Tie-back Wall

1 Introduction

This example simulates the sequential construction of a sheet-pile shoring wall tied back with pre-stressed anchors. The purpose is to demonstrate the steps involved in modeling a soil-structure interaction problem like this and to examine the affect of allowing for slip between the soil and the sheet-piling.

2 Problem configuration and setup

Figure 1 presents the problem layout. The height of the wall is 9 m with anchors at the 1/3 points on the wall.

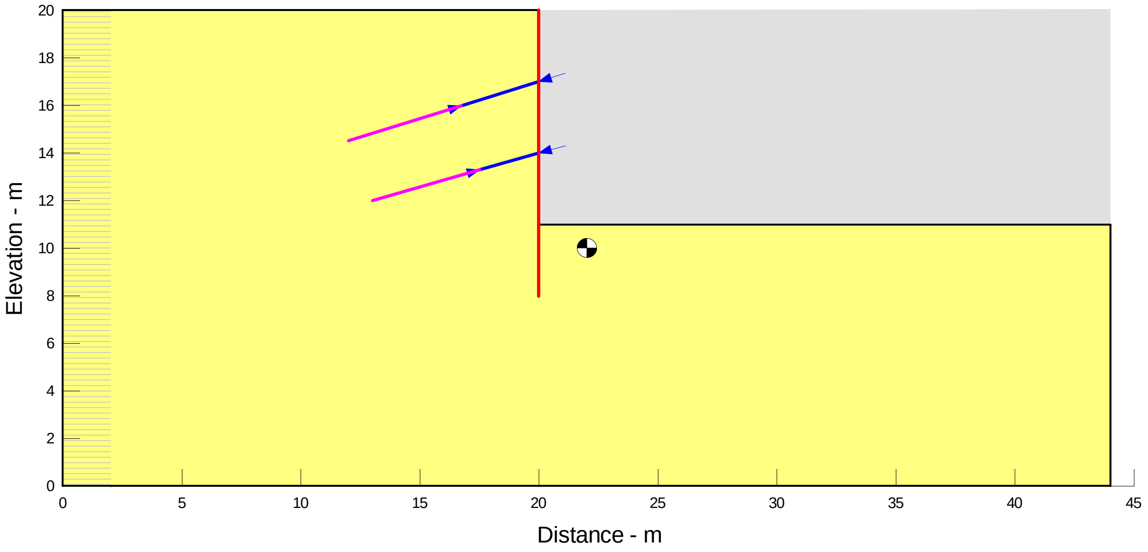
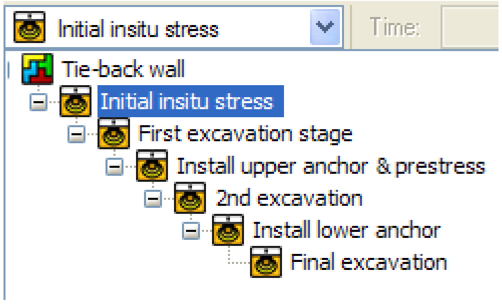


Figure 1 Problem configuration

The construction sequence is as follows:

- Establish the initial insitu stress conditions
- Install sheet-pile wall; in numerical modeling terminology this is often referred to as "wishing the wall in place" which means the wall just appears at a certain stage in the analysis.
- Excavate the upper 4 m
- Install the upper anchor and then pre-stress to 100 kN
- Excavate another 3 m
- Install the lower anchor and then pre-stress to 100 kN
- Excavate the last 2 m

The SIGMA/W analysis tree is shown in Figure 2. There are in essence six different finite element analyses where each analysis, except the first one, gets its initial conditions from the previous analysis. In SIGMA/W terminology, each analysis gets its initial conditions from its "Parent".



- Tie-back wall
  - Initial insitu stress
    - First excavation stage
      - Install upper anchor & prestress
        - 2nd excavation
          - Install lower anchor
            - Final excavation

Figure 2 Sequential analysis tree

Simple Linear-Elastic sol properties are used here for this illustrative example.

Eight-noded higher order elements are used as shown in Figure 3. The higher order elements offer superior performance for Linear-Elastic materials. Unfortunately, the 8-noded elements can become numerically unstable for non-linear constitutive relationships such as the Elastic-Plastic model. Consequently, these higher order elements must be used selectively. The eight-noded elements are used here for demonstration purposes.

