Design of diaphragm and sheet pile walls

D-Sheet Piling

Deltares systems

Deltares

Enabling Delta Life

Verification Report

D-SHEET PILING

Design of diaphragm and sheet pile walls

Verification Report

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Introduction

Deltares Systems commitment to quality control and quality assurance has led them to develop a formal and extensive procedure to verify the correct working of all of their geotechnical engineering tools. An extensive range of benchmark checks have been developed to check the correct functioning of each tool. During product development these checks are run on a regular basis to verify the improved product. These benchmark checks are provided in the following sections, to allow the user to overview the checking procedure and verify for themselves the correct functioning of D-SHEET PILING.

The benchmarks are subdivided into five separate groups as described below.

- **Group 1 [chapter 1] – Benchmarks from literature (exact solution)** Simple benchmarks for which an exact analytical result is available from literature.
- **Group 2 [chapter 2] – Benchmarks from literature (approximate solution)** More complex benchmarks described in literature for which an approximate solution is known.
- **Group 3 [chapter 3] – Benchmarks from spread sheets** Benchmarks which test program features specific to D-SHEET PILING.
- **Group 4 [chapter 4] – Benchmarks generated by D-SHEET PILING** Benchmarks for which the reference results are generated using D-SHEET PILING.
- **Group 5 [chapter 5] – Benchmarks compared with other programs** Benchmarks for which the results of D-SHEET PILING are compared with the results of other programs.

The number of benchmarks in group 1 will probably remain the same in the future. The reason for this is that they are very simple, using only the most basic features of the program.

The number of benchmarks in group 2 may grow in the future. The benchmarks in this chapter are well documented in literature. There are no exact solutions available for these problems, however in the literature estimated results are available. When verifying the program, the results should be close to the results found in the literature.

The number of benchmarks in groups 3, 4 and 5 will grow as new versions of the program are released. These benchmarks are designed so that (new) features specific to the program can be verified. The benchmarks are kept as simple as possible so that only one specific feature is verified from one benchmark to the next.

As much as software developers would wish they could, it is impossible to prove the correctness of any non-trivial program. Re-calculating all the benchmarks in this report, and making sure the results are as they should be, proves to some degree that the program works as it should. Nevertheless, there will always be combinations of input values that will cause the program to crash or to produce wrong results. Hopefully by using the verification procedure the number of ways this can occur will be limited. The benchmarks are all described in sufficient detail for reproduction to be possible at any time. The information given is enough to be able to make the calculation. The input files can be found on CD-ROM or can be downloaded from our website www.deltaressystems.com.

1 Group 1: Benchmarks from literature (exact solution)

The different benchmarks from literature with an exact solution (group 1) are described in the following paragraphs.

1.1 Load on beam on elastic foundation

1.1.1 Description

An Euler-Bernoulli beam of finite length on elastic spring foundation is simulated. The beam is loaded by a force in the middle as shown in Figure 1.1.

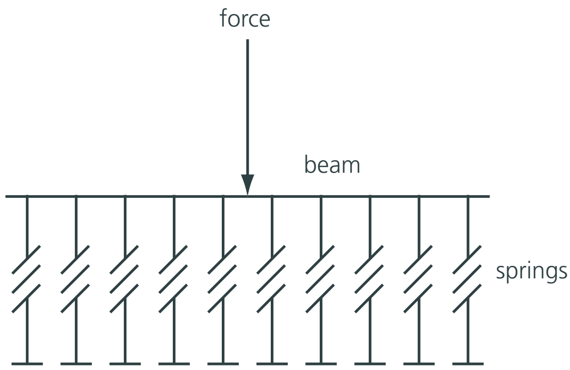


Figure 1.1: *Beam loaded by a force in the middle (bm1-1)*

The result is calculated by the analytical solution for a beam on elastic foundation given in Bouma (1981):

$$w\left(x\right) = e^{\omega x}\left[c_1 \cos\left(\omega x\right) + c_2 \sin\left(\omega x\right)\right] + e^{-\omega x}\left[c_3 \cos\left(\omega x\right) + c_4 \sin\left(\omega x\right)\right] \quad (1.1)$$

with:

$$4\omega^4 = \frac{k}{EI}$$

where:

w	is the displacement of the beam, in m;
k	is the stiffness of the foundation, in kN/m^3;
EI	is the stiffness of the beam, in kNm^2/m.

The constants in the analytical solution depend on the boundary conditions. At both ends the shear force and the bending moments are zero.

