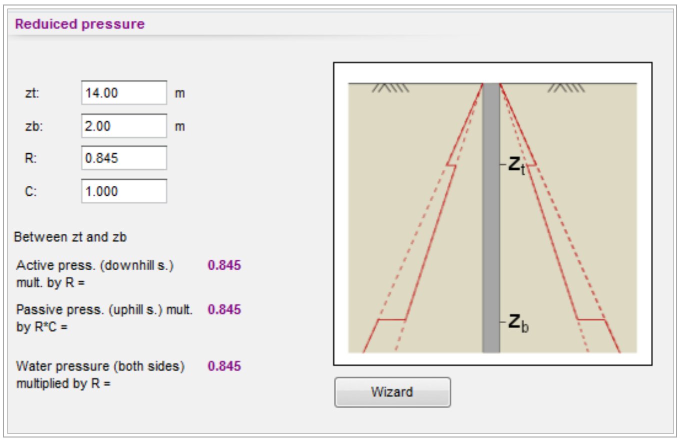
This action will then be gradually "cancelled out" during the phasing, as installation of the sheeting progresses. The effect of the sheeting is to make the wall continuous, so the active and passive earth pressures will once again be taken into account in full over the height at which the wall is continuous.

To define this action:

- Select **Reduced pressure** from the drop-down menu of "Soil characteristics" actions in the initial phase. Click transfer button [button].
- In the **"Reduced pressure"** definition frame, input the following information:
  - $z_t$ = +14.0 m
  - $z_b$ = +2.0 m
  - R = 0.845
  - C = 1

This action is represented by a dotted black line on both sides of the wall.




All the actions in the initial phase have now been defined.

To create a new calculation phase and continue to input the phasing data, click [+] next to the initial phase tab ("P00"). A new tab appears for this new phase. As no action has yet been defined for this new phase, the list of actions is blank and its graphic representation is the same as that of the previous phase.

**How to determine the reduced width for calculation of the limit active pressure and limit passive pressure according to standard NF P 94 282 for a composite wall?**

- Reduced width for calculation of limit active earth pressure (**NF P 94 282 Appendix B**):

  $\mathbf{L_a}$ = β x D = 3 x 0.62 m = **1.86 m**

  Where: β = ultimate passive earth pressure ratio = 1 + 2 x D / D = 3 (rubbing and cohesive soil)
  D = equivalent diameter of metal section taken as equal to pile diameter

- Reduced width for calculation of limit passive earth pressure (**French Standard P94 282 Appendix B**):

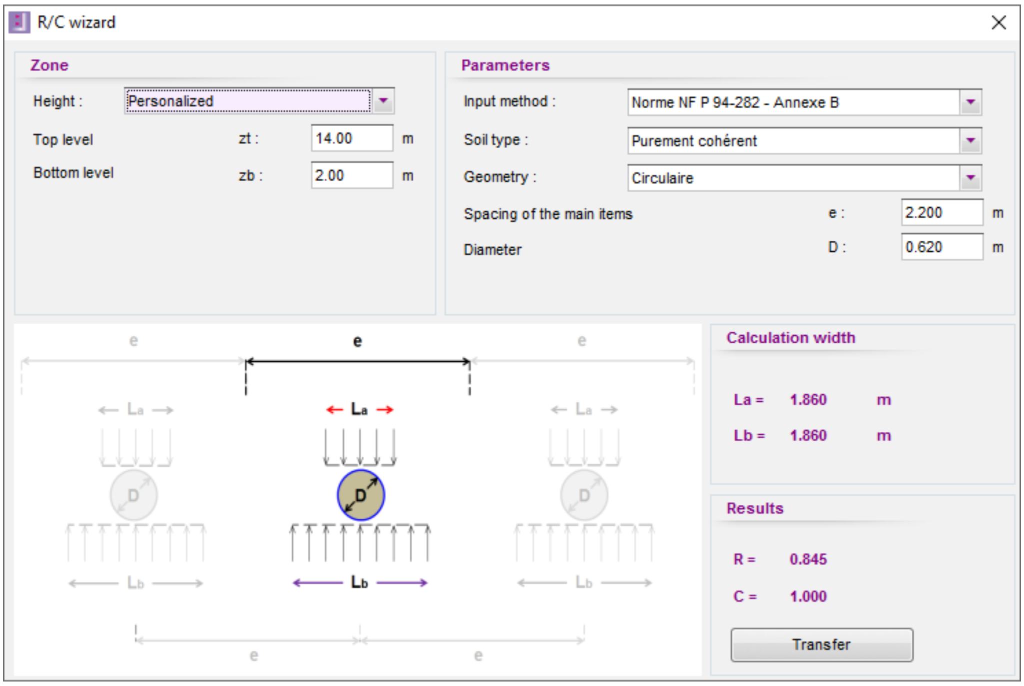
  $\mathbf{L_b}$ = $L_a$ = **1.86 m**

Calculation of R and C:

In K-Réa, we will prescribe these calculation widths for the limit active and passive earth pressures by means of reduction coefficients R and C. They apply directly to the theoretical Pa and Pb pressure values calculated for a continuous wall. They will be applied over the height between $z_t$ and $z_b$ inclusive.

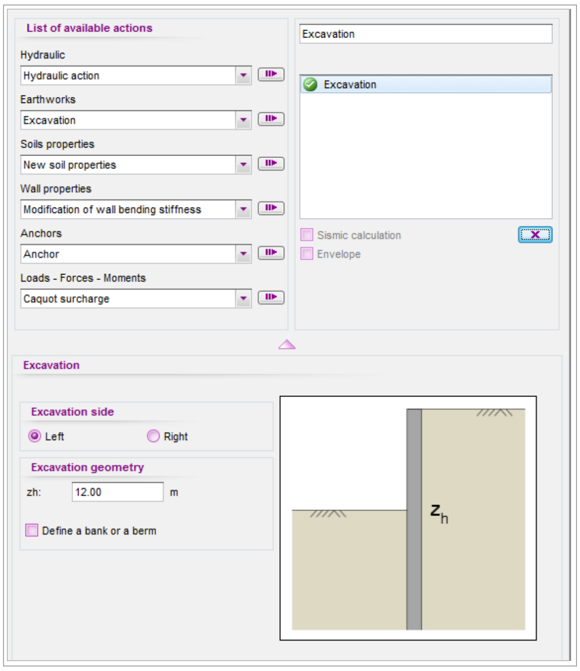
- Reduction coefficient for limit active earth pressure: **R** = $L_a$ / e = 1.86 m / 2.20 m = **0.845**
- Reduction coefficient for limit passive earth pressure: R x C = $L_b$ / e = 1.86 m / 2.20 m = 0.845, hence **C = 1** (same reduced calculation width for limit active and passive earth pressures).

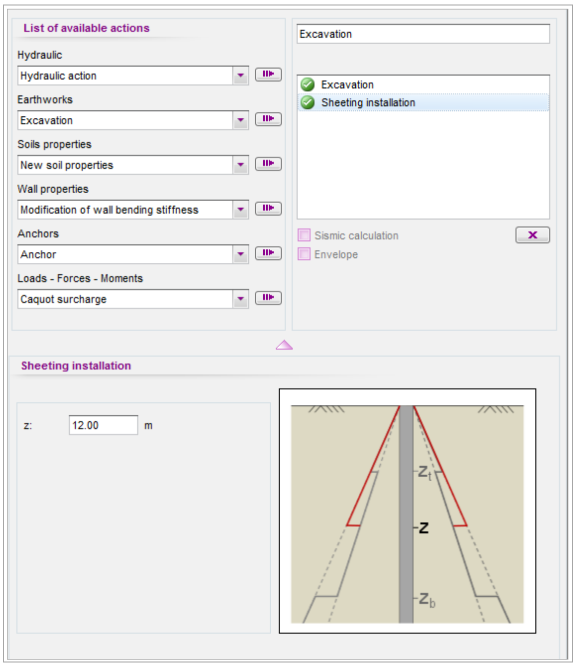
Using the wizard:

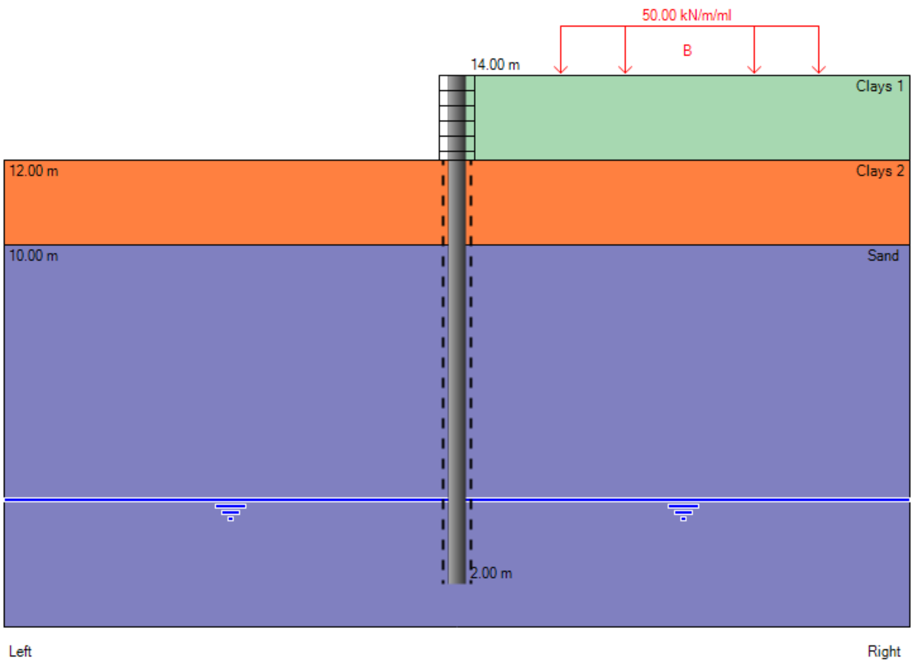


### D.1.2.2. Phase 1

- In the list of available actions frame**,** "Earthworks" category, select the **Excavation** option. Transfer the action and input the excavation level, left: $z_h$ = +12.0 m.
- In the List of available actions frame**,** "Earthworks" category, select the "**Sheeting installation"** option. Transfer the action and input the sheeting base: z = +12.0 m.



### D.1.2.3. Phase 2

To create this new calculation phase and continue to input the phasing data, click [+].

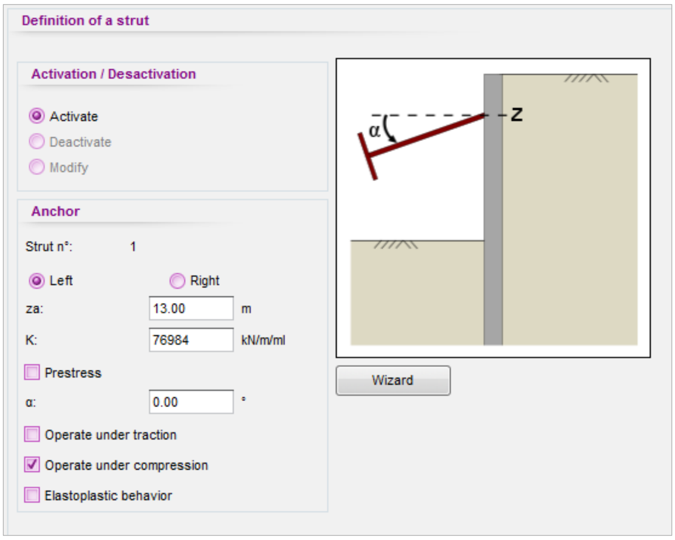
The first action in the second phase is installation of a Strut:

- In the List of available actions frame, "Anchors" category, select the "**Strut**" action and transfer [button] the action.
- In the "Definition of a strut" frame, fill out the following information:
  - "**Activate**" a new anchor "left"
  - $z_a$ = +13.0 m
  - Let us assume **HEB 320 struts spaced 4.4 metres axis-to-axis**.

    The Young's modulus of the steel is 210 GPa. Their steel section is 16.130 mm². The excavation is assumed to be perfectly symmetric and 20m wide, the useful length will thus be half the width of the excavation: Lu = 10 m.

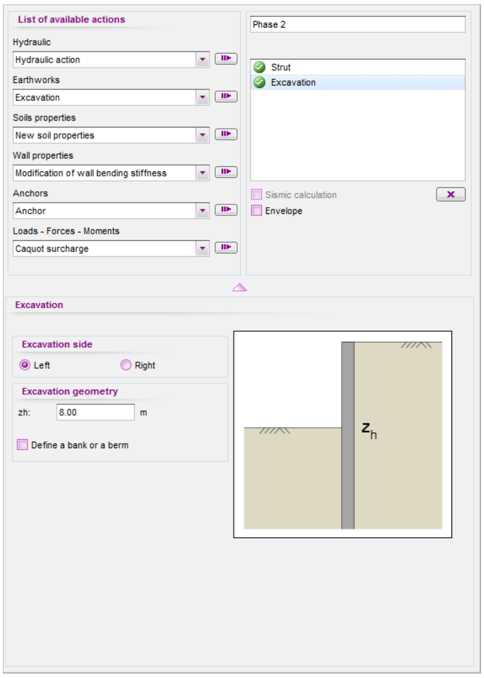
    The stiffness K will be:

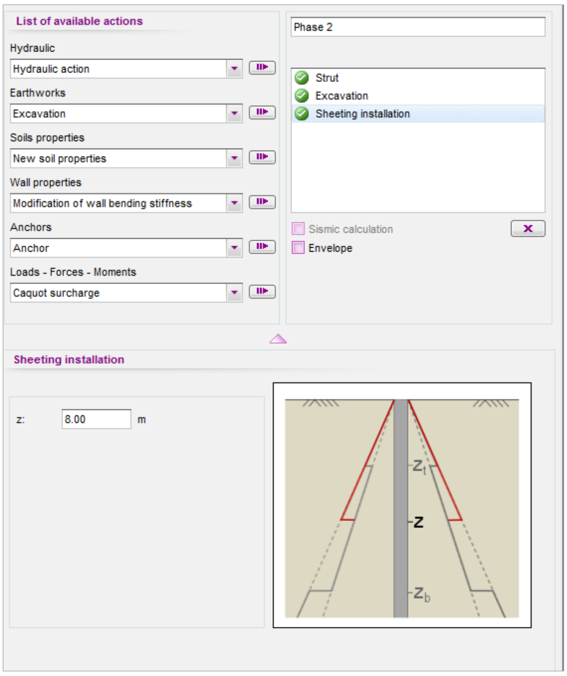
    $K_{layer\ struts}$ $= E \times S / L_u / Esp$
    $= 2.1 \times 10^8$ kN/m² x 16 130 $\times 10^{-6}$ m² / 10 m / 4.4 m = 76 984 kN/m/ml
  - No pre-stressing in our case: p = 0 kN/ml
  - We will consider a nil inclination for the strut: α = 0°
  - Only leave the "Operate under compression" box ticked (the strut will not be authorised to operate under traction).

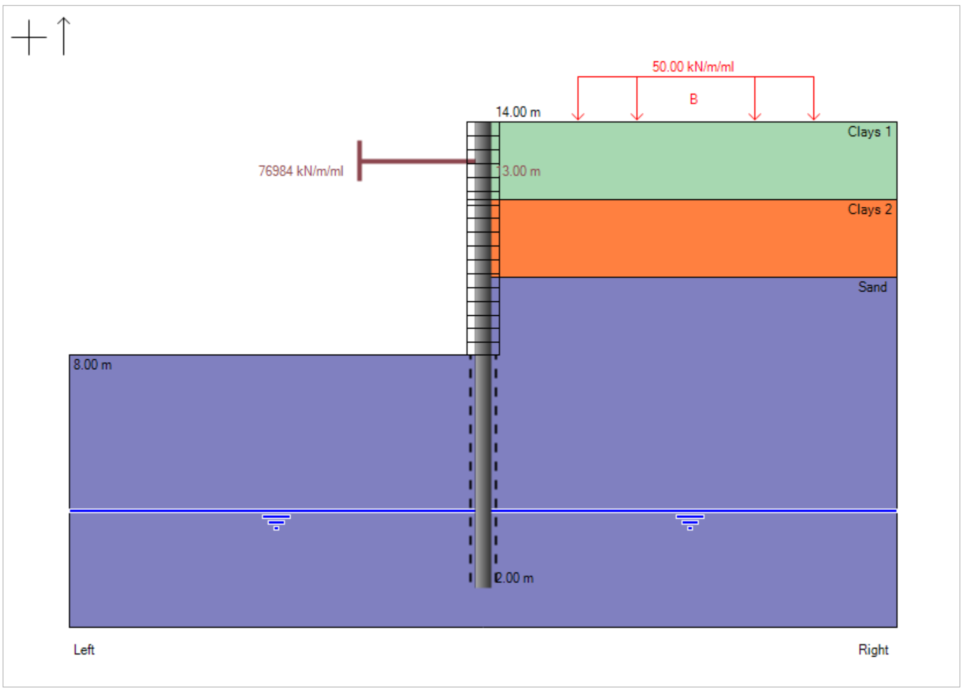


The second action of the 2nd phase is excavation with installation of sheeting. To model this, two actions must be used: the **Excavation** action followed by the **Sheeting installation** action:

- Define the **Excavation** action, enter the bottom of excavation level at +8.0 m.
- Then apply the **Sheeting installation** action and input the parameters necessary to define it, that is the level of the bottom of sheeting installation at the end of the excavation phase (here +8.0 m, default value proposed). In the upper part of the wall (between level +8.0 and the top of the wall), the wall is thus considered to be continuous and the R and C coefficients do not apply to this part anymore.



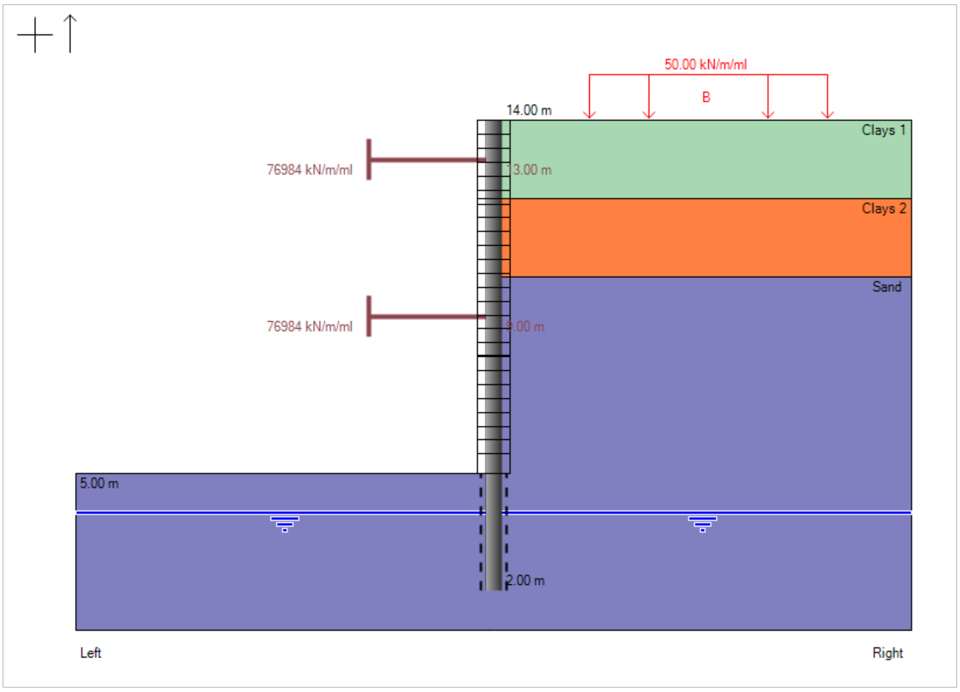
### D.1.2.4. Phase 3

To create this new calculation phase and continue to input the phasing data, click [+].

Using the operations described in phase 2, install a strut with:

- Level: $z_a$ = +9 m
- Stiffness: K = 76 984 kN/m/ml
- Pre-stressing: P = 0 kN/ml
- Inclination: α= 0°
- “Operate under compression” only.

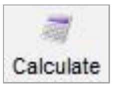
Then model an excavation with installation of sheeting down to height z = +5.0 m.




Save your project.

### D.1.3. Step 3: Calculations and results

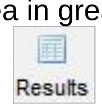
To start the calculations once all project parameters have been input, click the “Calculate” button on the buttons bar:




Note: the calculations can be started at any moment once the project, soil and wall characteristics have been saved.

The displacement, shear forces and bending moments curve appear on the tab for the phase in progress. The results of the various phases can be viewed by switching from one tab to another.

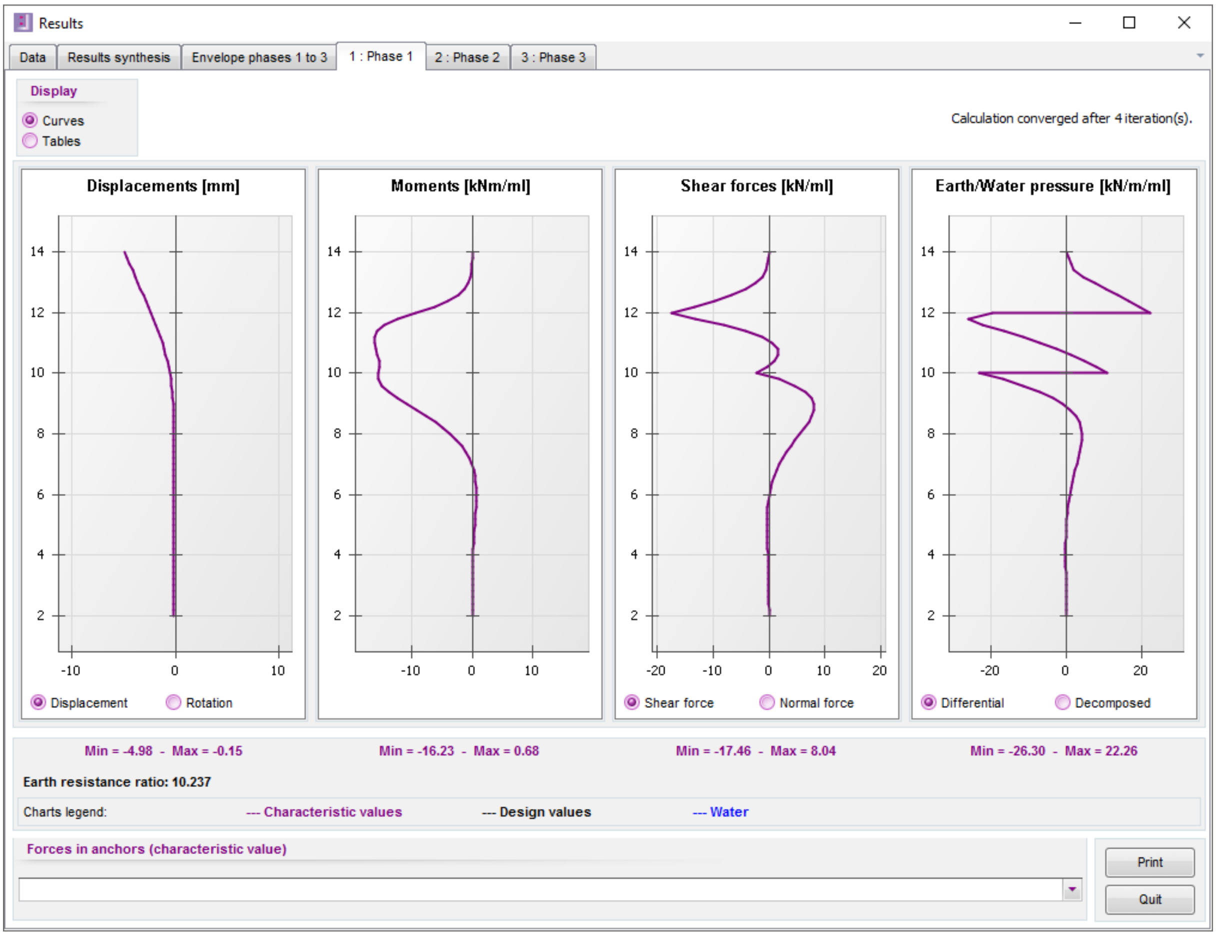
To consult all the results proposed in K-Réa in greater detail, click the following button:




Then click the “**Phase 1**” tab.

The results of phase 1 appear in graphic form.

They give the displacements, moments, shear forces and earth and water pressures ("differential” or “decomposed” pressures). The minimum and maximum values obtained are shown below each curve.

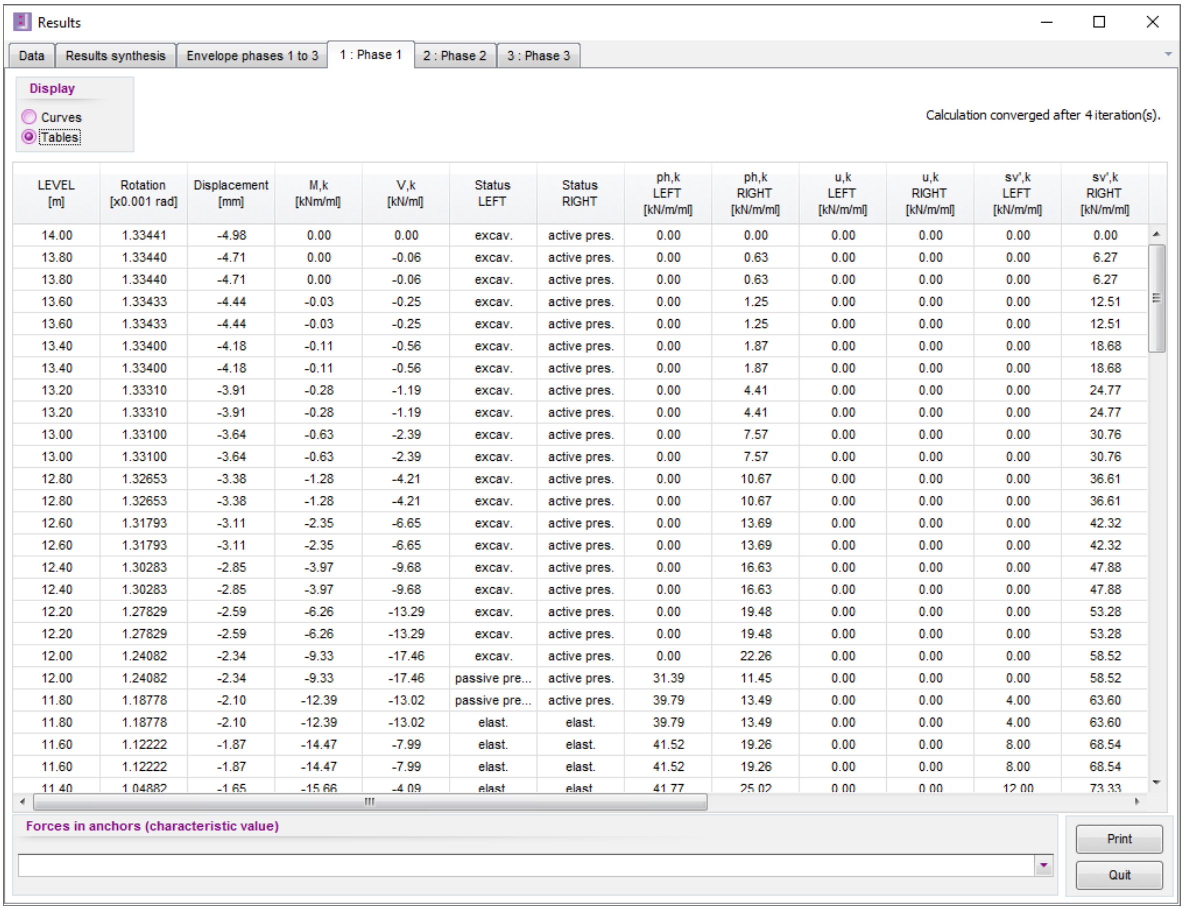


The shape of the curve clearly corresponds to the behaviour of a cantilever wall.

The maximum displacement obtained in phase 1 is less than 1 cm. The maximum moment is 16 kN.m/ml. The maximum shear force is 17.5 kN/ml.

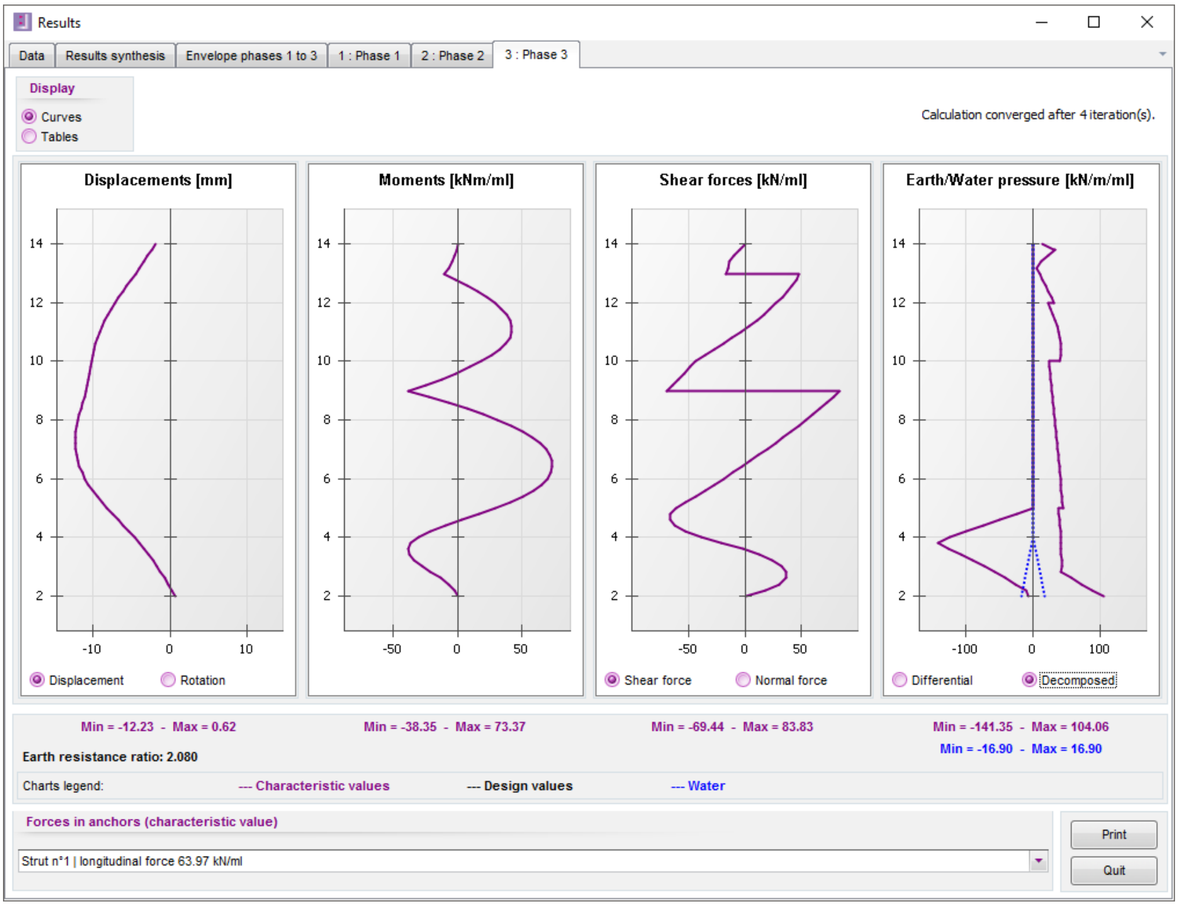
The last curve on the right shows either the differential pressure (resultant of earth and water pressures), or the separate earth and water pressure terms on either side of the wall. the screenshot illustrates the “differential” option.

It is also possible to switch to a results display in table format (at top-left of the window).




| LEVEL [m] | Rotation [x0.001 rad] | Displacement [mm] | M,k [kNm/ml] | V,k [kN/ml] | Status LEFT | Status RIGHT | ph,k LEFT [kN/m/ml] | ph,k RIGHT [kN/m/ml] | u,k LEFT [kN/m/ml] | u,k RIGHT [kN/m/ml] | sv',k LEFT [kN/m/ml] | sv',k RIGHT [kN/m/ml] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 14.00 | 1.33441 | -4.98 | 0.00 | 0.00 | excav. | active pres. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 13.80 | 1.33440 | -4.71 | 0.00 | -0.06 | excav. | active pres. | 0.00 | 0.63 | 0.00 | 0.00 | 0.00 | 6.27 |
| 13.80 | 1.33440 | -4.71 | 0.00 | -0.06 | excav. | active pres. | 0.00 | 0.63 | 0.00 | 0.00 | 0.00 | 6.27 |
| 13.60 | 1.33433 | -4.44 | -0.03 | -0.25 | excav. | active pres. | 0.00 | 1.25 | 0.00 | 0.00 | 0.00 | 12.51 |
| 13.60 | 1.33433 | -4.44 | -0.03 | -0.25 | excav. | active pres. | 0.00 | 1.25 | 0.00 | 0.00 | 0.00 | 12.51 |
| 13.40 | 1.33400 | -4.18 | -0.11 | -0.56 | excav. | active pres. | 0.00 | 1.87 | 0.00 | 0.00 | 0.00 | 18.68 |
| 13.40 | 1.33400 | -4.18 | -0.11 | -0.56 | excav. | active pres. | 0.00 | 1.87 | 0.00 | 0.00 | 0.00 | 18.68 |
| 13.20 | 1.33310 | -3.91 | -0.28 | -1.19 | excav. | active pres. | 0.00 | 4.41 | 0.00 | 0.00 | 0.00 | 24.77 |
| 13.20 | 1.33310 | -3.91 | -0.28 | -1.19 | excav. | active pres. | 0.00 | 4.41 | 0.00 | 0.00 | 0.00 | 24.77 |
| 13.00 | 1.33100 | -3.64 | -0.63 | -2.39 | excav. | active pres. | 0.00 | 7.57 | 0.00 | 0.00 | 0.00 | 30.76 |
| 13.00 | 1.33100 | -3.64 | -0.63 | -2.39 | excav. | active pres. | 0.00 | 7.57 | 0.00 | 0.00 | 0.00 | 30.76 |
| 12.80 | 1.32653 | -3.38 | -1.28 | -4.21 | excav. | active pres. | 0.00 | 10.67 | 0.00 | 0.00 | 0.00 | 36.61 |
| 12.80 | 1.32653 | -3.38 | -1.28 | -4.21 | excav. | active pres. | 0.00 | 10.67 | 0.00 | 0.00 | 0.00 | 36.61 |
| 12.60 | 1.31793 | -3.11 | -2.35 | -6.65 | excav. | active pres. | 0.00 | 13.69 | 0.00 | 0.00 | 0.00 | 42.32 |
| 12.60 | 1.31793 | -3.11 | -2.35 | -6.65 | excav. | active pres. | 0.00 | 13.69 | 0.00 | 0.00 | 0.00 | 42.32 |
| 12.40 | 1.30283 | -2.85 | -3.97 | -9.68 | excav. | active pres. | 0.00 | 16.63 | 0.00 | 0.00 | 0.00 | 47.88 |
| 12.40 | 1.30283 | -2.85 | -3.97 | -9.68 | excav. | active pres. | 0.00 | 16.63 | 0.00 | 0.00 | 0.00 | 47.88 |
| 12.20 | 1.27829 | -2.59 | -6.26 | -13.29 | excav. | active pres. | 0.00 | 19.48 | 0.00 | 0.00 | 0.00 | 53.28 |
| 12.20 | 1.27829 | -2.59 | -6.26 | -13.29 | excav. | active pres. | 0.00 | 19.48 | 0.00 | 0.00 | 0.00 | 53.28 |
| 12.00 | 1.24082 | -2.34 | -9.33 | -17.46 | excav. | active pres. | 0.00 | 22.26 | 0.00 | 0.00 | 0.00 | 58.52 |
| 12.00 | 1.24082 | -2.34 | -9.33 | -17.46 | passive pre... | active pres. | 31.39 | 11.45 | 0.00 | 0.00 | 0.00 | 58.52 |
| 11.80 | 1.18778 | -2.10 | -12.39 | -13.02 | passive pre... | active pres. | 39.79 | 13.49 | 0.00 | 0.00 | 4.00 | 63.60 |
| 11.80 | 1.18778 | -2.10 | -12.39 | -13.02 | elast. | elast. | 39.79 | 13.49 | 0.00 | 0.00 | 4.00 | 63.60 |
| 11.60 | 1.12222 | -1.87 | -14.47 | -7.99 | elast. | elast. | 41.52 | 19.26 | 0.00 | 0.00 | 8.00 | 68.54 |
| 11.60 | 1.12222 | -1.87 | -14.47 | -7.99 | elast. | elast. | 41.52 | 19.26 | 0.00 | 0.00 | 8.00 | 68.54 |
| 11.40 | 1.04882 | -1.65 | -15.66 | -4.09 | elast. | elast. | 41.77 | 25.02 | 0.00 | 0.00 | 12.00 | 73.33 |

Then click the "**Phase 3**" tab to view the results of the last phase.




The maximum displacement obtained in phase 3 is about 1 cm.

The maximum moment is 73 kN.m/ml, i.e. 73 kN.m/ml x 2.2 m = 160.6 kN.m per steel section, corresponding to a stress of 67 MPa.

## Forces taken up by the struts

The maximum axial forces taken up by the struts reach 75 kN/ml for the upper layer in phase 2 and 153 kN/ml for the lower layer in phase 3: they can both be found on the shear forces curve (peaks at levels +173.0 m and +169.0 m).

The maximum axial force on the upper layer is obtained in phase 2, at about 75 kN/ml, i.e. a force per strut of 75 kN/ml x 4.4 m = 330 kN/strut.

The maximum axial force on the lower layer is obtained in phase 3, at about 153 kN/ml, i.e. a force per strut of 153 kN/ml x 4.4 m ≈ 673 kN/strut.

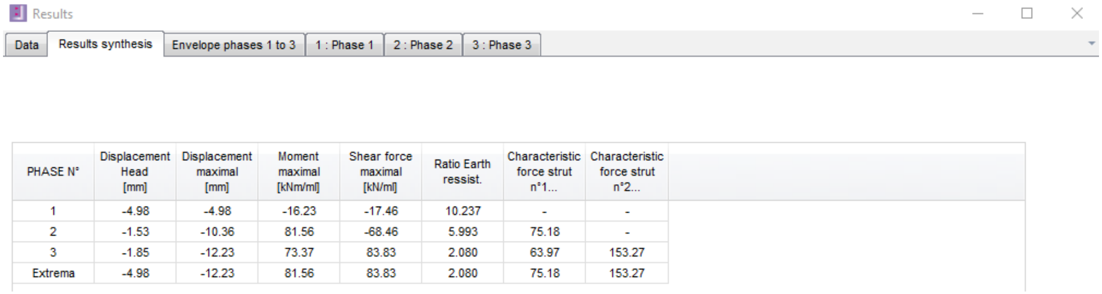
These forces are acceptable given the compression and buckling resistance.

## Passive earth pressure ratio

The passive earth pressure ratio remains greater than 2, which is usually acceptable for this type of structure.

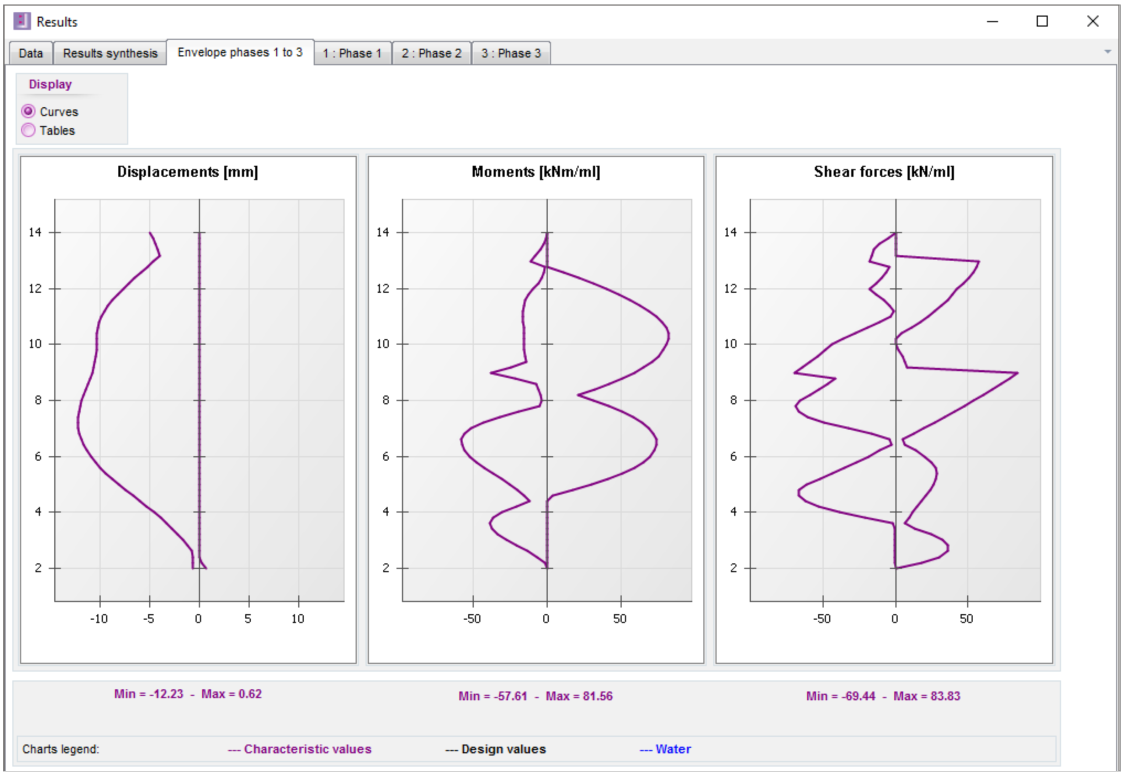
2 additional tabs can then be used to access summary results:

- **Results synthesis**: this screen gives the main results obtained for each phase and the extreme values obtained for the entire phasing, in table format. This table gives a rapid overview of the maximum values of displacements, moments, forces in the anchors, etc., but can also be used to easily check in which phase(s) the various extreme values are reached.




| PHASE N° | Displacement Head [mm] | Displacement maximal [mm] | Moment maximal [kNm/ml] | Shear force maximal [kN/ml] | Ratio Earth ressist. | Characteristic force strut n°1... | Characteristic force strut n°2... |
|---|---|---|---|---|---|---|---|
| 1 | -4.98 | -4.98 | -16.23 | -17.46 | 10.237 | - | - |
| 2 | -1.53 | -10.36 | 81.56 | -68.46 | 5.993 | 75.18 | - |
| 3 | -1.85 | -12.23 | 73.37 | 83.83 | 2.080 | 63.97 | 153.27 |
| Extrema | -4.98 | -12.23 | 81.56 | 83.83 | 2.080 | 75.18 | 153.27 |

- **Envelope phases 1 to 3**: this screen (with display either in curve or table format) shows the envelope curves for displacements, moments and shear forces. In our example, we submitted no particular request and the envelope curves presented were thus calculated for the entire phasing (phases 1 to 3).



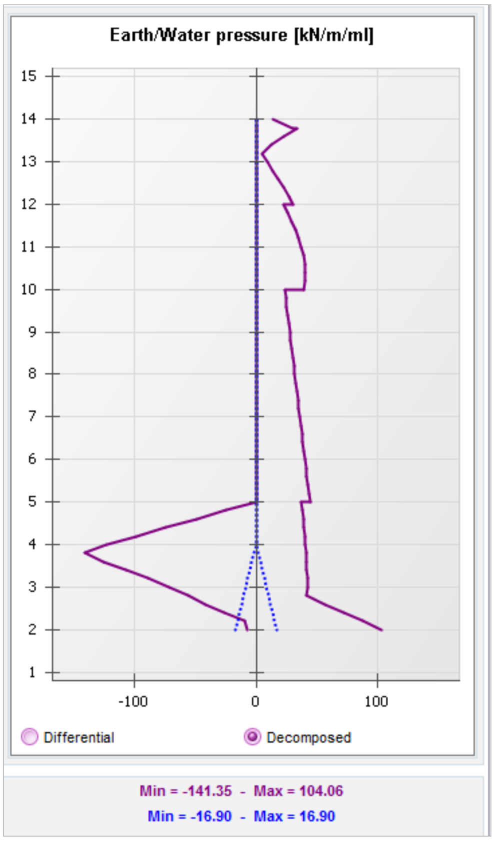
## D.1.4. Appendix: Processing of $p_{max}$

In the case of a composite wall, the limit passive earth pressure is bounded at $p_{max}$ per element, or R x $p_{max}$ for an equivalent continuous wall.