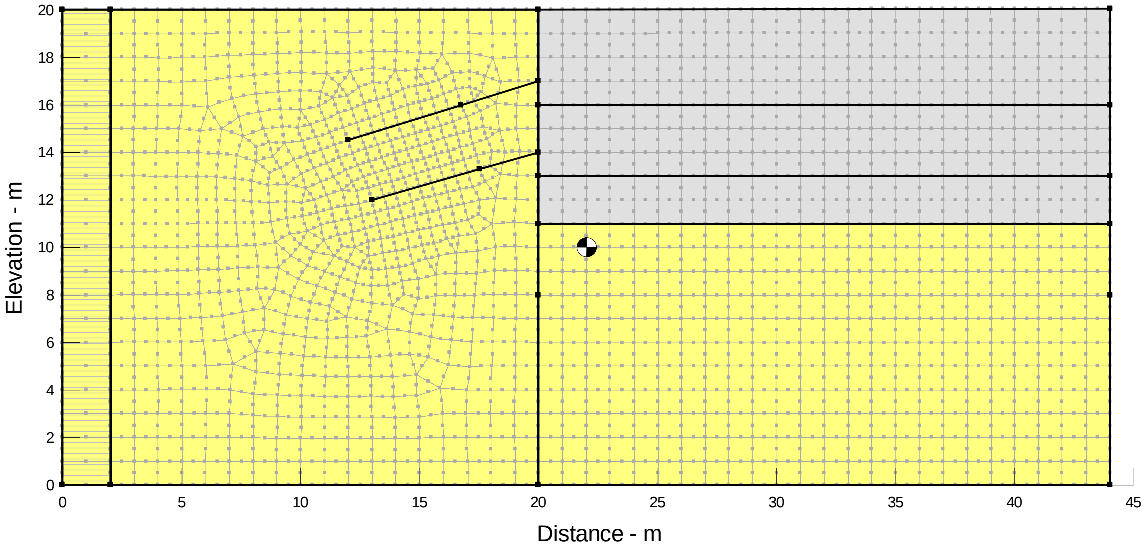


Figure 3

Notice the geometric Regions and the geometric Lines. Some of the Regions are required to simulate the excavation (taking away elements). The geometric Lines are required to apply the beams and bars representing the grouted or bonded anchor length and the free or un-bonded length. A special region is required at the left end to accommodate the infinite elements.

The only mesh constraint is that the element size should be approximately 1 m - other then that the mesh is generated more or less automatically.

The grouted or bonded portion of the anchors is modeled with beam elements. The free or un-bonded portion is modeled with bar elements.

The sheet-pile wall is included as beam elements.

It is important to remember that this is a 2D analysis with a unit thickness into the page so to speak. Structural properties consequently must be normalized per metre (unit length) along the wall (into the page).

Say for example that the force in the anchor is *F* and the anchor spacing is 2 m. The force in the anchor than is *F* divided by 2 per metre of wall. If the force *F* is divided by the spacing, then *E* or *A* must also be divided by the spacing. Think about it as if it is a spring. The force in a spring is,

$$\sigma = E\,\varepsilon$$

$$\frac{F}{A} = E\frac{\Delta L}{L}$$

$$F = A\,E\frac{\Delta L}{L}$$

The change in length and the length should be the same and therefore to divide *F* by the spacing, we must also divide *A* or *E* by the spacing.

It is important to normalize the anchor forces and properties so that they are per unit depth into the page.

The Poisson's ratio ν is 0.334. This means K_o is 0.5 for the insitu conditions. Re-call that for a 2-D analysis,

$$K_o = \frac{\nu}{(1-\nu)}$$

For other properties and definitions you can open the data file and see what has been done.

3 Insitu conditions

Figure 4 shows stress profiles at the wall location before the excavation starts. The vertical stress at the bottom is 400 kPa and the horizontal stress is 200 kPa since K_o is 0.5.

As discussed in the SIGMA/W Engineering Book, the excavation face becomes a stress boundary after the excavation soils have been removed. The excavation in essence simulates the removal of the initial insitu stresses. This is why the initial conditions are so important. The stresses acting on the wall is directly related to the insitu conditions, particularly the insitu horizontal stresses.

The most important part about simulating the excavation process is to establish the correct insitu effective stress conditions.