1.1.2 Benchmark results

For this symmetrical problem only the right-side of the beam is considered. With EI = 1042 kNm^2/m, k = 10 kN/m^3, L = 20 m and F = 10 kN/m, the constants of the general solution are solved from four boundary conditions as follows.

$$Q = -EI\frac{d^3w}{dx^3}\bigg|_{x=0} = -\frac{F}{2} \Rightarrow -2\omega^3\, c_1 + 2\omega^3\, c_2 + 2\omega^3\, c_3 + 2\omega^3\, c_4 = \frac{F}{2EI} \tag{1.2}$$

$$\frac{dw}{dx}\bigg|_{x=0} = 0 \Rightarrow c_1 + c_2 - c_3 + c_4 = 0 \tag{1.3}$$

$$M = -EI\,\frac{d^2\,w}{dx^2}\bigg|_{x=L/2} = 0 \tag{1.4}$$

$$\Rightarrow e^{\frac{\omega L}{2}}\left[-\tan\left(\frac{\omega L}{2}\right)c_1 + c_2\right] + e^{\frac{-\omega L}{2}}\left[\tan\left(\frac{\omega L}{2}\right)c_3 - c_4\right] = 0 \tag{1.5}$$

$$Q = -EI\frac{d^3w}{dx^3}\bigg|_{x=L/2} = 0 \tag{1.6}$$

$$\Rightarrow \quad e^{\frac{\omega L}{2}}\left[-\cos\left(\frac{\omega L}{2}\right) - \sin\left(\frac{\omega L}{2}\right)\right]c_1 + e^{\frac{\omega L}{2}}\left[\cos\left(\frac{\omega L}{2}\right) - \sin\left(\frac{\omega L}{2}\right)\right]c_2 \tag{1.7}$$

$$+\,e^{\frac{-\omega L}{2}}\left[\cos\left(\frac{\omega L}{2}\right) - \sin\left(\frac{\omega L}{2}\right)\right]c_3 + e^{\frac{-\omega L}{2}}\left[\cos\left(\frac{\omega L}{2}\right) + \sin\left(\frac{\omega L}{2}\right)\right]c_4 = 0 \tag{1.8}$$

This leads to four equations with four unknowns which can be solved. The solution reads: c_1 = 3.64255 $\times$ 10^{-3}, c_2 = 1.14302 $\times$ 10^{-1}, c_3 = -1.69783 $\times$ 10^{-3} and c_4 = 1.12357 $\times$ 10^{-1}.

1.1.3 D-SHEET PILING results

Modelling this problem in D-SHEET PILING is straightforward. Plasticity is avoided by a proper choice of the active and passive earth pressure coefficients.To compare D-SHEET PILING results and benchmark results, the modulus of subgrade reaction of the soil in D-SHEET PILING must be divided by a factor 2 (k = 5 kN/m^3) as the soil is present on both sides of the beam. Results are compared in Table 1.1.

Table 1.1: *Results of benchmark 1-1*

	Benchmark	**D-SHEET PILING**	**Rel. error [%]**
Max. displacement at x = 0 m [mm]	117.9	117.9	0.00
Min.displacement at x = 10 m [mm]	-30.0	-30.0	0.00
Max. shear force at x = 0 m [kN]	5.0	5.0	0.00
Max. bending moment at x = 0 [kNm]	11.6	11.6	0.00
Min. bending moment [kNm]	-0.8	-0.8	0.00

Use D-SHEET PILING input file bm1-1.shi to run this benchmark.

1.2 Beam with a prescribed displacement

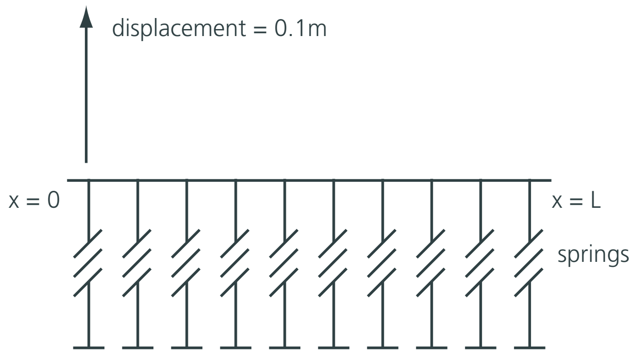


Figure 1.2: *Beam with displacement of one end (bm1-2)*

1.2.1 Description

An Euler-Bernoulli beam of finite length on an elastic spring foundation is simulated. The displacement of one end of the beam is prescribed as 0.1 m. This is illustrated in Figure 1.2. The data for the beam are presented in section 1.1.

1.2.2 Benchmark results

The analytical solution is given by equation (1.1) in section 1.1. The distributed load on the beam is zero.