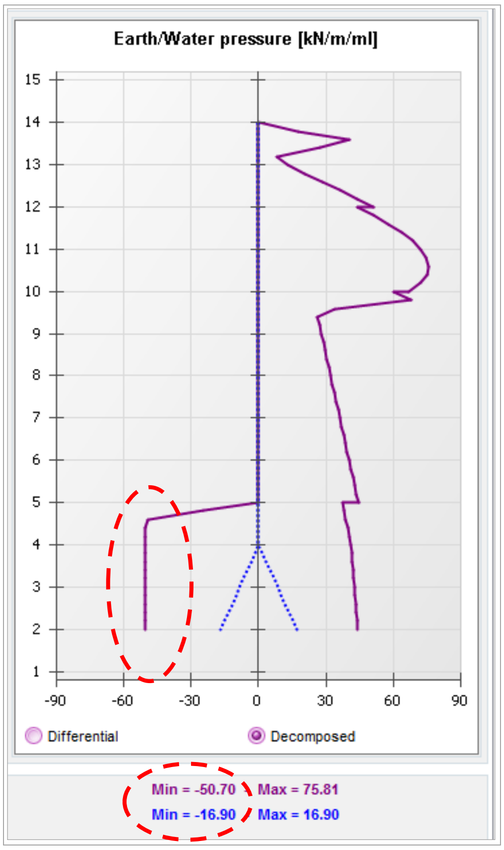
$p_{max}$ corresponds to the soil limit pressure (ULS case) or the creep pressure (SLS case).

We will intentionally reduce the value of $p_{max}$ for the Sands layer (where the passive earth pressure develops) in order to illustrate the capping of the passive earth pressure at R x $p_{max}$.

We thus define a value of $p_{max}$ = 60 kPa for the Sands layer in the **Soil layers** window accessible in the **Data** menu.




*Pressure profile before reduction of $p_{max}$*



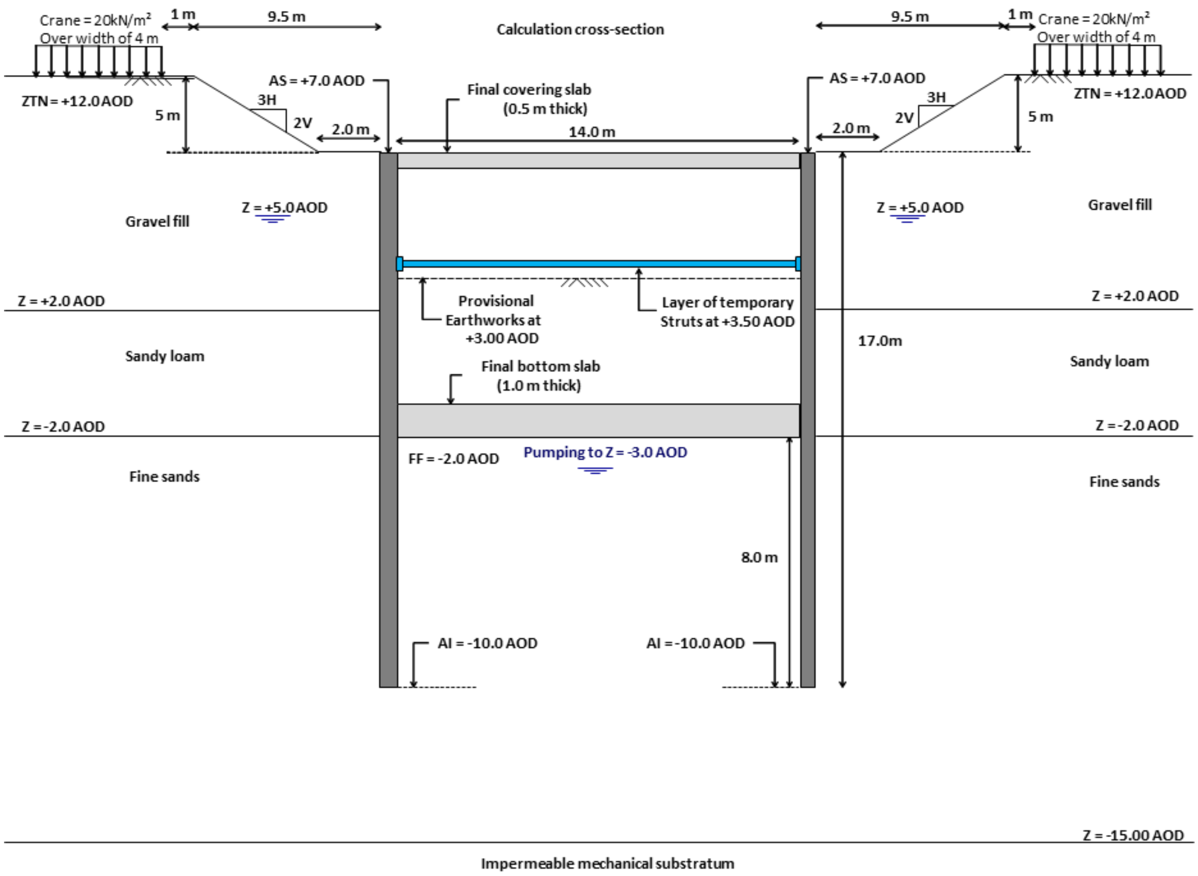

*Pressure profile after reduction of $p_{max}$*

We observe that the mobilised passive earth pressure was indeed capped at:

$$R \times p_{max} = 0.845 \times 60 \text{ kN/m}^2 = 50.7 \text{ kN/m/ml}$$

# D.2. Tutorial 2: Excavation with struts and drawdown of water level

The example studied is that of an excavation with struts consisting of two parallel diaphragm walls joined by 1 layer of temporary struts in the transitory phase and 2 concrete slabs in the final phase.




The GL level is initially at +12.0 AOD.

We will proceed with several steps in order to assess the effect of the hydraulic gradient and that of the symmetry/asymmetry of the model.

- **Step 1**: Case of a perfectly symmetric cross-section without gradient;
- **Step 2**: With gradient related to drawdown of water level;
- **Step 3:** Switch to a double-wall calculation;
- **Step 4:** Asymmetric cross-section.

The diaphragm walls have a thickness of 82 cm and are concreted over a total height of 17m. The top level (AS) of the walls is planned at +7.0 AOD, the bottom level (AI) at -10.0 AOD.

The earthworks sequence includes an initial excavation phase prior to drilling and concreting of the diaphragm wall. This implies creating a 3H/2V bank 5 m high, the base of which is situated at 2 m from the top of the walls.

The phasing comprises 7 successive steps with installation of temporary and final anchors:

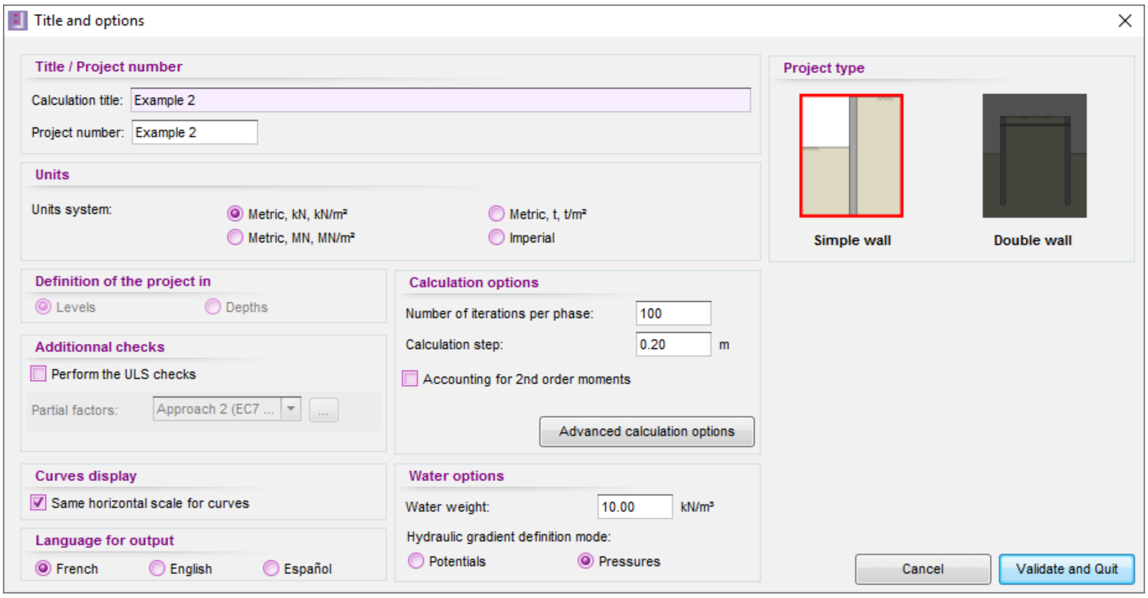
- **1 layer of temporary struts**
- **2 final anchor levels:**
    - **Covering slab**: 0.50 m thick
    - **Base slab**: 1.0 m thick

The level of the water table is at +5.0 AOD before the work starts. The level will then be systematically lowered 1 metre below the bottom of excavation level.

The concrete used will be of type C25/30. The concrete modulus is taken as equal to **20 GPa** in the transitory phases and **10 GPa** over the long-term.

## D.2.1. Step 1: Symmetric cross-section without gradient

### D.2.1.1. Project definition: Title and options



Specific parameters to be defined:

- In the **Project type** frame (right), select “Simple wall”.
- In the **Units** frame, choose the units system for your project, by ticking “Metric, kN, kN/m$^2$”.
- **Definition of the project in** “Levels”, enabling the vertical axis to be directed **upwards**.
- **Additional checks**: untick the “Perform the ULS checks” box.
- In the **Calculation options** frame, keep the default settings: 100 iterations per calculation phase and a calculation step of 0.2 m for the wall.
    - **Advanced calculation options**: Choose the bank/berm calculation method as “Simplified Method”.
- In the **Water options** frame, leave the water weight equal to 10.00 kN/m$^3$. Select “Pressures” as the hydraulic gradient definition mode (which will not affect the calculations because the project is above the water table).
- Click the [Validate and Quit] button.

### D.2.1.2. Definition of soil layers

The general characteristics of the three layers concerned by the exercise are summarised in the following table.

| Layer | $\gamma$ (kN/m$^3$) | $\gamma'$ (kN/m$^3$) | $\varphi$ (°) | c (kPa) | dc (kN/m$^2$/ml) | $\delta_a/\varphi$ (-) | $\delta_p/\varphi$ (-) | $k_h$ (kN/m$^2$/ml) |
|---|---|---|---|---|---|---|---|---|
| **Bank** | 18 | 9 | 33 | 0 | 0 | 0.667 | -0.667 | 10 000 |
| **Sandy loam** | 20 | 10 | 30 | 5 | 0 | 0.667 | -0.667 | 8 000 |
| **Fine sands** | 20 | 10 | 33 | 1 | 0 | 0.667 | -0.667 | 25 000 |

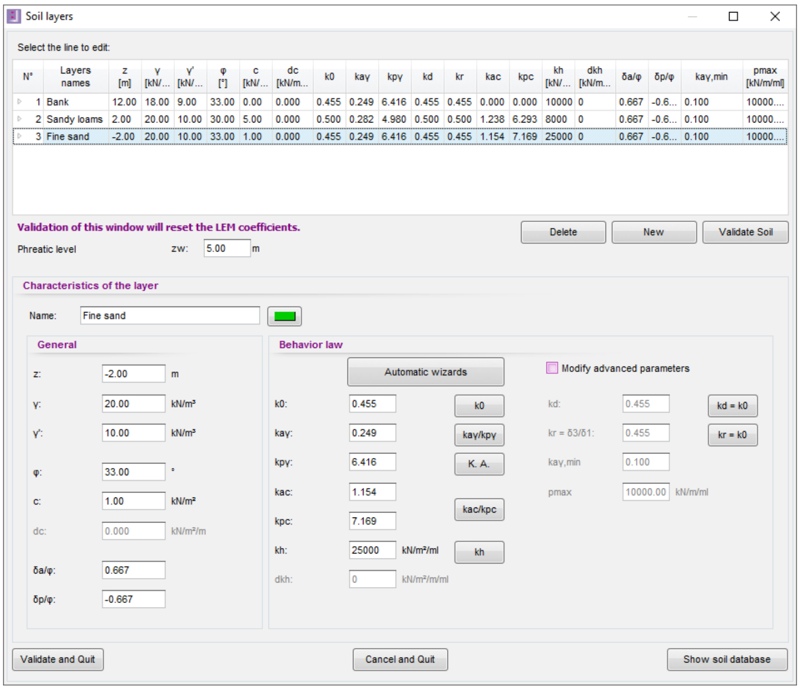
Then use the K-Réa wizards to calculate the parameters used to constitute the behaviour law for each layer.

The following parameters are obtained using the wizards.

| Layer | $k_0$ (-) | $k_{a\gamma}$ (-) | $k_{p\gamma}$ (-) | $k_{ac}$ (-) | $k_{pc}$ (-) |
|---|---|---|---|---|---|
| **Bank** | 0.455 | 0.249 | 6.416 | 0 | 0 |
| **Sandy loam** | 0.500 | 0.282 | 4.980 | 1.238 | 6.293 |
| **Fine sand** | 0.455 | 0.249 | 6.416 | 1.154 | 7.169 |

The other parameters remain at their default values. For this, leave the **Modify advanced parameters** box unticked.

The following screen is then obtained:



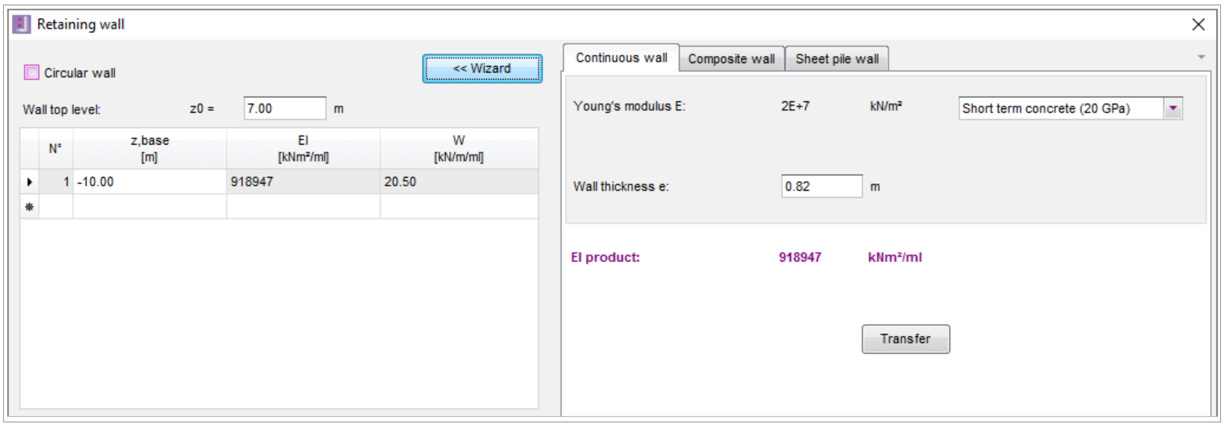

Click Validate and Quit.

### D.2.1.3. Definition of the wall

The following table specifies the characteristics of the wall.

| Section | **z0** Upper level (AOD) | **z,base** Lower level (AOD) | **E** Young's modulus (kN/m²) | **e** Thickness(m) | **EI** (kNm²/ml) | **W** (kN/m²) |
|---|---|---|---|---|---|---|
| **1** | +7.0 | -10.0 | $2 \times 10^{+7}$ | 0.82 | 918 947 | 20.5 |

The following screenshot illustrates the operations required in K-Réa.




Finally, click Validate and Quit to confirm the values input and make them appear with on graphic representation of the project initial data.

### D.2.1.4. Definition of phasing

The actions to be considered in each calculation phase must now be defined:

| PHASE | | ACTIONS |
|---|---|---|
| TRANSITORY PHASES | Initial | • Initial earthworks left of the wall in the form of a bank.<br>• Initial earthworks right of the wall at +7.0 AOD. |
| | 1 | • Earthworks right-hand side at +3.0 AOD.<br>• Drawdown water level right-hand side at +2.5 AOD.<br>• Boussinesq overload of 20 kN/m/ml at 10.5 metres behind the wall over a width of 4 metres. |
| | 2 | • Installation of a horizontal layer of struts at +3.5 AOD without pre-loading (K = 50 000 kN/m/ml)<br>• Earthworks right-hand side to bottom of excavation at -2.0 AOD.<br>• Drawdown water level right-hand side at -3.0 AOD. |
| | 3 | • Pouring of base slab concrete: we consider only its weight but not yet its stiffness.<br>• Pumping to -3.0 AOD operational until end of earthworks (safety). |
| | 4 | • Activation of base slab stiffness (ks = 2 860 000 kN/m²/ml).<br>• Pumping to -3.0 AOD still operational. |
| | 5 | • Construction of cover slab (ks = 2 860 000 kN/m²/ml)<br>• Removal of the layer of struts.<br>• Pumping to -3.0 AOD still operational. |
| SERVICE PHASES | 6 | • Start-up of the structure + Stop pumping |
| | 7 | • Concrete creep in diaphragm walls and slabs |

Comments:

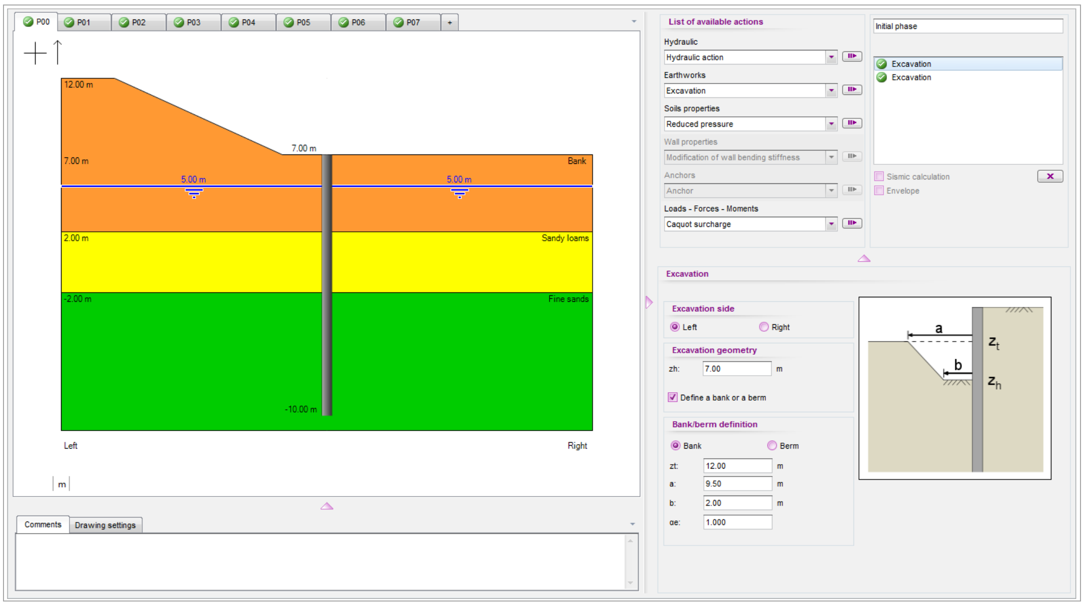
In general, the effect of a hydraulic gradient (or excess pore-pressure) must be taken into account in transitory situations, unless its effect is favourable.

In our case, stopping pumping has a favourable effect for the design of the diaphragm wall. Permanent conditions will not be reached immediately after pouring of the base slab (actual end of pumping), which is why we continue to simulate the presence of the gradient until the end of the earthworks (conservative approach).

### D.2.1.4.1. Initial phase

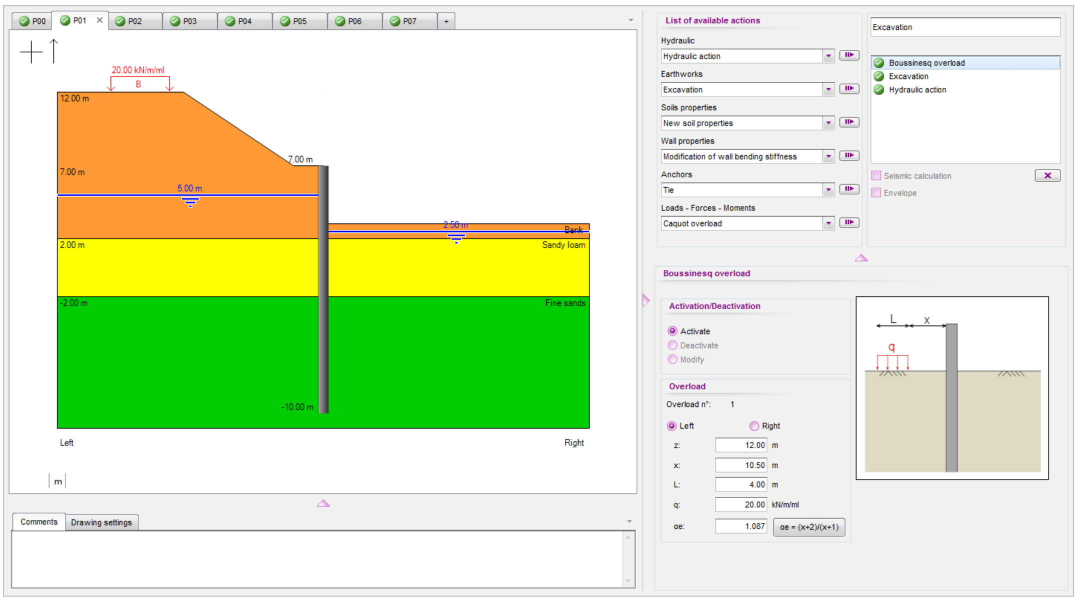
The initial soil is assumed to be horizontal to the right of the wall. However a bank is defined to the left of the wall.

- "Excavation" action on the left of "Bank" type:
  - $z_h$ = +7.0 AOD $z_t$ = +12.0 AOD
  - a = 9.5 m b = 2.0 m $\alpha_e$ = 1.0
- "Excavation" action on the right: $z_h$ =+7.0 AOD



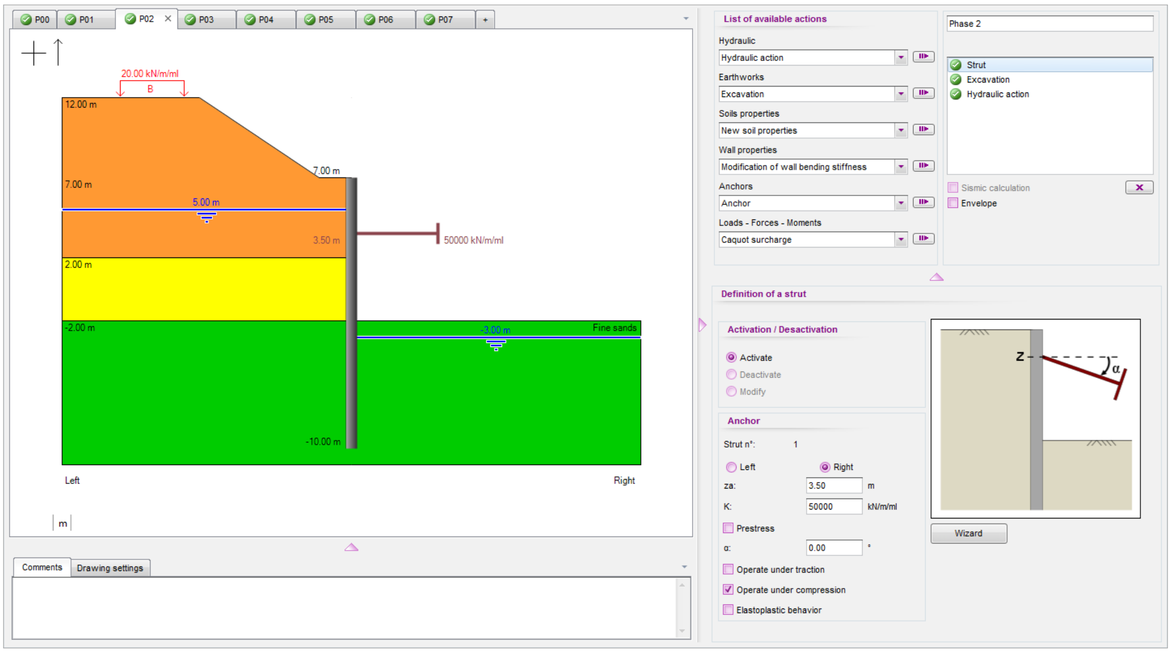
### D.2.1.4.2. Phase 1: Excavation

- "Excavation" action on the right: $z_h$ = +3.0 AOD
- "Hydraulic action" on the right: $z_w$ = +2.5 AOD
- "Boussinesq overload" action on the left (crane overload):
  - z = +12.0 AOD x = 10.50 m
  - L = 4.0 m q = 20 kN/m/ml $\alpha_e$ = 1.087



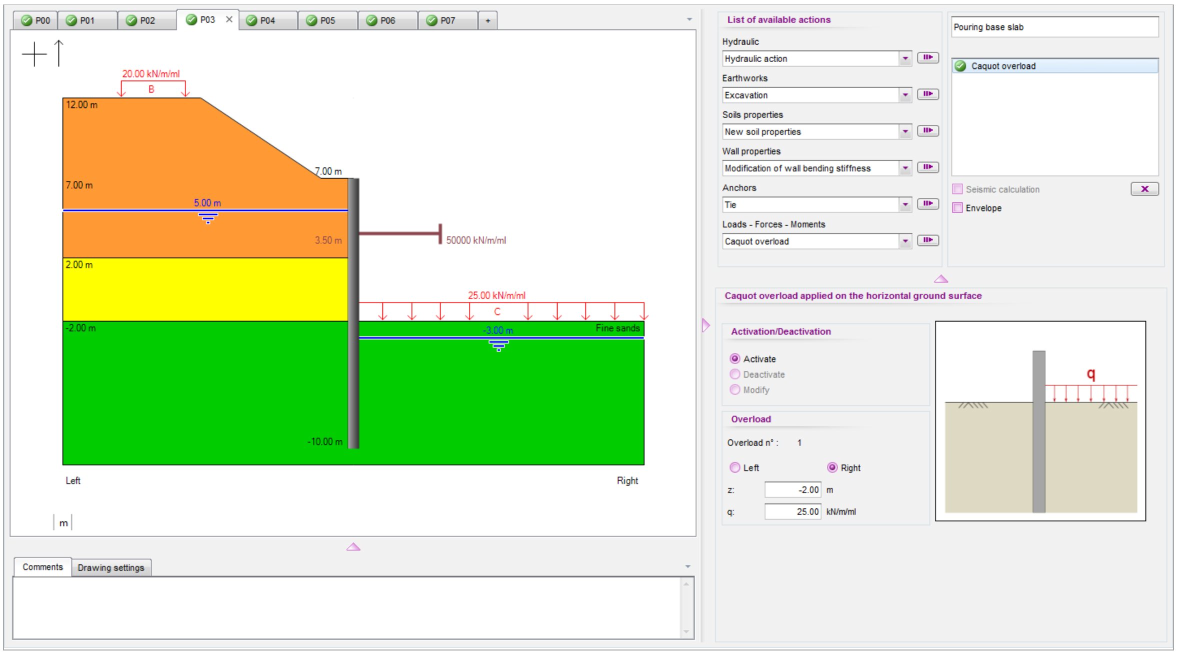
### D.2.1.4.3. Phase 2: Installing layer of struts + Excavation

- "Strut" action on the right with:
  - $z_a$ = +3.50 AOD K = 50 000 kN/m/ml
  - P = 0 kN/ml α = 0°
- "Excavation" action on the right: $z_h$ = -2.0 AOD
- "Hydraulic action" on the right: $z_w$ = -3.0 AOD



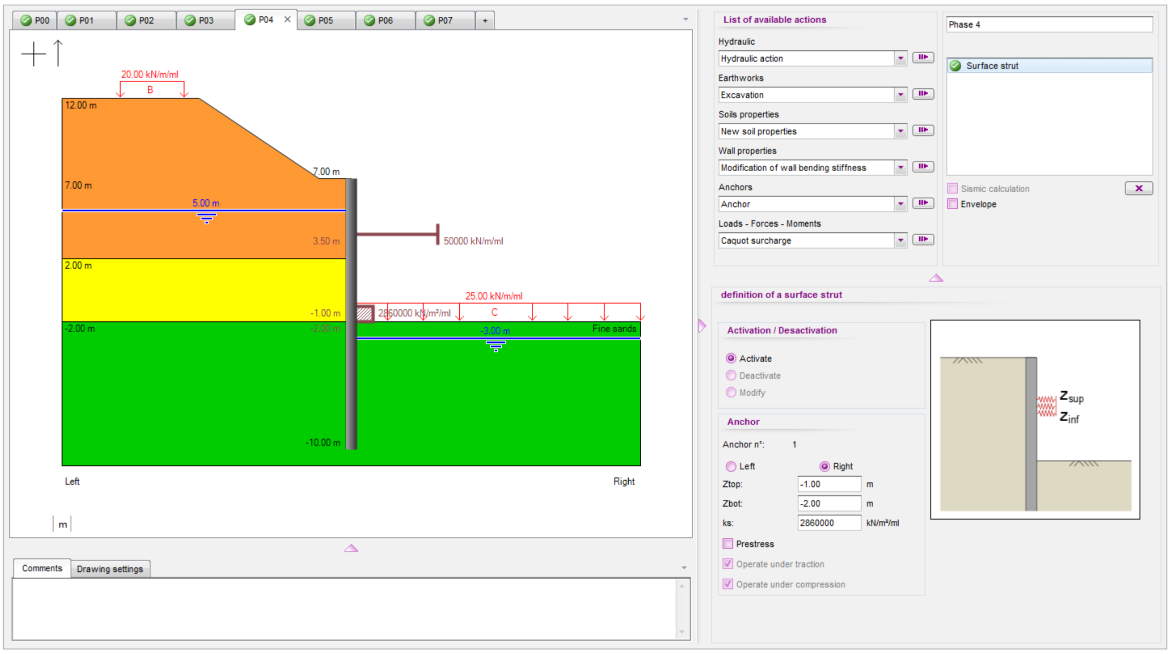
### D.2.1.4.4. Phase 3: Pouring base slab

- "Caquot overload" action on the right:
  - z = -2.0 AOD q = 25 kN/m/ml



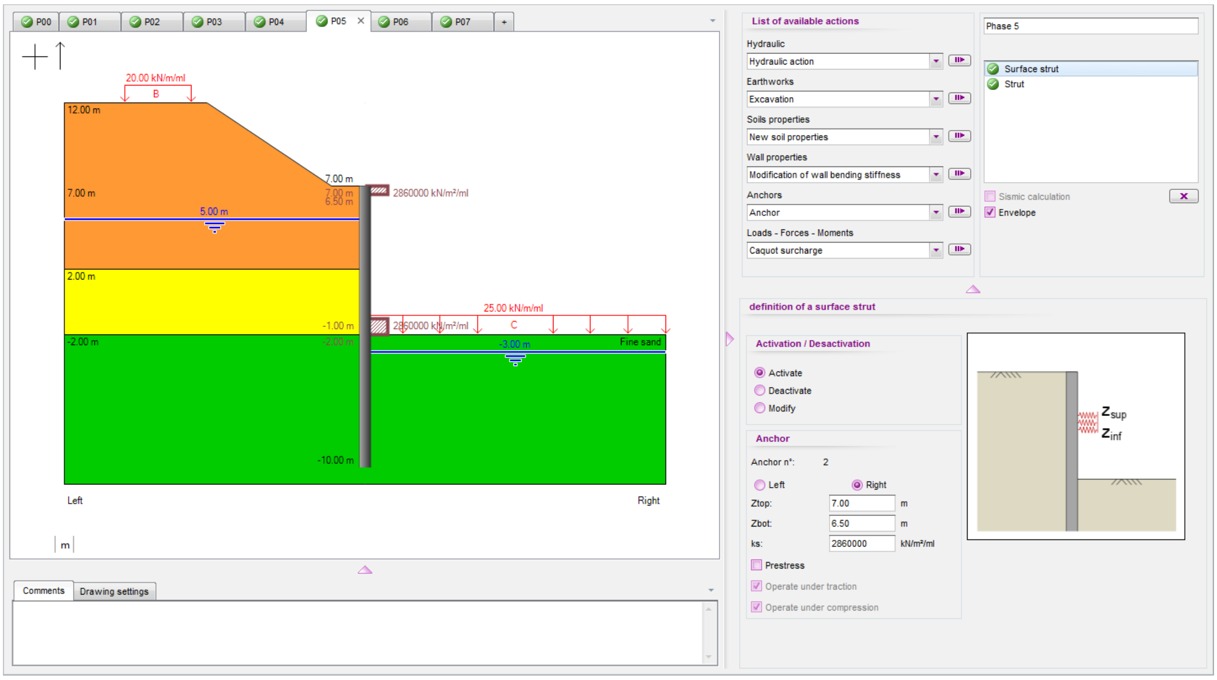
### D.2.1.4.5. Phase 4: Base slab setting

- "Surface strut" (base slab) action on the right:
  - $z_{sup}$ = -1.0 AOD  $z_{inf}$ = -2.0 AOD
  - ks = 2 860 000 kN/m²/ml  $p_s$ = 0 kN/m/ml




### D.2.1.4.6. Phase 5: Removal of the layer of struts + construction of cover slab

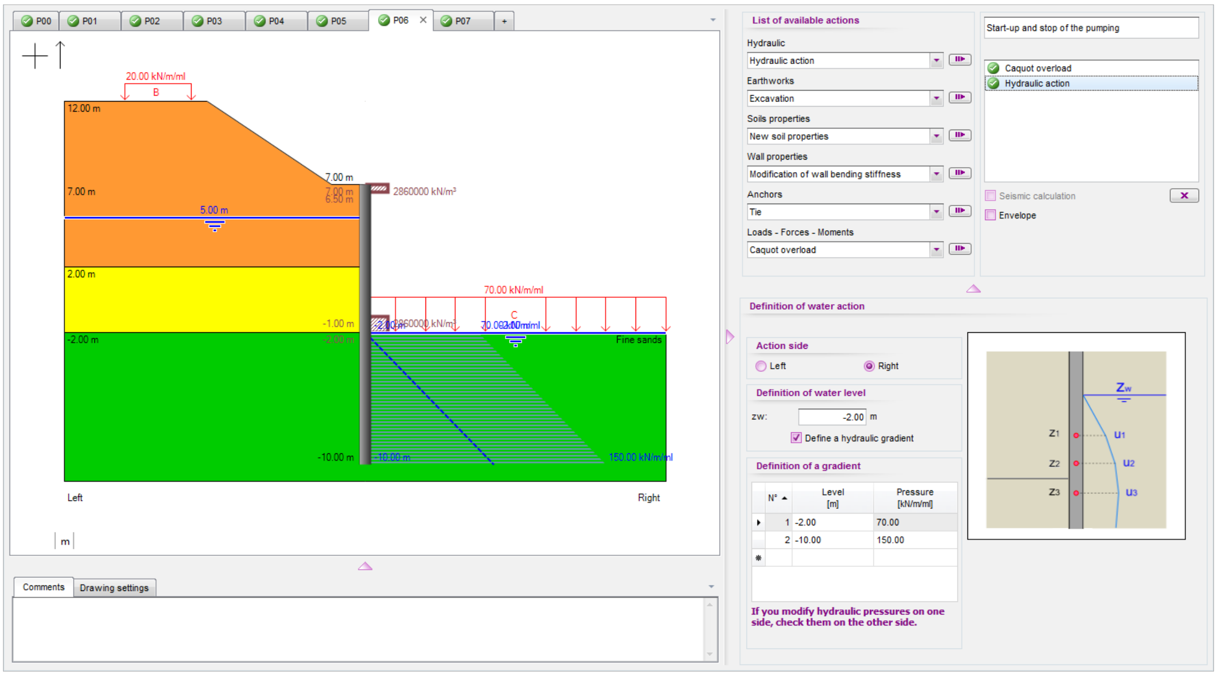
- "Surface strut" (cover slab) action on the right:
  - $z_{sup}$ = +7.0 AOD  $z_{inf}$ = +6.50 AOD
  - ks = 2 860 000 kN/m²/ml  $p_s$ = 0 kN/m/ml
- "Strut" action: deactivate the layer of struts



### D.2.1.4.7. Phase 6: Start-up of the structure and stop of the pumping

- "Caquot overload" action:
  - Modify overload n°1 (Phase 3) q = 70 kN/m/ml
- "Hydraulic action" to the right with a hydraulic gradient:
  - $z_w$ = -2.0 AOD
  - Tick "Definition of a gradient"

| Level (m) | Pressure (kN/m/ml) |
|---|---|
| -2 | 70.0 |
| -10 | 150.0 |



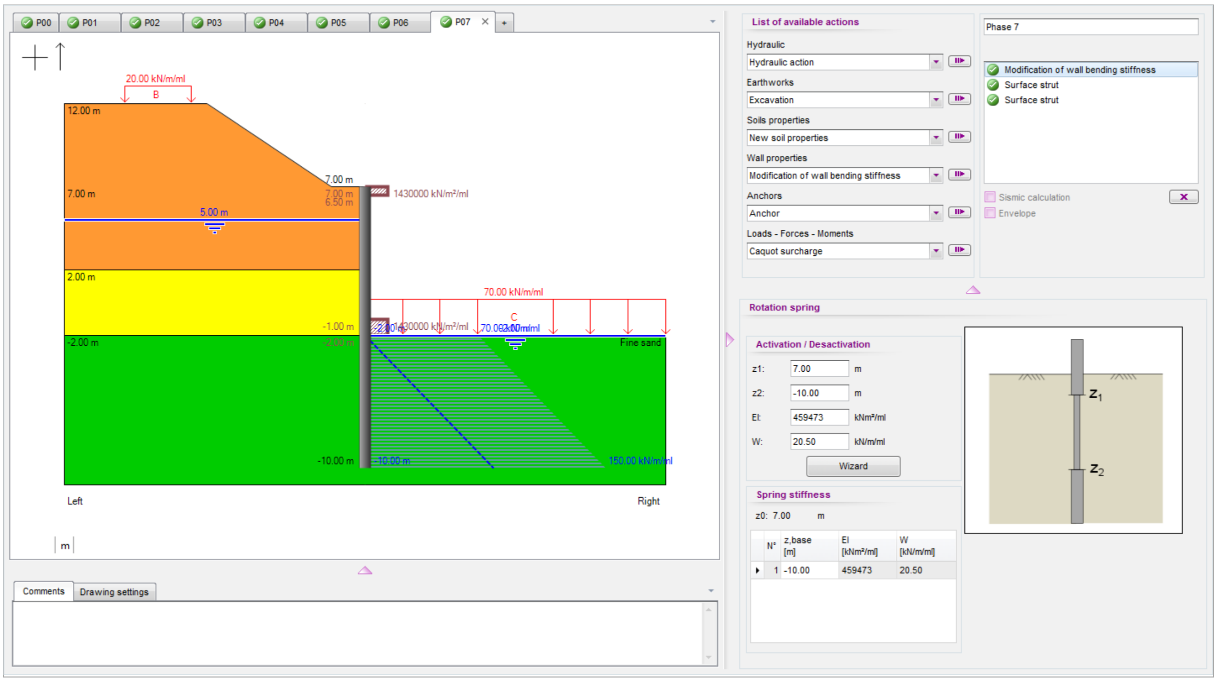
### D.2.1.4.8. Phase 7: Creep

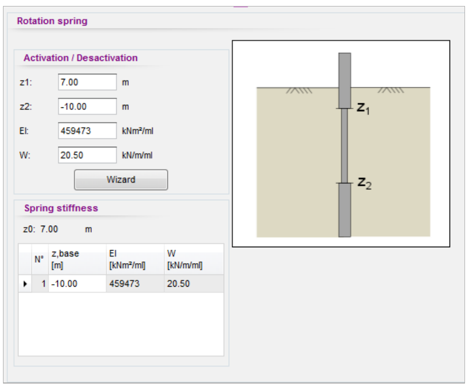
- “Modification of wall bending stiffness” action:
  - $z_1$ = +7.0 m $z_2$ = -10.0 m
  - EI = 459 473 kNm²/ml W = 20.5 kN/m/ml

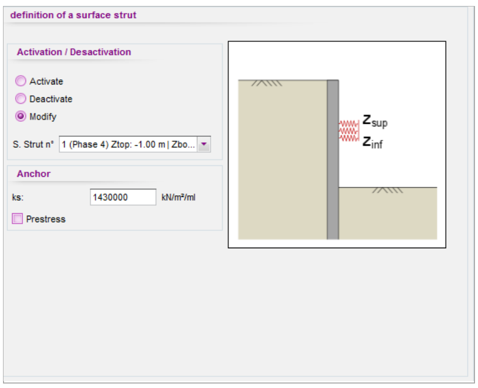
  With the wizard:
  - Young’s modulus = 10 GPa = 1 x 10$^{+7}$ kN/m²
  - Thickness = 0.82 m

- “Surface strut” action:
  - Modify surface strut n°1 ks = 1 430 000 kN/m²/ml

- “Surface strut” action:
  - Modify surface strut n°2 ks = 1 430 000 kN/m²/ml




<u>Activate calculation of forces envelope</u> by ticking the **“Envelope”** check box in **Phase 5**.

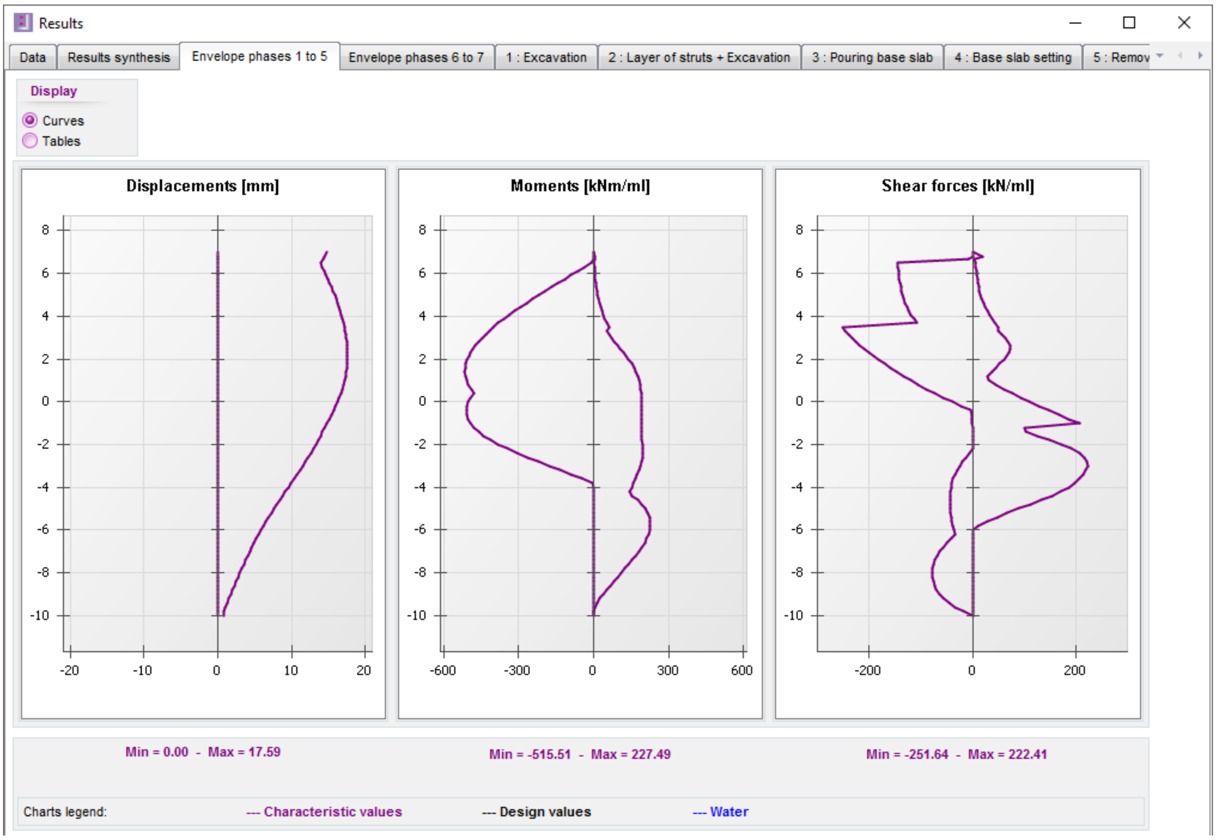
Save your project.