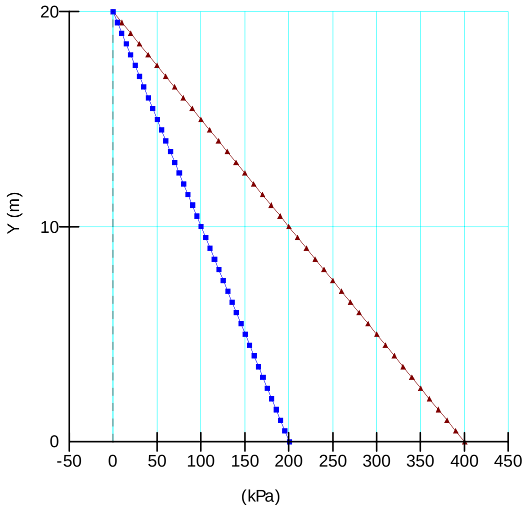


Figure 4 Initial insitu stress profiles

4 Simulating the soil removal

The horizontal stress in the ground prior to removing any soil varies from zero at the ground surface to 90 kPa at the proposed excavation base level. The rate of increase is 10 kPa per metre with depth. After the soil is removed this will in essence be the pressure on the wall. In a finite element analysis, the change in stress on the excavation side of the wall is simulated with forces that pull on the wall. The pulling stresses plus the original insitu stresses add up to zero.

SIGMA/W has what is called a hydrostatic pressure boundary condition. With this boundary condition, it is necessary to specify the elevation where the pressure is zero, and the rate at which the pressure increases with depth (Unit weight per unit depth). In this case the pressure is zero at the ground surface which is at elevation 20 m. The rate of increase with depth (Unit weight per unit depth) in this case is minus10 kN/m^3 (the minus means the force will act away from the wall or pull on the wall). Figure 5 shows this pulling force for the first excavation stage.

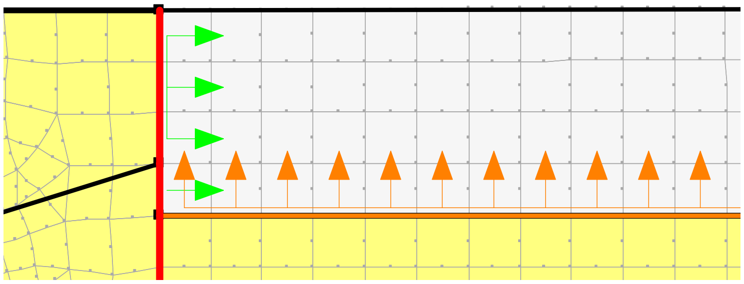


Figure 5 Boundary conditions for the first excavation stage

For the second excavation stage the lateral stress removal is between 40 and 70 kPa and for the last excavation stage the lateral stress removal is between 70 and 90 kPa. All three of these conditions are represented by the same specified hydrostatic boundary condition.

Along the base of the excavation in Figure 5, the stress reversal resulting from removing the soil is equivalent to 4 m of soil or 80 kPa. A y-stress boundary condition is specified to account for this.

For the second excavation stage the uplift stress along the base is 60 kPa (3 m of soil) and for the third and last excavation stage the uplift stress is 40 kPa (2 m of soil). These are represented by three different boundary conditions in SIGMA/W.

Further details on these boundary conditions can be examined by opening the GeoStudio file.

SIGMA/W automatically computes the excavation forces if no boundary conditions are applied along the excavation faces. While this is a convenient feature, the use of this feature is not recommended for simulating excavations with vertical (or very steep) walls. The automatic feature is better suited for excavations with inclined side slopes. Specified boundary conditions as used in this example are the recommended procedure for excavations with vertical walls.

5 Structural response

Figure 6 shows the lateral deflection of the wall and the ground under the wall. The maximum deflection occurs at the lower tip of the sheet-pile wall. This comes about because of the rebound of the soil due to the removal of the excavated soil.

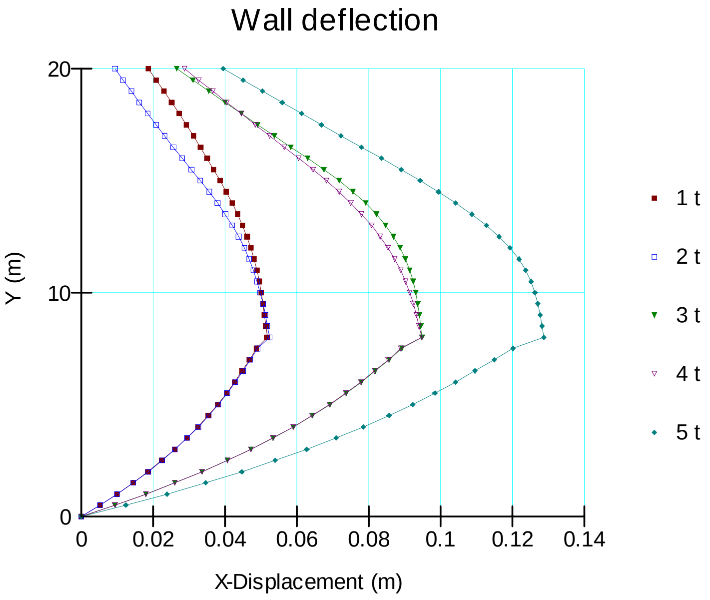


Figure 6 Lateral deflection of the wall

Also, note that the pre-stressing of the upper anchor pulls the wall back; the curve for 2t is further to the left than the curve for 1t.