The constants of the general solution are solved from four boundary conditions.

$$x = 0: \quad Q = -EI\frac{d^3 w}{dx^3} = -F$$
$$\Rightarrow \quad 2\omega^3(-c_1 + c_2 + c_3 + c_4) = \frac{F}{EI} \tag{1.9}$$

$$x = 0: \quad M = -EI\frac{d^2 w}{dx^2} = 0$$
$$\Rightarrow \quad 2\omega^2(c_2 - c_4) = 0 \tag{1.10}$$

$$x = L: \quad Q = -EI\frac{d^3 w}{dx^3} = 0$$
$$\Rightarrow \quad 2\omega^3 e^{\omega L}[-\cos(\omega L) - \sin(\omega L)]\, c_1 + 2\omega^3 e^{\omega L}[\cos(\omega L) - \sin(\omega L)]\, c_2$$
$$+ 2\omega^3 e^{-\omega L}[\cos(\omega L) - \sin(\omega L)]\, c_3 + 2\omega^3 e^{-\omega L}[\cos(\omega L) - \sin(\omega L)]\, c_4 = 0 \tag{1.11}$$

$$x = L: \quad M = -EI\frac{d^2 w}{dx^2} = 0$$
$$\Rightarrow \quad -2\omega^2 e^{\omega L}\sin(\omega L)\, c_1 + 2\omega^2 e^{\omega L}\cos(\omega L)\, c_2 + 2\omega^2 e^{-\omega L}\sin(\omega L)\, c_3$$
$$-2\omega^2 e^{-\omega L}\cos(\omega L)\, c_4 = 0 \tag{1.12}$$

These four equations with four unknowns can be solved. The solution reads:
$c_1 = 6.55727 \times 10^{-6}$, $c_2 = c_4 = -2.63254 \times 10^{-5}$ and $c_3 = 9.999934 \times 10^{-2}$.
The relation between the prescribed displacement $u_{top} = 0.1$ m and the force F is:

$$F = u_{top} \frac{2EI\omega^3 \left[1 - 4e^{2\omega L} + e^{4\omega L} + 2e^{2\omega L} \cos(2\omega L)\right]}{1 - e^{4\omega L} + 2e^{2\omega L} \sin(2\omega L)} = 2.2577 \text{ kN} \quad (1.13)$$

1.2.3 D-SHEET PILING results

In D-SHEET PILING, the active and passive earth pressure coefficients are chosen properly in order to avoid plasticity. To compare D-SHEET PILING results and benchmark results, the modulus of subgrade reaction of the soil in D-SHEET PILING must be divided by a factor 2 (k = 5 kN/m^3) as the soil is present on both sides of the beam. Results are compared in Table 1.2.

Table 1.2: *Results of benchmark 1-2*

	Benchmark	**D-SHEET PILING**	**Relative error [%]**
Maximum displacement [mm]	100	100	0.00
Minimum displacement [mm]	-6.9	-6.9	0.00
Maximum shear force [kN]	0.5	0.5	0.00
Minimum shear force [kN]	-2.3	-2.2	4.54
Maximum moment [kNm]	0.0	0.0	0.00
Minimum moment [kNm]	-3.3	-3.3	0.00

Use D-SHEET PILING input file bm1-2.shi to run this benchmark.

1.3 Beam on two supports, loaded by moment

1.3.1 Description

A beam (length L = 10 m and stiffness EI = 1042 kNm^2/m') with a central spring support (stiffness k_{spring} = 10 kN/m/m) and a pinned support at one end is loaded by an external moment of M = 1 kNm/m as shown in Figure 1.3.

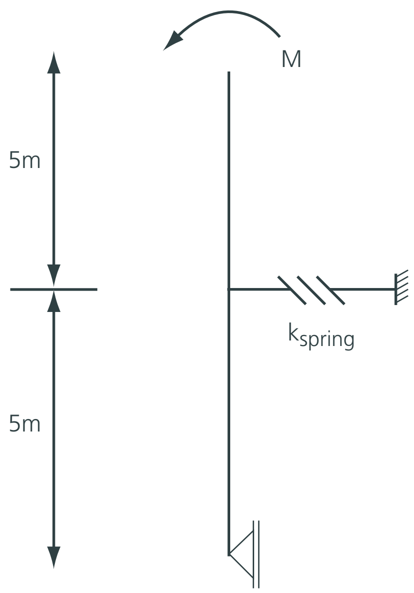


Figure 1.3: *Beam with two supports loaded by a moment (bm1-3)*

1.3.2 Benchmark results

The solution is calculated by basic applied mechanics. The problem to be solved is statically determinate. The moments and support forces can be calculated directly as shown in Figure 1.4.