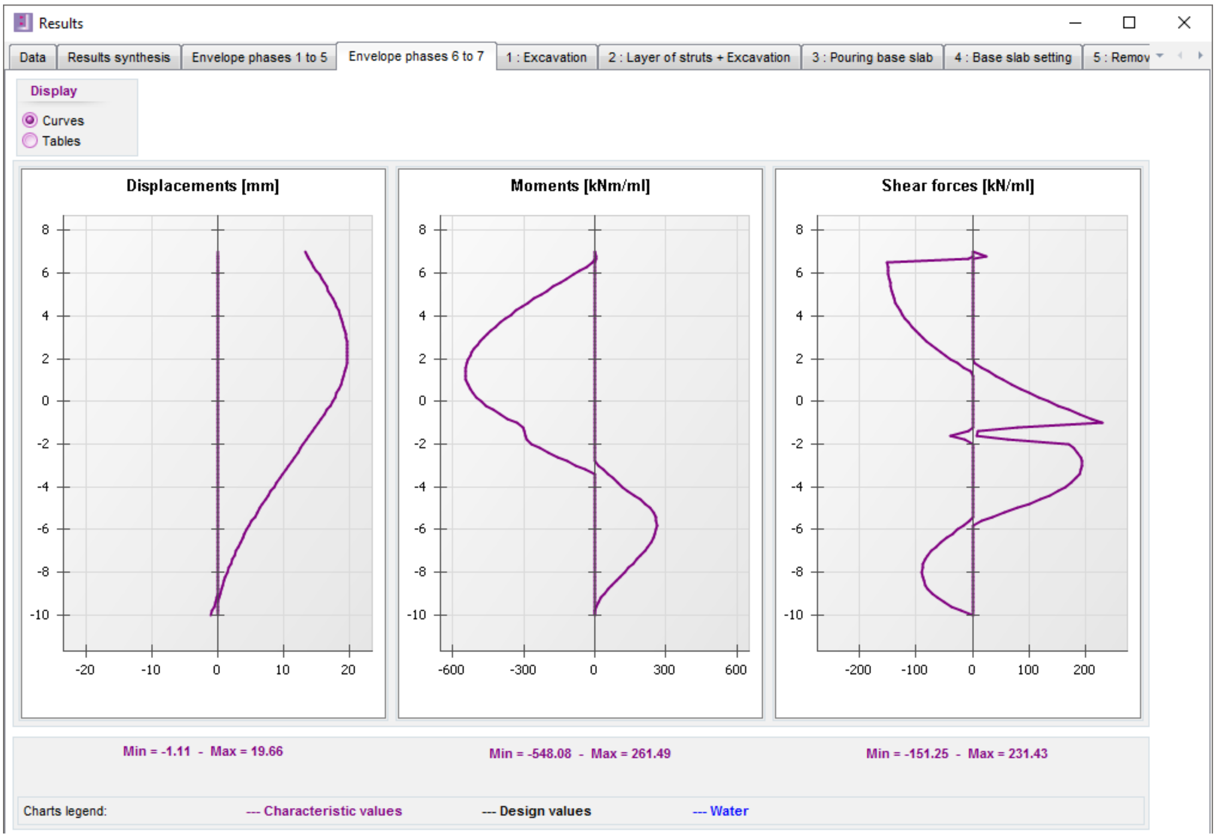
### D.2.1.5. Calculation and results

Start the calculation by clicking the **Calculate** button.

The results are now available and can be accessed with the **Results** button.

| PHASE N° | Displacement Head [mm] | Displacement maximal [mm] | Moment maximal [kNm/ml] | Shear force maximal [kN/ml] | Ratio Earth ressist. | Characteristic force strut n°1 [kN/ml] | Characteristic force strut n°1 [kN/ml] | Characteristic force strut n°2 [kN/ml] |
|---|---|---|---|---|---|---|---|---|
| 1 | 14.78 | 14.78 | 196.46 | 71.93 | 4.536 | - | - | - |
| 2 | 13.31 | 15.78 | -509.84 | -251.37 | 2.009 | 300.73 | - | - |
| 3 | 13.39 | 15.71 | -509.88 | -251.64 | 2.898 | 300.53 | - | - |
| 4 | 13.39 | 15.71 | -509.88 | -251.64 | 2.898 | 300.53 | 0.00 | - |
| 5 | 13.27 | 17.59 | -515.51 | 207.25 | 2.968 | - | 210.63 | 149.46 |
| 6 | 13.26 | 17.81 | -548.08 | 200.78 | 2.307 | - | 143.54 | 155.90 |
| 7 | 13.16 | 19.66 | -394.97 | 231.43 | 2.453 | - | 282.94 | 124.93 |
| Extrema | 14.78 | 19.66 | -548.08 | -251.64 | 2.009 | 300.73 | 282.94 | 155.90 |






During this first step, we obtain the following "envelope" results:

| | Transitory Phases | Final Phases |
|---|---|---|
| | *Ph. 1 to 5* | *Ph. 6 and 7* |
| **Displacement** | 1.7 cm | 1.9 cm |
| **Bending moment** | 520 kN.m/ml | 540 kN.m/ml |
| **Shear force** | 250 kN/ml | 230 kN/ml |
| **Passive earth pressures ratio** | 2.0 | 2.3 |

## D.2.2. Step 2: Taking account of hydraulic gradient

In this 2nd step, we model the hydraulic gradient generated by drawdown of the water table in each calculation phase.

Click the "**File**" menu and select **"Save as…".**

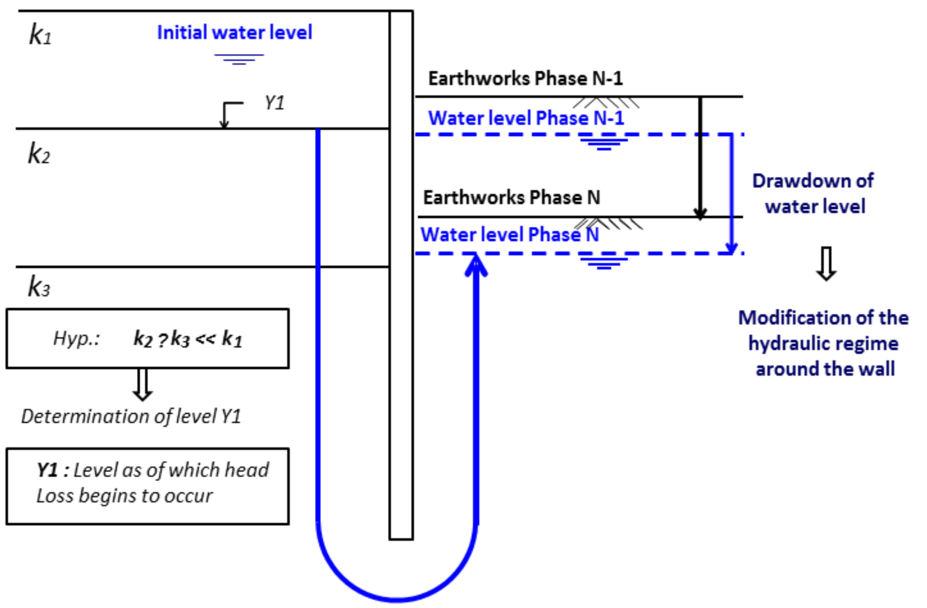
For example, name the file in the following way: "Example 2 – Step 2".

### D.2.2.1. About the hydraulic gradient

#### D.2.2.1.1. Theory reminder

Drawdown of the water level is accompanied by the development of a flow field around the wall base, which aims to restore the continuity of the hydraulic head between the two sides of the wall. Along a "stream" line, the hydraulic head varies continuously between that corresponding to the initial water level (soil side) and that corresponding to the imposed level at the bottom of the excavation.

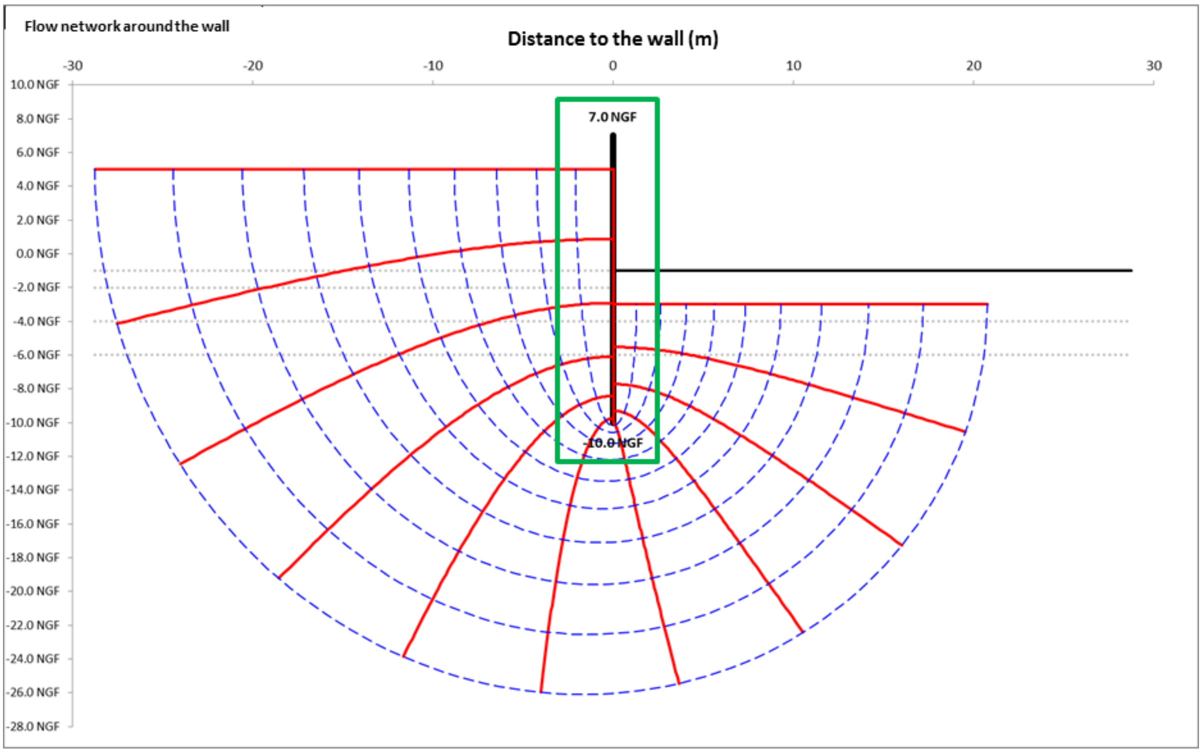
In the case of this exercise, we assume that the permeability levels of the fine sands and loam ($k_2$ and $k_3$) are comparable. The permeability of the bank ($k_1$) is assumed to be high by comparison with $k_2$ and $k_3$. The bank thus acts as an "open" horizon. The flow regime thus develops from the base of the bank (+2.00 AOD) as shown in the following figure.




The following figure illustrates the flow field which develops in the soil in the case of a homogeneous soil. This is characterised by:

- **Equipotential lines** (continuous curves): set of points in the medium with the same potential.
- **Streamlines** (dotted curves): trajectories of water particles subject to flow forces.

In the case of a wall calculation based on the reaction coefficients model, processing of the flow regime is limited to taking account of the pore pressure field located in the following rectangle.




By comparison with the hydrostatic regime in which all the points (on the same side of the wall) are associated with the same hydraulic head (corresponding to the top of the water table on the side concerned), the development of the flow regime leads to a hydraulic head that varies with depth on each side of the wall.

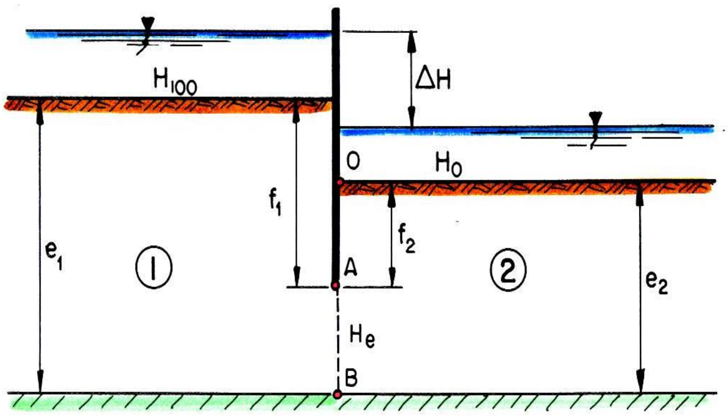
The pore pressure at a given point is linked to the hydraulic head by means of the following relation:

$$u_A = (h_A - z_A) \cdot \gamma_w$$

Where $\gamma_w$ is the specific weight of water.

### D.2.2.1.2. Calculation of hydraulic gradient

The hypothesis $k_2 \sim k_3$ compares the soil in which the flow regime is developing to a homogeneous single layer resting on a watertight base. This enables the Mandel model to be applied for estimation of the hydraulic head at the foot of the wall $H_A$.




- $H_{100}$ hydraulic head on soil side (corresponding to initial water table level)
- $H_0$ hydraulic head on excavation side
- $\Delta H$ total head loss
- $e_1$ total thickness of ground on soil side down to top of watertight base
- $f_1$ thickness of ground on soil side down to the base of the wall
- $e_2$ total thickness of ground on excavation side down to the top of the watertight base
- $f_2$ thickness of ground land on excavation side down to the base of the wall
- $H_A$ hydraulic head at base of wall

Where the “ground” refers to the medium in which the flow develops (in our case, the loam + dense sands assembly).

The hydraulic head at the base of the wall is estimated using the relation:

$$H_A = H_0 + \frac{\rho_2}{\rho_1 + \rho_2}(H_{100} - H_0)$$

With :

- $\rho_i = \pi / \left(2 \cdot ln\left\{2 \cdot cotg(\frac{\pi}{4} \cdot \frac{f_i}{e_i}\right\}\right)$ for $\frac{f_i}{e_i} \leq 0.5$
- $\rho_i = \frac{2}{\pi} ln\left\{2 \cdot cotg(\frac{\pi}{4} \cdot \left(1 - \frac{f_i}{e_i}\right)\right\}$ for $\frac{f_i}{e_i} > 0.5$

<u>Application to the project studied – case of phase 3</u>

- $H_{100}$ = +5.0 m (level of water table on left-hand side)
- $H_0$ = -3.0 m (level of drawdown on excavation side)
- $\Delta H$ = +5.0 – (-3.0) = 8 m
- $f_1$ = +2.0 – (-10.0) = 12 m
- $e_1$ = +2.0 – (-15.0) = 17 m
- $f_2$ = -3.0 – (-10.0) = 7 m
- $e_2$ = -3.0 – (-15.0) = 12 m

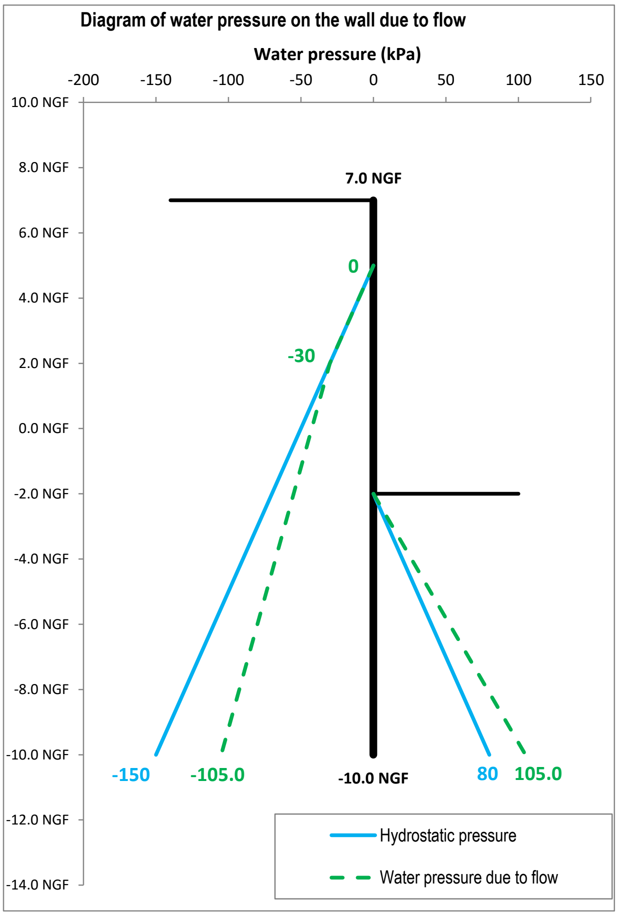
$$\frac{f_1}{e_1} = \frac{12}{17} = 0.706 > 0.5 \quad \rightarrow \quad \rho_1 = \frac{2}{\pi} ln\left\{2 \cdot cotg(\frac{\pi}{4} \cdot \left(1 - \frac{f_1}{e_1}\right)\right\} \approx 1.4$$
$$\frac{f_2}{e_2} = \frac{7}{12} = 0.583 > 0.5 \quad \rightarrow \quad \rho_2 = \frac{2}{\pi} ln\left\{2 \cdot cotg(\frac{\pi}{4} \cdot \left(1 - \frac{f_1}{e_1}\right)\right\} \approx 1.1$$

$$\boldsymbol{H_A} = H_0 + \frac{\rho_2}{\rho_1 + \rho_2}(H_{100} - H_0) = -3 + \frac{1.1}{1.4 + 1.1}\left(5 - (-3)\right) \approx \boldsymbol{+0.5m}$$

The pore pressure at the base of the wall will be:

$$\boldsymbol{u_A} = (H_A - z_A) \cdot \gamma_w = \left(0.5 - (-10.0)\right) \cdot 10\ kN/m^3 = 105\ kPa \approx \boldsymbol{105\ kPa}$$

The following figure presents the “average” profile of the pore pressures on each side of the wall, superposed over that of the hydrostatic regime.



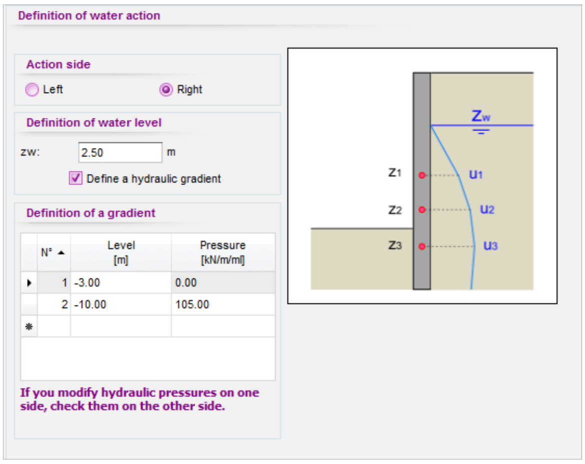

Note 1: It should be noted that in the absence of a watertight base, application of the Mandel model leads to $H_A = (H_{100}+H_0) / 2 = 1.00$ m and $u_A = 110$ kPa.

Note 2: In practice, a hydrostatic regime is considered on the soil side, even in the presence of a flow regime (conservative approach).

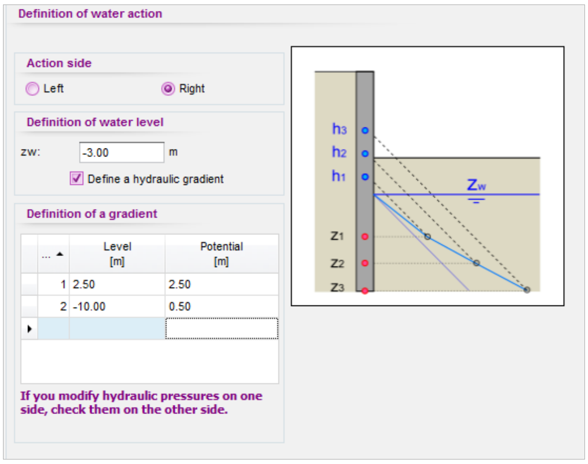
### D.2.2.1.3. Definition of hydraulic gradient with K-Réa

The hydraulic gradient can be modelled in K-Réa in two ways:

- **Option 1**: definition of a pressure profile (z, u(z));




- **Option 2**: definition of a hydraulic potential (or head) profile (u, h(z))



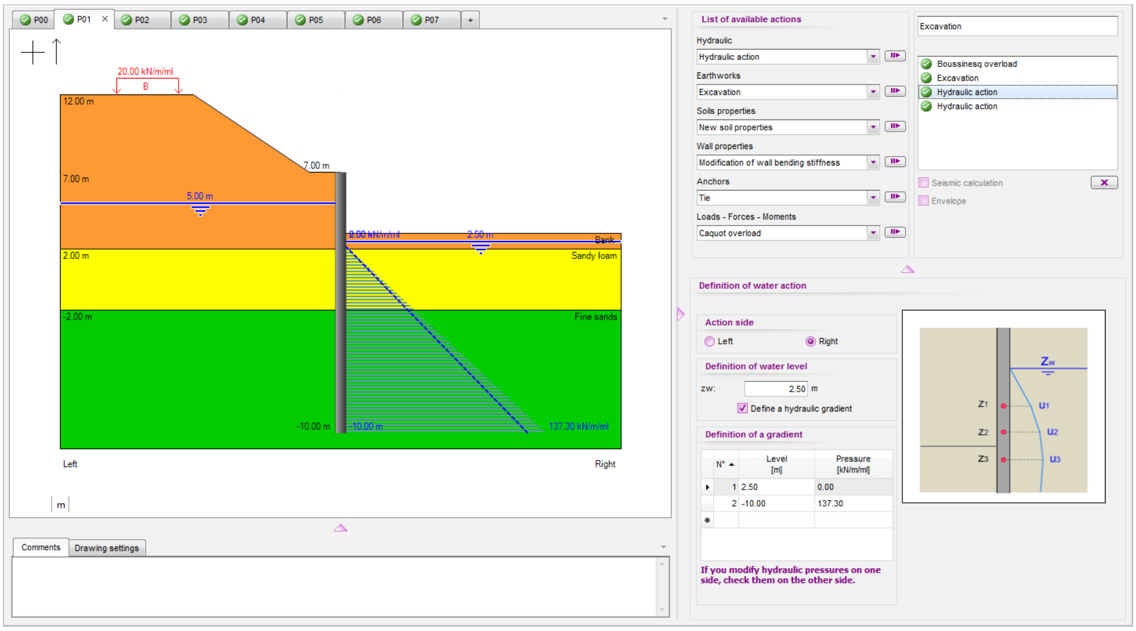
### D.2.2.1.4. Phasing

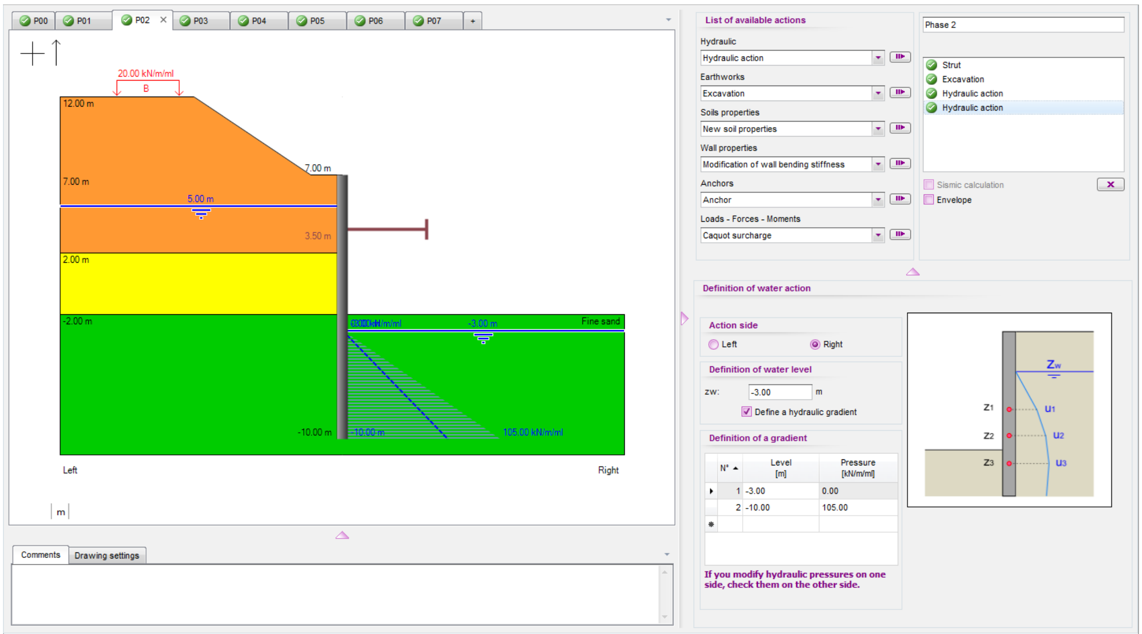
Taking account of the hydraulic gradient requires that the following modifications be made.

Phases 1 and 2:

- "Hydraulic action" on the right with "definition of a gradient":

| **Phase 1:** | $z_w$ = +2.50 m | **Phase 2:** | $z_w$ = -3.0 m |
|---|---|---|---|
| Level (m) | Pressure (kN/m/ml) | Level (m) | Pressure (kN/m/ml) |
| +2.5 | 0.0 | -3.0 | 0.0 |
| -10.0 | 137.3 | -10.0 | 105.0 |

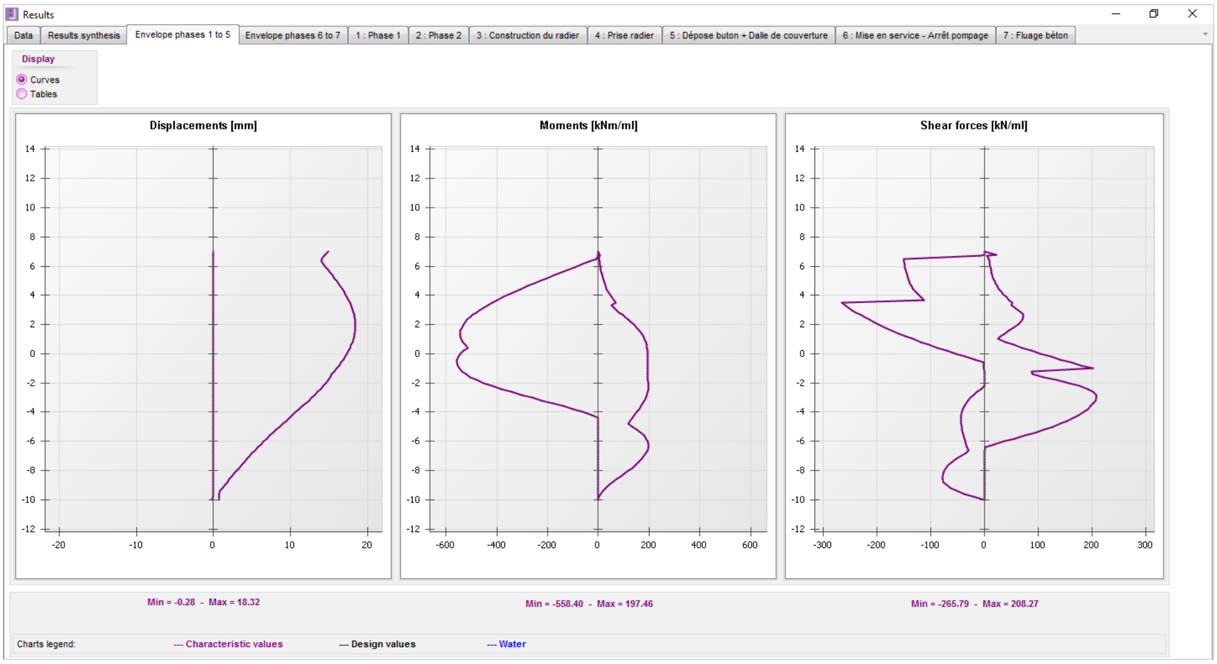


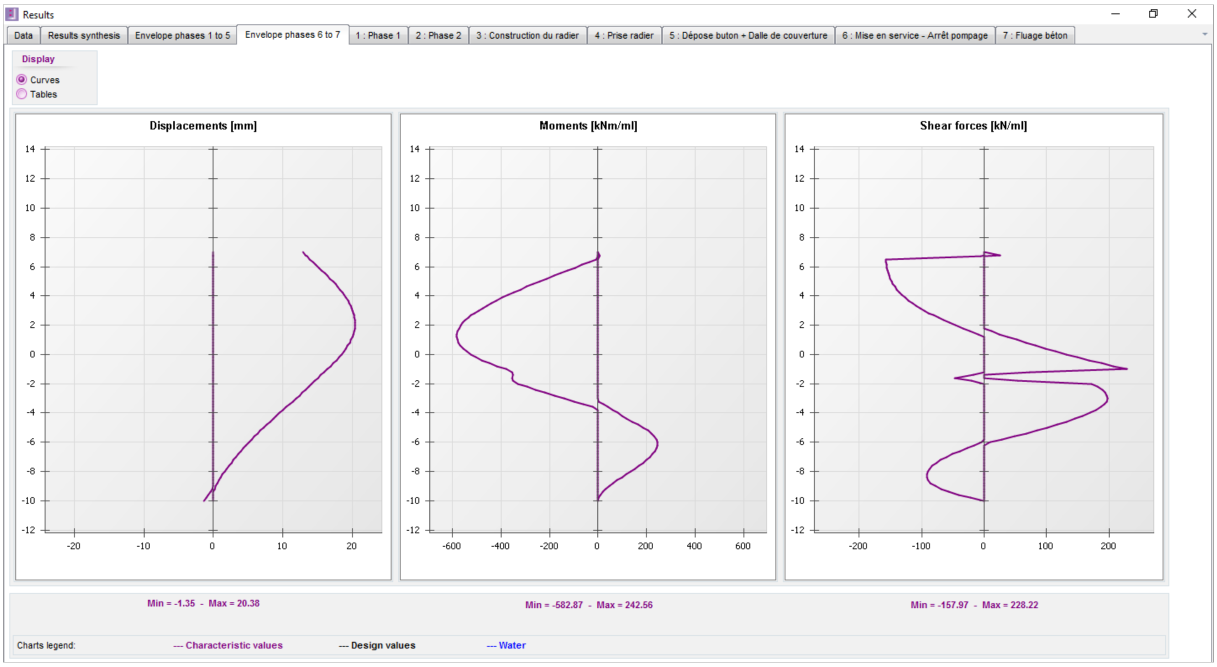


## D.2.2.2. Calculation and results

Restart the calculation and access the results. The following figure presents a summary of the results obtained.

| PHASE N° | Displacement Head [mm] | Displacement maximal [mm] | Moment maximal [kNm/ml] | Shear force maximal [kN/ml] | Ratio Earth ressist. | Characteristic force strut n°1 [kN/ml] | Characteristic force strut n°1 [kN/ml] | Characteristic force strut n°2 [kN/ml] |
|---|---|---|---|---|---|---|---|---|
| 1 | 14.79 | 14.79 | 197.46 | 71.93 | 4.354 | - | - | - |
| 2 | 12.90 | 16.64 | -558.40 | -265.52 | 1.546 | 317.44 | - | - |
| 3 | 12.97 | 16.56 | -558.20 | -265.79 | 2.542 | 317.16 | - | - |
| 4 | 12.97 | 16.56 | -558.20 | -265.79 | 2.542 | 317.16 | 0.00 | - |
| 5 | 12.84 | 18.32 | -545.44 | 201.37 | 2.614 | - | 222.37 | 157.21 |
| 6 | 12.83 | 18.57 | -582.87 | 197.52 | 2.312 | - | 135.10 | 164.49 |
| 7 | 12.73 | 20.38 | -410.01 | 228.22 | 2.464 | - | 282.03 | 130.00 |
| Extrema | 14.79 | 20.38 | -582.87 | -265.79 | 1.546 | 317.44 | 282.03 | 164.49 |






During this 2nd step, we obtain the following “envelope” results:

| | **Transitory phases** | **Final phases** |
|---|---|---|
| | *Ph. 1 to 5* | *Ph. 6 and 7* |
| **Displacement** | 1.8 cm | 2.0 cm |
| **Bending moment** | 560 kNm/ml | 580 kNm/ml |
| **Shear force** | 270 kN/ml | 230 kN/ml |
| **Ratio of passive earth pressures** | 1.5 | 2.3 |

We note that in the transitory phase, the ratio of passive earth pressures is lower than that obtained in step 1 (1.5 < 2.0). This can be explained by the reduction in the effective stress on the excavation side, itself generated by the increased water pressure owing to flow.

We observed that taking account of a flow increases the loadings on the wall. The maximum bending moment and shear force rose between steps 1 and 2. The maximum increase is about 8%.

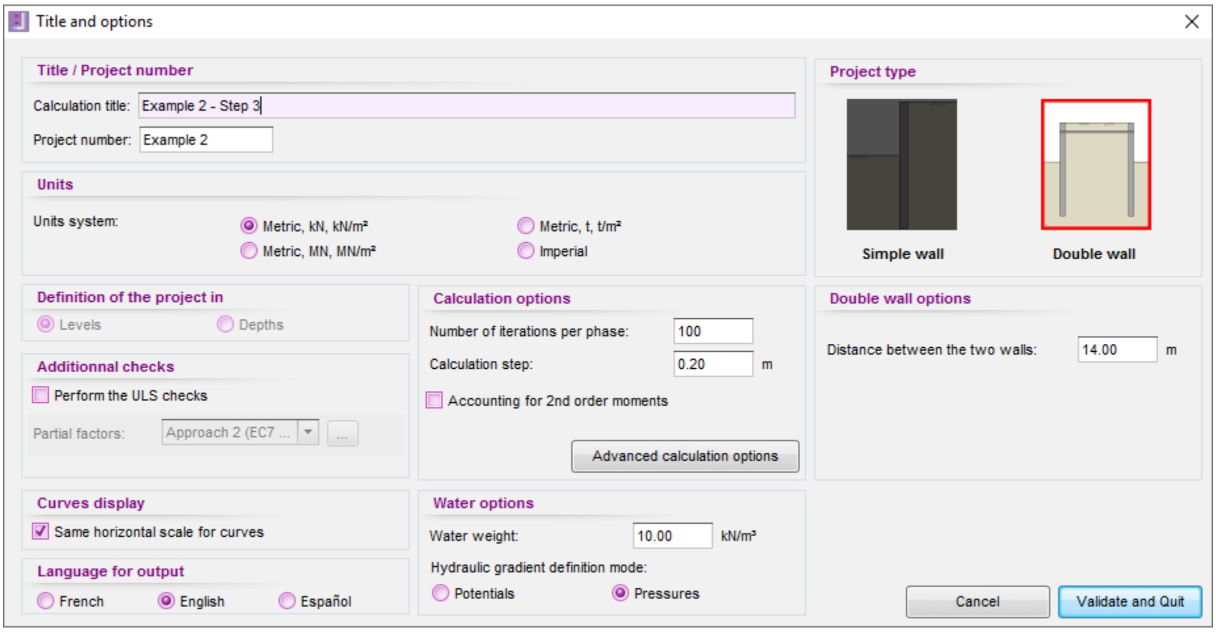
## D.2.3. Step 3: Switch to a double wall calculation

### D.2.3.1. General data

This step aims to illustrate the equivalence of the previous calculation with that of a perfectly symmetric double wall.

Click “Save as” in the File menu. For example name the file “Example 2 – Step 3”.

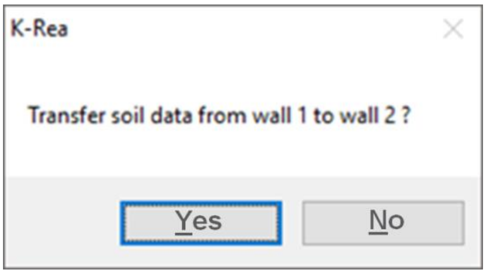
Go to the “Data” menu and click “Title and Options”. In the Project Type part, click “double wall”.



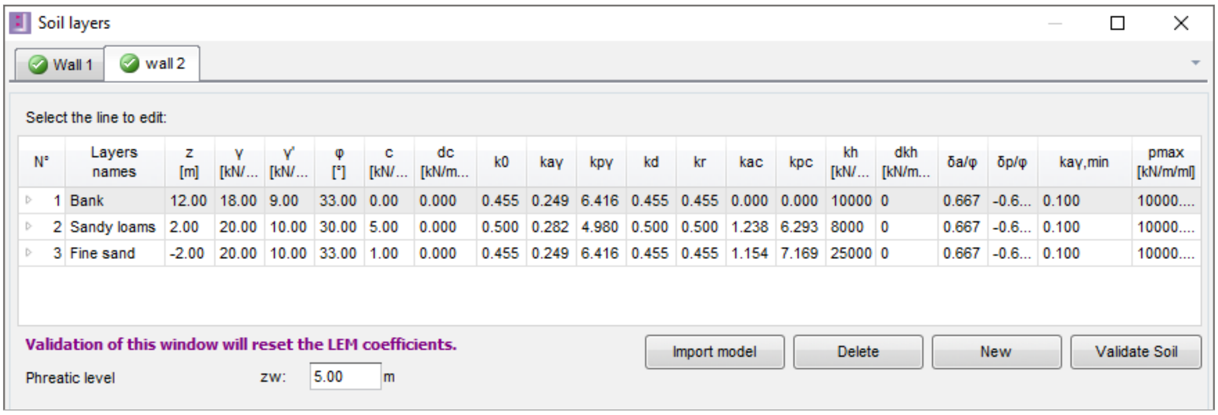

Click .



K-Réa then proposes transferring the soil data from wall 1 to wall 2.



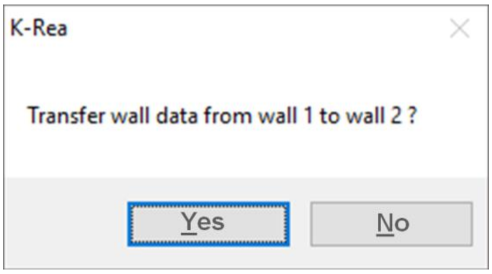

Click  to automatically copy the soil layers from wall 1 to wall 2.

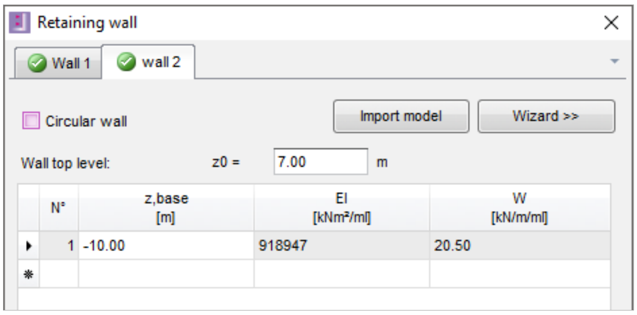



| N° | Layers names | z [m] | γ [kN/... | γ' [kN/... | φ [°] | c [kN/... | dc [kN/m... | k0 | kaγ | kpγ | kd | kr | kac | kpc | kh [kN/... | dkh [kN/m... | δa/φ | δp/φ | kaγ,min | pmax [kN/m/ml] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Bank | 12.00 | 18.00 | 9.00 | 33.00 | 0.00 | 0.000 | 0.455 | 0.249 | 6.416 | 0.455 | 0.455 | 0.000 | 0.000 | 10000 | 0 | 0.667 | -0.6... | 0.100 | 10000.... |
| 2 | Sandy loams | 2.00 | 20.00 | 10.00 | 30.00 | 5.00 | 0.000 | 0.500 | 0.282 | 4.980 | 0.500 | 0.500 | 1.238 | 6.293 | 8000 | 0 | 0.667 | -0.6... | 0.100 | 10000.... |
| 3 | Fine sand | -2.00 | 20.00 | 10.00 | 33.00 | 1.00 | 0.000 | 0.455 | 0.249 | 6.416 | 0.455 | 0.455 | 1.154 | 7.169 | 25000 | 0 | 0.667 | -0.6... | 0.100 | 10000.... |

Then click Validate and Quit.

Proceed in the same way to transfer the data from wall 1 to wall 2: click Yes.




Then click Validate and Quit.

### D.2.3.2. Phasing

The “struts” must now be replaced by “”linking anchors” and the “surface struts” by “slab anchors”.

The useful length of these new linking anchors will be the distance between the walls, **14 m**.

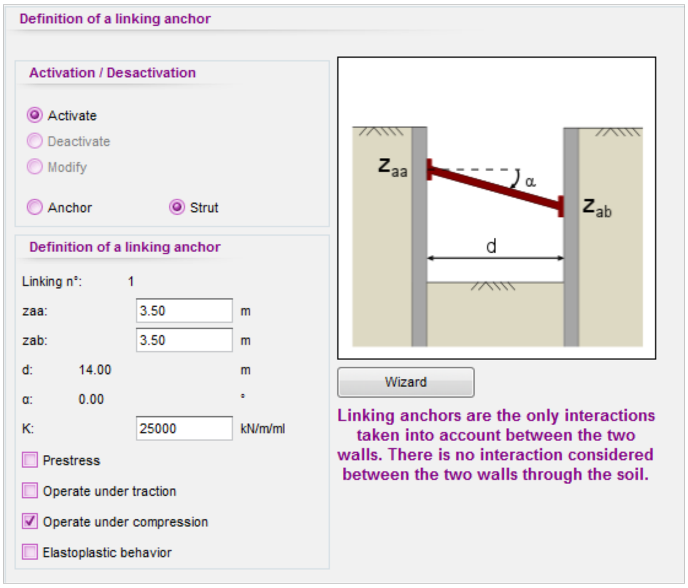
First of all delete the actions linked to the “strut” and “surface strut” type anchors, beginning by those of the “deactivate” type.

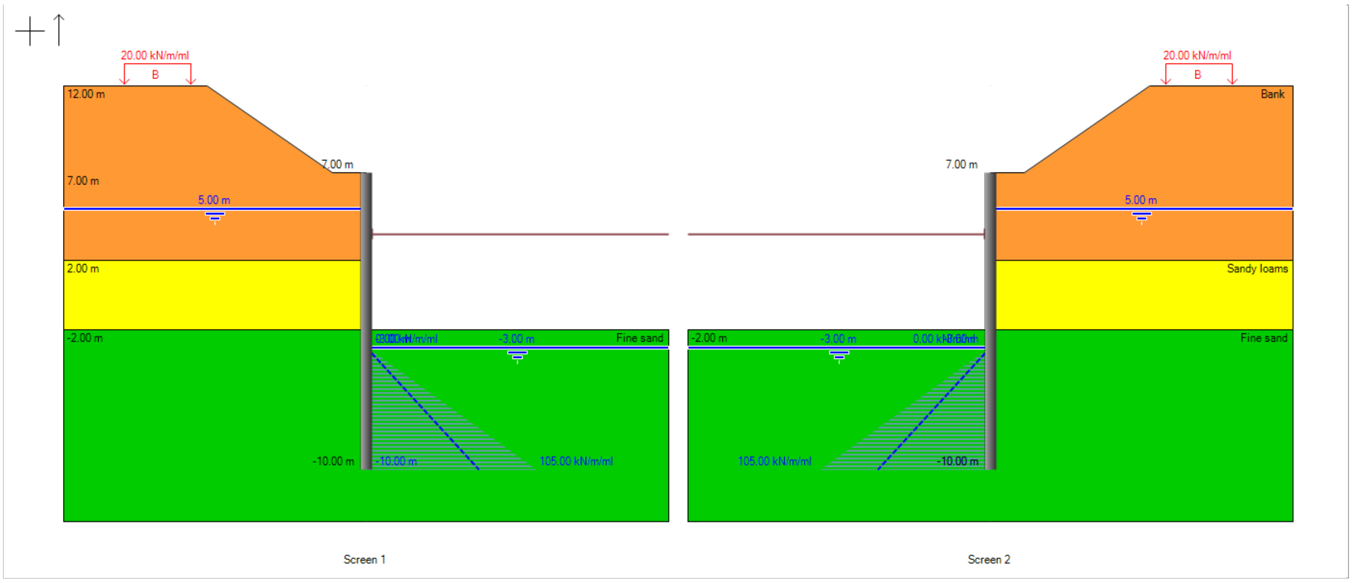
Then define the “linking anchors” and the “slab anchors”.