There is a great tendency to look at the wall deflections at an exaggerated scale as on the left in Figure 7. This makes look like the deflections are a serious issue. If the deflections at viewed at a true scale as on the right in Figure 7, the wall movements are hardly perceptible.

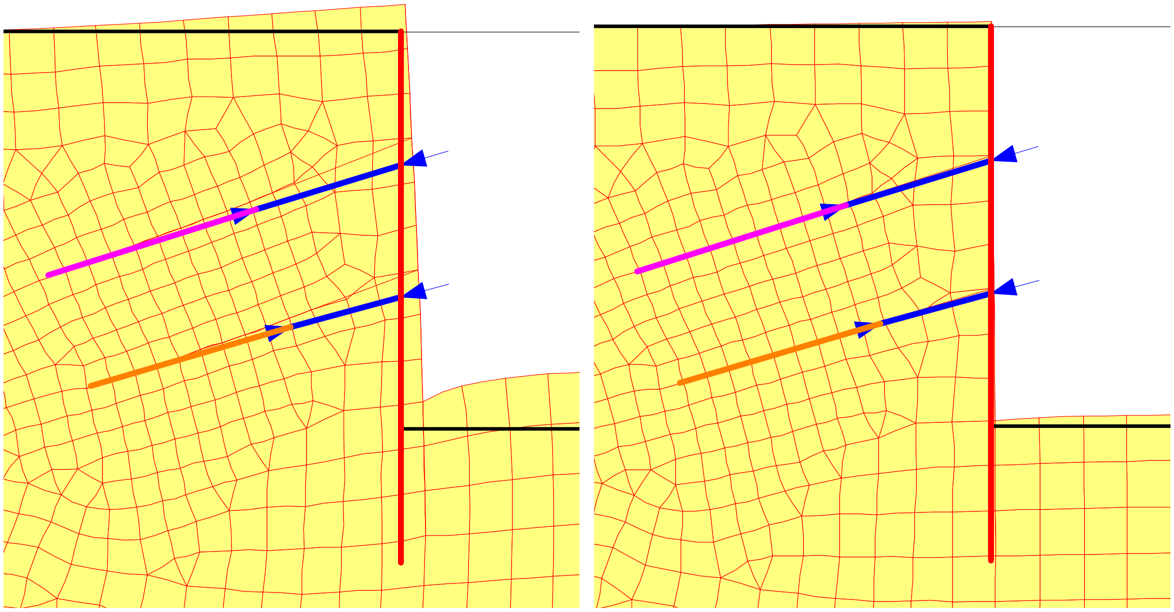


Figure 7 Wall deflection at 5X exaggeration and no exaggeration

Great care is required to not look at the deflections at an exaggerated scale which gives an erroneous impression of the deflections. At some point in the evaluation, you should always look at the deflections at a true scale to gain a correct mental image of the issue.

The images in Figure 7 indicate that there is some wall uplift and that the ground behind the wall has rebounded due to the unloading.   This issue is discussed more later on.

6 Wall moments and shear

The moment distributions in the sheet-pile wall are presented in Figure 8 and the shear distributions are shown in Figure 9.

Ultimately, the purpose of an analysis like this is to check that the structural members are not being over stressed.   Including the structural elements in the analysis makes this possible.

Furthermore, the benefit of analysis like this is that it fully includes the soil-structure interaction. The structural stiffness affects the soil stresses and the soil stiffness affects the structural stresses.   This interaction can only be accounted for properly with a SIGMA/W type of analysis.

It is very useful to recognize that when doing this type of analysis, that it is the **relative** stiffness between the soil and the structural members that controls the response.