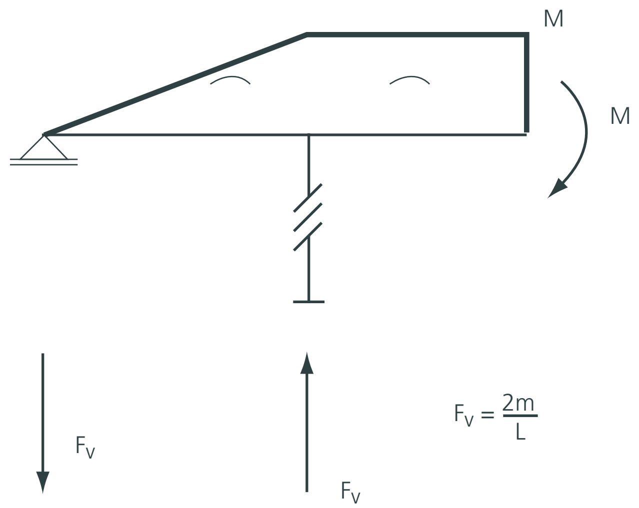


Figure 1.4: Analytical solution supports (bm1-3)

The relation of displacement to force at the spring support is: $u_{spring} = \dfrac{F_v}{k_{spring}}$.

The displacement at the loaded end is the summation of three parts:

- ◇ Bending of left-part of the beam (u_2)
- ◇ Bending of right-part of the beam (u_3)
- ◇ Displacement of spring support (u_1)

These contributions can be calculated from standard cases, as illustrated in Figure 1.5.

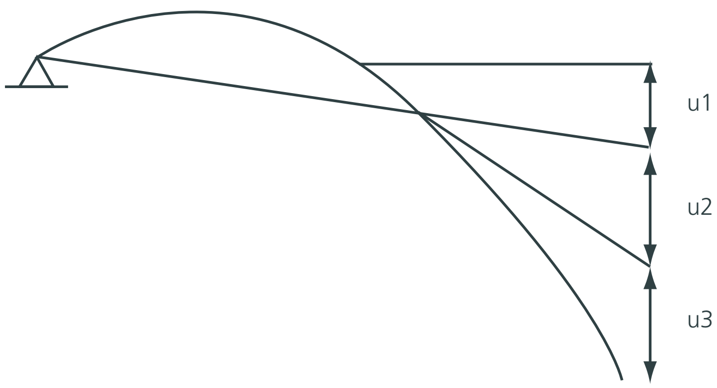


Figure 1.5: Analytical solution displacements (bm1-3)

$$u_1 = 2 \times u_{spring} = \frac{4M}{k_{spring}L} = 40 \text{ mm} \tag{1.14}$$

$$u_2 = \frac{1}{2}L \times \varphi_{spring} = \frac{1}{L} \times \frac{1}{6}\frac{ML}{EI} = \frac{1}{12}\frac{ML^2}{EI} \tag{1.15}$$

$$u_3 = \frac{1}{8}\frac{ML^2}{EI} \tag{1.16}$$

$$\begin{aligned} u_{tip} &= u_1 + u_2 + u_3 \\ &= \frac{4M}{k_{spring}L} + \frac{2}{24}\frac{ML^2}{EI} + \frac{3}{24}\frac{ML^2}{EI} = \frac{4M}{k_{spring}L} + \frac{5}{24}\frac{ML^2}{EI} = 60.8 \text{ mm} \end{aligned} \tag{1.17}$$

1.3.3 D-SHEET PILING results

The modulus of subgrade reaction is chosen as its minimum value in D-SHEET PILING (k = 0.01 kN/m^3). The D-SHEET PILING results and benchmark results are compared in Table 1.3.

Table 1.3: *Results of benchmark 1-3*

	Benchmark	D-SHEET PILING	Error [%]
Displacement of spring at x = –5 m [mm]	20	19.7	1.52
Displacement of tip at x = 0 m [mm]	60.8	59.3	2.53
Maximum moment [kNm]	1.0	1.0	0.00

Use D-SHEET PILING input file bm1-3.shi to run this benchmark.

1.4 Beam with distributed non-uniform load

1.4.1 Description

An Euler-Bernoulli beam of finite length $L_1 + L_2$ on an elastic spring foundation is simulated. The beam is loaded by a distributed force which is constant over the first L_1 meters of the beam and linearly decreasing over the other L_2 meters of the beam, as illustrated in Figure 1.6.