## Phase 2:

Stiffness of linking anchor:

K = E S / Lu ≈ 25 000 kN/m/ml

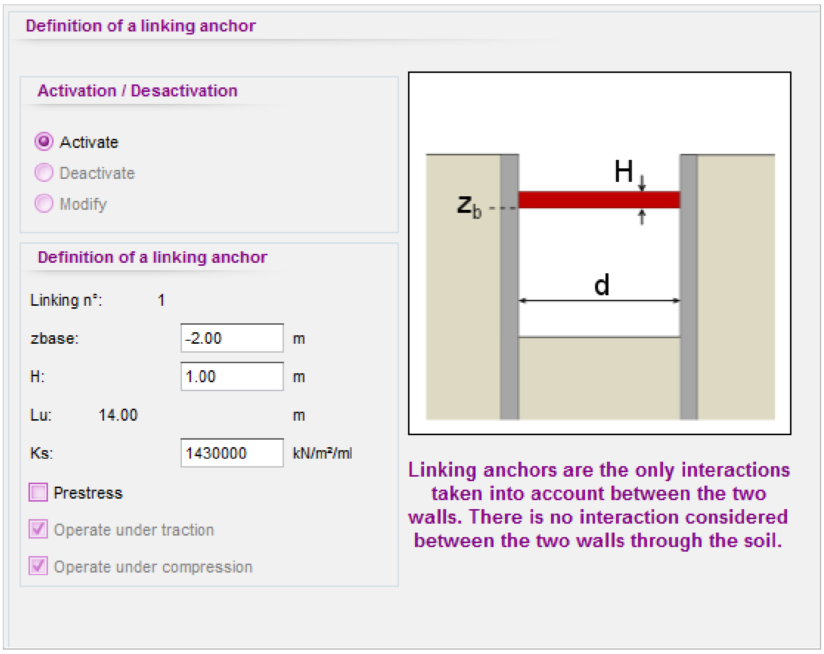


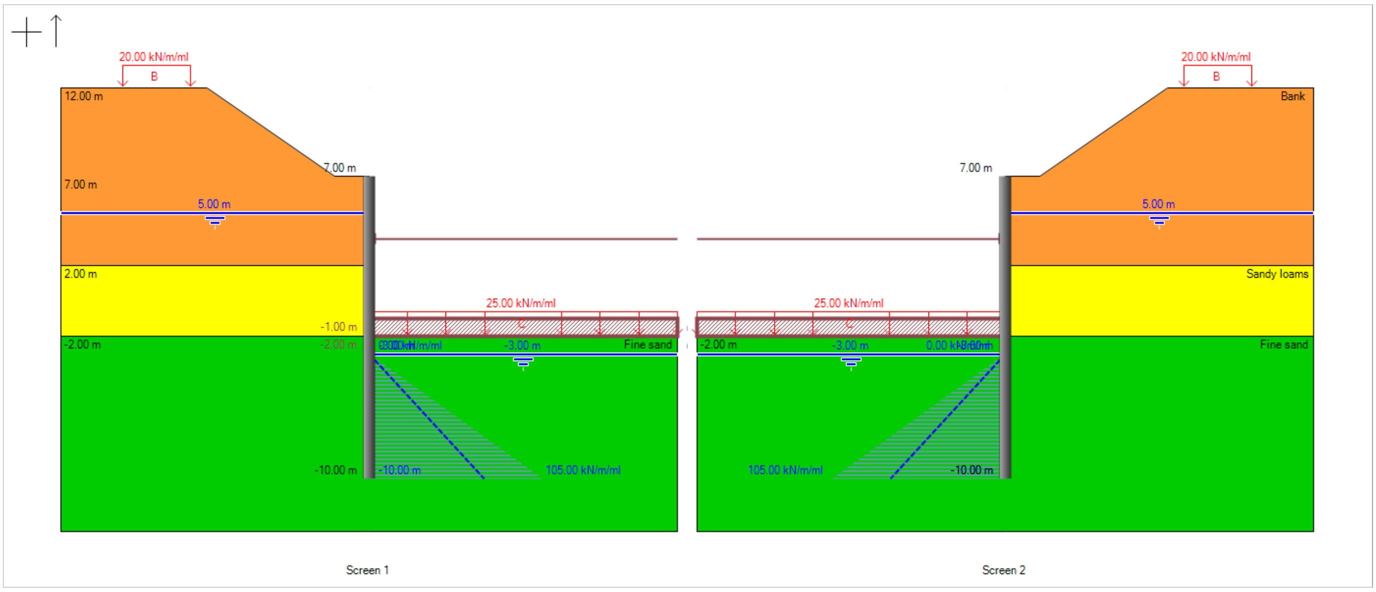



## Phase 4

Stiffness of slab anchor:

ks = E / Lu ≈ 1 430 000 kN/m²/ml

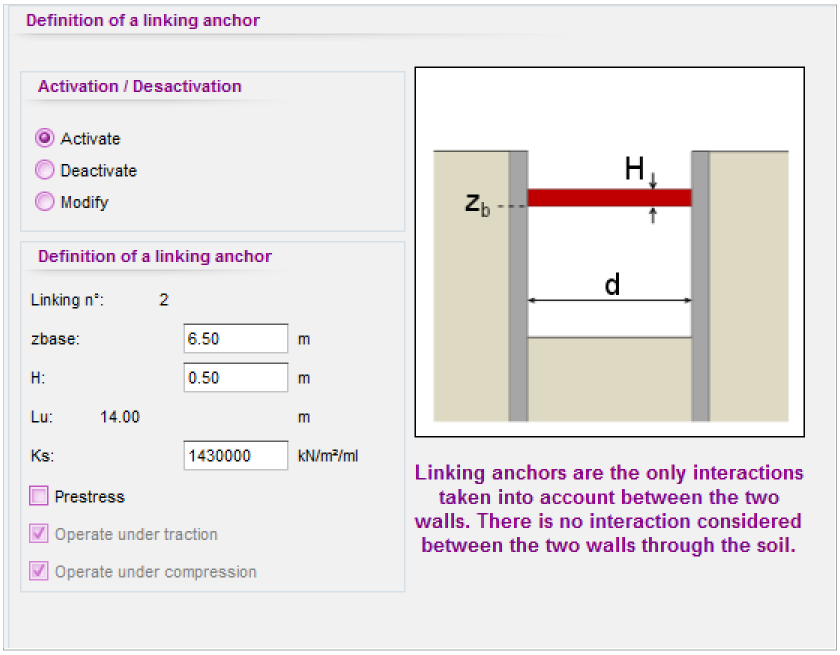


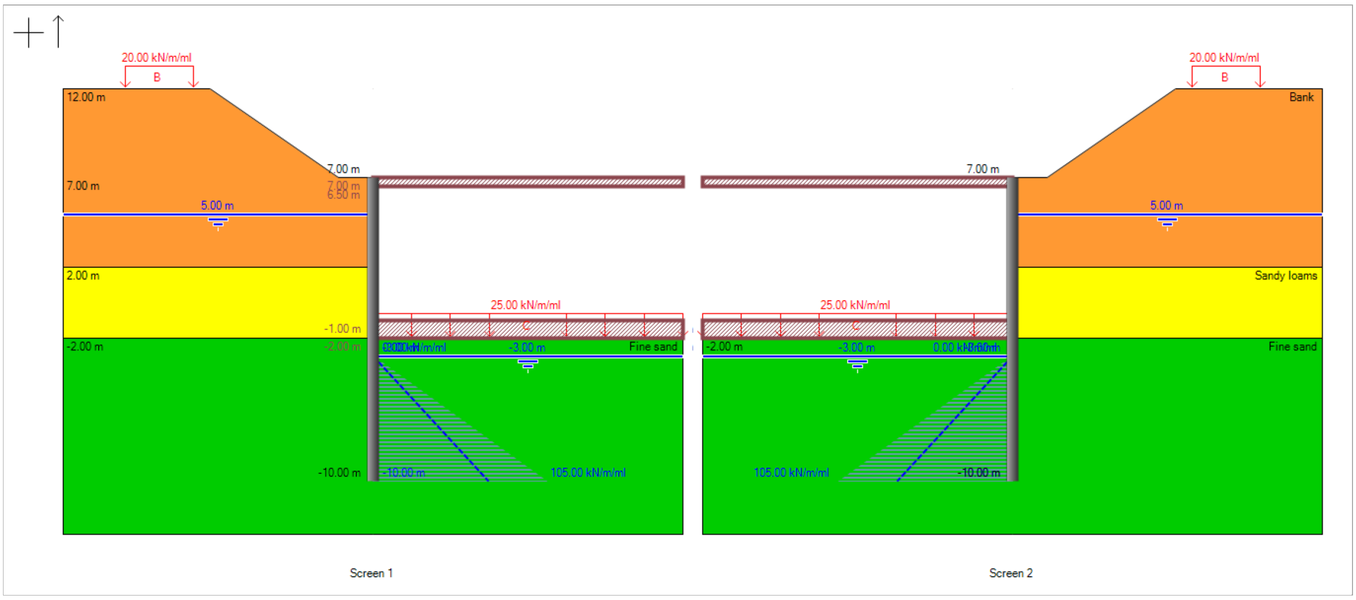



## Phase 5

Stiffness of slab anchor:

ks = E / Lu ≈ 1 430 000 kN/m²/ml

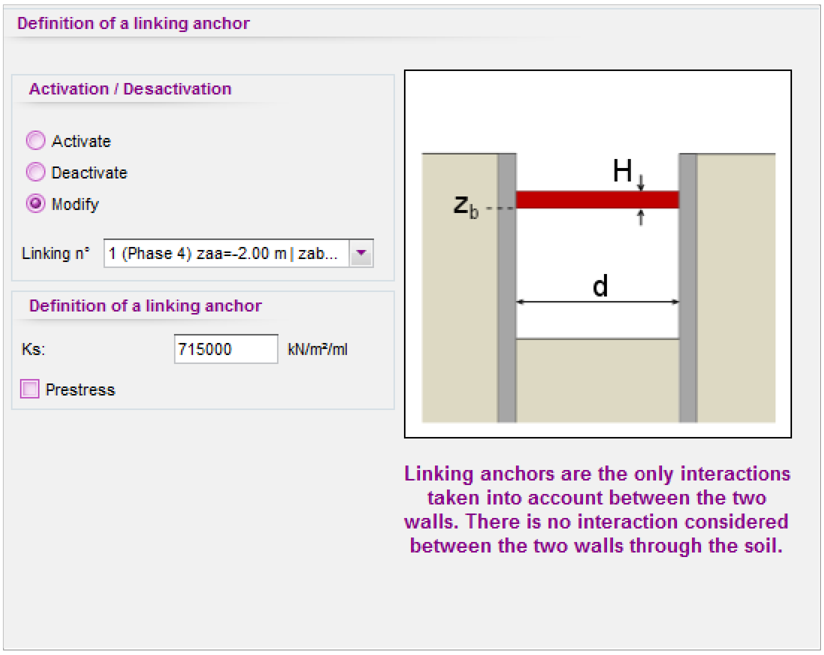


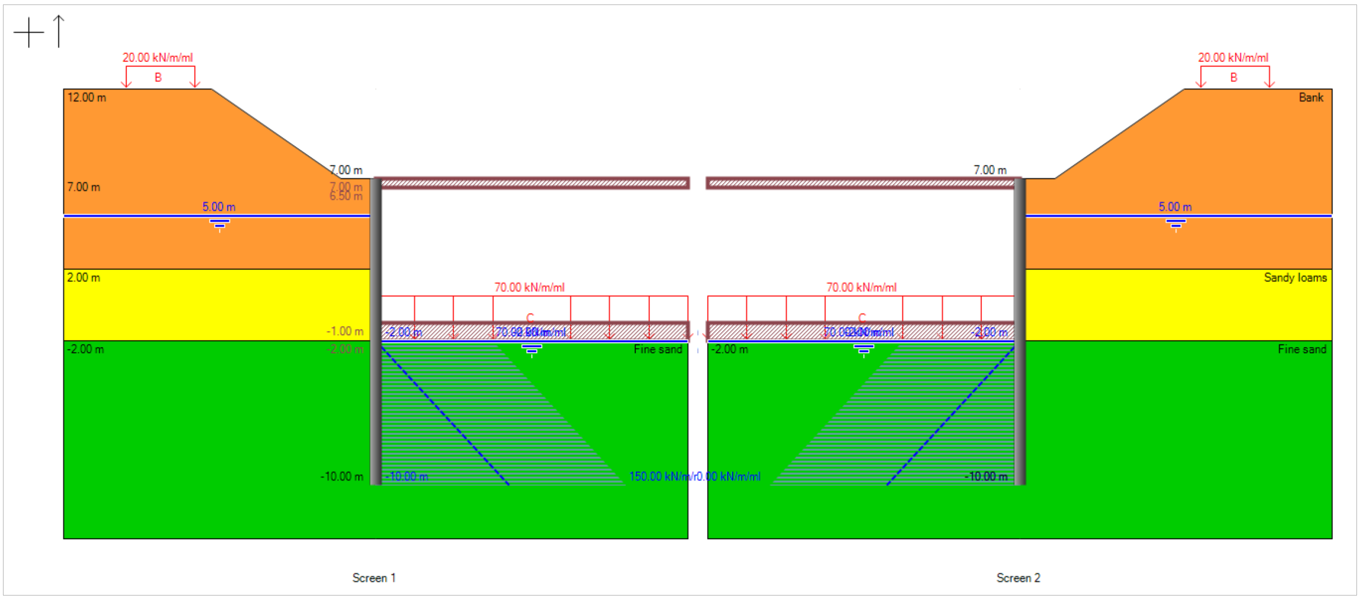



## Phase 7

Stiffness of slab anchor:

K = E / Lu ≈ 715 000 kN/m/ml



### D.2.3.3. Calculation and results

Start the calculation and access the results. These are exactly the same as those from the simple wall calculation (because the excavation is perfectly symmetric).

| | Wall 1 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| PHASE N° | Displacement Head [mm] | Displacement maximal [mm] | Moment maximal [kNm/ml] | Shear force maximal [kN/ml] | Ratio Earth ressist. | Characteristic force link. anchor n°1 [kN/ml] | Characteristic force slab n°1 [kN/ml] | Characteristic force slab n°2 [kN/ml] |
| 1 | 14.79 | 14.79 | 197.46 | 71.93 | 4.354 | - | - | - |
| 2 | 12.90 | 16.64 | -558.40 | -265.52 | 1.546 | 317.44 | - | - |
| 3 | 12.97 | 16.56 | -558.20 | -265.79 | 2.542 | 317.16 | - | - |
| 4 | 12.97 | 16.56 | -558.20 | -265.79 | 2.542 | 317.16 | 0.00 | - |
| 5 | 12.84 | 18.32 | -545.44 | 201.37 | 2.614 | - | 222.37 | 157.21 |
| 6 | 12.83 | 18.57 | -582.87 | 197.52 | 2.312 | - | 135.10 | 164.49 |
| 7 | 12.73 | 20.38 | -410.01 | 228.22 | 2.464 | - | 282.03 | 130.00 |
| Extrema | 14.79 | 20.38 | -582.87 | -265.79 | 1.546 | 317.44 | 282.03 | 164.49 |

| | Wall 2 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| PHASE N° | Displacement Head [mm] | Displacement maximal [mm] | Moment maximal [kNm/ml] | Shear force maximal [kN/ml] | Ratio Earth ressist. | Characteristic force link. anchor n°1 [kN/ml] | Characteristic force slab n°1 [kN/ml] | Characteristic force slab n°2 [kN/ml] |
| 1 | -14.79 | -14.79 | -197.46 | -71.93 | 4.354 | - | - | - |
| 2 | -12.90 | -16.64 | 558.40 | 265.52 | 1.546 | 317.44 | - | - |
| 3 | -12.97 | -16.56 | 558.20 | 265.79 | 2.542 | 317.16 | - | - |
| 4 | -12.97 | -16.56 | 558.20 | 265.79 | 2.542 | 317.16 | 0.00 | - |
| 5 | -12.84 | -18.32 | 545.44 | -201.37 | 2.614 | - | 222.37 | 157.21 |
| 6 | -12.83 | -18.57 | 582.87 | -197.52 | 2.312 | - | 135.10 | 164.49 |
| 7 | -12.73 | -20.38 | 410.01 | -228.22 | 2.464 | - | 282.03 | 130.00 |
| Extrema | -14.79 | -20.38 | 582.87 | 265.79 | 1.546 | 317.44 | 282.03 | 164.49 |

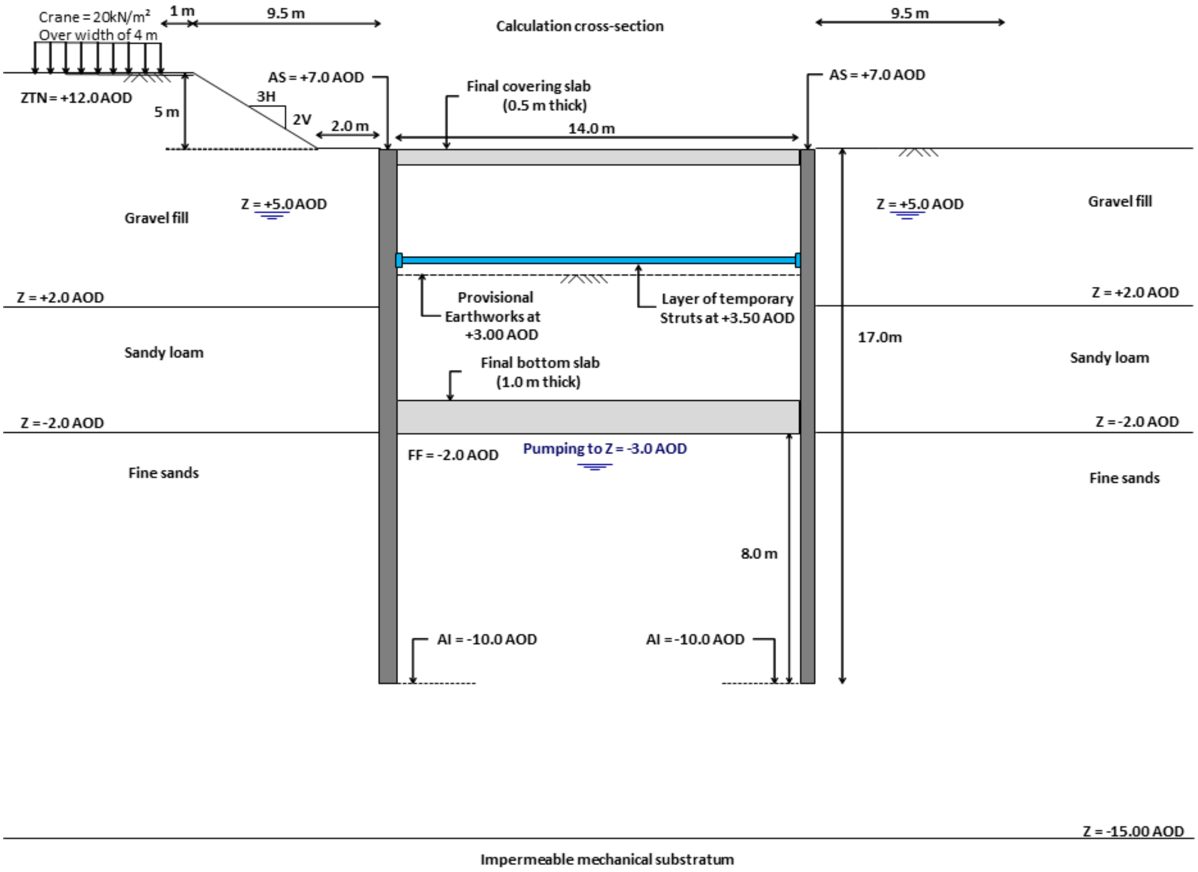
During this 3rd step, we obtain "envelope" values that are identical to the 2nd step. The values are given below as a reminder:

| | **Transitory phases** | **Final phases** |
|---|---|---|
| | *Ph. 1 to 5* | *Ph. 6 and 7* |
| **Displacement** | 1.8 cm | 2.0 cm |
| **Bending moment** | 560 kNm/ml | 580 kNm/ml |
| **Shear force** | 270 kN/ml | 230 kN/ml |
| **Ratio of passive earth pressures** | 1.5 | 2.3 |

## D.2.4. Step 4: Case of an asymmetric excavation

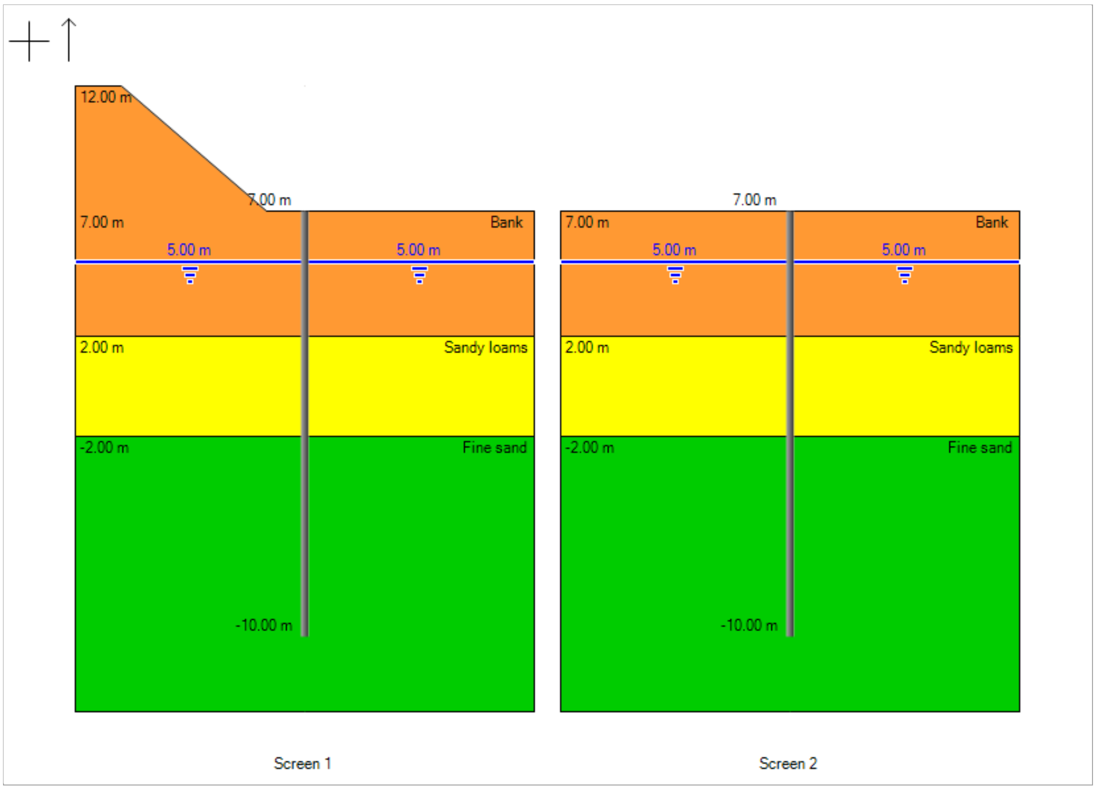
In this step, we prepare to assess the effect of an asymmetric cross-section by comparison with the symmetric cross-section calculated in step 3.

We intentionally eliminate the bank and the overload at the right-hand side of the right wall and the aim will be to compare the results with those of step 3.

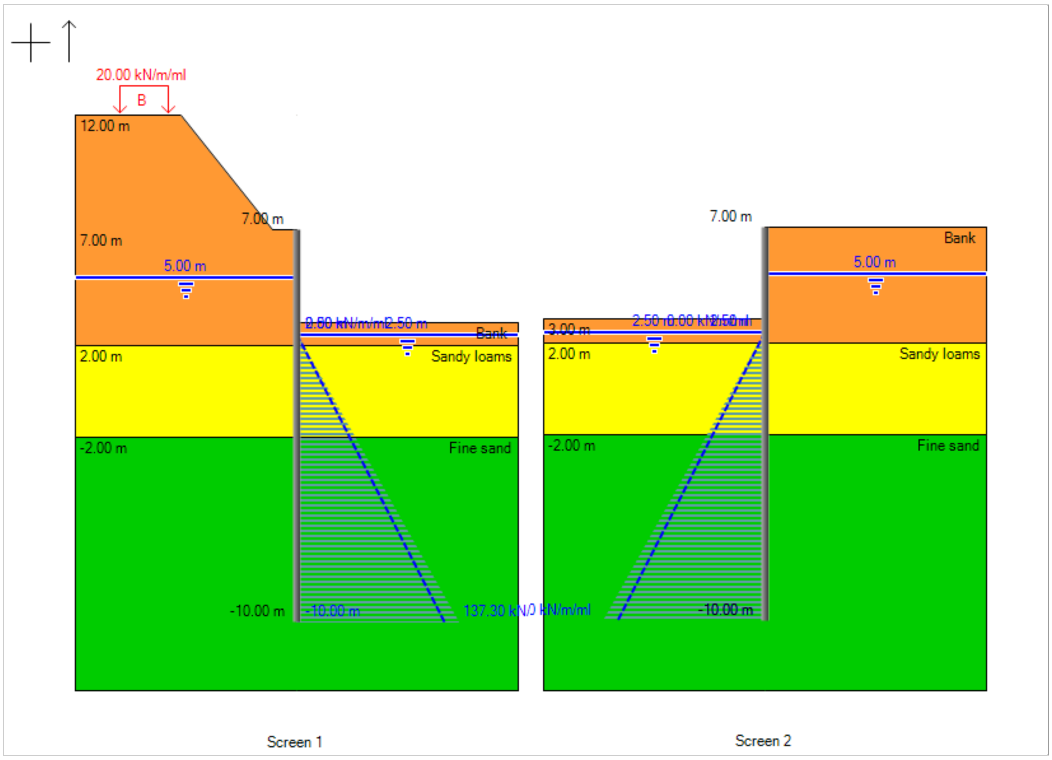


For this, we will follow the instructions below.

**Initial phase**: elimination of the bank behind the right-hand diaphragm wall (Wall 2)




**Phase 1**: elimination of the Boussinesq overload behind the right-hand diaphragm wall (Wall 2)



Restart the calculation and display the results.

| Wall 1 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| PHASE N° | Displacement Head [mm] | Displacement maximal [mm] | Moment maximal [kNm/ml] | Shear force maximal [kN/ml] | Ratio Earth ressist. | Characteristic force link. anchor n°1 [kN/ml] | Characteristic force slab n°1 [kN/ml] | Characteristic force slab n°2 [kN/ml] |
| 1 | 14.79 | 14.79 | 197.46 | 71.93 | 4.354 | - | - | - |
| 2 | 19.11 | 20.48 | -555.90 | -258.92 | 1.527 | 303.25 | - | - |
| 3 | 19.25 | 20.45 | -554.62 | -259.03 | 2.513 | 303.35 | - | - |
| 4 | 19.25 | 20.45 | -554.62 | -259.03 | 2.513 | 303.35 | 0.00 | - |
| 5 | 20.20 | 23.13 | -539.87 | 202.77 | 2.577 | - | 211.16 | 150.16 |
| 6 | 20.28 | 23.44 | -576.94 | 205.36 | 2.275 | - | 124.24 | 157.46 |
| 7 | 20.09 | 25.72 | -424.64 | 225.66 | 2.397 | - | 247.01 | 127.51 |
| Extrema | 20.28 | 25.72 | -576.94 | -259.03 | 1.527 | 303.35 | 247.01 | 157.46 |

| Wall 2 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| PHASE N° | Displacement Head [mm] | Displacement maximal [mm] | Moment maximal [kNm/ml] | Shear force maximal [kN/ml] | Ratio Earth ressist. | Characteristic force link. anchor n°1 [kN/ml] | Characteristic force slab n°1 [kN/ml] | Characteristic force slab n°2 [kN/ml] |
| 1 | -14.03 | -14.03 | -175.65 | -56.79 | 6.977 | - | - | - |
| 2 | -9.57 | -10.15 | 320.56 | 208.60 | 1.998 | 303.25 | - | - |
| 3 | -9.62 | -10.07 | 320.77 | 209.21 | 3.248 | 303.35 | - | - |
| 4 | -9.62 | -10.07 | 320.77 | 209.21 | 3.248 | 303.35 | 0.00 | - |
| 5 | -8.43 | -11.46 | 342.81 | -175.76 | 3.364 | - | 211.16 | 150.16 |
| 6 | -8.32 | -11.64 | 376.73 | -168.37 | 3.243 | - | 124.24 | 157.46 |
| 7 | -8.36 | -12.69 | 272.10 | -189.28 | 3.508 | - | 247.01 | 127.51 |
| Extrema | -14.03 | -14.03 | 376.73 | 209.21 | 1.998 | 303.35 | 247.01 | 157.46 |

During this 4th step, we obtain the following "envelope" results:

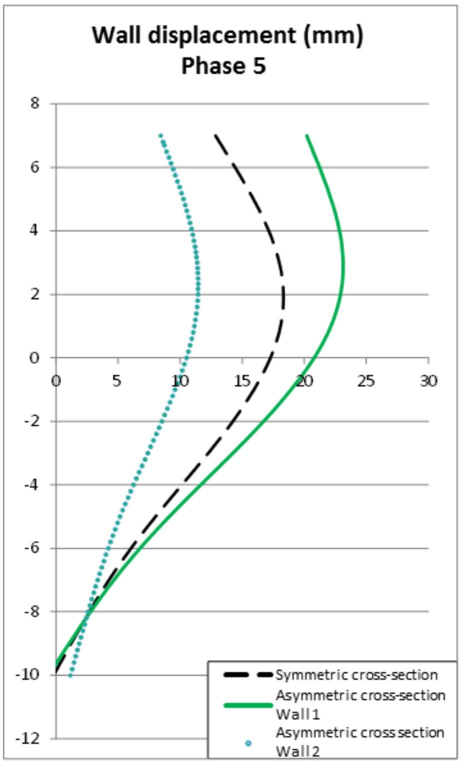
| **WALL 1** | **Transitory phases** | **Final phases** |
|---|---|---|
| | *Ph. 1 to 5* | *Ph. 6 and 7* |
| **Displacement** | 2,3 cm | 2,6 cm |
| **Bending moment** | 560kNm/ml | 580 kNm/ml |
| **Shear force** | 260 kN/ml | 226 kN/ml |
| **Ratio of passive earth pressures** | 1.5 | 2.2 |

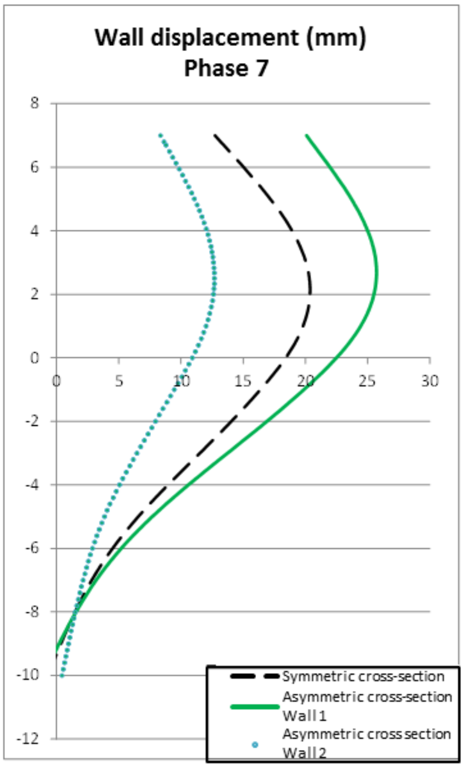
| **WALL 2** | **Transitory phases** | **Final phases** |
|---|---|---|
| | *Ph. 1 to 5* | *Ph. 6 and 7* |
| **Displacement** | 1.4 cm | 1.3 cm |
| **Bending moment** | 340 kNm/ml | 380 kNm/ml |
| **Shear force** | 210 kN/ml | 190 kN/ml |
| **Ratio of passive earth pressures** | 2.0 | 3.2 |

Reminder of the symmetric calculation results (step 3):

| | Transitory phases | Final phases |
|---|---|---|
| | *Ph. 1 to 5* | *Ph. 6 and 7* |
| **Displacement** | 1.8 cm | 2.0 cm |
| **Bending moment** | 560 kNm/ml | 580 kNm/ml |
| **Shear force** | 270 kN/ml | 230 kN/ml |
| **Ratio of passive earth pressures** | 1.5 | 2.3 |

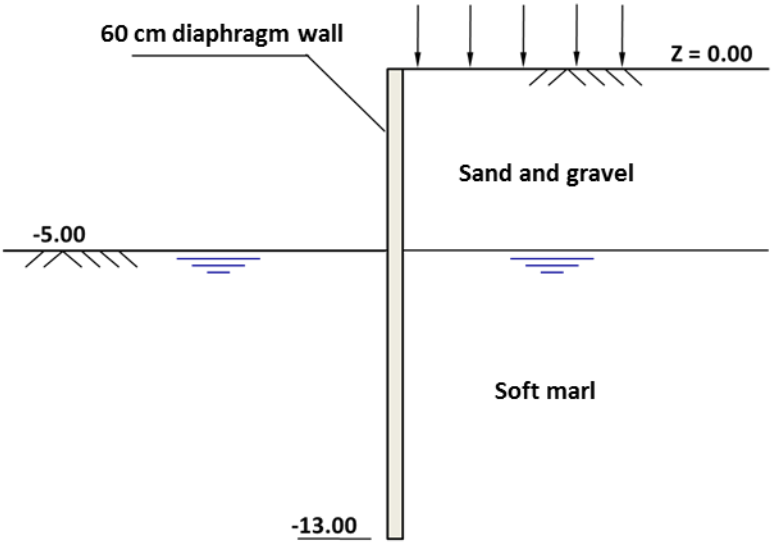
Comparison of the displacement curves in phase 5 (end of transitory phases) and phase 7 (end of service phases) between steps 3 and 4.



# D.3. Tutorial 3: Excavation supported by cantilever wall

The example studied is that of a cantilever diaphragm wall 60 cm thick and anchored 6m in marly soil. The following figure illustrates the characteristics of the example.




In this example, we will detail the ULS checks for this type of configuration.

This example will in particular be used as a basis for illustrating the following points:

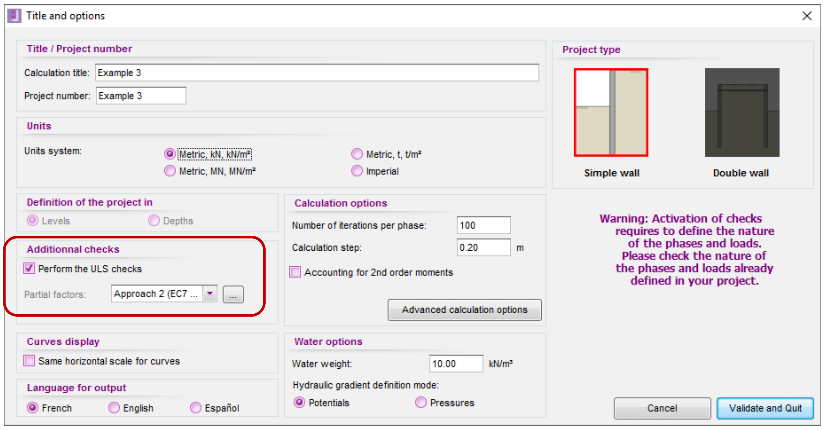
- Comparison of different LEM methods proposed in K-Réa;
- Comparison of weighting systems;
- Vertical equilibrium and automatic correction of the angle of counter passive earth pressure;
- Effect of over-excavation.

## D.3.1. Data input

To start K-Réa:

- Double-click the **K-Réa** icon.
- Choose the appropriate protection mode, select the appropriate language (**French**) and click **OK.**
- Choose **New project** to access the **Title and Options** page.

### D.3.1.1. Title and options




- In the **Project type** frame (right) select “Simple wall”.
- In the **Title / Project number** frame, click the blank “Title” line and input the title of your choice. Click the blank “Project number” line to enter the number of your choice.
- In the **Units** frame, choose the units system of your project, by ticking ‘Metric, kN, kN/m$^2$’.
- Choose **Definition of the project in** Levels, which enables the vertical axis to be directed **upwards.**
- **Additional checks**: tick the “Perform the ULS checks” box to activate calculation at the ultimate limit states for this example.
- In the **Curves display** frame, keep the “Same horizontal scale for curves” box ticked.
- Choose the **Language for output**.
- In the **Calculation options** frame, keep the default settings: 100 iterations per calculation phase and a calculation step of 0.2 m for the wall.
- In the **Water options** frame, leave the water weight at 10.00 kN/m³. Choose potentials as the hydraulic gradient definition mode (this will not influence the calculations because the project does not include drawdown of the water table).

#### D.3.1.2. Definition of soil layers

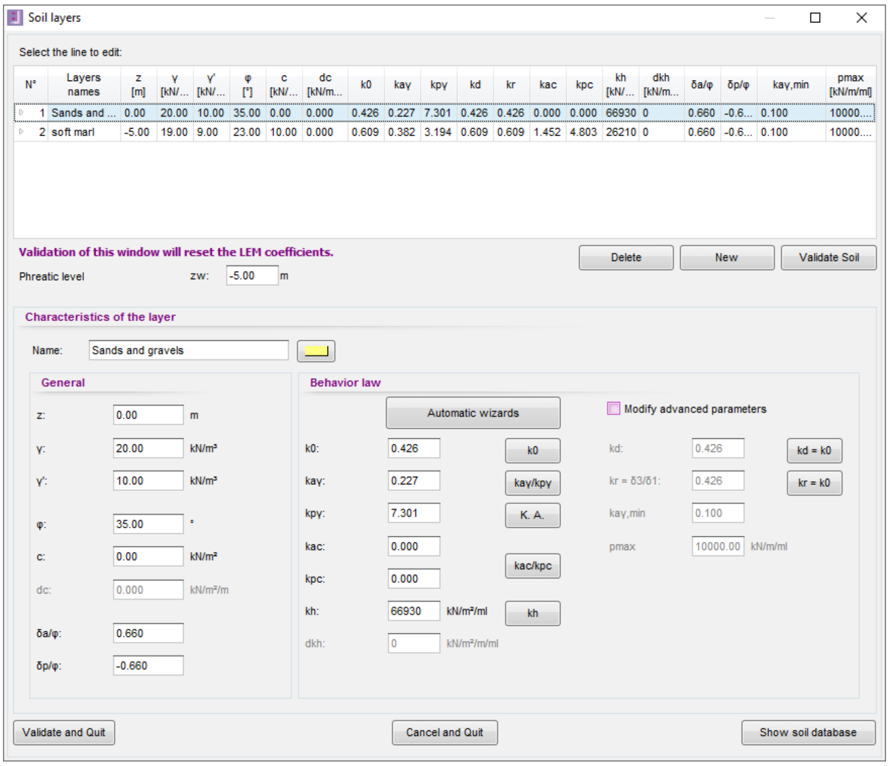
The general characteristics of the two layers of interest for the exercise are summarised in the following table.

| Layer | γ (kN/m³) | γ' (kN/m³) | φ (°) | c (kN/m²) | dc (kPa/m²/m) | $\delta_a/\varphi$ (-) | $\delta_p/\varphi$ (-) |
|---|---|---|---|---|---|---|---|
| Sands and gravel | 20 | 10 | 35 | 0 | 0 | 0.66 | -0.66 |
| Soft marls | 19 | 9 | 23 | 10 | 0 | 0.66 | -0.66 |

Then use the K-Réa wizards to calculate the parameters of the behaviour law for each layer. The reaction coefficient $k_h$ is to be considered with the values given in the table below.

| Layer | $k_0$ (-) | $k_{ay}$ (-) | $k_{py}$ (-) | $k_{ac}$ (-) | $k_{pc}$ (-) | $E_M$ (kPa) | α (-) | $k_h$ (kN/m³) |
|---|---|---|---|---|---|---|---|---|
| Sands and gravel | 0.426 | 0.227 | 7.301 | 0 | 0 | 20 000 | 0.33 | 66 930 |
| Soft marls | 0.609 | 0.382 | 3.194 | 1.452 | 4.803 | 19 800 | 0.66 | 26 210 |

The other parameters are kept at their default values. For this, leave the **Modify advanced parameters** box unticked. The following screen illustrates that of K-Réa on completion of these operations:




Click Validate and Quit.
To consult or modify the soil layers subsequently, click the **Data menu**, then **Soil layers**.

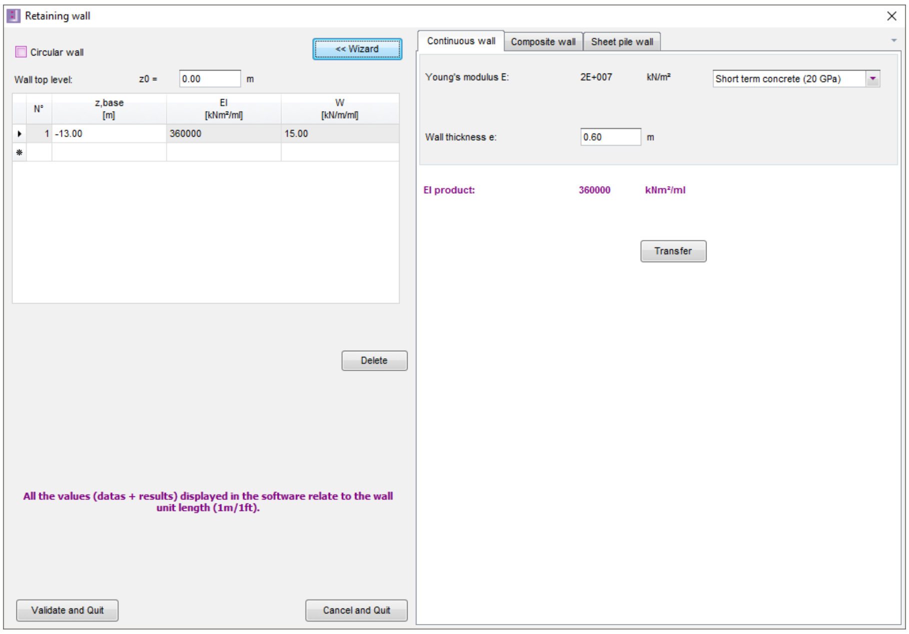
### D.3.1.3. Definition of the wall

After validating the characteristics of the layers, those of the wall must be defined.

- Click the input box to enter the upper level of the wall: $z_0$ = +0.00 m.
- Click the first line of the table (corresponding to the first wall section to be defined, which will in fact be the only one for this example), enter the base of the section in the first column, here level $z_{base}$ = -13.0 m.
- Then click the Wizard >> button to determine the EI product of the wall
  - Choose the Continuous wall tab, then select "Short term concrete (20 GPa)".
  - Then input the wall thickness e = 0.60 m.
- Click Transfer then quit the wizard.

Then fill out the weight per unit area of the wall W = 0.6 m x 25 kN/m$^3$ = 15 kN/m/ml.

The following screenshot illustrates the above operations:




Finally, click Validate and Quit to take account of the values entered and have them appear with the graphic representation of the project initial data.

To edit on the wall characteristics later, click the **Data** menu, then **Retaining wall**.

## D.3.2. Definition of phasing

The actions to be considered in each construction phase must now be defined.

These actions are summarised in the following table:

| PHASE | ACTIONS |
|---|---|
| **Initial** | • Blank |
| **Phase 1 Transitory** | • Excavation to level – 5.00 m<br>• Caquot overload on the right of 25 kN/m/ml – variable nature |
| **Phase 2 Permanent** | • Modification of Caquot overload 10 kN/m/ml – variable nature<br>• Switch to “permanent phase” |

### D.3.2.1. Initial phase

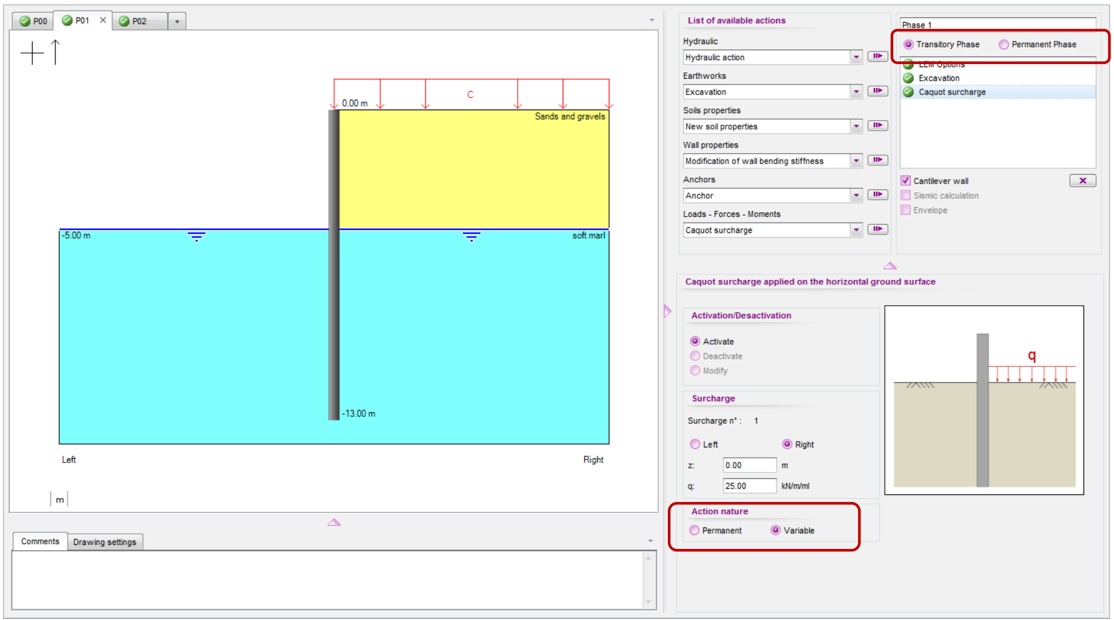
No action is to be defined in this phase.

### D.3.2.2. Phase 1

To create this new calculation phase, click [+] next to the initial phase tab (“P00”).

This phase is to be defined as a “transitory phase”. Two actions then need to be defined:

- “Excavation” action with $z_h$ = -5.00 m on the left;
- “Overload” action with q = 25 kN/m/ml, “variable” nature, applied on the right, at z = +0.00.

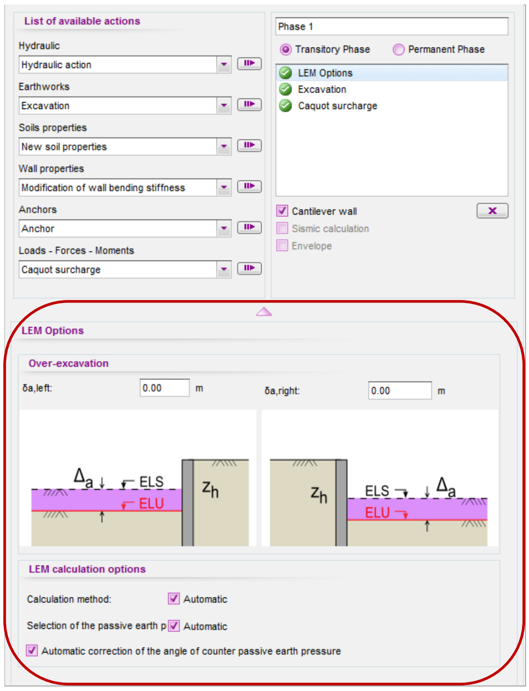


This project (and thus this phase) includes no anchors and the wall is cantilever. Moreover, we activated the ULS checks when defining the properties of the project.