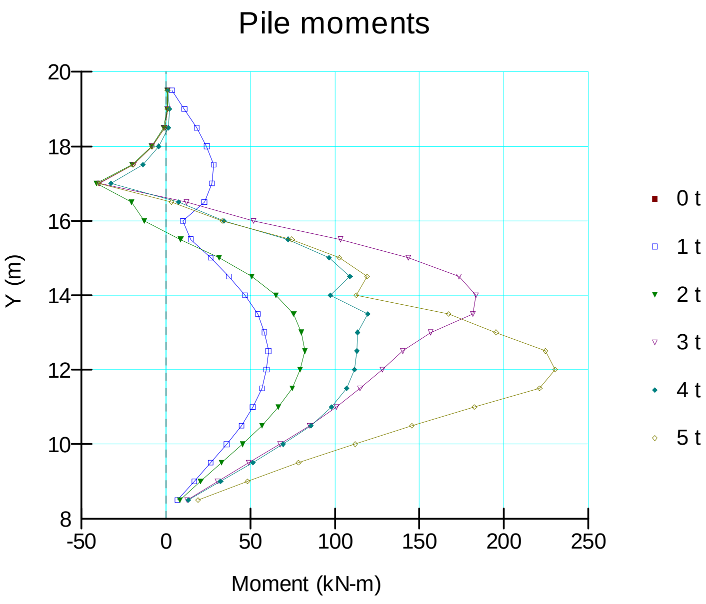


Figure 8 Moment distributions in the wall

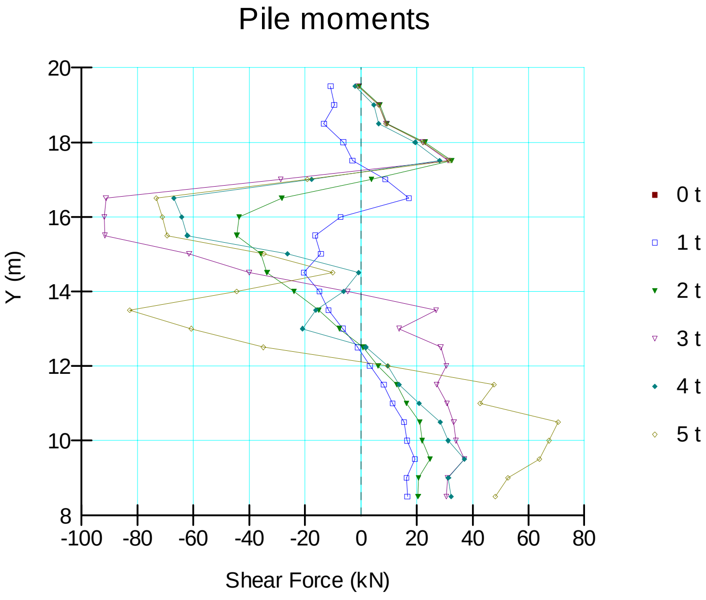


Figure 9 Shear distributions in the wall

7 Free anchor length

The forces in the upper anchor are presented in Figure 10. The force starts at the prescribed pre-stress of 100 kPa. Then when the second layer of soil is excavated the force increases to157 kPa. The forces then decreases to 130 kPa when the pre-stress of the lower anchor is applied. Finally, the load ends up at 144 kPa after all the soil has been excavated.

Of great significance is that the maximum force in the upper anchor occurs during construction, not when the excavation reaches its maximum depth.

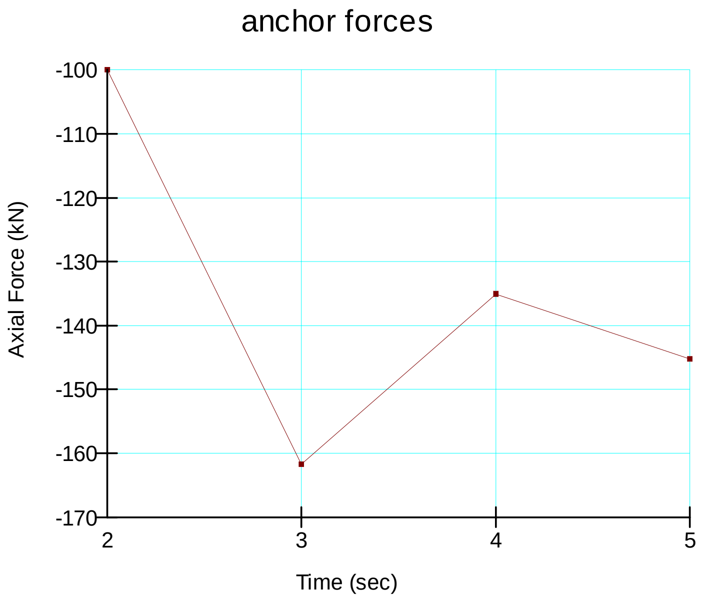


Figure 10 Forces in the upper anchor free length

8 Grouted anchor length

Figure 11 shows the axial force in the grouted length of the upper anchor. The highest axial force is at the end where the grouted length connects to the free length (x=16.75) and then diminishes toward the back end of the grouted length as the load is transferred to the soil.