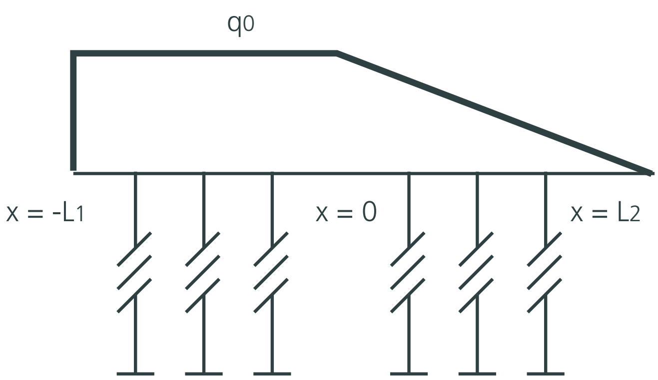


Figure 1.6: *Beam with distributed non- uniform load*

The solution for both parts ($x \leq 0$ and $x \geq 0$) must be calculated. According to Bouma (1981):
For $-L_1 < x \leq 0$:

$$w(x) = e^{\omega x}\left[c_1 \cos(\omega x) + c_2 \sin(\omega x)\right] + e^{-\omega x}\left[c_3 \cos(\omega x) + c_4 \sin(\omega x)\right] - \frac{q_0}{k} \tag{1.18}$$

For $0 \leq x \leq L_2$:

$$w(x) = e^{\omega x}\left[c_5 \cos(\omega x) + c_6 \sin(\omega x)\right] + e^{-\omega x}\left[c_7 \cos(\omega x) + c_8 \sin(\omega x)\right] - \frac{q_0}{k}\left(1 - \frac{x}{L_2}\right) \tag{1.19}$$

The constants c_1 to c_4 refer to the part of the beam for which $x \leq 0$. The constants c_5 to c_8 refer to the part of the beam for which $x \geq 0$. The values of these constants can be found from the boundary conditions at $x = L_1$ and $x = L_2$ and the required continuity at $x = 0$.

1.4.2 Benchmark results

The result is calculated using the analytical solution for a beam on elastic foundation with length L_1 + L_2. The parameters are assigned the following values:
EI =1042 kNm^2/m
k = 100 kN/m^3
L_1= 10 m
L_2= 2 m
q_0 = 20 kN/m.

Therefore:

$$x = -L_1: \quad Q = -EI\frac{d^3 w}{d x^3} = 0$$
$$\Rightarrow e^{-\beta L_1}[-\cos(\beta L_1) + \sin(\beta L_1)]c_1 + e^{-\beta L_1}[\cos(\beta L_1) + \sin(\beta L_1)]c_2$$
$$+e^{\beta L_1}[\cos(\beta L_1) + \sin(\beta L_1)]c_3 - e^{\beta L_1}[-\cos(\beta L_1) + \sin(\beta L_1)]c_4 = 0 \quad (1.20)$$

$$x = -L_1: \quad M = -EI\frac{d^2 w}{d x^2} = 0$$
$$\Rightarrow e^{-\beta L_1}\sin(\beta L_1)c_1 + e^{-\beta L_1}\cos(\beta L_1)c_2 - e^{\beta L_1}\sin(\beta L_1)c_3 \quad (1.21)$$
$$-e^{\beta L_1}\cos(\beta L_1)c_4 = 0$$

$$x = 0: \quad w(0^-) = w(0^+)$$
$$\Rightarrow c_1 + c_3 - \frac{q_0}{k} = c_5 + c_7 - \frac{q_0}{k} \quad (1.22)$$

$$x = 0: \quad \frac{dw}{dx}(0^-) = \frac{dw}{dx}(0^+)$$
$$\Rightarrow \beta(c_1 + c_2 - c_3 + c_4) = \beta(c_5 + c_6 - c_7 + c_8) + \frac{q_0}{kL_2} \quad (1.23)$$

$$x = L_2: \quad Q = -EI\frac{d^3 w}{d x^3} = 0$$
$$\Rightarrow e^{\beta L_2}[-\cos(\beta L_2) - \sin(\beta L_2)]c_5 + e^{\beta L_2}[\cos(\beta L_2) - \sin(\beta L_2)]c_6$$
$$-e^{-\beta L_2}[-\cos(\beta L_2) + \sin(\beta L_2)]c_7 + e^{-\beta L_2}[\cos(\beta L_2) + \sin(\beta L_2)]c_8 = 0 \quad (1.24)$$

$$x = L_2: \quad M = -EI\frac{d^2 w}{d x^2} = 0$$
$$\Rightarrow -e^{\beta L_2}\sin(\beta L_2)c_5 + e^{\beta L_2}\cos(\beta L_2)c_6 + e^{-\beta L_2}\sin(\beta L_2)c_7 \quad (1.25)$$
$$-e^{-\beta L_2}\cos(\beta L_2)c_8 = 0$$

$$x = 0: \quad -EI\frac{d^2w}{dx^2}(0^-) = -EI\frac{d^2w}{dx^2}(0^+)$$
$$\Rightarrow c_2 - c_4 = c_6 - c_8 \quad (1.26)$$

$$x = 0: \quad -EI\frac{d^3w}{dx^3}(0^-) = -EI\frac{d^3w}{dx^3}(0^+)$$
$$\Rightarrow -c_1 + c_2 + c_3 + c_4 = -c_5 + c_6 + c_7 + c_8 \quad (1.27)$$