Consequently:

- The Cantilever wall box is automatically ticked, which implies that a "LEM" model will be considered to verify the equilibrium of the wall at ULS;
- The LEM Options action was automatically added and concerns the following options:
  - Input of over-excavation, left or right (leave at zero for the time being);
  - Choice of the calculation method: automatic or manual (LEM – F / LEM – D and choice of calculation level for the base of the wall);
  - Selection of side of passive earth pressure: automatic or manual (left or right);
  - Correction of angle of counter passive earth pressure: automatic / manual.

These options will be described in detail at the end of the exercise.



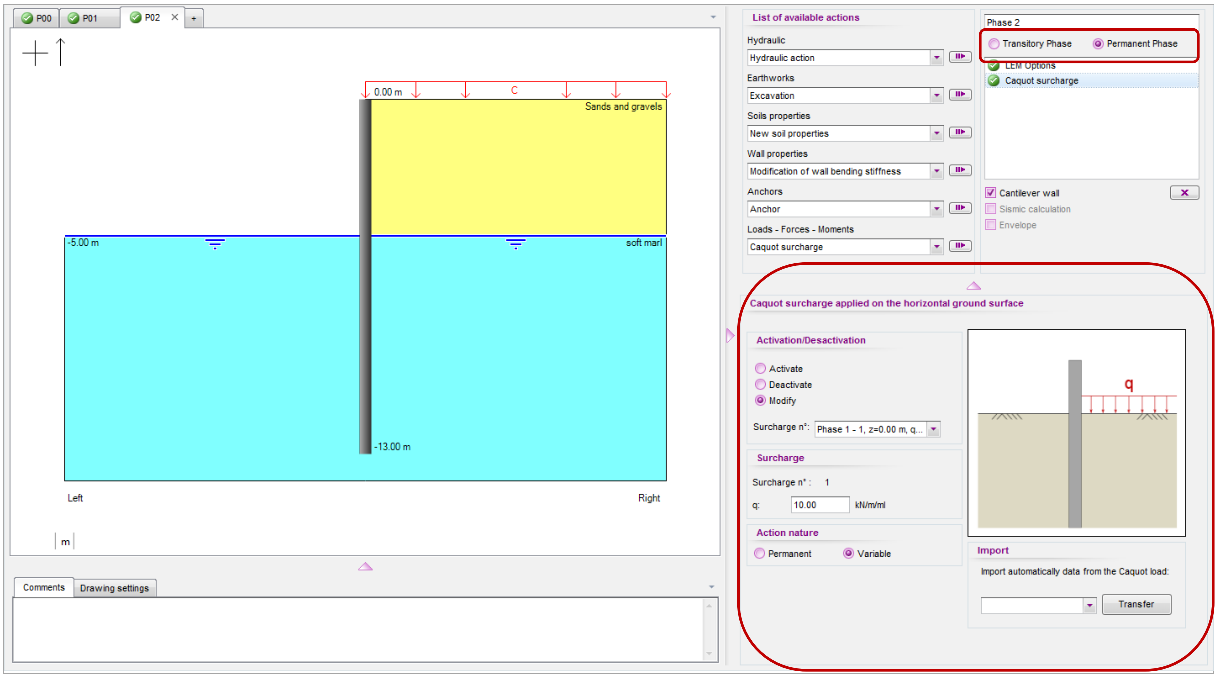
#### D.3.2.3. Phase 2

Add a new calculation phase by clicking  next to the tab of the previous phase (“P01”).

This phase is to be defined as “Permanent phase”.

Modify the “Caquot overload” defined in the previous phase:

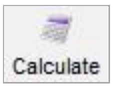
- Density q = 10 kN/m/ml instead of 25 kN/m/ml
- Nature unchanged (“variable”).




### D.3.3. Calculations and results

#### D.3.3.1. Main results

To start the calculations at the end of input of all project parameters, click “Calculate” on the buttons bar:

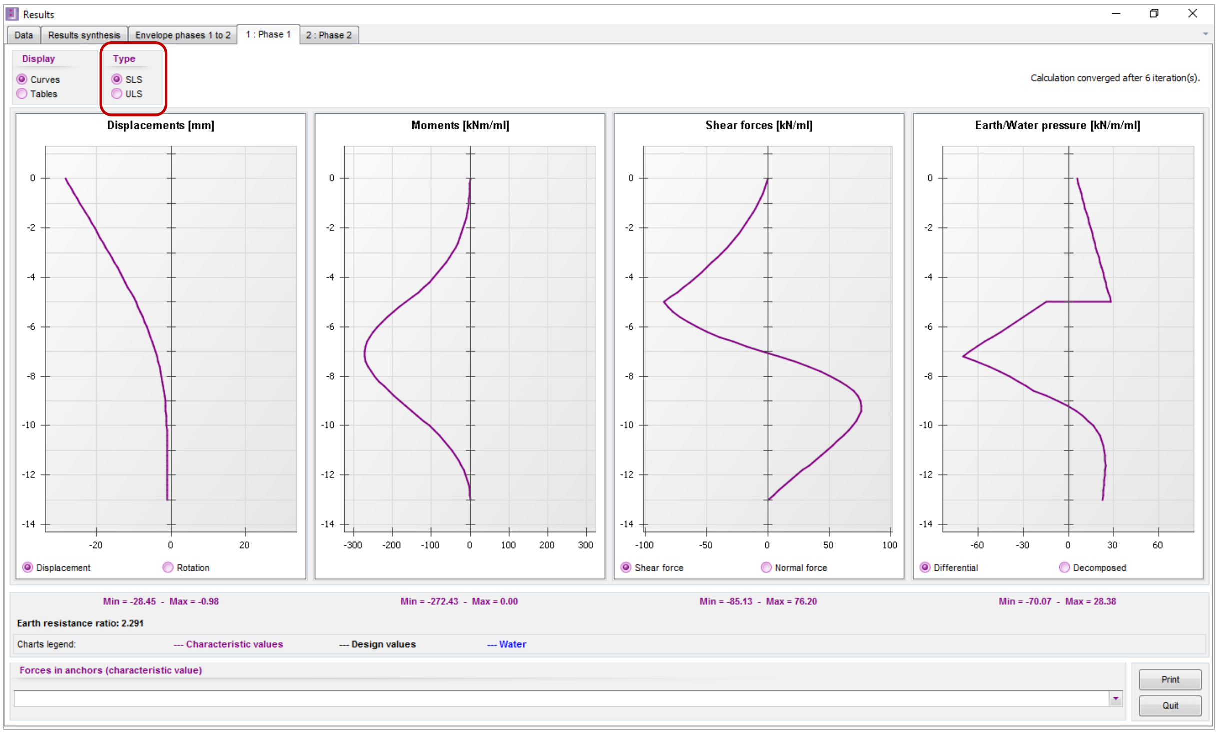



To check all the results proposed in K-Réa in more detail, click button:


Then click the "Phase 1" tab.

We will first of all analyse the “SLS” results: in parallel with the “LEM” calculation, K-Réa also gives the results of a SLS calculation based on a “MISS” model. This calculation is in particular able to verify the displacements of the wall with respect to the structure’s design criteria. Here, the maximum deflection is about 3 cm.

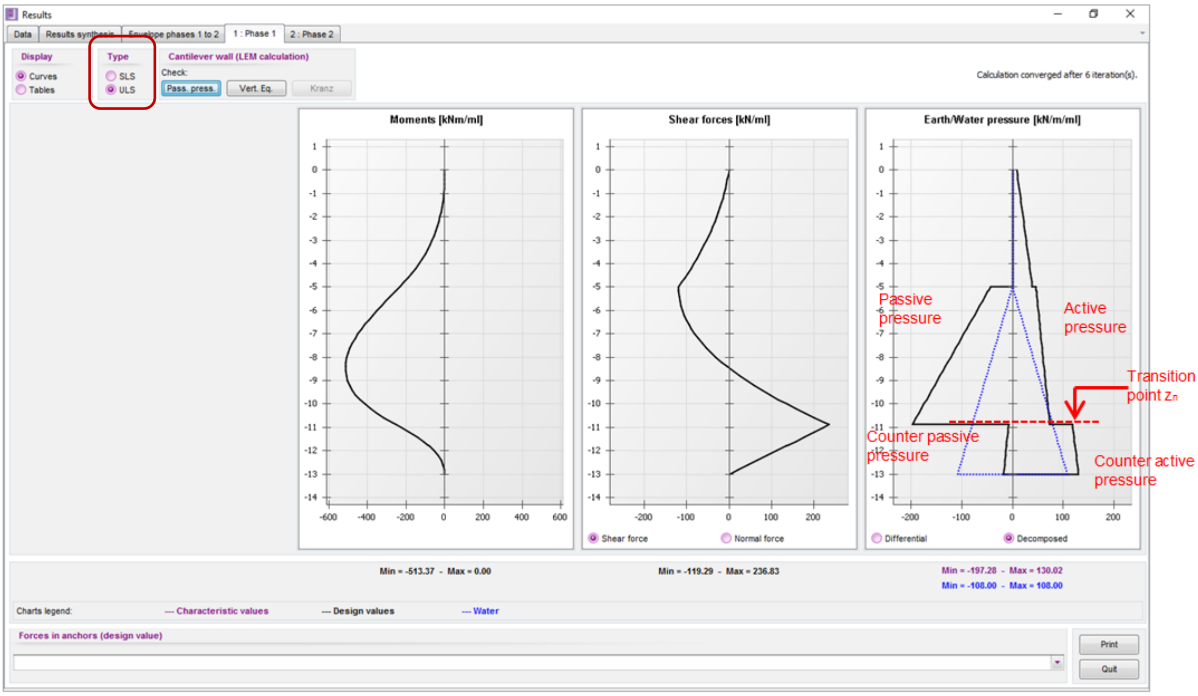
We can see that the ratio of passive earth pressures is also displayed at the bottom of the graphs (here 2.29): as this is a cantilever wall, this ratio has no physical meaning and should not be used to justify the wall embedment depth with respect to the passive earth pressure safety check. In this type of configuration, the embedment depth must be justified in accordance with the regulations by a limit equilibrium model available by selecting the "ULS" option at the top-left of the results window.




The following figure presents the ULS results of phase 1: only the moments, shear forces and pressures diagrams are available (no displacements with the LEM model). The forces and pressures are expressed directly in calculation values (ULS). The maximum values are as follows:

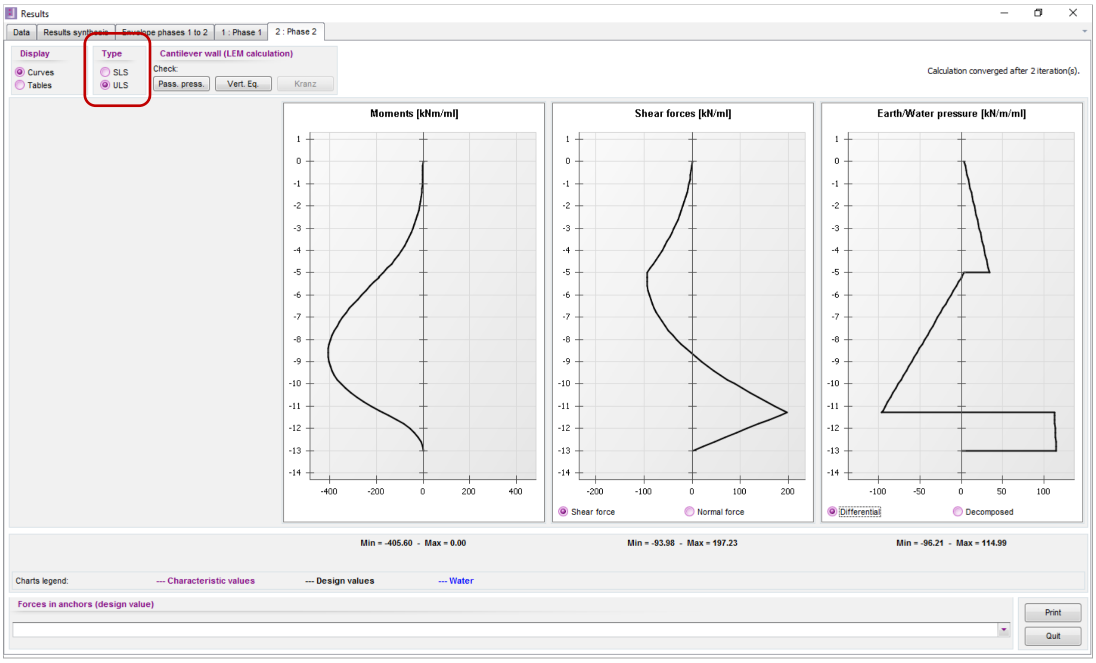
- Bending moment: 514 kNm/ml at ULS
- Shear force: 237 kN/ml at ULS
- Normal force: 190 kN/ml at ULS

The diagram of soil pressures (right) is an illustration of the principle of the LEM model, which consists in working directly with the soil pressure limit values: limit active earth pressure on the right (weighted) and limit passive earth pressure on the left (weighted) down to the transition point $z_n$. Below this transition point, the counter passive earth pressure is (partially) mobilised on the right of the wall and the counter active earth pressure is mobilised on the left.




In this phase, the passive earth pressure side was automatically chosen by K-Réa as being the left side. This automatic choice may be forced by the user in the "LEM options" action accessible for each phase in which the wall is declared as cantilever.

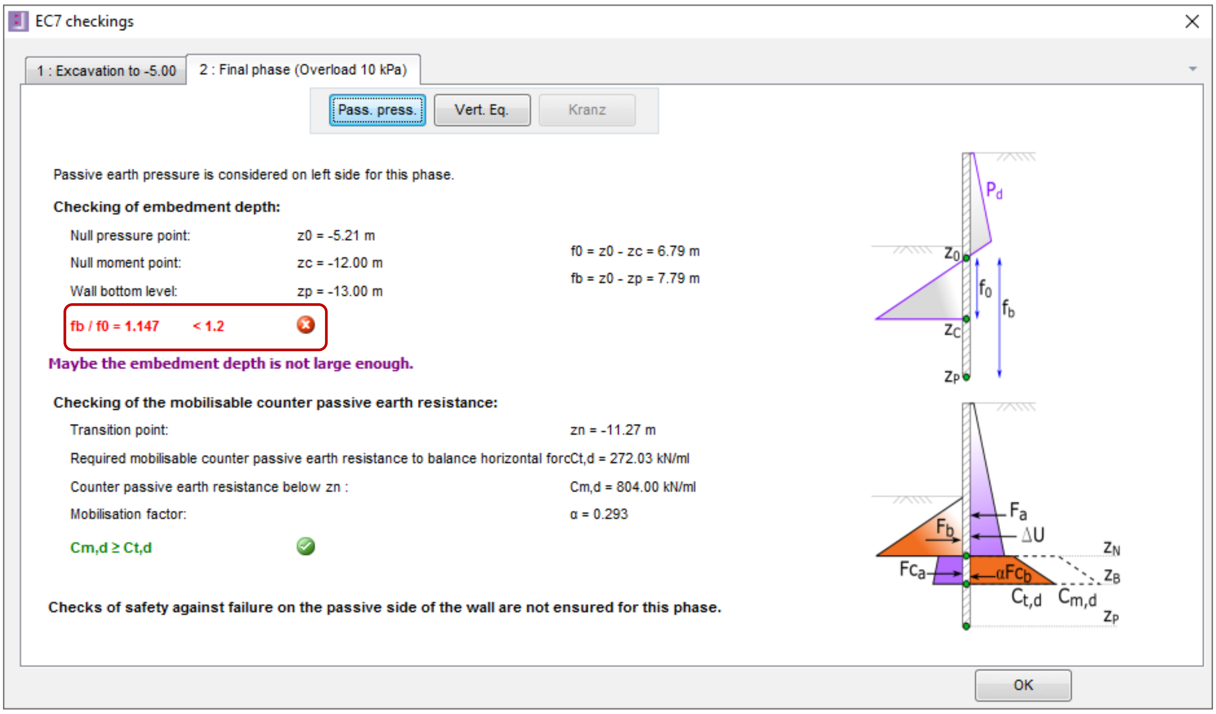
Then access the "Phase 2" tab to view the corresponding ULS results. The Caquot overload having been reduced to 10 kN/m/ml in this phase, the amplitude of the loading is reduced accordingly.



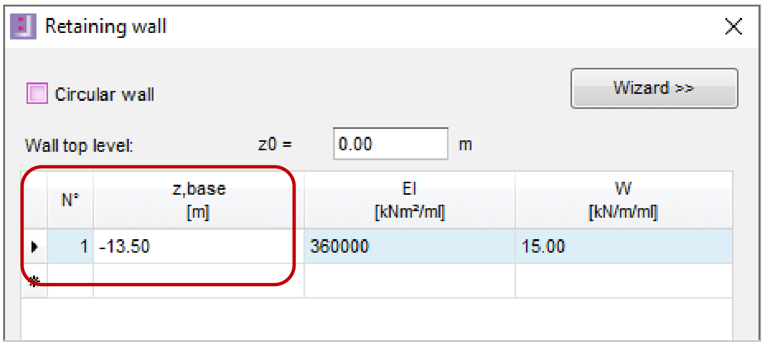

### D.3.3.2. Passive earth pressure safety check

Now click the "Pass. press." button to access details of the ULS checks run by K-Réa in parallel with the forces calculation.

We will look at phase 2. The wall embedment depth is conventionally counted as of the null differential pressure point $z_0$: $f_b = z_0 - z_p$. According to the regulations, the justification of the embedment depth with respect to the passive earth pressure safety check requires that this be at least equal to 1.2 times the critical embedment depth $f_0$ allowing equilibrium of the moments. In this case, we have $f_b = 1.15\ f_0 < 1.20\ f_0$. The wall embedment depth is therefore insufficient with respect to the passive earth pressure safety check. Elongation of the embedment depth is necessary in order to meet the regulatory requirements.



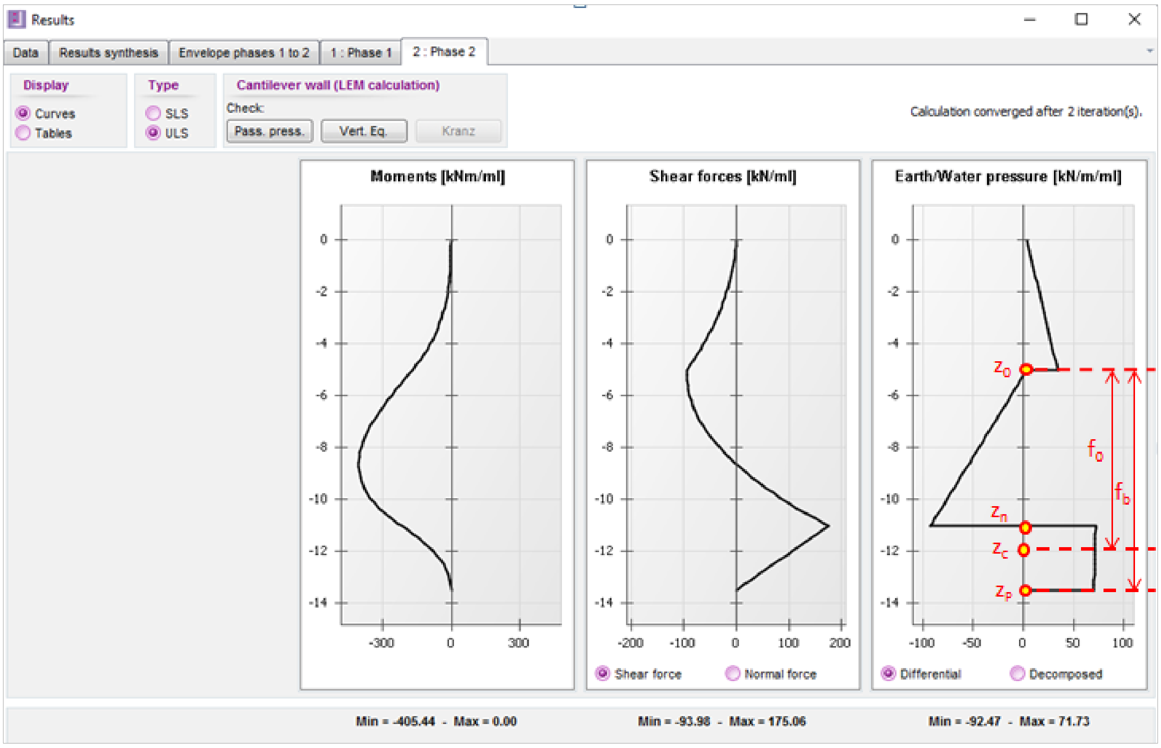

Return to the “Data” menu and then the “Retaining wall” tab, in order to extend the embedment depth. Modify the level of the base to -13.50 m instead of -13.00 m.




Restart the calculation and click the “EC7 checkings” tab.

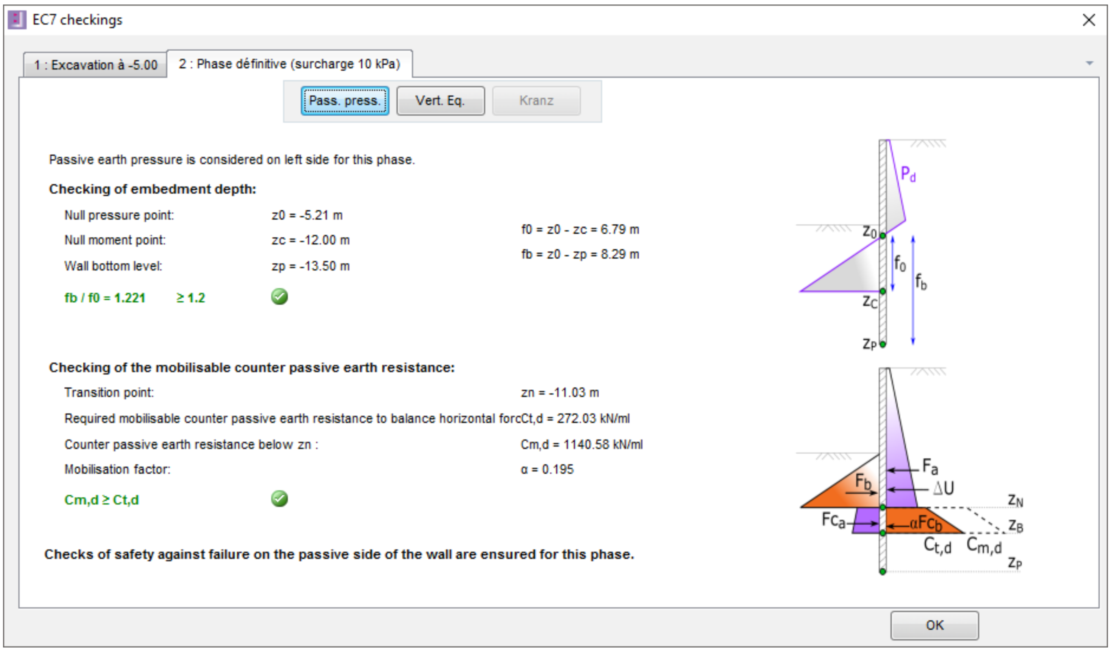
Let’s check phase 2. The following figure summarizes the meaning of the intermediate parameters used in the LEM model:

- The null differential pressure point: $z_0 = -\ 5.21$ m
- The critical point allowing equilibrium of moments: $z_c = -12.00$ m
- The available wall embedment depth as of point $z_0$: $f_b = z_0 - z_p = 8.29$ m
- The critical embedment depth allowing equilibrium of moments: $f_0 = z_0 - z_c = 6.79$ m




The following figure provides the details of the check of the passive earth pressures for this phase. In the present case, we have $f_b = 1.22\ f_0$. The wall embedment depth is thus optimum for the passive earth pressure safety check.

This verification is supplemented by that of the counter passive earth pressure: the aim is to check that the counter passive earth pressure available (Cm,d) below the transition point $z_n$ (= -11.03 m here) is greater than that required for equilibrium of forces (Ct,d). This condition is equivalent to that of a mobilisation factor α ≤ 1. It is met in the case of this example.



### D.3.3.3. Vertical equilibrium

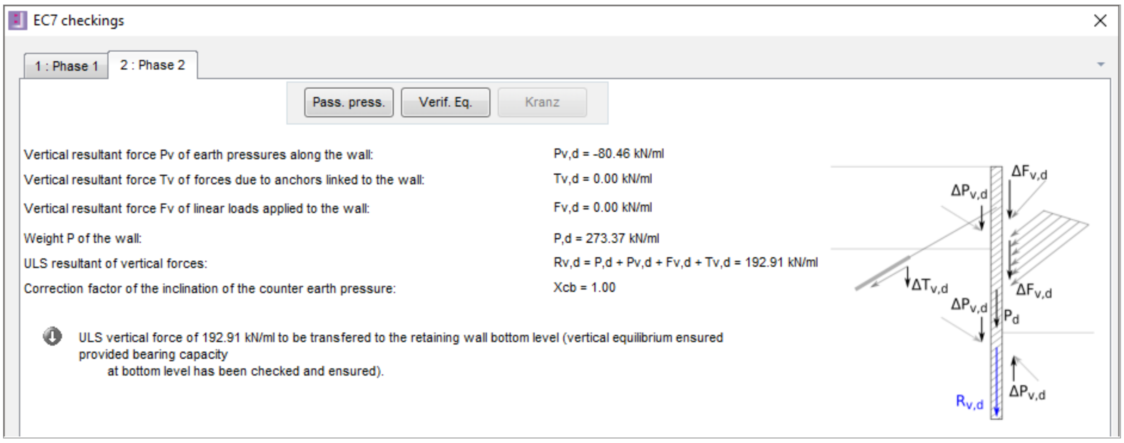
Still in “ULS checks” now click “Vert. eq.” to access the verification of the vertical forces equilibrium. This verification has a dual purpose:

- To examine the relevance of the assumptions considered for the active/passive earth pressures;
- To examine the wall bearing capacity as a deep foundation element: it is the responsibility of the user to check that the stress at the base of the wall is compatible with the soil resistance.

As shown in the following figure, this verification involves the following intermediate parameters:

- Vertical resultant force of earth pressures: $P_{v,d}$ = 81 kN/ml;
- Vertical resultants of external forces $F_{v,d}$ and of anchors $T_{v,d}$: null in the present exercise;
- Weight of the wall: $P_{,d}$ = 1.35 x 13.5 x 15 = 273 kN/ml

All of these forces are expressed in calculation values. In particular in the context of approach 2, the weight of the wall is multiplied by 1.35.



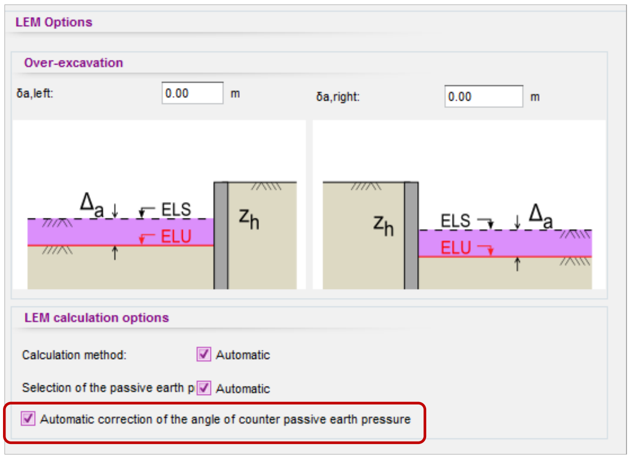

The above window also shows a factor Xcb, known as the “Correction factor of the inclination of the counter earth pressure” the meaning of which will be detailed in the next chapter.

## D.3.4. Parametric study

The subject of this chapter is to illustrate the role played by each of the “LEM Options” in the context of a cantilever wall. **The following paragraphs are to be dealt with independently**.

### D.3.4.1. Correction of active/passive earth pressure angles

In this paragraph, we will look at the “automatic correction of the angle of counter passive earth pressure” option (accessible from the “LEM options” action, which appears automatically for each phase declared to be “Cantilever”).



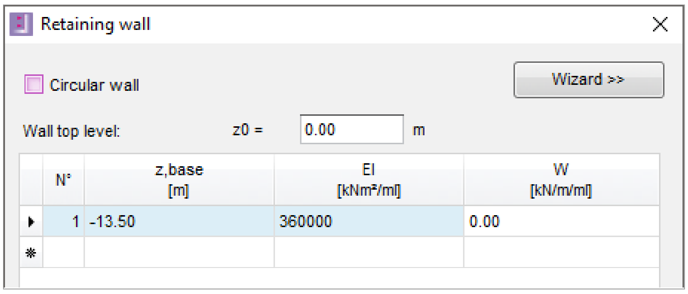

This option allows automatic readjustment of the counter passive earth pressure angles if the vertical equilibrium verification leads to an upwards resultant. The counter earth pressure angle considered in the calculation is as follows:

$$(\delta/\varphi)_{\text{counter passive earth pressure}} = Xcb \times (\delta/\varphi)_{\text{passive earth pressure}}$$

The Xcb factor has an initial value of 1.00 and is then gradually reduced (if necessary) until a downwards vertical resultant is obtained. The process stops in any case when Xcb reaches the value of -1.00. It should be noted that the modification of the angle of counter passive earth pressure involves that of the counter passive earth pressure coefficients $k_{p,cb}$ and $k_{pc,cb}$ which are used in the calculation of the counter passive earth pressure available below transition point $z_n$. These coefficients are automatically recalculated by the programme using the “reference” calculation method designated by the user (by default “Kérisel and Absi”).

In the previous exercise, the vertical verification led to a downwards resultant with Xcb = 1. The fact of obtaining Xcb = 1.00 implicitly means that no correction of the counter passive earth pressure angles was considered to be necessary by the programme.

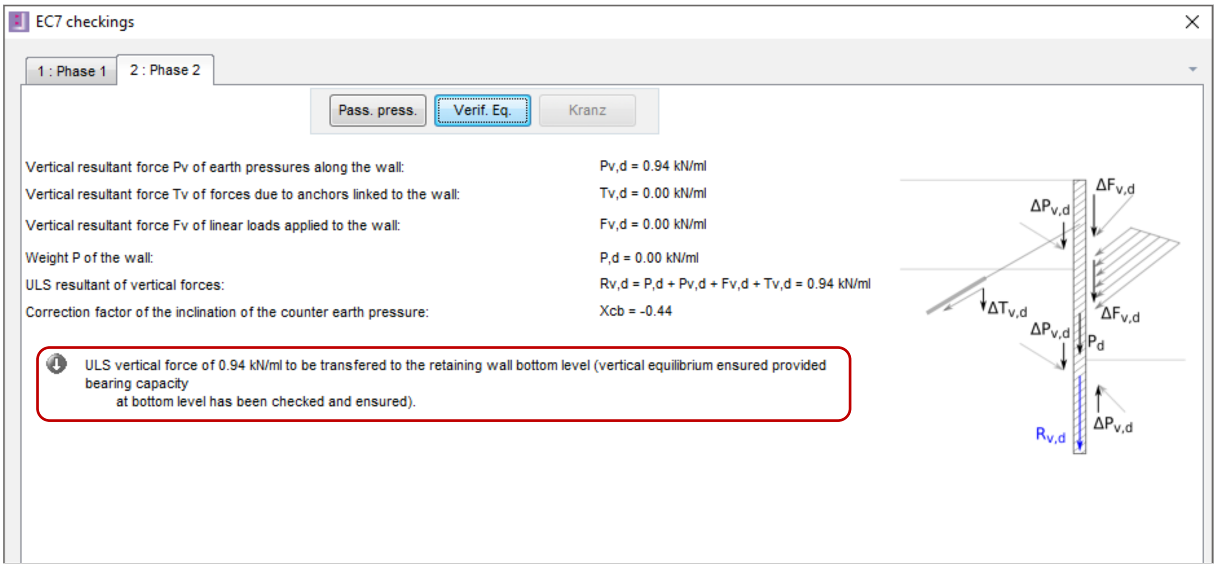
In order to illustrate the effect of this automatic correction, we propose restarting the wall calculation, ignoring its own weight. To do this, go to the “Data” menu and click “Retaining wall”: then set W = 0.




Restart the calculation and directly access the “EC7 checkings” / “Verif. Eq.”.

Let us examine the case of phase 2 for example. The value obtained for Xcb is -0.44 < 0. It should be recalled that, in this exercise, the angle of the passive earth limit pressures was taken at -2/3φ (upwards). Obtaining a negative value for Xcb therefore means that the automatic correction process led to the counter passive earth pressure being directed downwards with an angle of -0.44 x -2/3φ = + 0.29φ for the levels situated below the transition point $z < z_n = -11.04$ m.




By accessing the “Passive earth pressure safety check”, it can be checked that the available counter passive earth pressure resultant Cm,d below the transition point has changed (dropped) by comparison with the initial calculation result:

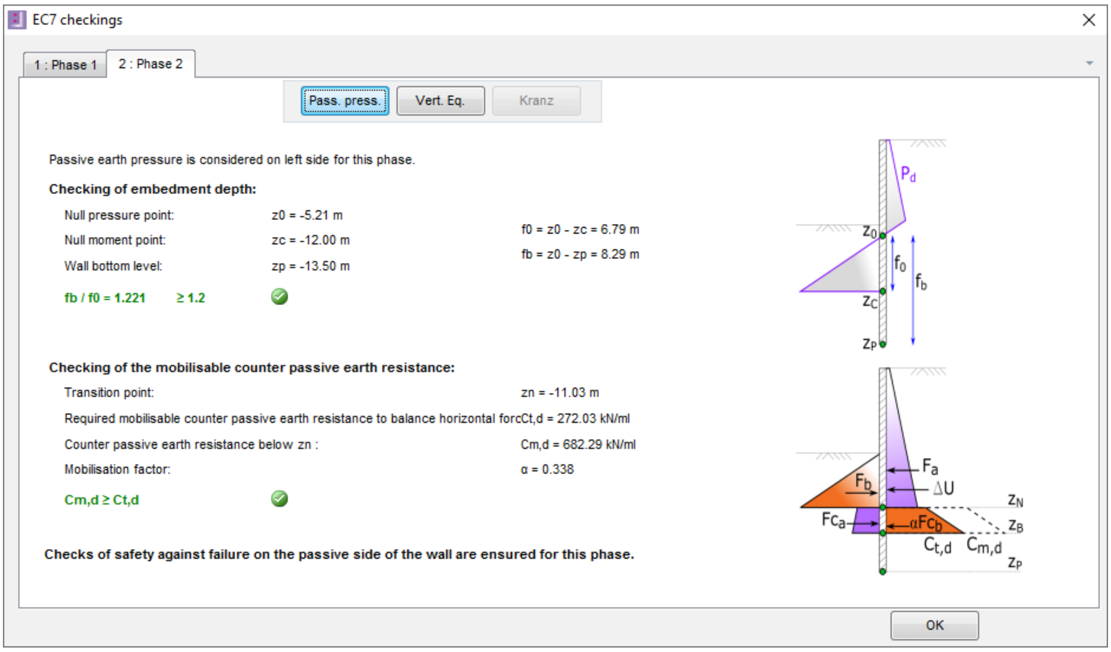
- With the weight of the wall:

$$Xcb = +1.00 \text{ and } C_{m,d} = 1138 \text{ kN/ml}$$

- With the weight of the wall:

$$Xcb = -0.44 \text{ and } C_{m,d} = 682 \text{ kN/ml}$$

The reduction in $C_{m,d}$ can be explained by the programme reassessing the limit counter passive earth pressure coefficients $k_{p,cb}$: $k_{p,cb}$ ($\delta/\varphi = +0.29$) < $k_{p,cb}$ ($\delta/\varphi = -0.66$).



### D.3.4.2. Comparison of LEM models "F" and "D"

In this paragraph, we propose comparing the calculation scenarios proposed by K-Réa for a limit equilibrium calculation (LEM).

**Caution**: when carrying out this parametric study, one must start with the basic model.

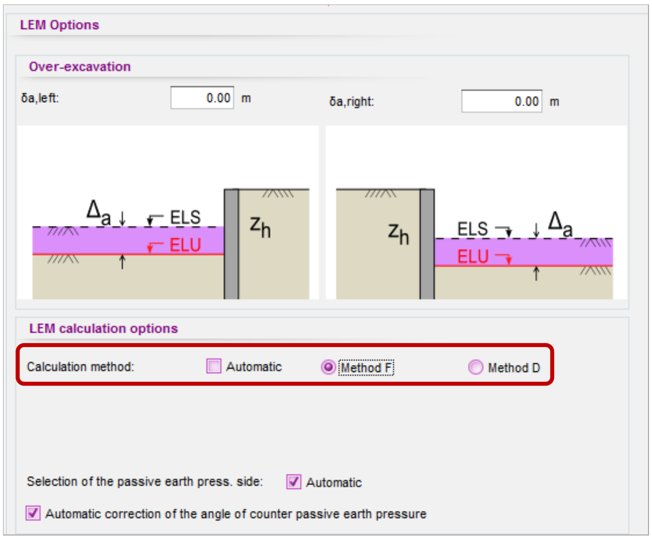
K-Réa proposes two calculation methods:

- Method F: this is based on the assumption of a counter passive earth pressure comparable to a uniform additional pressure applied between levels $z = z_c + 0.2f_0$ and $z = z_c - 0.2f_0$. The value of this additional pressure is sought so that limit equilibrium between the forces is obtained;
- Method D (default choice): this is based on the assumption of a counter passive earth pressure calculated as a fraction α of the mobilisable (or limit) counter passive earth pressure below transition point $z_n$. The values of α and $z_n$ are sought simultaneously so as to obtain the (limit) equilibrium of the moments and forces over the height of the wall (two equations, two unknowns).

The "effective" level $z_{eff}$ of the base of the wall considered in the calculation differs from one method to the other:

- LEM – F: $z_{eff} = z_c - 0.2f_0$;
- LEM – D, three options are available:
  - $z_{eff} = z_{base}$ (default option);
  - $z_{eff} = z_c - 0.2f_0$;
  - $z_{eff} = z_{user}$ (imposed by the user).

Go to "LEM option" in phase 2 and untick the "Automatic" box in "Calculation method", then select "Method F".

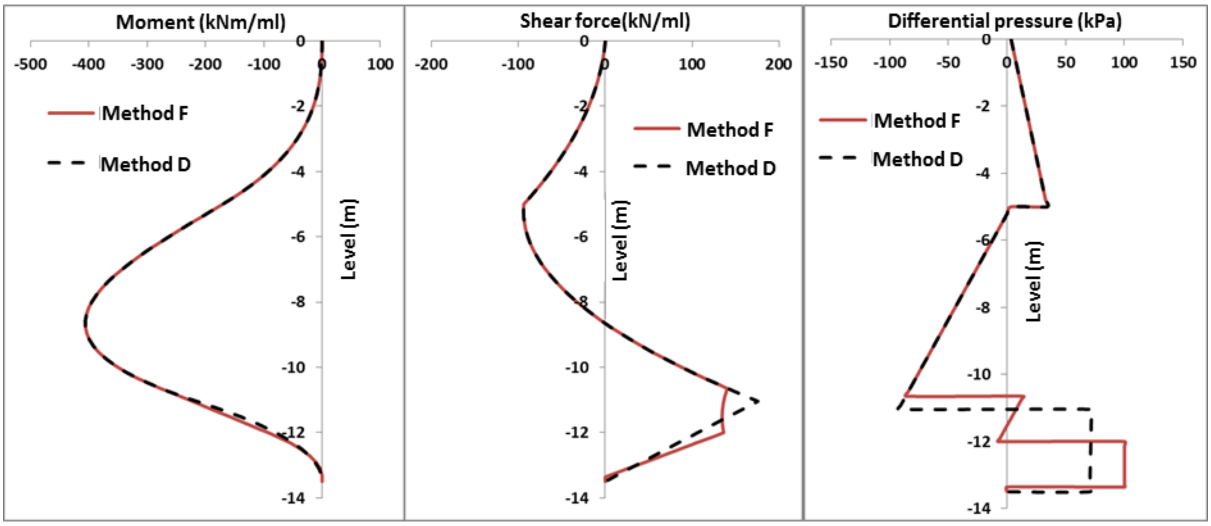



Start the calculation and compare the results obtained (moment diagrams, details of ULS checks) with those of a LEM-D calculation. The following table summarises this comparison.

| | $M_{max}$ (kNm/ml) | $V_{max}$ (kN/ml) | $z_c$ (m) | $z_n$ (m) | $f_0$ (m) | $C_{m,d}$ (kN/ml) | $C_{t,d}$ (kN/ml) |
|---|---|---|---|---|---|---|---|
| Method F | 406 | 140 | -12.00 | - | 6.79 | 645 | 272 |
| Method D | 406 | 176 | -12.00 | -11.04 | 6.79 | 1138 | 272 |

The two methods lead strictly to the same maximum moment, at the same critical point and therefore the same critical embedment depth $f_0$. The resultant of the mobilised passive earth pressure (that necessary to balance the forces) is identical with the two approaches.
However, the calculation height for the counter passive earth pressure differs owing to the construction of the two methods, hence a difference in the value of the mobilisable passive earth pressure $C_{m.d}$. We also observe a difference in the shear force which can be explained by the approximation made with method F on the "uniform" distribution of the additional counter passive earth pressure.

The following graphs compare the diagrams of moments, shear forces and differential pressures from the two methods. They corroborate the findings in the previous table.



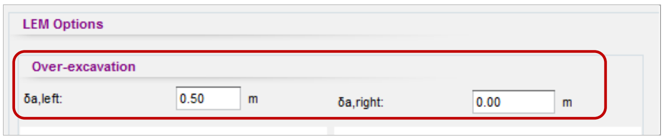
### D.3.4.3. Influence of over-excavation

In this paragraph, we will look at the "over-excavation" option in K-Réa. Taking account of over-excavation in the ULS justifications is required by the regulations if there is no strict inspection of the bottom of the excavation. In this case, it is taken as being equal to:

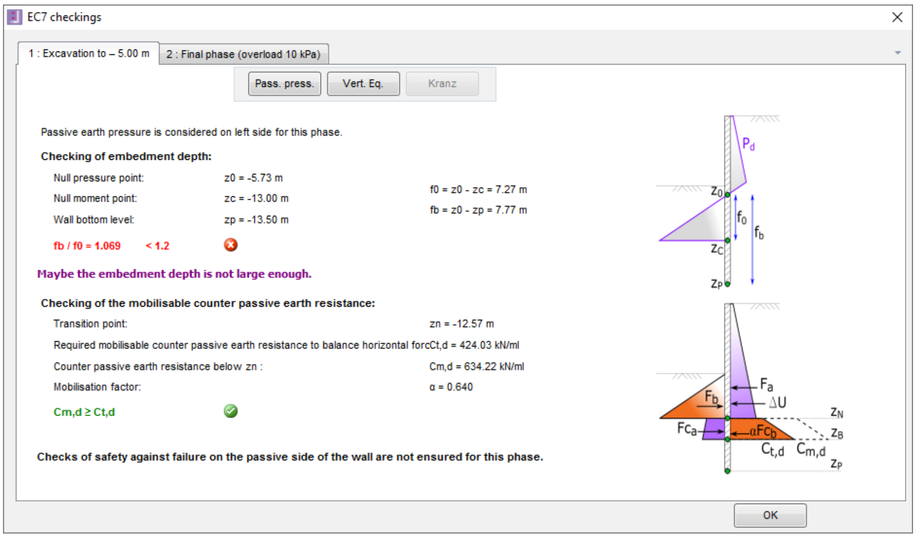
$$\Delta a_{left} = \min(50\ \text{cm};\ 10\%\ H_{supported}) = 50\ \text{cm}$$

**Caution**: when dealing with this parametric study, it is necessary to start with the basic model.

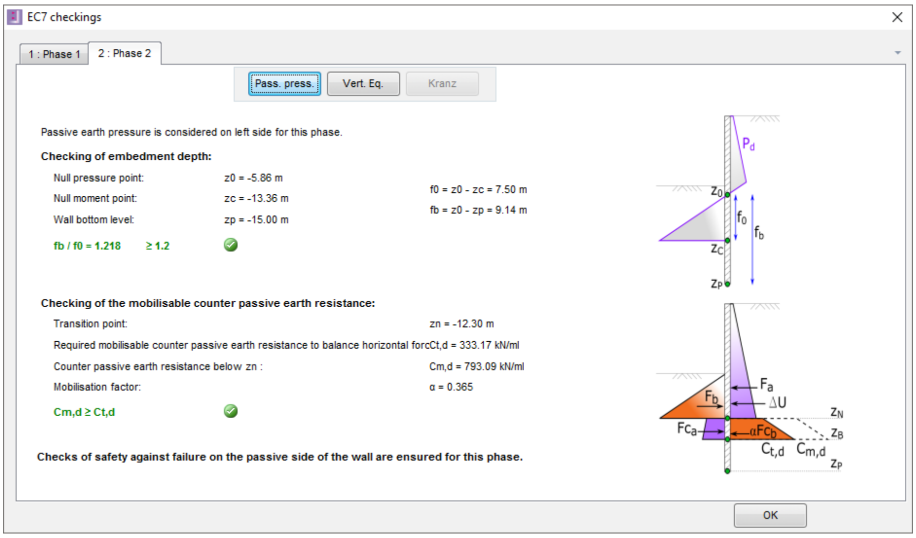
We thus propose restarting the calculation assuming an over-excavation of 50 cm on the left, in phases 1 and 2.