Ideally, the total axial force at the far deep end should be zero but in a discretized environment this is not exactly the case although the trend is towards zero (left end of curves).

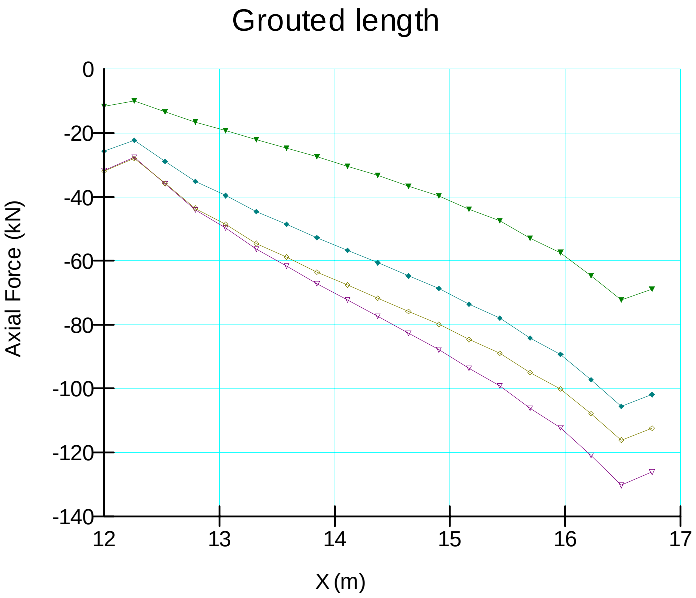


Figure 11 Axial forces in the upper grouted length

It is also possible to plot the bending moments in the grouted length of the anchor as in Figure 12. This shows that the bending resistance of the grouted portion is actually included in the analysis although the effect is rather small.

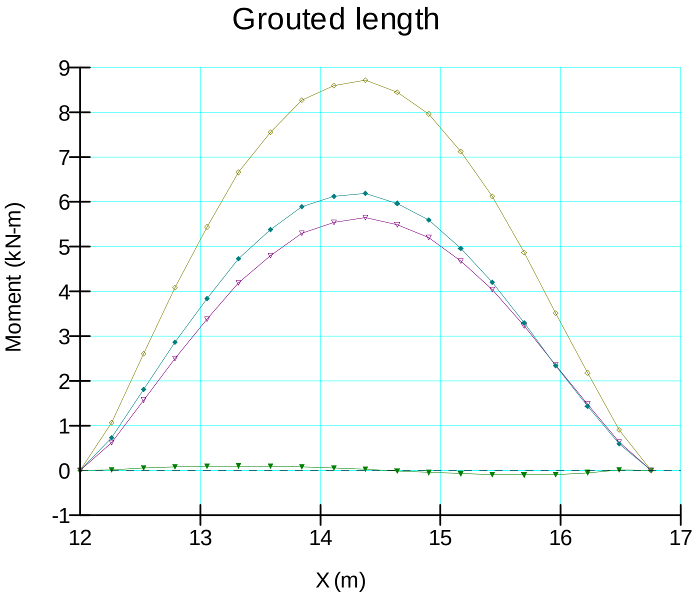


Figure 12 Bending moments in the grouted length of the upper anchor

9 Wall with slip

The problem can be repeated but allowing for some slip between the sheet-pile wall and the surrounding soil. In this case the mesh will be altered and therefore we cannot do the analysis within the same data file. The original data file was saved under a different name without the solution and then was modified to include interface elements. The next diagram (Figure 13) shows a portion of the wall with the interface elements.

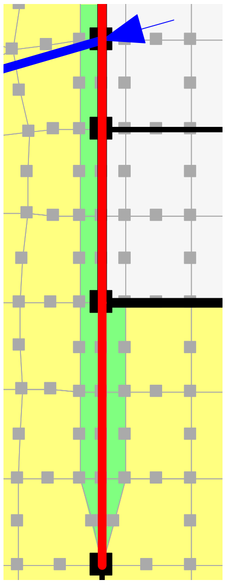


Figure 13 Slip elements along the sheet-pile wall

The potential slip between the steel wall and the soil and be model several different ways. The interface material can be assigned elastic-plastic properties or the interface can be treated as a slip surface. The slip elements in SIGMA/W are formulated on the basis of equivalent normal and tangential springs. Unfortunately, these slip elements can be numerically unstable under some circumstances, particularly if there is a tendency for the slip surface to open up. This possibility exists in a case like a tie-back wall because of the excavation forces pull on the wall as discussed earlier. Treating the interface soil as an elastic-plastic material with a reduced strength tends to give more numerical stability for a case like the wall under discussion here.