The constants are therefore:

$c_1 = 5.04161 \times 10^{-2}$	$c_2 = 2.40163 \times 10^{-2}$
$c_3 = -9.00103 \times 10^{-6}$	$c_4 = 3.78931 \times 10^{-5}$
$c_5 = -1.311056 \times 10^{-2}$	$c_6 = -3.95054 \times 10^{-2}$
$c_7 = 6.35127 \times 10^{-2}$	$c_8 = -6.34938 \times 10^{-2}$

1.4.3 D-SHEET PILING results

The distributed load is introduced by lowering the water table by 2 m. This leads to a value of $q_0 = 20$ kN/m^2. To compare D-SHEET PILING results and benchmark results, the modulus of subgrade reaction of the soil in D-SHEET PILING must be divided by a factor 2 (k = 50 kN/m^3) as the soil is present on both sides of the beam. The D-SHEET PILING results and the benchmark results are compared in Table 1.4.

Table 1.4: *Results of benchmark 1-4*

	Benchmark	D-SHEET PILING	Relative error [%]
Maximum displacement [mm]	206.1	206.1	0.00
Displacement at the top [mm]	81.9	81.9	0.00
Displacement at the bottom [mm]	198.6	198.6	0.00
Minimum moment [kNm]	-9.05	-9.0	0.55
Maximum moment [kNm]	0.1	0.1	0.00
Minimum shear force [kN]	-5.2	-5.2	0.00
Maximum shear force [kN]	2.3	2.3	0.00

Use D-SHEET PILING input file bm1-4.shi to run this benchmark.

1.5 Beam loaded by tangent and normal forces

1.5.1 Description

A beam of length L = 20 m is loaded by a tangent force F = 100 kN/m at x = L and a linearly varying normal force: $N_{\max}$ = 10000 kN at x = L and $N_{\min}$ = 8000 kN at x = 0 (Figure 1.7).

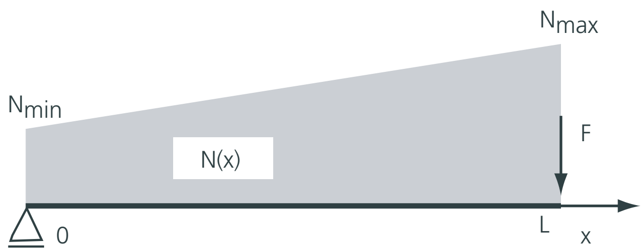


Figure 1.7: *Beam loaded by a tangent force and a normal force (bm1-5)*

1.5.2 Benchmark results

The solution is calculated by basic applied mechanics. The shear force is constant along the beam (equal to F) and the bending moment is nil, which leads to the following differential equation:

$$N(x)\frac{dw}{dx} = F \tag{1.28}$$

where *w* is the displacement of the beam.
Therefore:

$$N(x) = N_{\min} + \frac{N_{\max} - N_{\min}}{L}x \tag{1.29}$$

The analytical solution is:

$$w(x) = \frac{FL}{N_{\max} - N_{\min}} \ln\left(N_{\min} + \frac{N_{\max} - N_{\min}}{L}x\right) + c_1 \tag{1.30}$$

The pinned support at x = 0 prevents any displacement, which leads to:

$$c_1 = -\frac{FL}{N_{\max} - N_{\min}} \ln\left(N_{\min}\right) \tag{1.31}$$

Therefore:

$$w\left(x\right) = \frac{FL}{N_{\max} - N_{\min}} \ln\left(1 + \frac{N_{\max} - N_{\min}}{LN_{\min}} x\right) \tag{1.32}$$

1.5.3 D-SHEET PILING results

In D-SHEET PILING, the modulus of subgrade reaction is set equal to its minimum (k = 0.01 kN/m^3) in order to neglect the stiffness of the soil.

Table 1.5: *Results of benchmark 1-5*

	Benchmark	D-SHEET PILING	Relative error [%]
Displacement at the bottom [mm]	0	0	0.00
Displacement at the top [mm]	223.1	223.2	0.04

Use D-SHEET PILING input file bm1-5.shi to run this benchmark.

1.6 Beam/wall with soil displacement

1.6.1 Description

An Euler-Bernoulli beam of finite length on elastic spring foundation is simulated Bouma (1981). The data for the beam are presented in section 1.1. The soil displacement on one side of the beam is prescribed as 0.1 m and a rigid support at one end of the beam prevents translation.