The result of the EC7 checkings indicates that the wall embedment depth is no longer sufficient and that an extension of the wall is therefore necessary in these conditions.




The search for the optimum embedment depth shows that the verification of the passive earth pressure safety check taking account of an over-excavation of 0.5 m requires extension of the wall by 1.50 m by comparison with the length initially validated in the absence of over-excavation. The result obtained with a wall base at -15.00 is presented below.



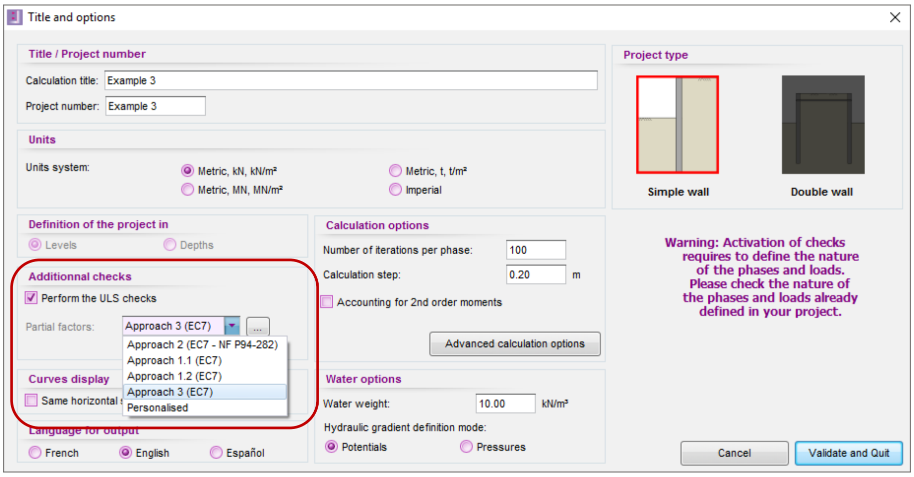
### D.3.4.4. Comparison of calculation approaches 2 and 3

The previous ULS results were obtained by applying approach 2 required by the French standard for ULS – GEO and ULS – STR verifications.

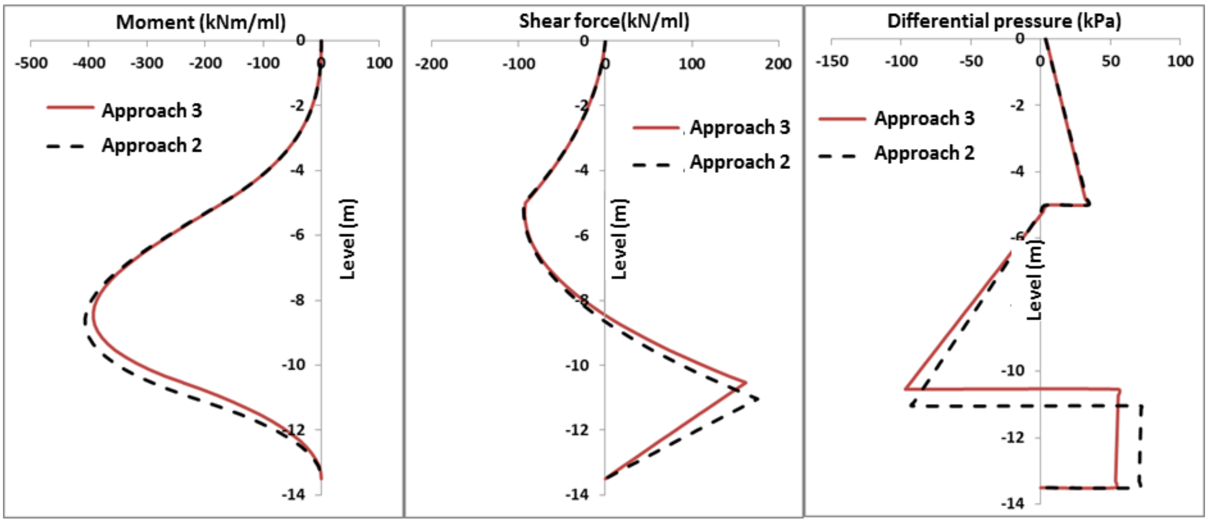
We propose comparing the previous results with those taken from application of approach 3 in Eurocode 7 (applied by other European countries). To do this, simply go to “Title and options” and select approach 3 from the “Partial factors” drop-down list.

**Caution**: when dealing with this parametric study, it is necessary to start with the basic model.

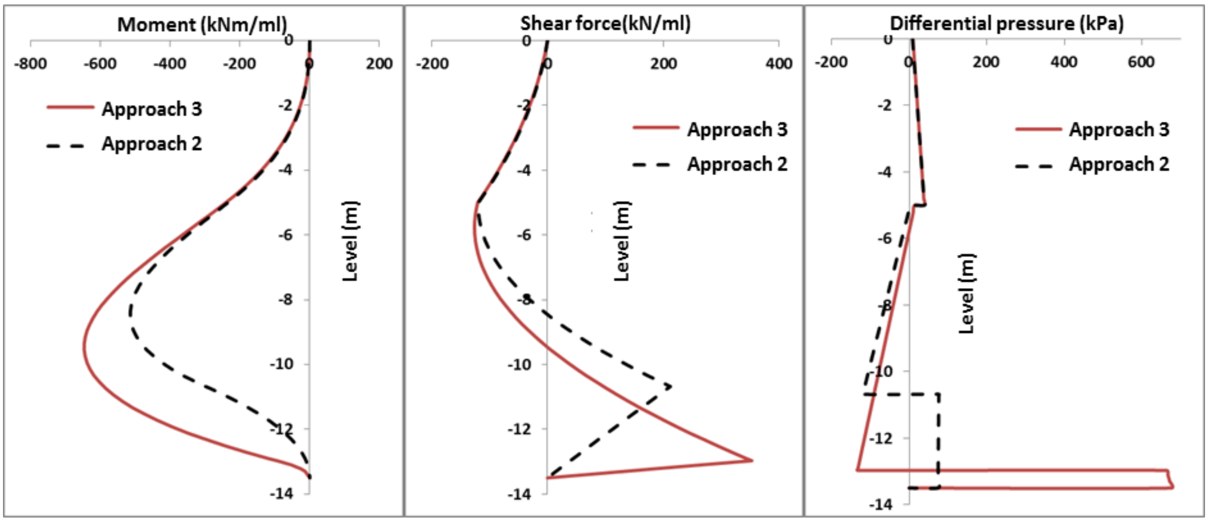
Then restart the calculations and compare the results with those obtained previously.




The following graphs illustrate this comparison for phase 2, in which the two approaches would appear to lead to comparable results for a “permanent” phase.




However, approach 3 is unable to differentiate the transitory phases from the permanent phases (approach 2 considers a smaller safety margin on the passive earth pressure in the case of a transitory phase). The comparison with approach 2 in phase 1 (transitory) therefore gives diverging results. Approach 3 leads to more unfavourable results.



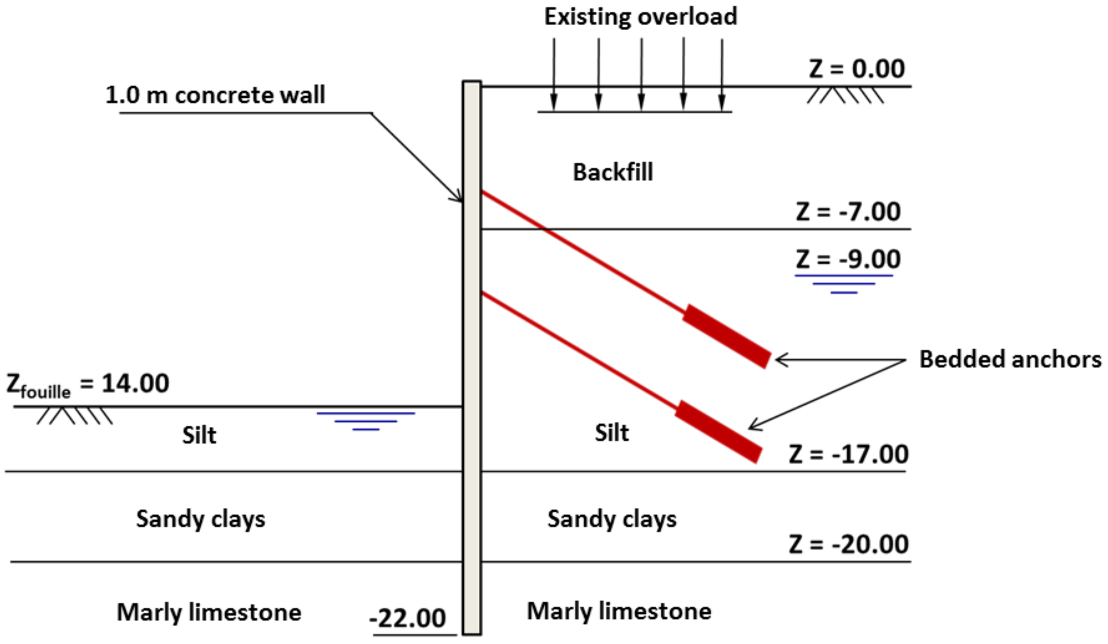
Moment (kNm/ml)
-800
-600
-400
-200
0
200
Approach 3
Approach 2
Level (m)
0
-2
-4
-6
-8
-10
-12
-14
Shear force(kN/ml)
-200
0
200
400
Approach 3
Approach 2
Level (m)
Differential pressure (kPa)
-200
0
200
400
600
Approach 3
Approach 2
Level (m)

# D.4. Tutorial 4: Excavation with anchors and stability of anchor block

This example presents the calculation of a diaphragm wall 1.0 m thick, which descends to a depth of 22 m and is anchored by two layers of bedded anchors angled 30° from the horizontal.

The length of the bedding of the anchors is set at 10 m. The mesh of the lower anchors is about 1.50 times denser than that of the upper anchors. We initially assume a free length of 7 m for all the anchors, which corresponds to a "useful" length of 7 + 10/2 = 12 m.

The following figure gives a schematic representation of the geometry of the problem studied.



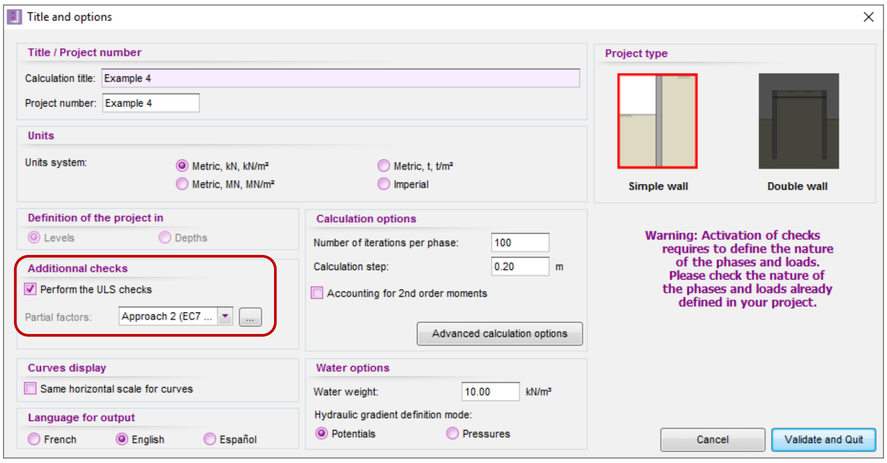

This example mainly aims to demonstrate the K-Réa functionalities linked to the ULS checks according to EC7, more specifically with regard to the stability of the anchor block in the case of a wall anchored by one or more layers of bedded anchors.

## D.4.1. Data input

To start K-Réa:

- Double-click the **K-Réa** icon.
- Choose the appropriate protection mode, keep the select the appropriate language (**French**) and click **OK.**
- Choose **New project** to access the **Title and Options** page.

### D.4.1.1. Title and options




- In the **Project type** frame (right), select “Simple wall”.
- In the **Title / Project number** frame, click on the blank “Title” line and enter the title of your choice.
  Click on the blank “Project number” line to enter the number of your choice.
- In the **Units** frame, choose the units system of your project, by ticking ‘Metric. kN. kN/m$^2$’.
- Choose **Definition of the project in** Levels, which enables the vertical axis to be directed **upwards.**
- **Additional checks**: tick the “Perform the ULS checks” box to activate the calculation at the ultimate limit states for this example.
- In the **Curves display** frame, keep the ”Same horizontal scale for curves” box ticked.
- Choose the **Language for output**.
- In the **Calculation options** frame, keep the default settings: 100 iterations per calculation phase and a calculation step of 0.2 m for the wall.
- In the **Water options** frame, leave the water weight equal to 10.00 kN/m³. Choose Potentials as the definition mode for the hydraulic gradient
- Click the Validate and Quit button.
- K-Réa then asks you to save the new project: define the name and directory.

### D.4.1.2. Definition of soil layers

The general characteristics of the 4 layers of interest for the exercise are summarised in the following table.

| Layer | $\gamma$ (kN/m$^3$) | $\gamma'$ (kN/m$^3$) | $\varphi$ (°) | c (kPa) | dc (kN/m²/ml) | $\delta_a/\varphi$ (-) | $\delta_p/\varphi$ (-) | $E_M$ (MPa) | $\alpha$ (-) |
|---|---|---|---|---|---|---|---|---|---|
| Backfill | 18 | 10 | 30 | 0 | 0 | 0.66 | -0.66 | 10 | 0.50 |
| Silt | 20 | 10 | 35 | 0 | 0 | 0.66 | -0.66 | 20 | 0.33 |
| Sandy clays | 20 | 10 | 28 | 0 | 0 | 0.66 | -0.66 | 8 | 0.67 |
| Marly limestone | 22 | 12 | 30 | 40 | 0 | 0.66 | -0.66 | 40 | 0.50 |

Then use the K-Réa wizards to calculate the parameters for constituting the behaviour law for each layer.

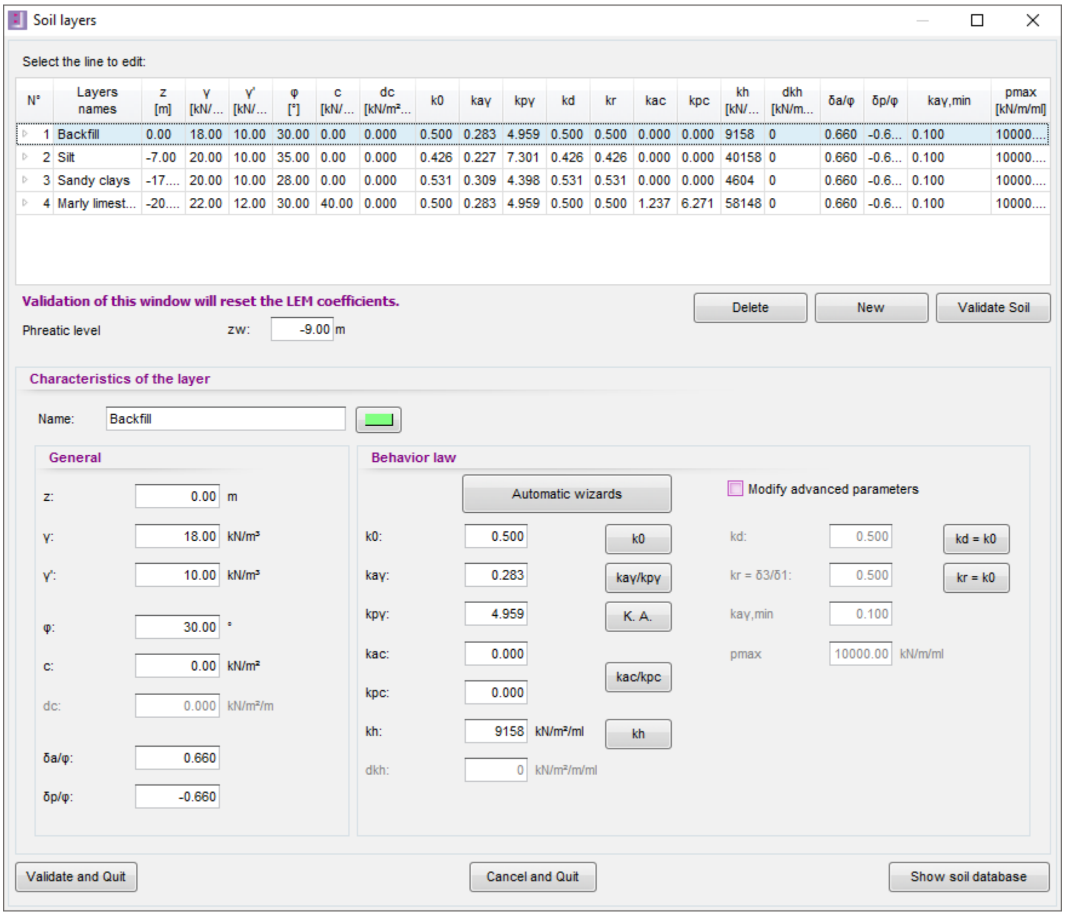
The reaction coefficient $k_h$ is evaluated using the Schmitt model, considering a product of inertia EI = 1 667 MNm²/ml (calculated for a continuous wall 1m thick, with E = 20 GPa).

The parameters obtained using the wizards are as follows.

| Layer | $k_0$ (-) | $k_{a\gamma}$ (-) | $k_{p\gamma}$ (-) | $k_{ac}$ (-) | $k_{pc}$ (-) | $k_h$ (kN/m$^3$) |
|---|---|---|---|---|---|---|
| Backfill | 0.500 | 0.283 | 4.959 | 0 | 0 | 9 158 |
| Silt | 0.426 | 0.227 | 7.301 | 0 | 0 | 40 158 |
| Sandy clays | 0.531 | 0.309 | 4.398 | 0 | 0 | 4 604 |
| Marly limestone | 0.500 | 0.283 | 4.959 | 1.237 | 6.271 | 58 148 |

The other values keep their default values. For this, leave the **Modify advanced parameters** box unticked.

The following screenshot illustrates that of K-Réa following these operations:



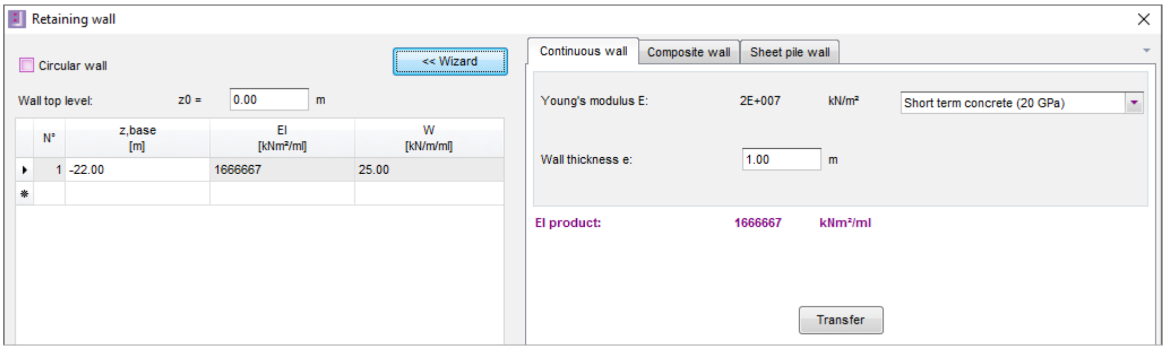

Click Validate and Quit.

### D.4.1.3. Retaining wall

After validating the characteristics of the layers, those of the wall must be defined:

- Wall top level: $z_0$ = +0.00 m
- Wall bottom level: $z_{base}$ = -22.0 m
- Product of inertia: EI = 1 666 667 kNm²/ml
- Weight per unit area: W = 25 kN/m/ml

The following screenshot illustrates the previous operations:



## D.4.2. Definition of phasing

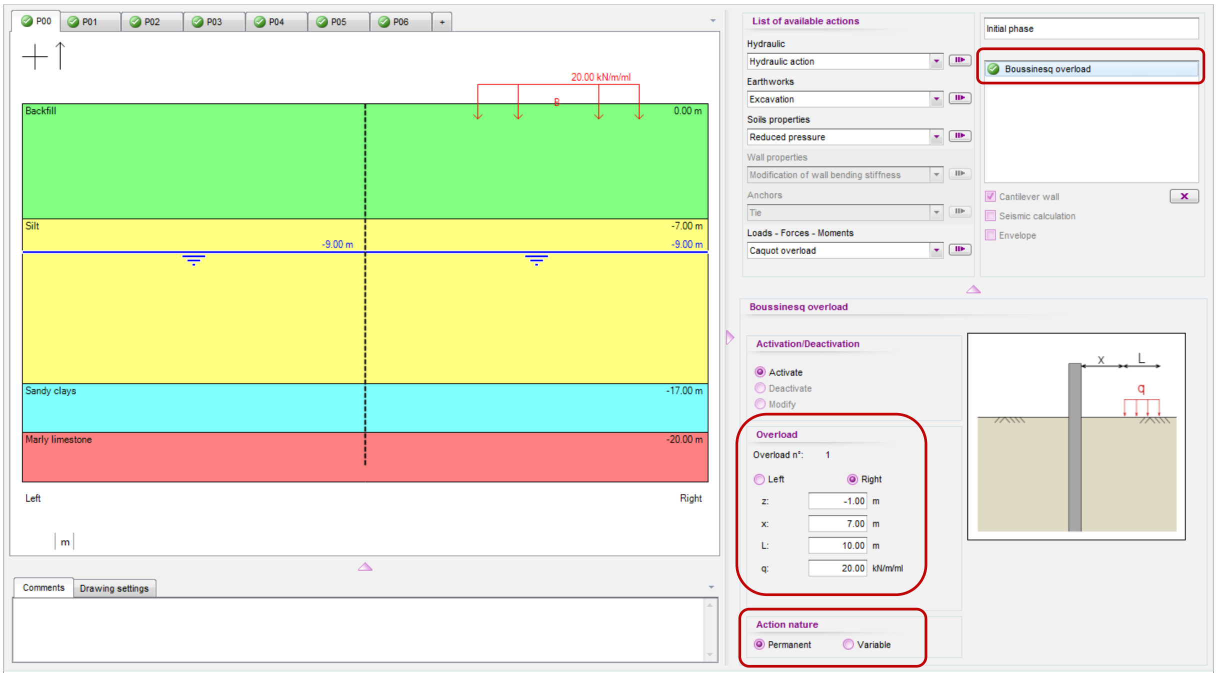
We must now define the actions to be considered in each construction phase. These actions are summarised in the following table.

| PHASE | ACTIONS |
|---|---|
| **Initial** | • Existing Boussinesq overload of 20 kN/m/ml |
| **Phase 1 - Transitory** | • Excavation to level -5.00 m |
| **Phase 2 - Transitory** | • First layer of active anchors at -4.00 m |
| **Phase 3 - Transitory** | • Excavation to level -9.00 m |
| **Phase 4 - Transitory** | • Second layer of active anchors at -8.00 m |
| **Phase 5 - Permanent** | • Excavation to level -14.00 m |
| **Phase 6 - Permanent** | • Wall creep (E = 10 GPa) |

### D.4.2.1. Initial phase

In this phase, we define an initial localised overload representative of an existing building. Define the following:

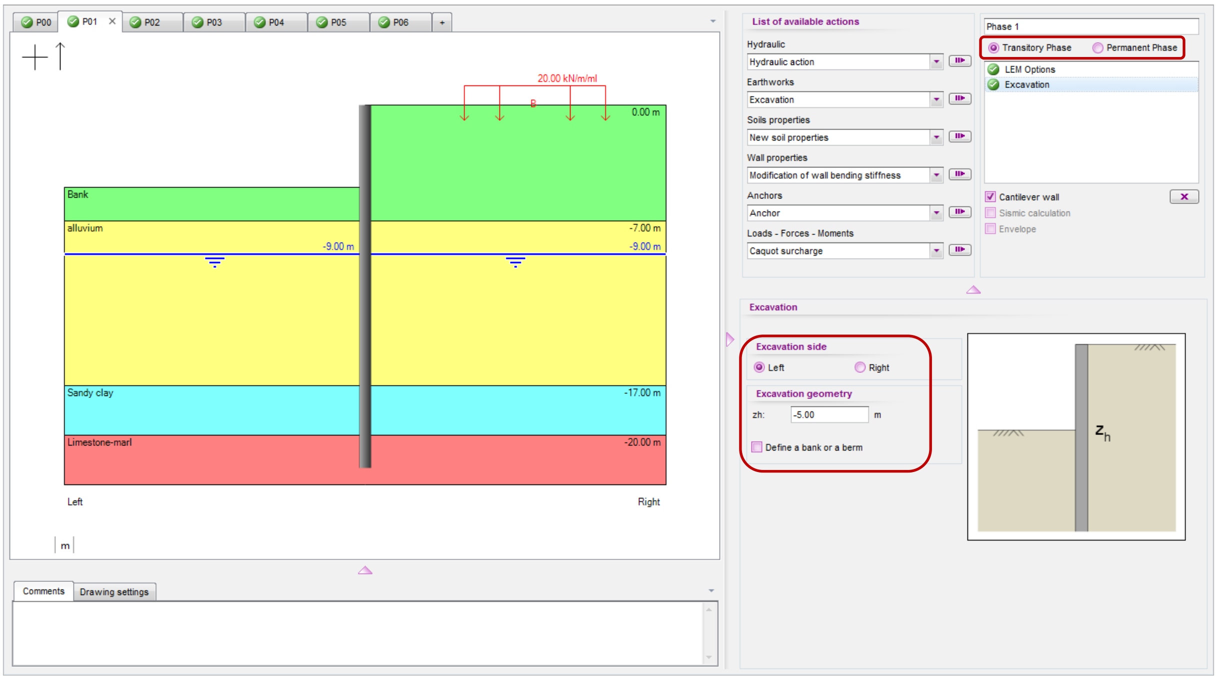
- Boussinesq overload action with
  - z = -1.00 x = 7.00 m
  - L = 10 m q = 20 kN/m/ml
  - Permanent action nature



### D.4.2.2. Phase 1: Excavation to level -5.00

This phase is to be defined as a “transitory phase”. A single action is to be input:

- “Excavation” action on left with $z_h$ = -5.00;

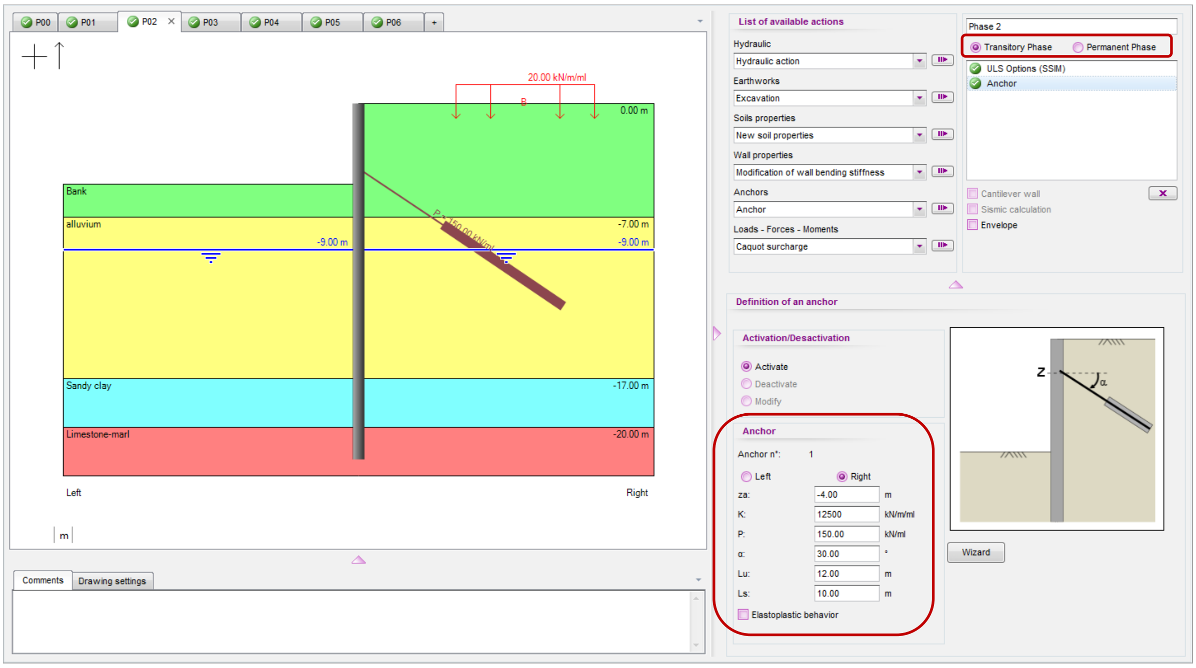



The “Cantilever wall” box is automatically ticked: the ULS equilibrium of the wall will thus be checked by a “LEM” model in this phase.

### D.4.2.3. Phase 2: Anchors at level -4.00

This phase is to be defined as a “transitory phase”. A single action is to be input:

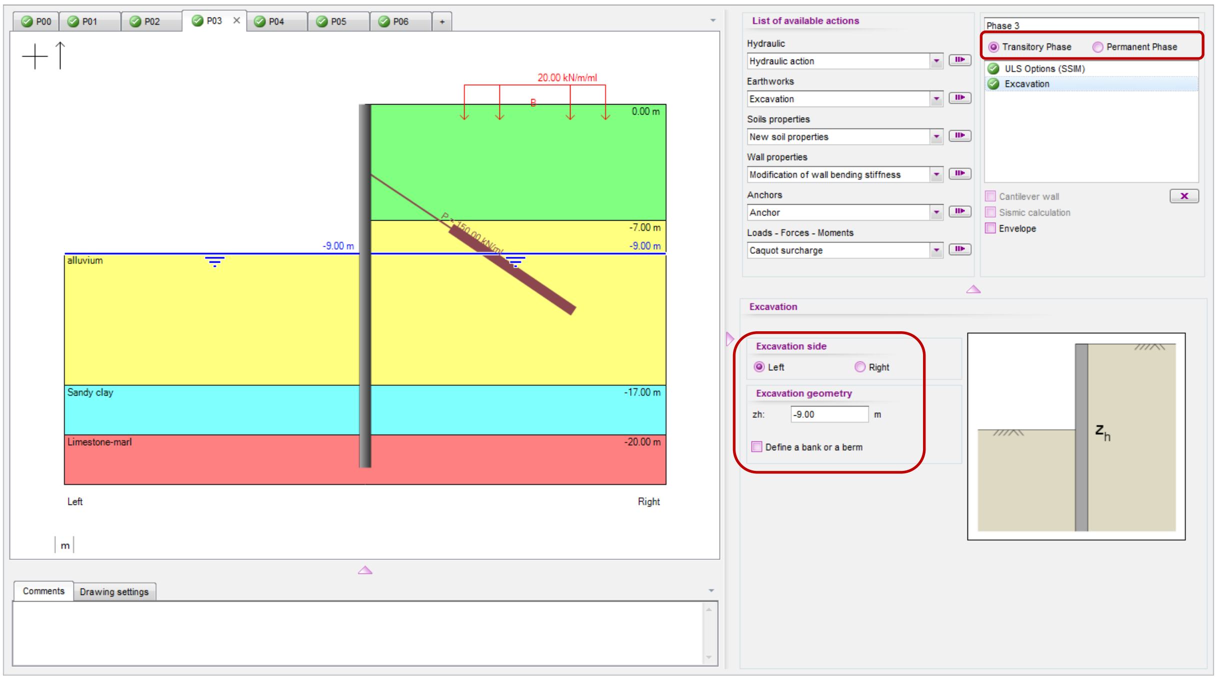
- “Anchor” action to the right at za = -4.00 with:
  - K = 12 500 kN/m/ml P = 150 kN/ml α = 30° Lu =12 m Ls = 10 m



### D.4.2.4. Phase 3: Excavation to level -9.00

This phase is to be defined as a “transitory phase”. A single action is to be input:

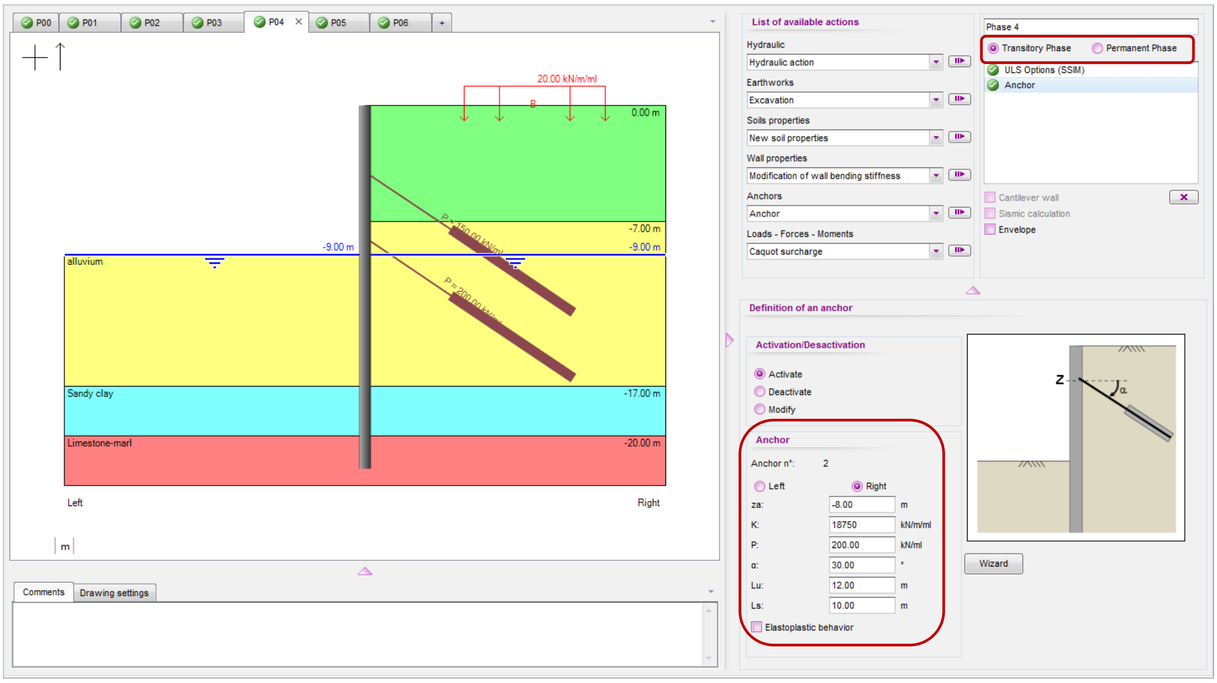
- “Excavation” action on left with $z_h$ = -9.00




### D.4.2.5. Phase 4: Anchors at level -8.00

This phase is to be defined as a “transitory phase”. A single action is to be input:

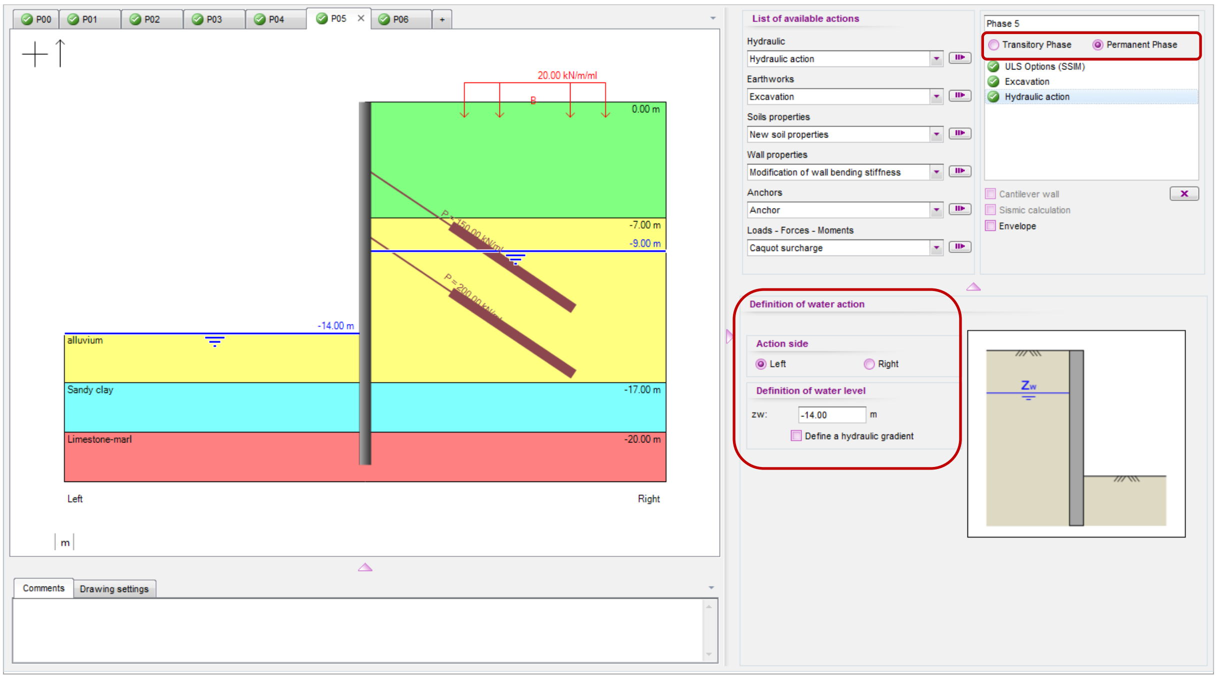
- “Anchor” action on the right at $z_a$ = -8.00 with:
  - K = 18 750 kN/m/ml P = 200 kN/ml α = 30° Lu =12 m Ls = 10 m



### D.4.2.6. Phase 5: Excavation to level -14.00

This phase is to be defined as a "permanent phase". Two actions are to be input:

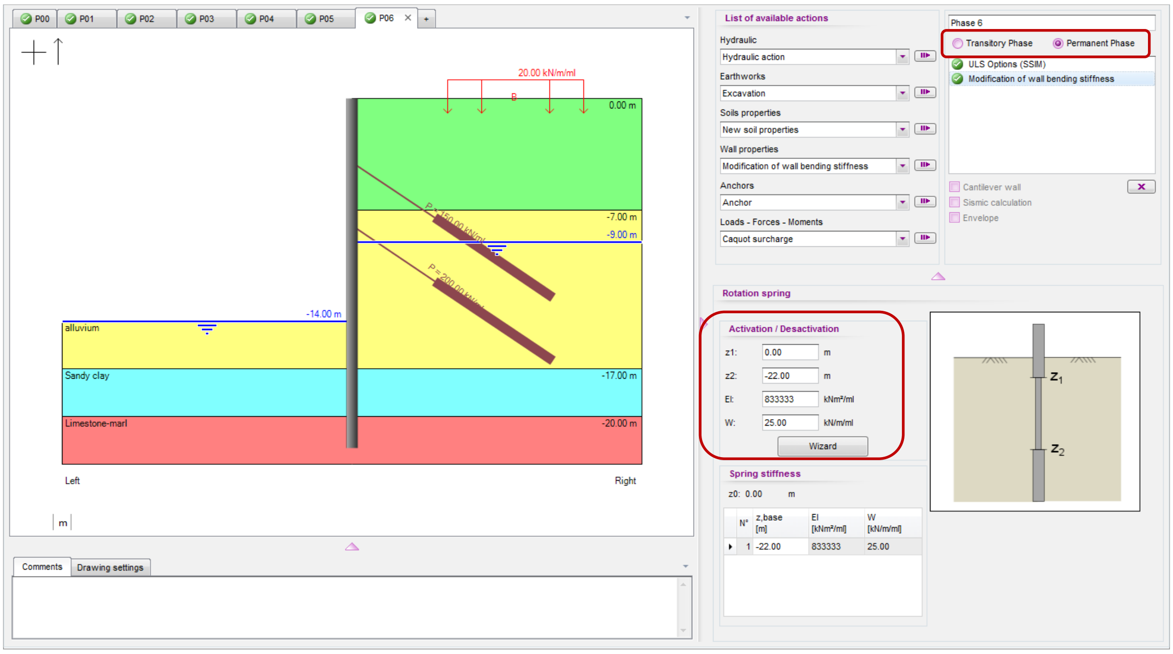
- "Excavation" action with $z_h$ = -14.00 on left;
- "Hydraulic" action" with $z_w$ = -14.00 on left (no gradient).




### D.4.2.7. Phase 6: Wall creep

This phase is also defined as a "permanent phase" and aims to simulate the creep of the wall. A single action is thus to be defined:

- "Modification of wall stiffness" action with:
  - z1 = 0.00     z2 = -22.00     EI = 833 333 kNm²/ml     W = 25 kN/m/ml



## D.4.3. Calculation and results

### D.4.3.1. General overview

For each phase, K-Réa proposes two types of results:

- SLS results: displacements, SLS loadings and anchor reactions at SLS;
- ULS results: with or without displacements (if LEM calculation). The ULS loadings are expressed in calculation values and in characteristic values (if MISS calculation).

The following figures give a summary of the results obtained at SLS and ULS.

The maximum ULS moment in the wall reaches Md = 1 270 kNm/ml in phase 5. The maximum normal force for its part reaches Nd =1209 kN/ml in this same phase. The maximum displacement (at SLS) reaches 2.4 cm at -12.80 AOD following wall creep (less than 2 cm if creep not taken into account). Displacement at the top remains less than one centimetre.

The anchor force reaches 574 kN/ml for the lower anchors layer and 279 kN/ml for the upper layer. These values, expressed in ml (linear metres) must then be multiplied by the spacing between anchors to obtain the force per anchor element.

The summary of the ULS results also indicates that the verification of the passive earth pressure safety check is confirmed for all phases (sufficient embedment depth) and that the vertical equilibrium at the base of the wall leads to a downwards resultant.

It should however be noted that the stability of the anchor block (Kranz) is not demonstrated for phases 5 and 6, which means that the free length of the anchors is insufficient.

Results

Data | Results synthesis | Envelope phases 1 to 6 | 1 : Excavation to -5.00 | 2 : Anchors at -4.00 | 3 : Excavation to -9.00 | 4 : Anchors at -8.00 | 5 : Excavation to -14.00 | 6 : Wall creep

Type: (•) SLS ( ) ULS

| PHASE N° | Displacement Head [mm] | Displacement maximal [mm] | Moment maximal [kNm/ml] | Shear force maximal [kN/ml] | Ratio Earth ressist. | Characteristic force tie n°1 [kN/ml] | Characteristic force tie n°2 [kN/ml] |
|---|---|---|---|---|---|---|---|
| 1 | -8.78 | -8.78 | -287.54 | -72.01 | 9.040 | - | - |
| 2 | -7.05 | -7.05 | -200.71 | -96.73 | 9.262 | 150.00 | - |
| 3 | -7.50 | -7.50 | -200.38 | 119.94 | 5.237 | 167.84 | - |
| 4 | -7.37 | -7.37 | 172.71 | 114.87 | 5.441 | 161.85 | 200.00 |
| 5 | -3.87 | -18.87 | 936.42 | 314.81 | 2.133 | 206.49 | 394.68 |
| 6 | -3.05 | -24.52 | 766.33 | 312.19 | 2.088 | 201.93 | 424.67 |
| Extrema | -8.78 | -24.52 | 936.42 | 314.81 | 2.088 | 206.49 | 424.67 |

Results

Data | Results synthesis | Envelope phases 1 to 6 | 1 : Excavation to -5.00 | 2 : Anchors at -4.00 | 3 : Excavation to -9.00 | 4 : Anchors at -8.00 | 5 : Excavation to -14.00 | 6 : Wall creep

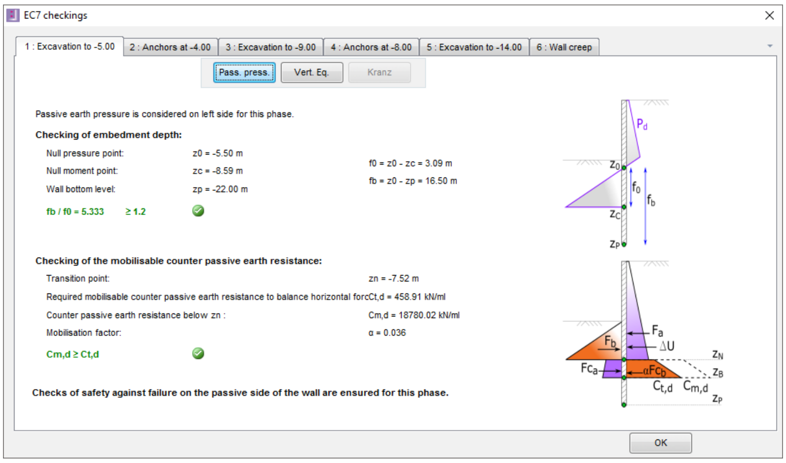
Type: ( ) SLS (•) ULS

| PHASE N° | Type | M,d maximal [kNm/ml] | V,d maximal [kN/ml] | Design force tie n°1 [kN/ml] | Design force tie n°2 [kN/ml] | Check Pass. press. | Check Vert. Eq. [kN/ml] | Check Kranz |
|---|---|---|---|---|---|---|---|---|
| 1 | LEM | -309.16 | 101.96 | - | - | OK | 648.90 | |
| 2 | SSIM | -270.95 | -130.59 | 202.50 | - | OK | 788.24 | OK |
| 3 | SSIM | -270.52 | 161.92 | 226.59 | - | OK | 858.14 | OK |
| 4 | SSIM | 233.16 | 155.08 | 218.50 | 270.00 | OK | 927.66 | OK |
| 5 | SSIM | 1264.17 | 424.99 | 278.76 | 532.82 | OK | 1105.54 | Not OK |
| 6 | SSIM | 1034.54 | 421.46 | 272.60 | 573.31 | OK | 1099.29 | Not OK |
| Extrema | | 1264.17 | 424.99 | 278.76 | 573.31 | | 1105.54 | |

### D.4.3.2. Passive earth pressure safety check

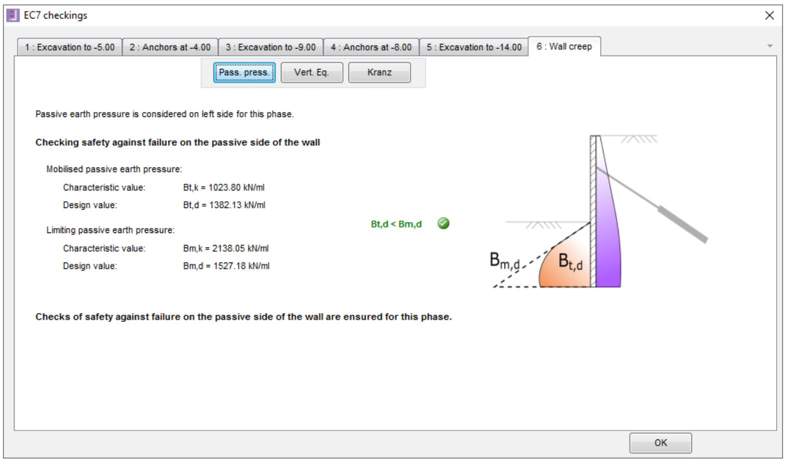
Based on the ULS results screen, for each of the phases, 3 buttons give access to detailed results of the 3 types of ULS checks. Let us first of all look at the passive earth pressure safety check.