For illustrative purposes, the interface soil here is given a cohesive strength equal to 5 kPa and a friction angle equal to 20 degree.

The wall deflection exaggerated 5 times is shown in Figure 14. Note the small off-sets at the bottom of the wall between the wall and the excavation base representing some slip between the wall and the soil.

There is no value in attempting to make the interface too thin. It is better to think of the interface as a slip zone rather than a slip surface. In all likelihood if there is some slip it will be within a zone or layer and not along a paper-thin slip surface. As a minimum, the interface elements should be readily visible at a zoom factor of 100%.

This analysis can be repeated by simply changing the interface material from being elastic-plastic to a Slip Surface with the same frictional properties. For this example the Slip Surface elements give a converged solution.

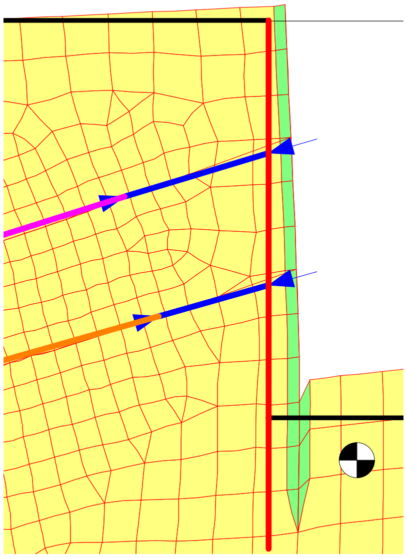


Figure 14 Wall deflection at 5X exaggeration

10 Lateral wall deflections

Figure 15 shows the lateral wall deflections when the interface elements are used. Comparing this with deflections presented in Figure 6, you will notice that the maximum deflection is about the same in both cases but the horizontal movements at the top of the wall are slightly larger.

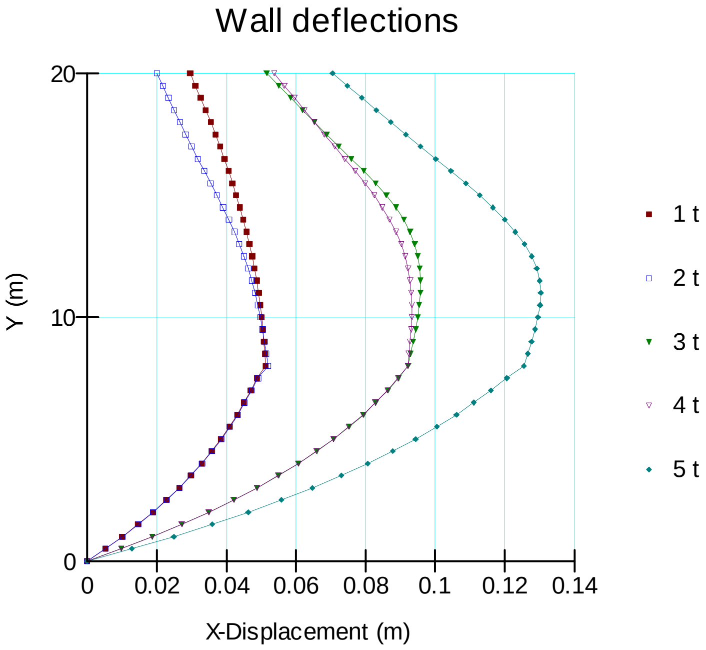


Figure 15 Lateral wall deflections with interface elements

11 Structural moments and forces

The moment distributions in the wall are shown in Figure 16 and the forces in the upper free length are shown in Figure 17.

When these moments and forces are compared with those without slip as in Figure 8 and Figure 10, you will note that they are very similar.