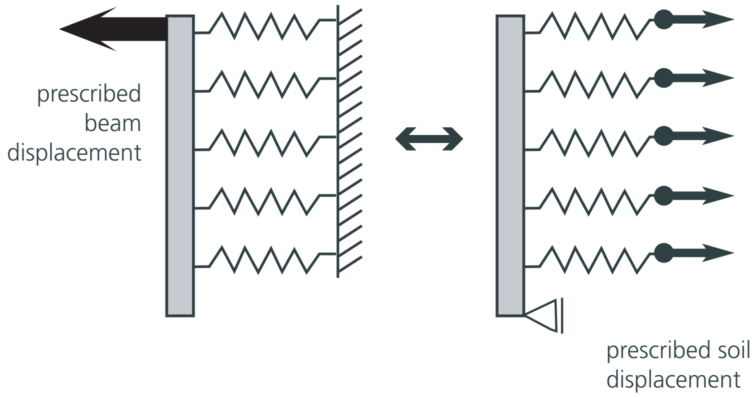


Figure 1.8: *Beam with prescribed displacement*

This problem is therefore identical to benchmark bm3-2 in section 1.2 where a beam has a prescribed displacement of 0.1 m.

1.6.2 Benchmark results

The analytical results are identical to those from section 1.2 as illustrated in Figure 1.8.

1.6.3 D-SHEET PILING results

In D-SHEET PILING, the active and passive earth pressure coefficients must be chosen properly in order to avoid plasticity. To compare D-SHEET PILING results and benchmark results, the stiffness of the soil in D-SHEET PILING must be divided by a factor 2 (k = 5 kN/m^3) as the soil is present at both side of the beam. The maximum relative variation of displacement, shear force and moment are compared in Table 1.6.

Table 1.6: *Results of benchmark 1-6*

	Benchmark	D-SHEET PILING	Relative error [%]
Displacement [mm]	100 –(– 6.9) = 106.9	106.9 – 0 = 106.9	0.00
Shear force [kN]	0.5 –(–2.2) = 2.7	2.2 –(–0.5) = 2.7	0.00
Moment [kNm]	0.0 –(-3.3) = 3.3	3.3 – 0.0 = 3.3	0.00

Use D-SHEET PILING input file bm1-6.shi to run this benchmark.

1.7 Load on beam/wall on elastic foundation, in stratified soil

1.7.1 Description

An Euler-Bernoulli beam of finite length (L = 20 m) on two different sections of elastic spring foundation is simulated. The different foundations are analogous to different soil layers. The beam is loaded by a force in the middle. See Figure 1.9.

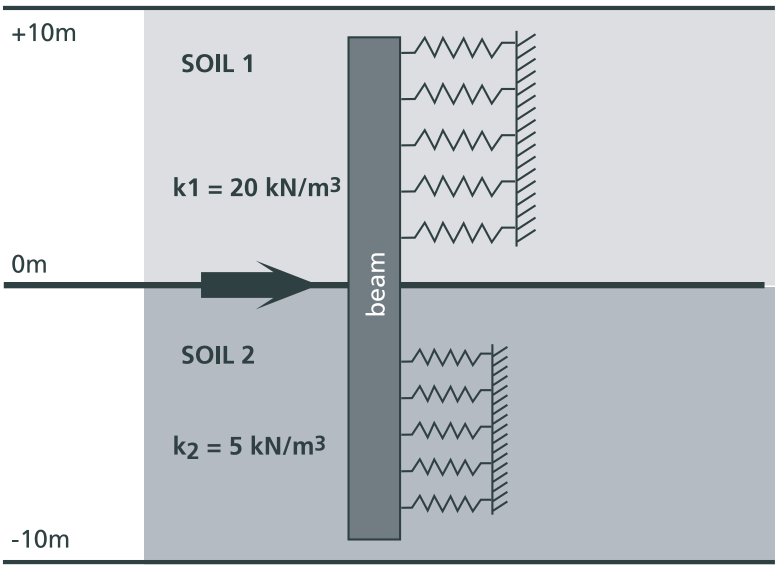


Figure 1.9: *Beam in stratified soil*

1.7.2 Benchmark results

This problem is similar to benchmark in section 1.1 but with different expressions for the displacement in the different layers:

soil 1: $w_1\left(x\right) = e^{\omega_1 x}\left[c_1 \cos\left(\omega_1 x\right) + c_2 \sin\left(\omega_1 x\right)\right] + e^{-\omega_1 x}\left[c_3 \cos\left(\omega_1 x\right) + c_4 \sin\left(\omega_1 x\right)\right]$

soil 2: $w_2\left(x\right) = e^{\omega_2 x}\left[c_5 \cos\left(\omega_2 x\right) + c_6 \sin\left(\omega_2 x\right)\right] + e^{-\omega_2 x}\left[c_7 \cos\left(\omega_2 x\right) + c_8 \sin\left(\omega_2 x\right)\right]$

with:

w_1	is the displacement of the beam in soil 1
w_2	is the displacement of the beam in soil 2
$4\omega^4 = k/EI$	
k_1, k_2	are the modulus of subgrade reaction of soils 1 and 2 respectively
EI	is the stiffness of the beam (1042 kNm/m)