For phase 1, the passive earth pressure safety check was checked using the LEM model, the main parameters of which are summarised in the results window (see the tutorial on "Excavation supported by cantilever wall" for more details on this model).




For the following phases (2 to 6), the wall is considered to be "anchored" and therefore the passive earth pressure safety check is based on the MISS calculation. It consists in checking that the mobilisable (or limit) passive earth pressure is greater than the mobilised passive earth pressure, with a sufficient safety margin. For example, for phase 6:

- Calculation value of mobilisable passive earth pressure: $B_{m.d}$ = 2 138 / 1.40 = 1 527 kN/ml.
- Calculation value of mobilised passive earth pressure: $B_{t.d}$ = 1 024 x 1.35 = 1 383 kN/ml < $B_{m.d}$.



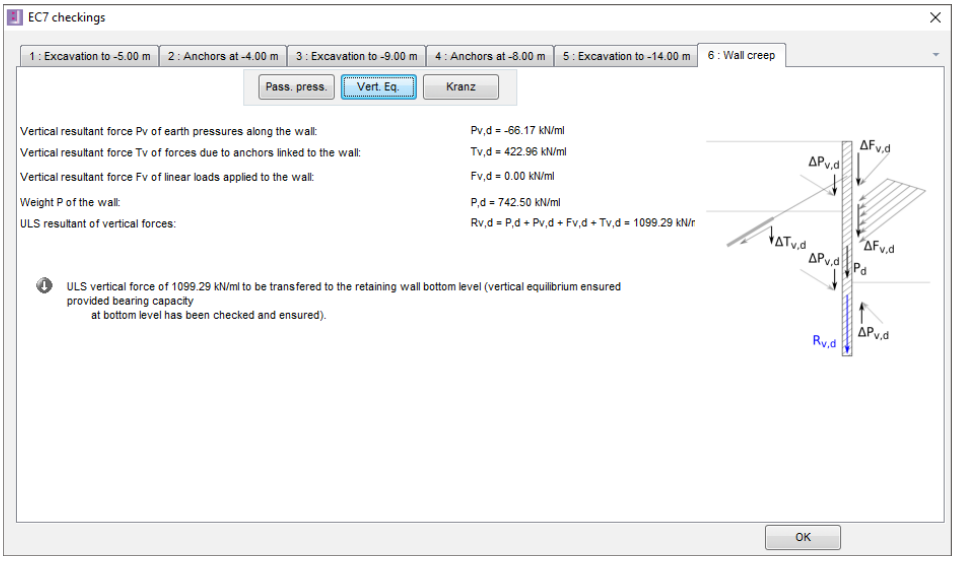

Application of a "1.40" factor to the mobilisable passive earth pressure can be explained by the fact that phase 6 (just like phase 5) is considered to be "permanent".

## D.4.4. Vertical equilibrium

The second "Verif. Eq." button gives access to the vertical balance of forces. The following figure presents the result obtained for phase 6.

The balance of vertical forces takes account of integration of the following terms over the entire height of the wall:

- The vertical component of the mobilised earth pressure. It is calculated from the horizontal equilibrium of the wall (MISS calculation);
- The vertical component of the forces in the anchors;
- Any external forces applying directly to the wall[2];
- The weight of the wall itself.



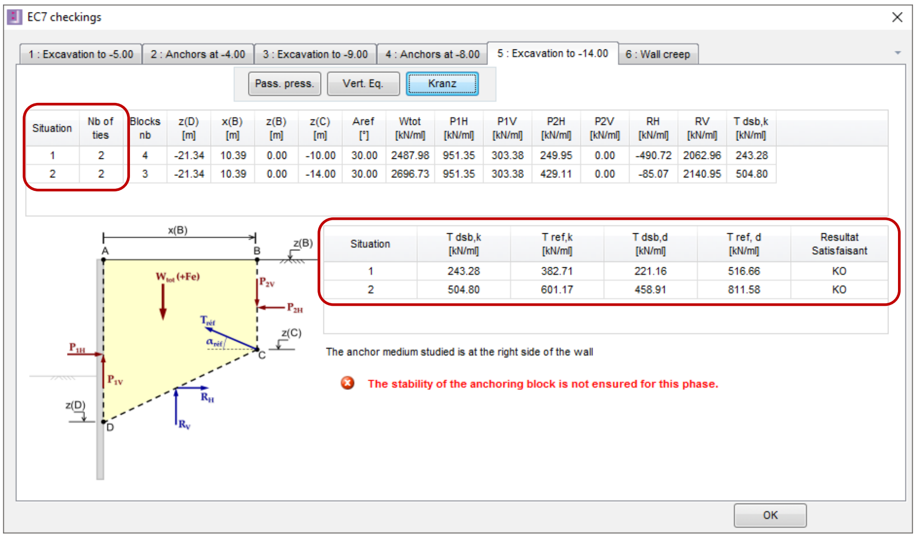

Here, for phase 6, the vertical resultant of the forces is evaluated (at ULS) at about 1 100 kN/ml, which corresponds to a base resistance of 1 100 / 1.0 = 1.1 Mpa, which is acceptable given the nature of the supporting soil (Marls with pl > 3 MPa).
It should be noted that for the case of an anchored wall (phases 2 to 6), the evaluation of the vertical component of the earth pressures along the wall is based on a "prorata" approach: for a horizontal earth pressure component which is "intermediate" (between limit active earth pressure and limit passive earth pressure), the corresponding vertical component is calculated prorata the horizontal mobilisation ratio, assuming that the vertical component is nil for a nil displacement (reference point). This is detailed and illustrated in part C of the manual. It is important to recall that this approach is only valid in the case of initially horizontal ground.

## D.4.5. Stability of anchor block (Kranz)

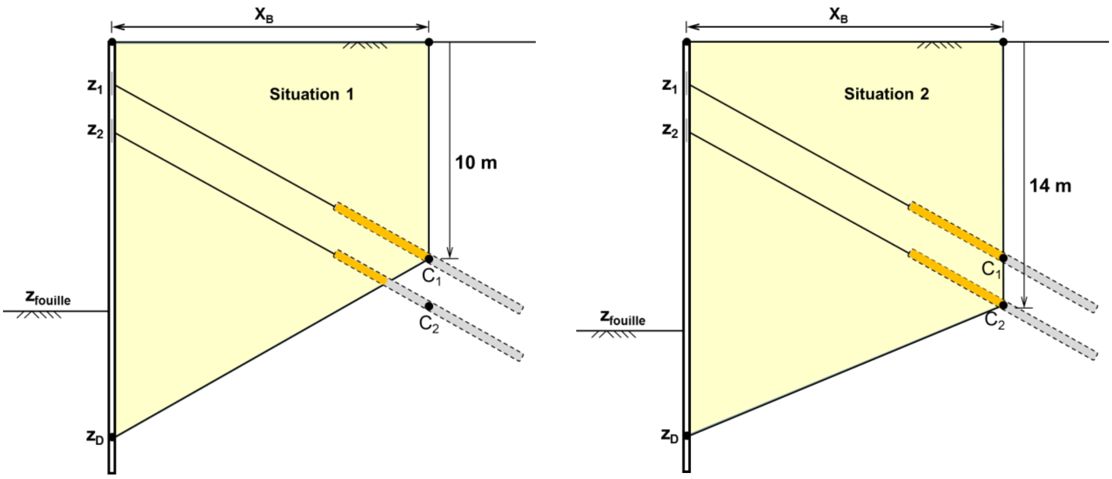
For phases 2 to 6, the presence of anchors triggers performance of an additional check, which is a check on the stability of the anchor block.

This check is performed using the "Kranz" model: for each phase, we consider several situations as necessary (corresponding to the anchor block associated with each active anchor in a given phase). Then, for each situation, the calculation takes account of one or more anchors, depending on whether their bedding zone is partly or entirely outside the anchor block in question.

For example, let us consider the case of phase 5 for which two situations are examined.




- **Situation 1** corresponding to the anchor block of the upper anchor (figure below - left). The reference anchor force considered in this situation is equal to that of anchor 1 + a part of the force of anchor 2:
    - Anchor 1:
        - ✓ The calculation value of its force is $T_{1.d}$ = 279 kN/ml;
        - ✓ Effective anchor point (middle of bedding) situated within the anchor block => force taken into account 100%;
    - Anchor 2:
        - ✓ The calculation value of its force is $T_{2.d}$ = 533 kN/ml;
        - ✓ Effective anchor point situated outside the anchor block, but a part of the bedding is inside the medium (about 2.24 m) => force taken into account prorata of 2.24 m / 5.00 m, i.e. 45%.
    - Result: the calculation value of the reference anchor force for this situation is thus $T_{ref.d}$ = (1.00 x $T_{1.d}$ + 0.45 x $T_{2.d}$) = 517 kN/ml.



- **Situation 2** corresponds to the anchor block of the lower anchor (figure above - right). The anchor points of the two anchors are situated inside the medium. The forces of the two anchors are then taken into account in full in the check, or a reference anchor force (in calculation value) for this situation of 279 + 533 = 812 kN/ml.

The stability of the anchor block is confirmed if the reference anchor force $T_{ref.d}$ thus calculated is lower than that causing destabilisation of the medium $T_{dsb.d}$ for all situations examined. In the present case, this condition is not confirmed, which reflects the insufficiency of the free length initially chosen for the anchors.

## D.4.6. Review of free length of anchors

We will now return to the previous project and increase the free length of the anchors. This was initially considered to be $L_0$ = 7 m, which corresponded to a useful length of $L_u = L_0 + L_s/2$ = 7 + 10/2 = 12 m.

We propose repeating the calculations with the following values of $L_0$, updating the value of the useful length $L_u$ and that of the stiffness K each time, for the two anchors (anchor action parameters in phases 2 and 4).

| | Free length $L_0$ | Bedding length $L_s$ | Useful length $L_u$ | $K_{upper\ anchor}$ (kN/m/ml) | $K_{lower\ anchor}$ (kN/m/ml) |
|---|---|---|---|---|---|
| Initial case (0) | 7.0 m | 10.0 m | 12.0 m | 12 500 | 18 750 |
| Case 1 | 8.0 m | 10.0 m | 13.0 m | 11 500 | 17 310 |
| Case 2 | 9.0 m | 10.0 m | 14.0 m | 9 900 | 14 835 |
| Case 3 | 10.0 m | 10.0 m | 15.0 m | 7 900 | 11 870 |

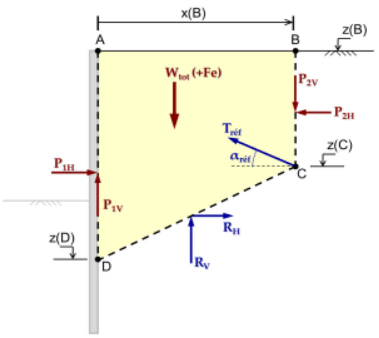
By repeating the calculations for each case above and analysing the results of the Kranz check, we can see that confirmation of the stability of the anchor block requires a free length at least equal to 10 m for the two anchors (case 3). The result obtained in this case ($L_u$ = 15 m) is presented in the following figure (phase 5).

EC7 checkings

1 : Phase 1 | 2 : Phase 2 | 3 : Phase 3 | 4 : Phase 4 | 5 : Phase 5 | 6 : Phase 6

Pass. press. | Verif. Eq. | Kranz

| Situation | Nb of anch... | Blocks nb | z(D) [m] | x(B) [m] | z(B) [m] | z(C) [m] | Aref [°] | Wtot [kN/ml] | P1H [kN/ml] | P1V [kN/ml] | P2H [kN/ml] | P2V [kN/ml] | RH [kN/ml] | RV [kN/ml] | T dsb,k [kN/ml] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 4 | -21.21 | 12.99 | 0.00 | -11.50 | 30.00 | 3233.44 | 918.70 | 314.26 | 306.10 | 0.00 | -153.52 | 2654.13 | 530.10 |
| 2 | 2 | 3 | -21.21 | 12.99 | 0.00 | -15.50 | 30.00 | 3494.62 | 918.70 | 314.26 | 498.29 | 0.00 | 377.16 | 2719.88 | 920.96 |




| Situation | T dsb,k [kN/ml] | T ref,k [kN/ml] | T dsb,d [kN/ml] | T ref, d [kN/ml] | Resultat Satisfaisant |
|---|---|---|---|---|---|
| 1 | 530.10 | 310.81 | 481.91 | 419.59 | OK |
| 2 | 920.96 | 558.86 | 837.24 | 754.47 | OK |

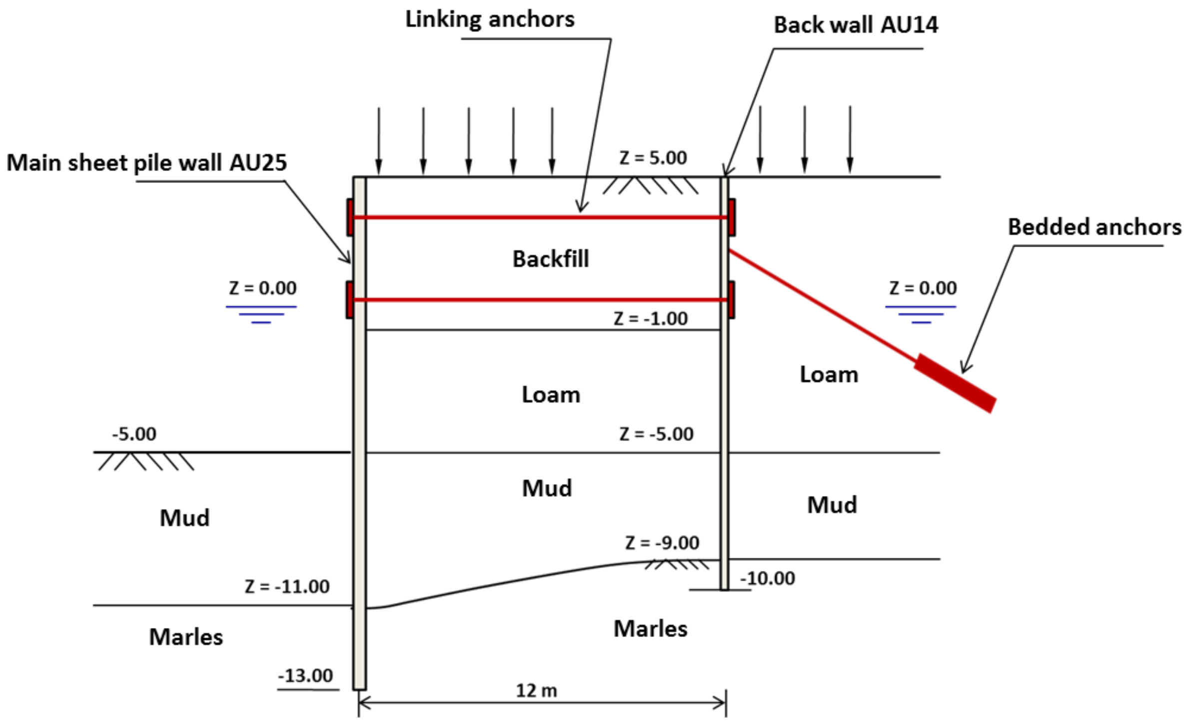
The massive studied is at the right side of the wall

The stability of the anchoring block is ensured for this phase.

OK

# D.5. Tutorial 5: Development of a marine wharf

The example studied is that of a marine wharf consisting of a sheet pile wall anchored to a back wall. This is itself anchored by a layer of bedded anchors.




This exercise aims to illustrate the following points:

- Modelling approach for a “sheet pile wall / back wall” system;
- Modelling of earthworks;
- ULS checks for a double-wall calculation.

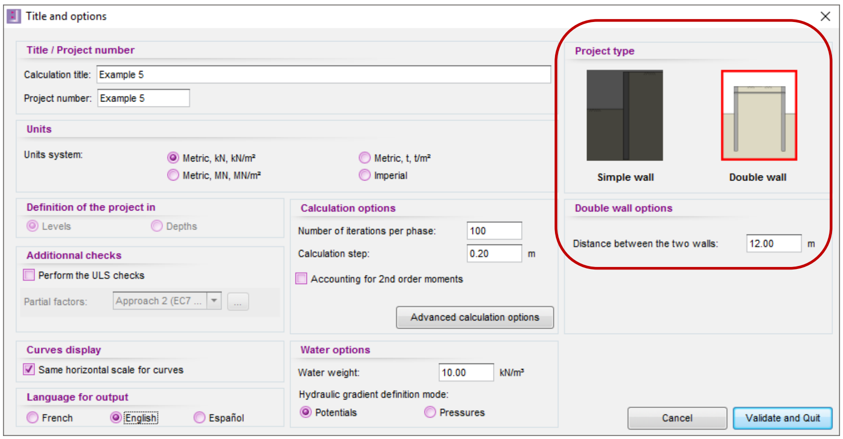
## D.5.1. Data input

### D.5.1.1. Title and options

After starting K-Réa in “New project” mode, access the Title and options window. Fill out the “Title and “Project number”.

In this window, select a “Double wall” project type. The “Distance between the two walls” must then be given; this is taken at being equal to 12.00 m for the purpose of this exercise.

Then leave the other parameters at their default values.




K-Réa then asks you to save the new project: define the appropriate name and directory.

### D.5.1.2. Definition of soil layers

The soil in place and interacting with the structure comprises three layers. Enter their general characteristics as summarised in the following table.

| Layer | z (m) | $\gamma$ (kN/m$^3$) | $\gamma'$ (kN/m$^3$) | $\varphi$ (°) | c (kPa) | dc (kN/m²/m) | $\delta_a/\varphi$ (-) | $\delta_p/\varphi$ (-) |
|---|---|---|---|---|---|---|---|---|
| Sandy loams | +5.00 | 20 | 10 | 30 | 0 | 0 | 0.66 | -0.33 |
| Clayey mud | -5.00 | 19 | 9 | 25 | 5 | 0 | 0.66 | -0.33 |
| Marly substratum | -9.00 to -11.00 | 20 | 10 | 30 | 30 | 0 | 0.66 | -0.33 |

Then use the K-Réa wizards to calculate the parameters for generation of the $k_0/k_a/k_p$ coefficients. The reaction coefficient $k_h$ is imposed for each layer as shown in the following table.

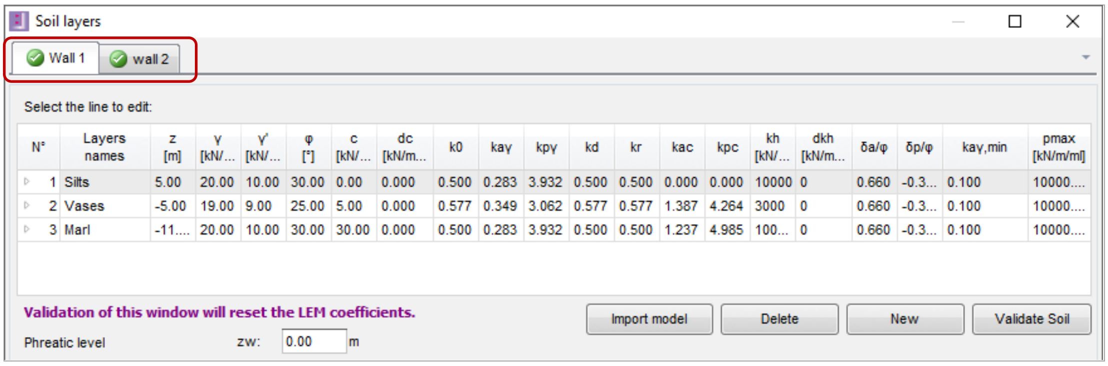
| Layer | $k_0$ (-) | $k_{a\gamma}$ (-) | $k_{p\gamma}$ (-) | $k_{ac}$ (-) | $k_{pc}$ (-) | $k_h$ (kN/m²/ml) |
|---|---|---|---|---|---|---|
| Sandy loams | 0.500 | 0.283 | 3.932 | 0 | 0 | 10 000 |
| Clayey mud | 0.577 | 0.349 | 3.062 | 1.387 | 4.264 | 3 000 |
| Marly substratum | 0.500 | 0.283 | 3.932 | 1.237 | 4.985 | 100 000 |

The other parameters are left with their default values. To do this, leave the **Modify advanced parameters** box unticked.

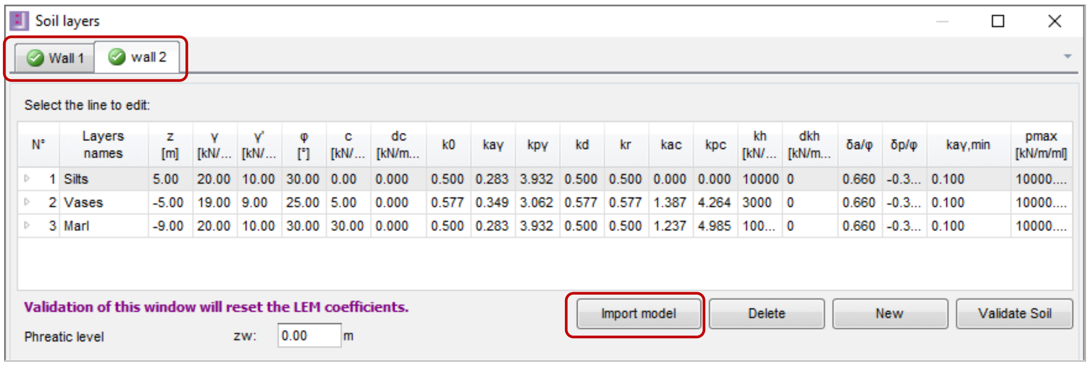
The initial water level is zw = +0.00.

The top of the marly substratum is taken at -11.00 by wall 1 (main wall) and at -9.00 by wall 2 (back).

The following figures illustrate the summary produced once the soil parameters have been filled out for the two walls.




It is possible to import into wall 2 the parameters already filled out for wall 1 by going to the "Wall 2" tab and clicking Import model. Then modify the level of the top of the Marl to -9.00 for wall 2.




Click Validate and Quit.

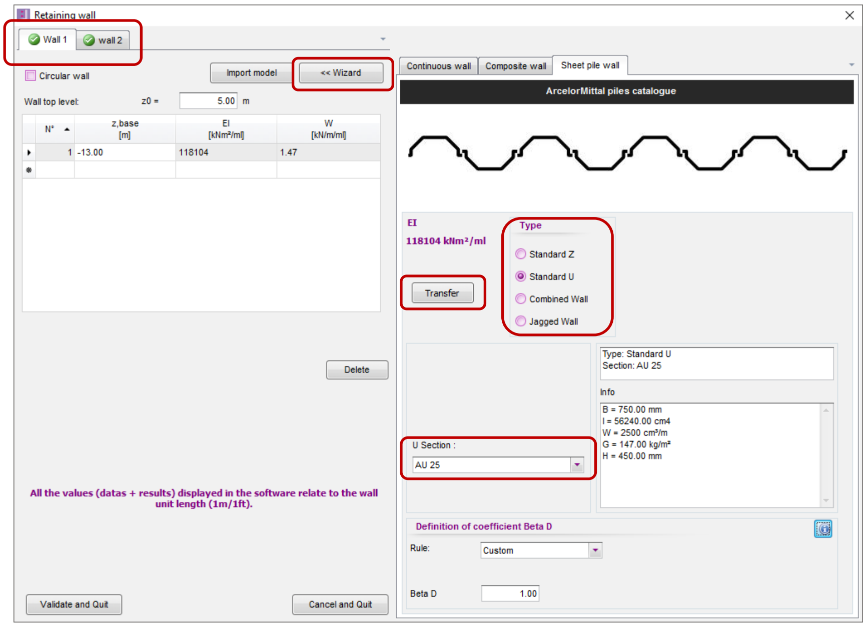
To consult or modify the soil layers subsequently, click the **Data Menu** then **Soil Layers**.

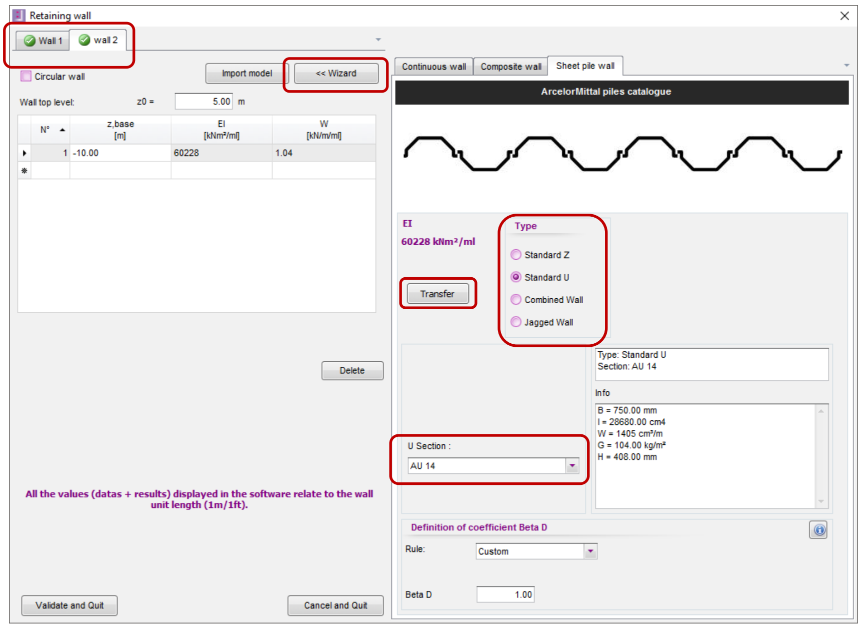
### D.5.1.3. Definition of walls

After validating the characteristics of the soil layers, those of the walls must now be defined. The characteristics to be input are as follows:

| | $z_0$ (-) | $z_{base}$ (-) | Type | EI (kNm$^2$/ml) | W (kN/m/ml) |
|---|---|---|---|---|---|
| Wall 1 | +5.00 | -13.00 | AU25 | 118 104 | 1.47 |
| Wall 2 | +5.00 | -10.00 | AU14 | 60 228 | 1.04 |

Note: It is possible to use the “Sheet pile wall” wizard to directly import the EI and W parameters of each wall.



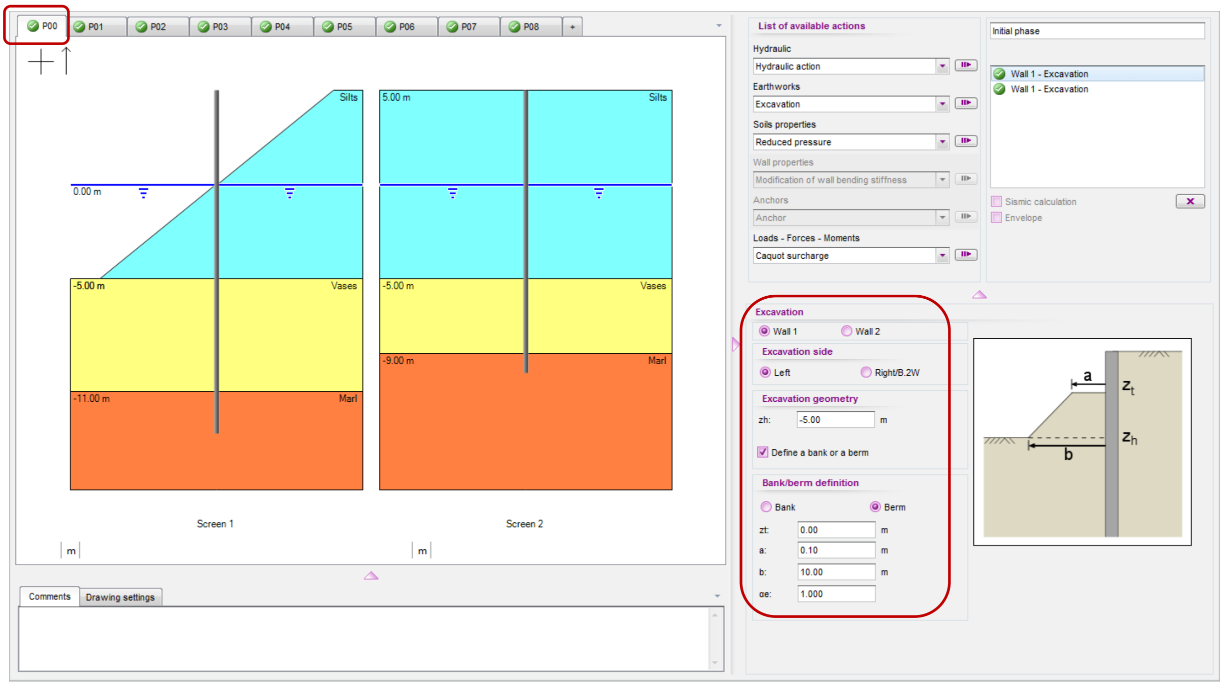
## D.5.2. Definition of phasing

### D.5.2.1. Initial phase

The initial ground is represented by a 2H/1V bank on either side of wall 1. The ground is assumed to be horizontal by wall 2. The following actions must therefore be defined:

- "Excavation" action on the left, of "Berm" type
  - $z_h$ = -5.00 m $z_t$ = +0.00 m
  - a = 0.10 m b = 10.00 m

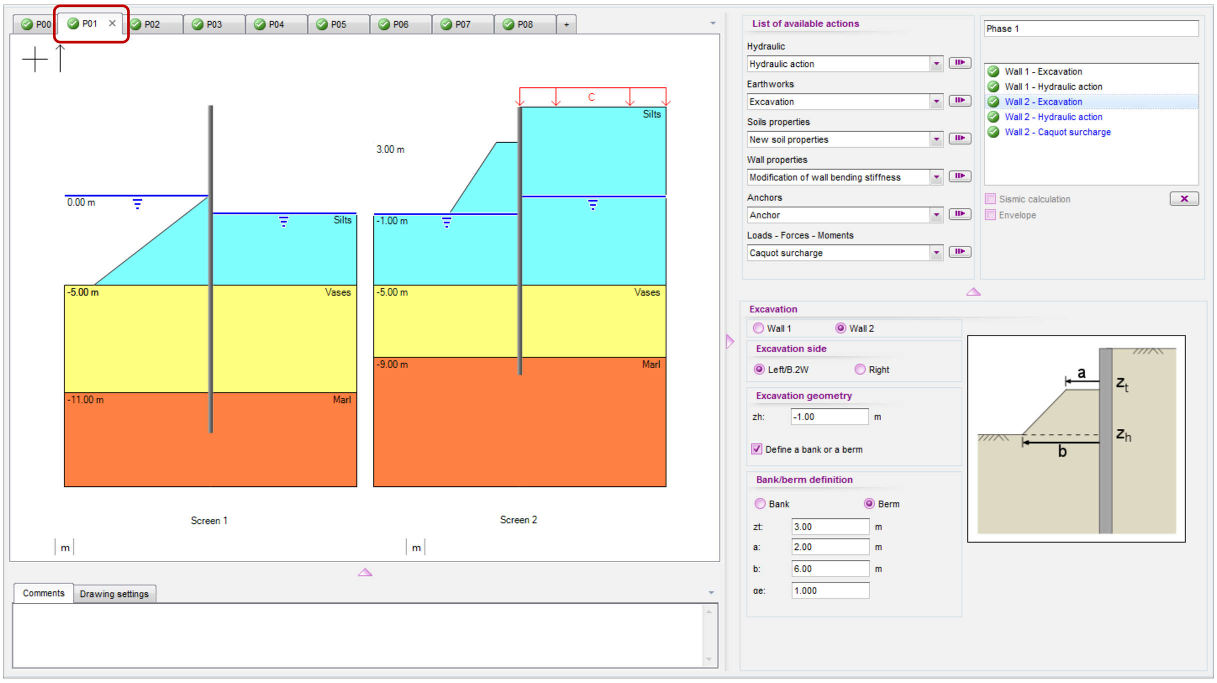
- "Excavation" action on the right, of "Bank" type
  - $z_h$ = +0.00 m $z_t$ = +5.00 m
  - a = 10.00 m b = 0.10 m




### D.5.2.2. Phase 1: Earthworks to level -1.00

In this phase, we simulate the earthworks between the two sheet pile walls at -1.00 m with the creation of a berm to the left of wall 2. The actions to be defined are as follows:

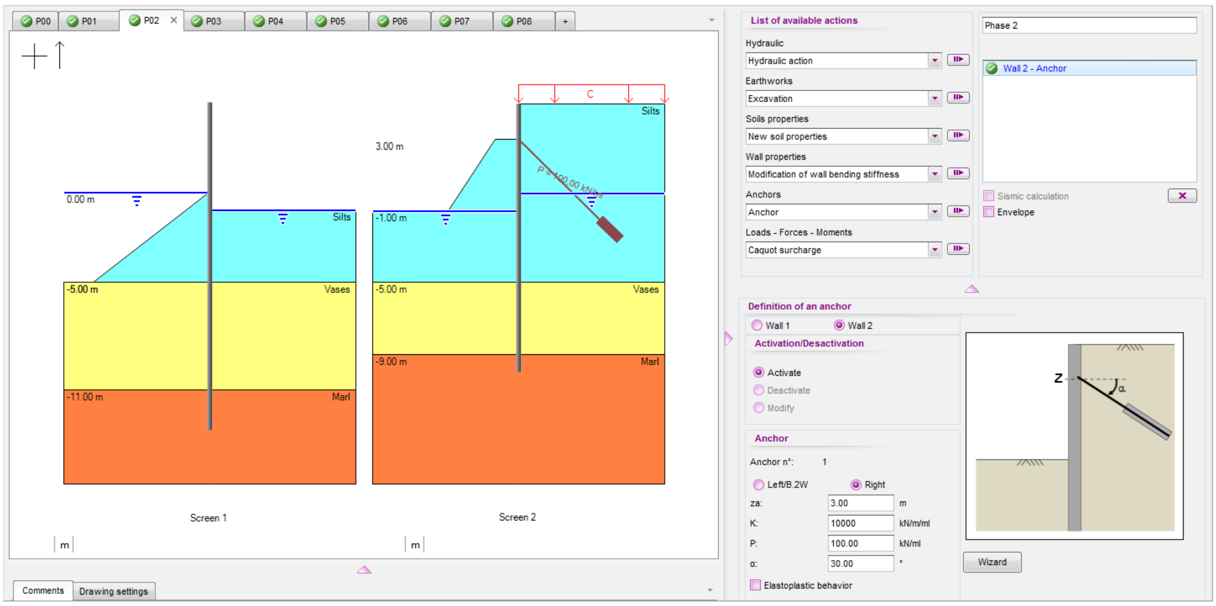
| Wall 1 | Wall 2 |
|---|---|
| Excavation action on right to -1.00 m | Excavation action on left to -1.00 m with Berm:<br>• $z_h$ = -1.00 m $z_t$ = +3.00 m<br>• a = 2.00 m b = 6.00 m |
| Hydraulic action on right to -1.00 m | Hydraulic action on left at -1.00 m |
| | Caquot overload of 10 kN/m/ml on right at z = +5.00 m |




## D.5.2.3. Phase 2: Bedded anchors

In this phase, we simulate the installation of a layer of anchors bedded behind the back wall. The following actions must thus be defined:

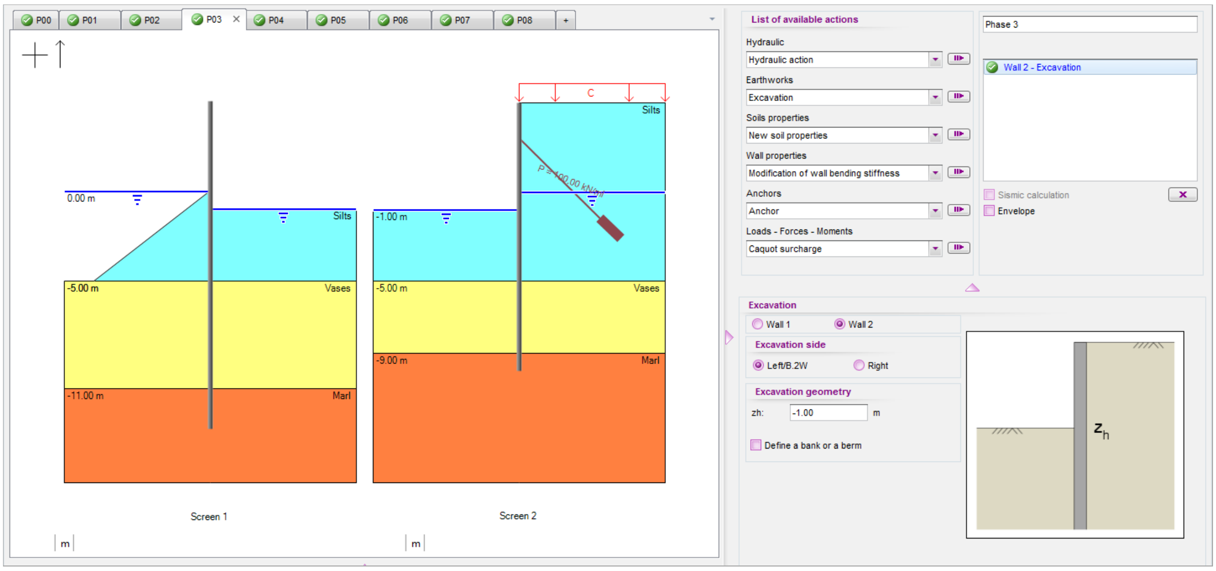
| Wall 1 | Wall 2 |
|---|---|
| | "Anchor" action on right with:<br>• za = +3.00 m<br>• K = 10 000 kN/m/ml<br>• P = 100 kN/ml<br>• α = 30° |



### D.5.2.4. Phase 3: Earthworks to level -1.00 (cont.)

Elimination of the berm to the left of wall 2. For wall 2, the following must thus be defined:

- "Excavation" action on left with:
    - zh = -1.00 m



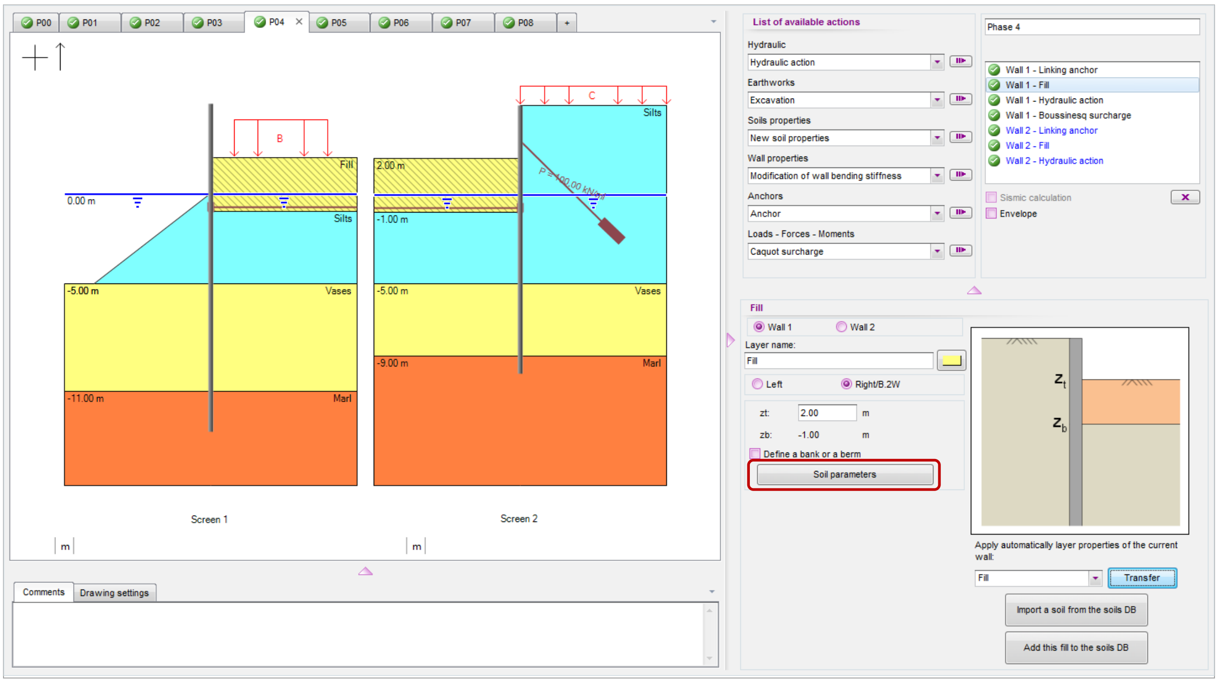

### D.5.2.5. Phase 4: Backfill and linking anchors 1

In this phase, we simulate the installation of the first layer of linking anchors followed by backfill to +2.00 between the two sheet pile walls. The actions to be defined in this phase are:

| Wall 1 | Wall 2 |
|---|---|
| Linking anchor action on right with<br>• Type: Anchor<br>• zaa = zab = -0.75 m<br>• K = 10 000 kN/m/ml<br>• P = 0 kN/ml | The same action is automatically copied to the left of wall 2. |
| Backfill action on right up to level +2.00 with:<br>• Layer name: Fill<br>• Soil parameters: see below | Backfill action on left up to level +2.00 with:<br>• Layer name: Fill<br>• Soil parameters: see below |
| Hydraulic action on right at +0.00 | Hydraulic action on left at +0.00 m |
| Boussinesq overload action on right at z = +2.00 m with :<br>• x = 2.0 m L = 8.0 m<br>• q = 50 kN/m/ml $\alpha_e$ = 1.33 | |

**Note**: when defining the backfill action for wall 2, it is possible to retrieve the parameters already input for the wall 1 backfill using the import wizard situated under the figure, using the backfill action (remember to use the soils database: DB).