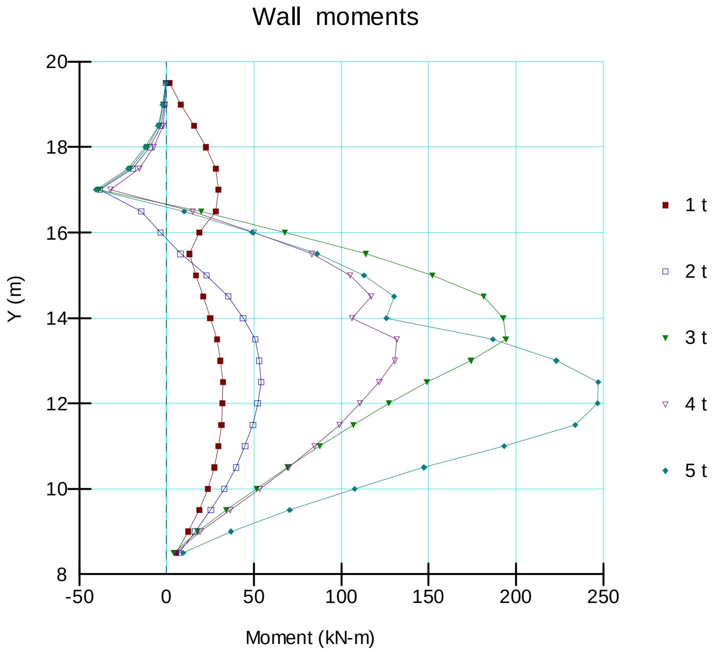


Figure 16 Moment distributions with slip elements

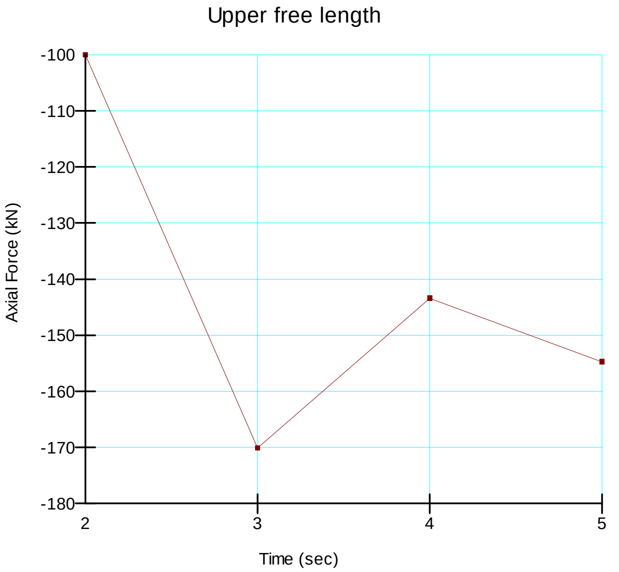


Figure 17 Forces in upper free length

12 Commentary on analysis of shoring walls

One of the bigger concerns with temporary shoring is always the settlement behind the wall. The results here indicate there will be up-lift instead of settlement. This leads to the question, where is the inconsistency? Why does the analysis not reflect the field observations?

Figure 7 and Figure 14 show the computed movement of the soil outside the excavation. Basically, the movement results from rebound due to the unloading. In the exaggerated view, it looks like the rebound is significant, but in actual fact it is relatively small.

The rebound along the excavation base is, of course, not evident at the actual site, since the excavators keep removing materials to the design elevation.

Of more significance and interest is the rebound of the ground surface just outside of the wall. Usually, a major concern is the settlement that often occurs behind the retaining wall. The analysis results seem to suggest that it is not an issue. At a first glance, it would seem that the numerical model has not provided the correct response. Upon further reflection, however, it is reasonable that the soil will rebound when it is unloaded. Why does the modeling not match the observed field behavior?

One aspect of shoring wall construction that the modeling does not capture is the loss of ground behind the wall. This can be particularly problematic in a pile-lagging system, where portions of the excavation face are exposed for a period of time before the lagging is installed. Furthermore, there may be some settlement before the lagging picks up the load; that is, slack in the system.

In the case of a carefully constructed diaphragm wall where there is likely little or no loss of ground behind the wall, there may indeed be a slight amount of rebound outside of the wall, but in the field it may be too small to be noticeable.

As a very broad principle in this industry, more expensive shoring systems like diaphragm walls are used in cases where settlement outside the wall is a major concern. Less expensive systems like piles with lagging are used when settlement is less of a concern. The point is that the potential for settlement is related to the shoring system behavior and the installation procedures. The modeling unfortunately cannot capture this aspect of the shoring behavior.

From a modeling perspective, the results should not be dismissed because of the small rebound behind the wall. The results related to aspects like lateral deflections and structural stresses are nonetheless useful in the shoring design.

13 Concluding remarks

This example illustrates how SIGMA/W can be used to simulate the staged construction of a tie-back shoring wall. The example is sufficient to demonstrate the techniques and procedures.

The example also offers some comments on how to look at and use the computed results.

This example is not based on any field case; all properties have been selected purely for illustrative purpose.