The backfill characteristics are to be filled out in the window accessible via the Soil parameters button.

| γ (kN/m³) | γ' (kN/m³) | φ (°) | c (kPa) | dc (kN/m²/m) | $\delta_a/\varphi$ (-) | $\delta_p/\varphi$ (-) |
|---|---|---|---|---|---|---|
| 20 | 10 | 33 | 0 | 0 | 0.66 | -0.33 |

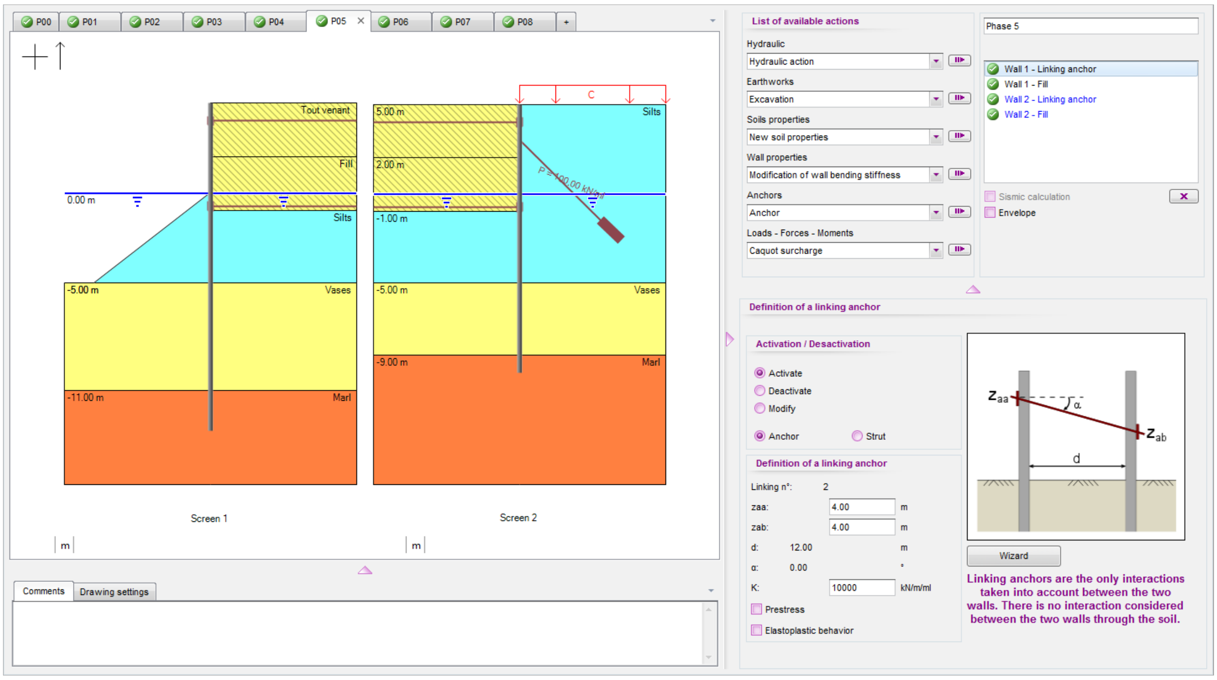
| $k_0$ (-) | $k_{ay}$ (-) | $k_{py}$ (-) | $k_{ac}$ (-) | $k_{pc}$ (-) | $k_h$ (kN/m²/ml) |
|---|---|---|---|---|---|
| 0.455 | 0.249 | 4.740 | 0 | 0 | 10 000 |

The other parameters are to be kept at their default values. To do this, leave the **Modify advanced parameters** box unticked.

### D.5.2.6. Phase 5: End of backfill and linking anchors 2

In this phase, we simulate the installation of the second layer of linking anchors followed by backfill up to +5.00 m between the two sheet pile walls. The actions to be defined in this phase are:

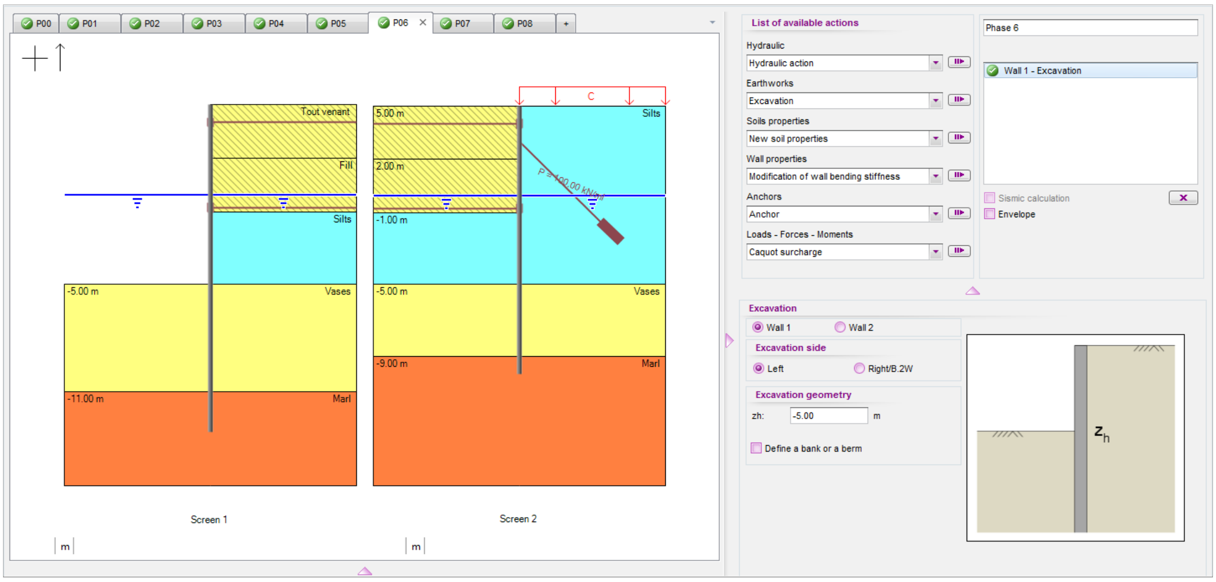
| Wall 1 | Wall 2 |
|---|---|
| Linking anchor action on right with<br>• Type: Anchor<br>• zaa = zab = +4.00 m<br>• K = 10 000 kN/m/ml<br>• P = 0 kN/ml | The same action is automatically copied on the left of wall 2. |
| Backfill action on right up to level +5.00 with:<br>• Layer name: Fill<br>• Soil parameters: same as previous phase | Backfill action on left up to level +5.00 avec:<br>• Layer name: Fill<br>• Soil parameters: same as previous phase |




## D.5.2.7. Phase 6: Dredging to level -5.00

In this phase, we simulate dredging downstream of the main sheet pile wall. This entails horizontal earthworks to level -5.00. For wall 1, the following must therefore be defined:

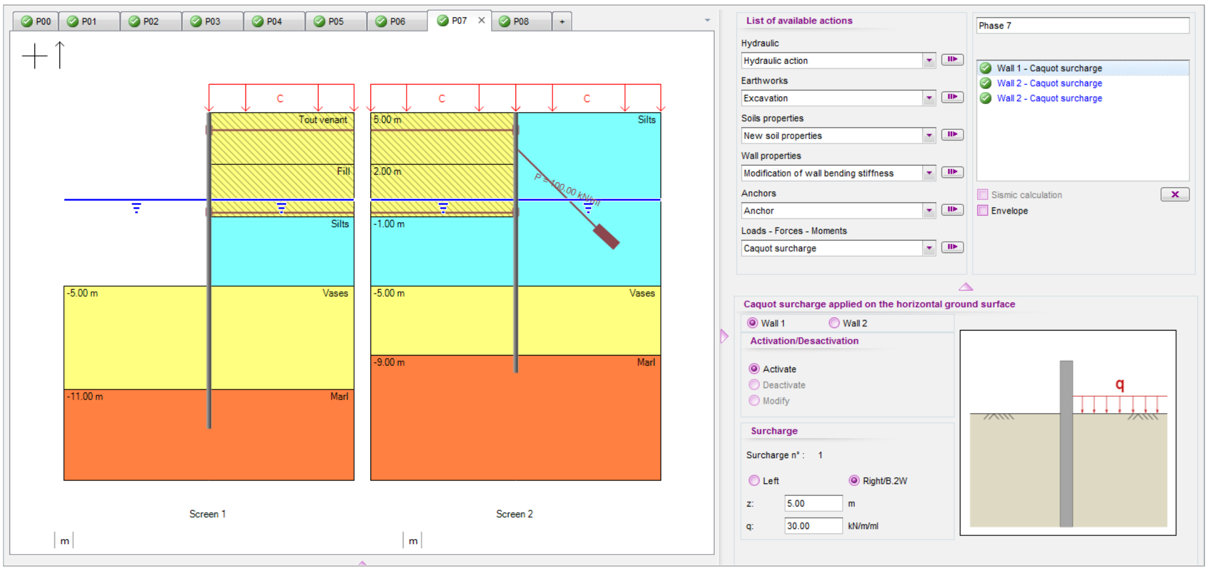
- Excavation action on left to -5.00 m



### D.5.2.8. Phase 7: Start-up

In this phase, we apply the overloads representative of operation of the wharf. The following actions are to be defined:

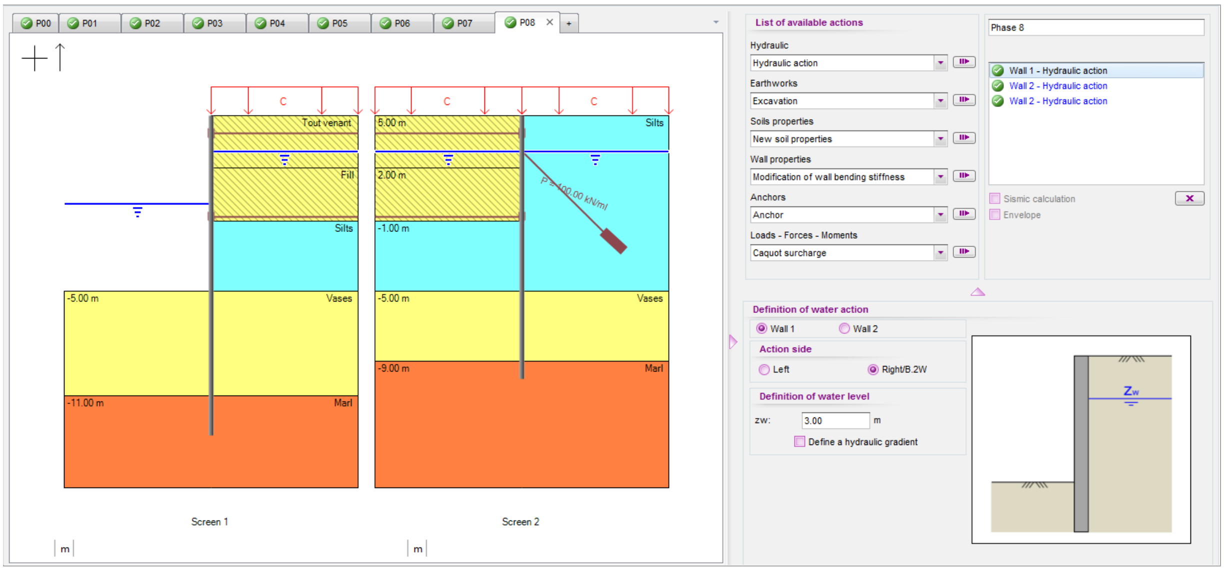
| Wall 1 | Wall 2 |
|---|---|
| Caquot overload action of 30 kN/m/ml on right at z = +5.00 m | Modification of Caquot overload action on right, new value q = 30 kN/m/ml. |
| | Caquot overload action of 30 kN/m/ml on left at z = +5.00 m |




### D.5.2.9. Phase 8: Tidal range situation

This phase simulates the transitory phase which follows a tidal range situation (high water at +3.00) in which the hydraulic equilibrium has not yet been restored on both sides of the main wall.

| Wall 1 | Wall 2 |
|---|---|
| Hydraulic action on right at $z_w$ = +3.00 m | Hydraulic action on right at $z_w$ = +3.00 m |
| | Hydraulic action on left at $z_w$ = +3.00 m |

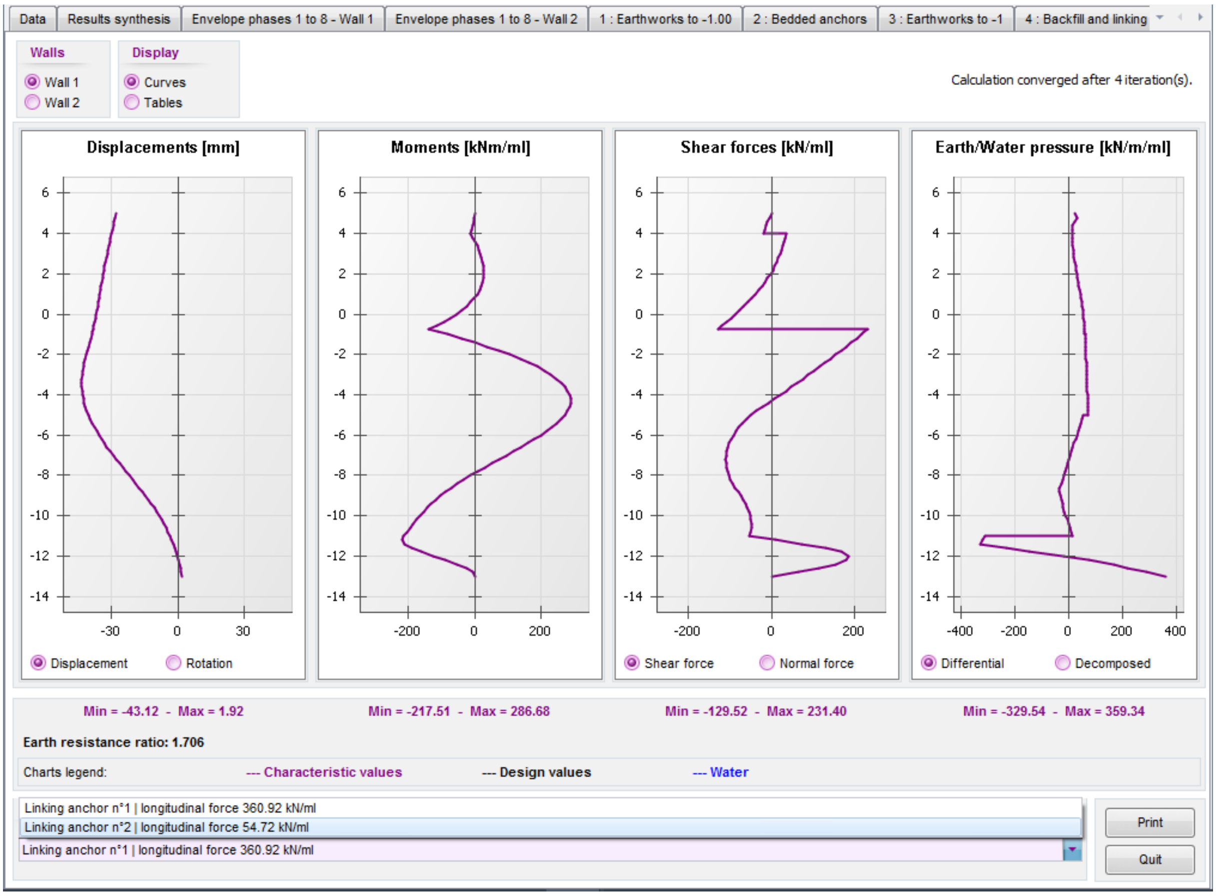


## D.5.3. Results

### D.5.3.1. Forces and displacements

An analysis of the results obtained leads us to make the following comments:

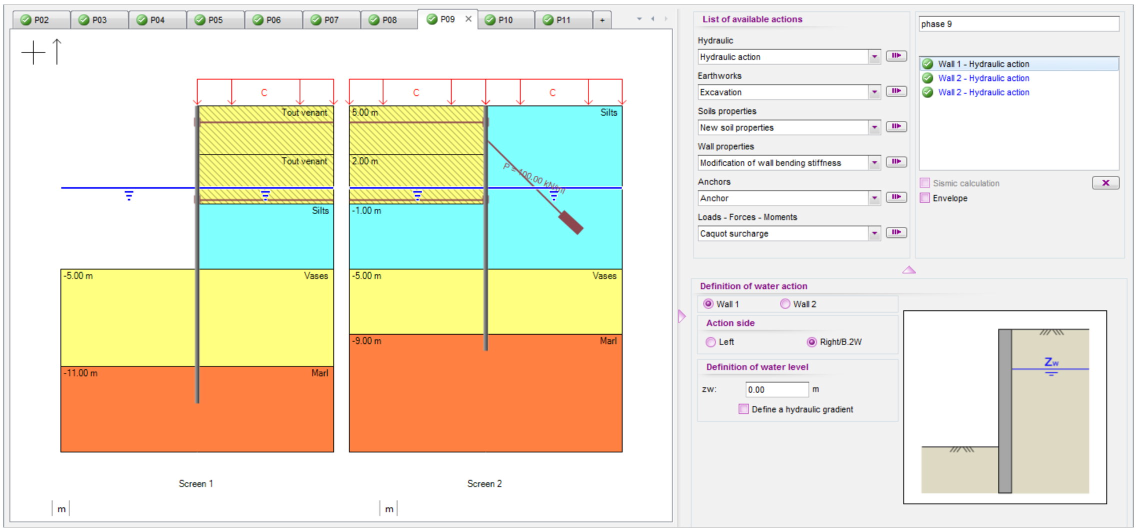
- The most unfavourable phase is the tidal range phase for which the deflection of the main sheet pile wall exceeds 4 cm. The maximum bending moment is about 287 kNm/ml on wall 1 and 266 kNm/ml on wall 2;
- The displacement in the service phase remains less than or equal to 3.0 cm;
- The passive earth pressures ratio is about 2.1 for the service phase (main wall) and 1.8 for the tidal range situation (main wall also), which is acceptable;
- The linking anchors work at a maximum of 361 kN/ml (tidal range – lower layer). The maximum axial force in the bedded anchors reaches 138 kN/ml in the tidal range situation.



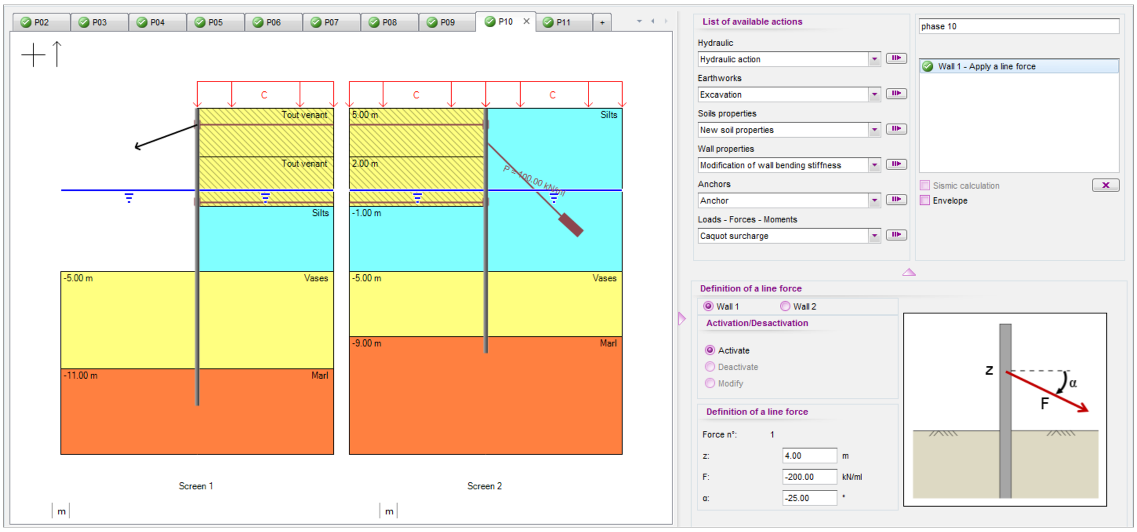
### D.5.3.2. Mooring / Berthing

We now propose examining the effect of mooring and berthing forces on the behaviour of the structure. The phasing already defined is supplemented by three additional phases:

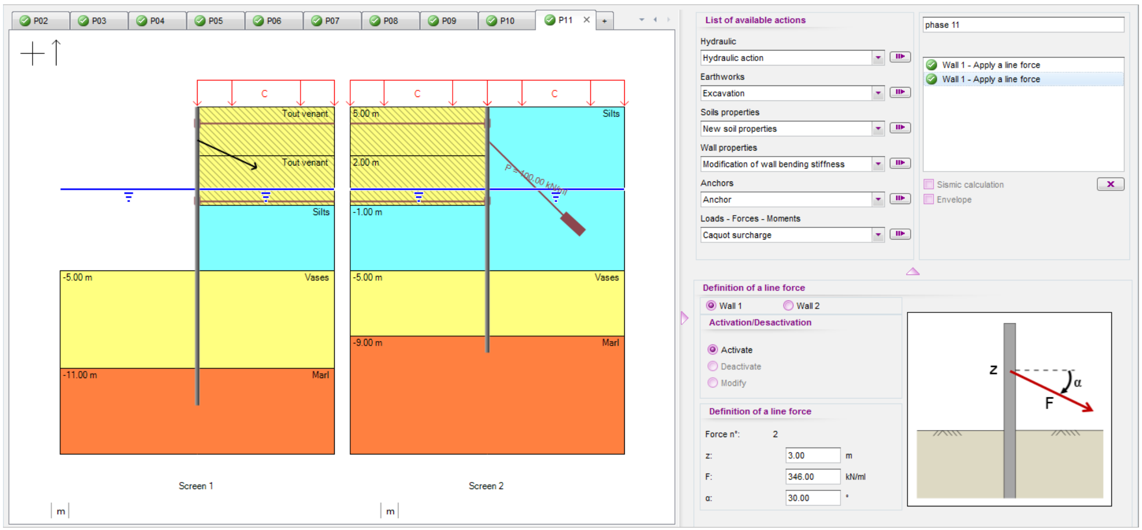
- **Phase 9**: restoration of hydraulic equilibrium with water level at +0.00 everywhere.



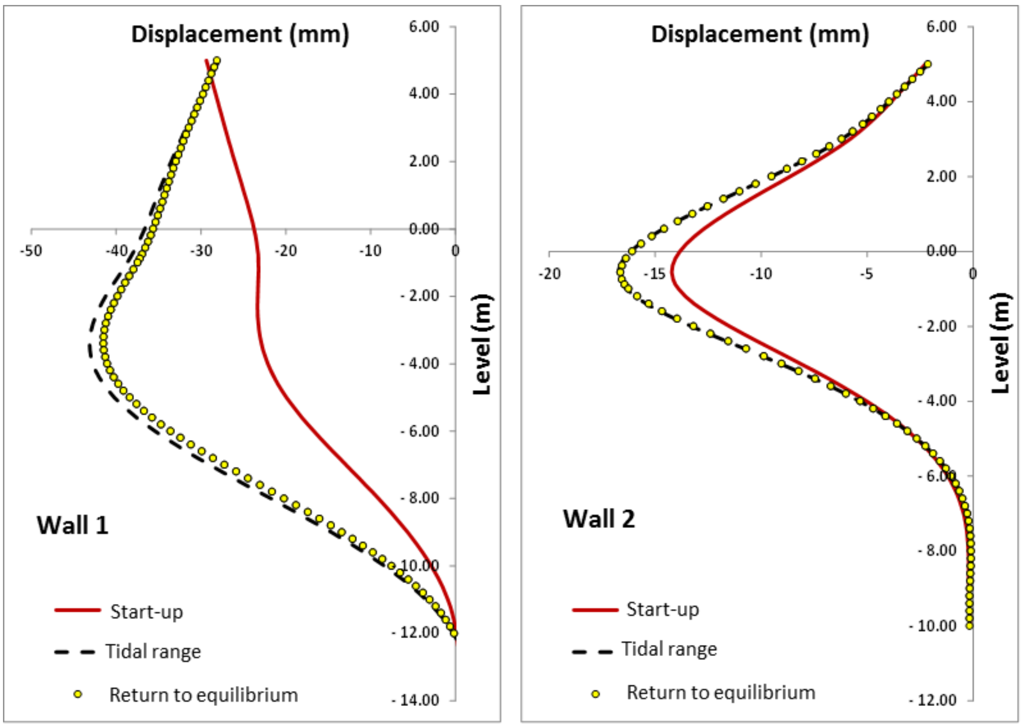
- **Phase 10**: docking situation represented by application of a linear force of intensity equal to -200 kN/ml directly on wall 1 at level +4.00 and angled at α = -25° from the horizontal;



- **Phase 11**: berthing situation represented by application of a linear force of intensity equal to +346 kN/ml directly on wall 1 at level +3.00 and angled at α = +30° from the horizontal. In this phase the linear force defined in the previous phase must be deactivated.




Restart the calculation and access the results obtained. The next figure compares the results of phase 9 corresponding to restoration of hydraulic equilibrium, with those of phases 8 (tidal range) and 7 (start-up). The "tidal range" situation causes an additional displacement of about 2 cm with respect to the service situation. The return to hydraulic equilibrium is unable to cancel out this additional displacement: the deformation of the wall after restoration of the water level at +0.00 m remains close to that which was obtained in the tidal range situation, which means an "irreversible" behaviour of the structure linked to plastification of the soil under the effect of the additional loadings in the tidal range situation. The same behaviour is observed for the back wall.

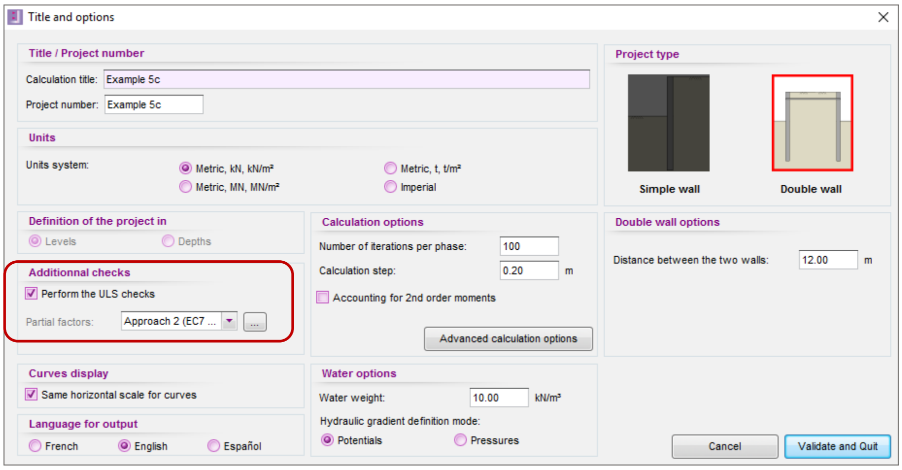


The results of the mooring and berthing phases are summarised in the following table, by comparison with phase 9.

| | Deflection (mm) | $M_{max.1}$ (kNm/ml) | $M_{max.2}$ (kNm/ml) | $T_{upper\ anchor}$ (kN/ml) | $T_{lower\ anchor}$ (kN/ml) | $T_{bedding}$ (kN/ml) |
|---|---|---|---|---|---|---|
| Phase 09 | 42 | 282 | 262 | 54 | 350 | 138 |
| Phase 10 | 49 | 265 | 260 | 191 | 363 | 157 |
| Phase 11 | 41 | 277 | 259 | 100 | 353 | 148 |

### D.5.3.3. ULS checks

The previous results can be supplemented by those concerning the ultimate limit states calculation. For this, go to the “Title and Options” tab and tick the “Perform the ULS checks” box. The approach selected by default is that of the NF P 94 282 wall model (approach 2/2*).

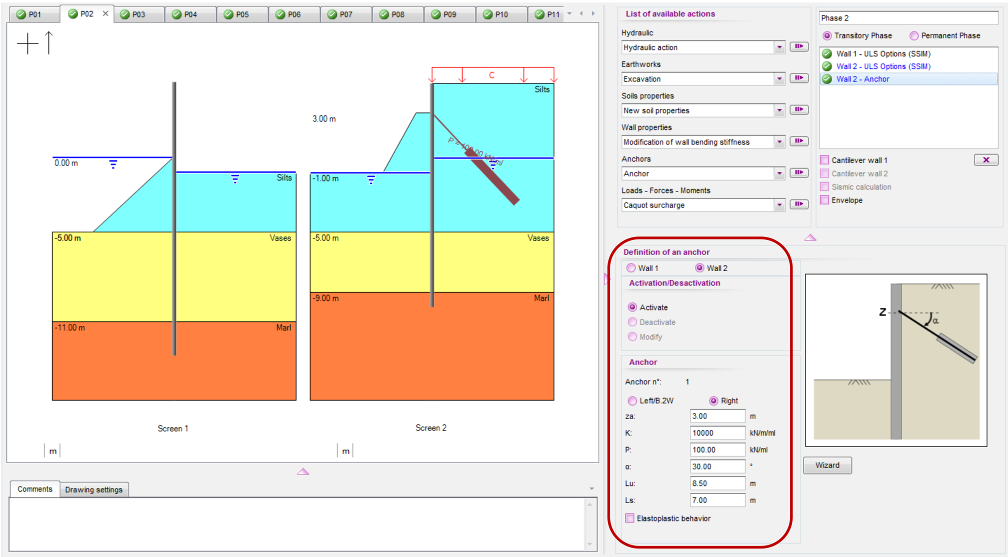



The fact of activating the ULS checks in particular allows:

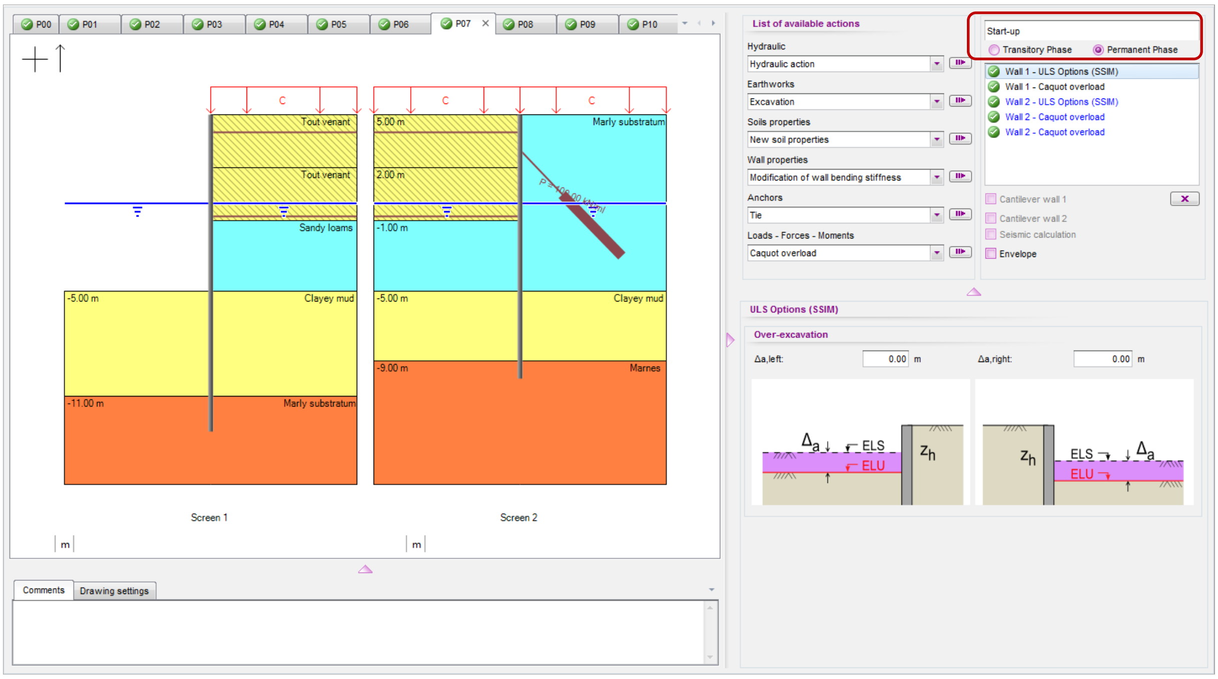
- Determination of the ULS loadings used to demonstrate the structural strength of the retaining structure elements (sheet piles, anchors, etc.);
- Justification of the distance between the two walls with regard to the stability of the anchor block (Kranz model);
- Verification of the pertinence of the active/passive earth pressure angles and evaluation, as applicable, of the force to be taken into account to check the punching stability of the walls.

Before restarting the calculation, the phasing must be supplemented by the following elements:

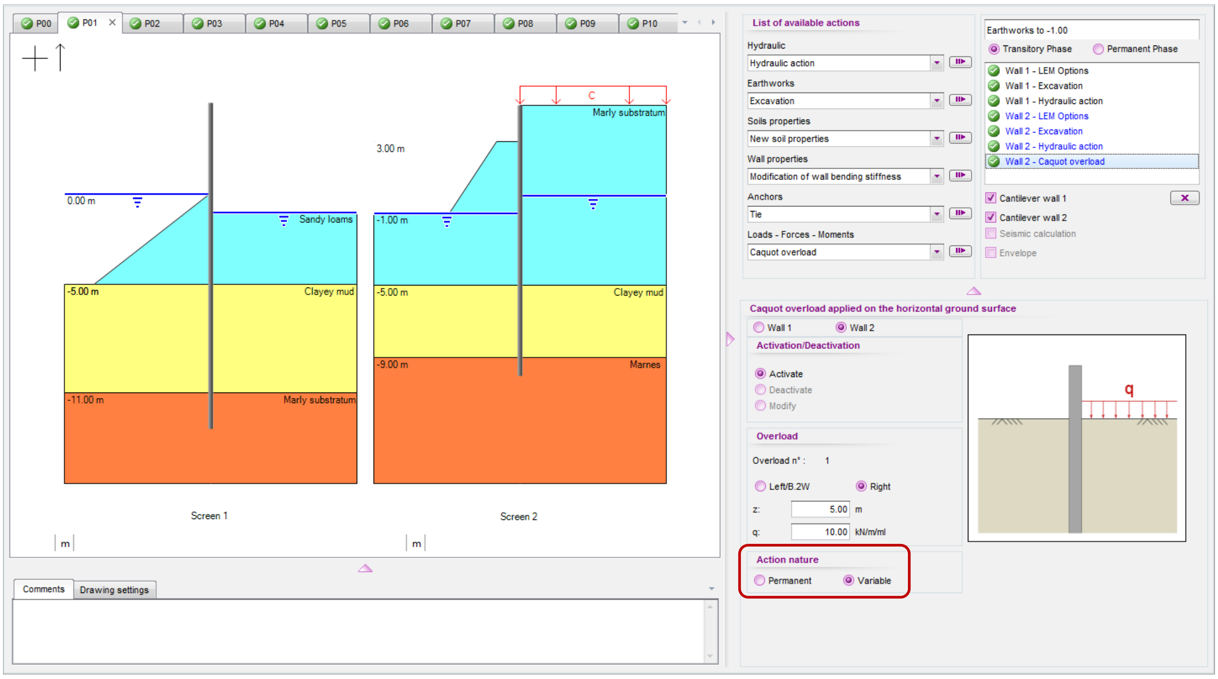
- **Phase 02** / Wall 2 / “Anchor” action – input the following information:
    - Useful length of anchor Lu = 8.5 m
    - Bedded length of anchor Ls = 7.0 m.




- **Phases 07 (start-up) and 09 (return to hydraulic equilibrium)** to be declared as “permanent phase”. The other phases are declared by default to be “transitory phases”.

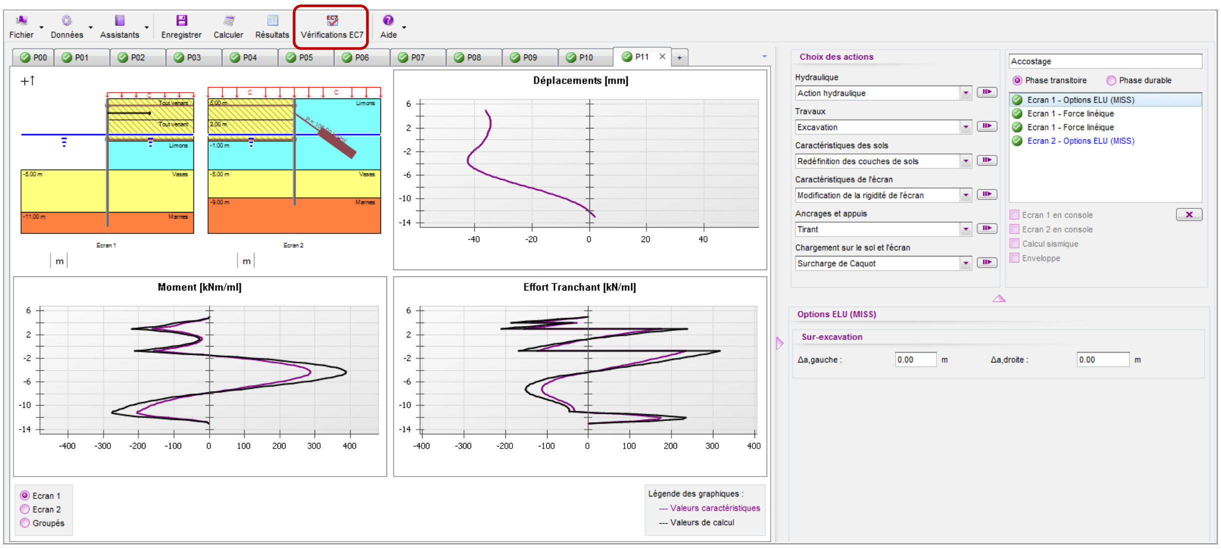


- **Phase 01** / Wall 2 / Right / “Caquot overload” - Nature = Variable.

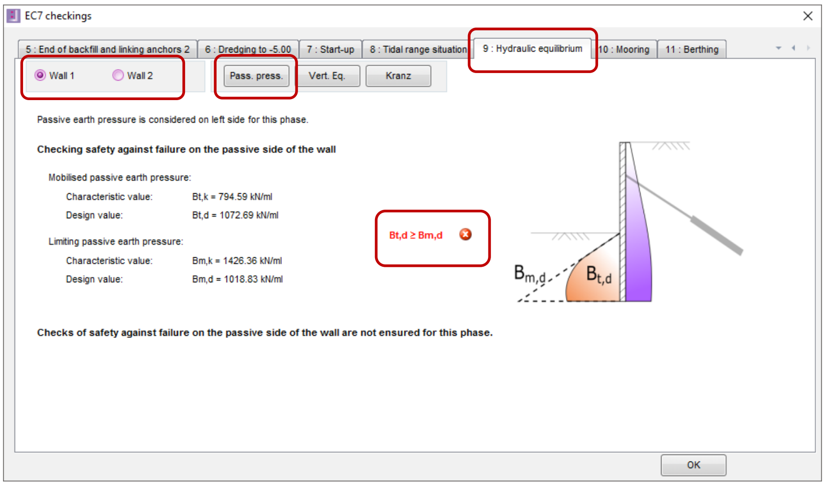



- **Phase 04** / Wall 1 / Right / “Boussinesq overload” - Nature = Variable.
- **Phase 07** / Wall 1 / Right / “Caquot overload 1” - Nature = Variable.
- **Phase 07** / Wall 2 / Right / “Caquot overload 1” - Nature = Variable.
- **Phase 07** / Wall 2 / Left / “Caquot overload 2” - Nature = Variable.
- **Phase 10** / Wall 1 / “Linear force 1”
- **Phase 11** / Wall 1 / “Linear force 2”.

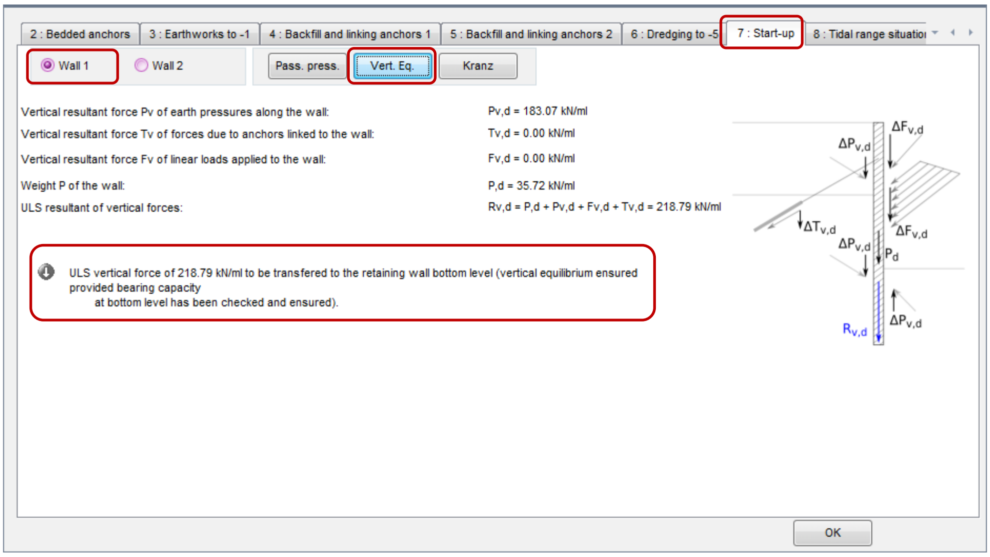
Restart the calculations and directly access the EC7 checkings.



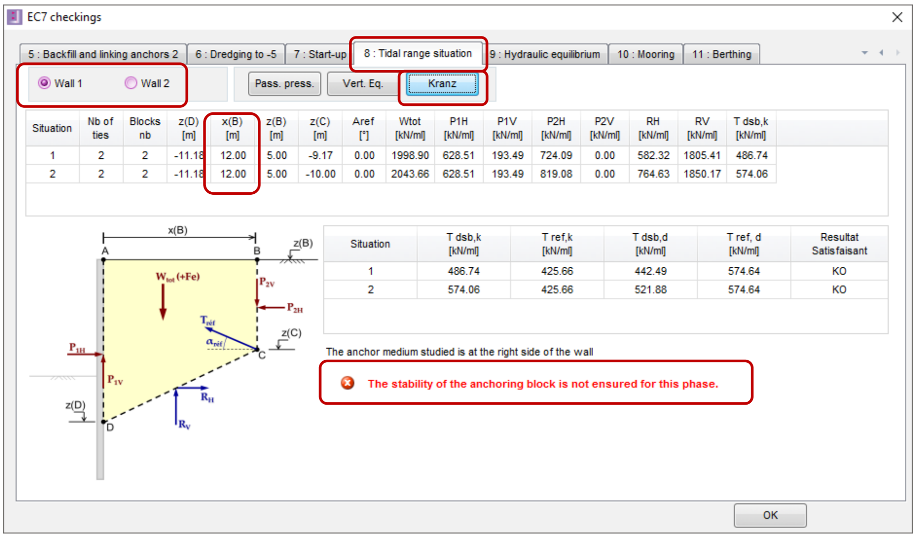
- **Passive earth pressure safety check**: the stability of the wall is demonstrated with respect to the passive earth pressure safety check for all the phases and for the two walls, except for the return to hydraulic equilibrium phase considered to be permanent (irreversible plastic deformation developed during the tidal range situation), in which the embedment depth of the main wall (wall 1) does not offer sufficient margin with respect to the passive earth pressure safety check rupture mechanism. Elongation of wall 1 is therefore necessary.




- **Vertical equilibrium**: the verification of the vertical forces balance leads to a downwards resultant for all the phases and for both walls. The maximum vertical force to be taken up (at ULS) at the base of the wall is:
  - $\mathbf{R_{v.d}}$ = 219 kN/ml for wall 1 – reached in phase 7 (start-up);
  - $\mathbf{R_{v.d}}$ = 171 kN/ml for wall 2 – reached in phase 3 (elimination of berm).




- **Kranz**: the verification of the stability of the anchor block aims to validate the useful lengths of the bedded anchors and the linking anchors. The result of the analysis validates the useful length chosen for the bedded anchor of wall 2. The stability of the anchor block is not however confirmed for wall 1 in phases 8 (tidal range) and 10 (mooring). This therefore requires a revision of the retaining structure design by increasing the distance between the two walls (and thus the length of the linking anchors).



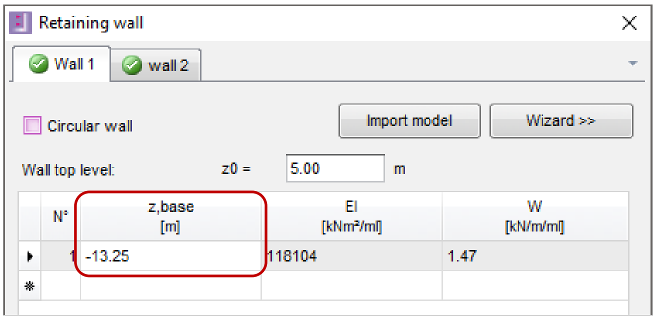

### D.5.3.4. Revision of structure design

The purpose of this paragraph is to present corrective actions required by the structure's lack of stability with respect to the following mechanisms:

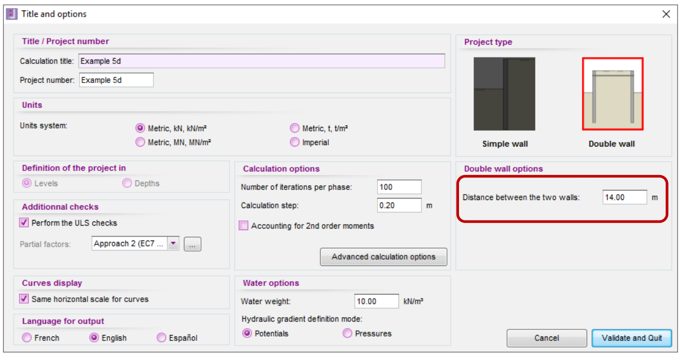
- Rotational instability of wall 1 by passive earth pressure safety check;
- Instability of the anchor block associated with the sheet pile wall / back wall system.

For this, we propose the following:

- **Increase in the embedment depth** of the main wall by 25 cm: Open the "Retaining wall" menu, select "Wall 1" and modify the level of the base to -13.25 instead of -13.00;




- **Increase the distance** between the two walls by 2 m: open the "Title and Options" menu and change distance "d" to 14 m instead of 12 m.




Restart the calculation. The result obtained shows that the proposed adjustment this time enables all the ULS verifications to be validated.