The constants in the analytical solution depend on the boundary conditions. At both ends the shear force and the bending moments are zero. At the interface of both soils, the displacement and the moment must be continuous. Thus:

$$x = 0 : w_1 = w_2 \qquad \Rightarrow c_1 + c_3 = c_5 + c_7 \tag{1.33}$$

$$x = 0 : \frac{dw_1}{dx} = \frac{dw_2}{dx} \qquad \Rightarrow \omega_1(c_1 + c_2 - c_3 + c_4) = \omega_2(c_5 + c_6 - c_7 + c_8) \tag{1.34}$$

$$x = 0 : M = -EI\,\frac{d^2\,w_1}{dx^2} = -EI\,\frac{d^2\,w_2}{dx^2} \qquad \Rightarrow \omega_1^2(c_2 - c_4) = \omega_2^2(c_6 - c_8) \tag{1.35}$$

$$x = 0 : Q = -EI(\frac{d^3\,w_1}{dx^3} - \frac{d^3 w_2}{dx^3}) = F \qquad \Rightarrow \omega_1^3(c_1 - c_2 - c_3 - c_4) - \omega_2^3(c_5 - c_6 - c_7 - c_8) = \frac{F}{2} \tag{1.36}$$

$$x = -1/2L : M = -EI\,\frac{d^2\,w_1}{dx^2} = 0 \qquad \Rightarrow \cos(\frac{\omega_1 L}{2})(-c_2 + c_4 e^{\omega_1 L}) - \sin(\frac{\omega_1 L}{2})(c_1 - c_3 e^{\omega_1 L}) = 0 \tag{1.37}$$

$$x = -1/2L : Q = -EI\frac{d^3\,w_1}{dx^3} = 0 \qquad \Rightarrow \cos(\frac{\omega_1 L}{2})(-c_1 + c_2 + (c_3 + c_4)e^{\omega_1 L}) + \sin(\frac{\omega_1 L}{2})(c_1 + c_2 + (c_3 - c_4)e^{\omega_1 L}) = 0 \tag{1.38}$$

$$x = 1/2L : M = -EI\,\frac{d^2\,w_2}{dx^2} = 0 \qquad \Rightarrow \cos(\frac{\omega_2 L}{2})(-c_8 + c_6 e^{\omega_2 L}) + \sin(\frac{\omega_2 L}{2})(c_7 - c_5 e^{\omega_2 L}) = 0 \tag{1.39}$$

$$x = 1/2L : Q = -EI\frac{d^3\,w_2}{dx^3} = 0 \qquad \Rightarrow \cos(\frac{\omega_2 L}{2})(c_7 + c_8 - (c_5 - c_6)e^{\omega_2 L}) - \sin(\frac{\omega_2 L}{2})(c_7 - c_8 + (c_5 + c_6)e^{\omega_2 L}) = 0 \tag{1.40}$$

This leads to eight equations with eight unknowns which can be solved. Solving these equations gives:

$c_1 = 1.5981 \times 10^{-3}$	$c_5 = 1.0314 \times 10^{-1}$
$c_2 = -2.0442 \times 10^{-1}$	$c_6 = -1.4514 \times 10^{-1}$
$c_3 = 1.0598 \times 10^{-1}$	$c_7 = 4.4372 \times 10^{-3}$
$c_4 = 7.3864 \times 10^{-2}$	$c_8 = 2.9949 \times 10^{-3}$

1.7.3 D-Sheet Piling results

Modelling this problem in D-Sheet Piling is straightforward. The active and passive earth pressure coefficients must be chosen properly in order to avoid plasticity. To compare D-Sheet Piling results and benchmark results, the modulus of subgrade reaction of the soil in D-Sheet Piling must be divided by a factor 2 (k_1 = 10 kN/m^3 and k_2 = 2.5 kN/m^3) as the soil is present on both sides of the beam. Results are compared in the following table.

Table 1.8: *Results of benchmark 1-7*

	Benchmark	**D-Sheet Piling**	**Relative error [%]**
Maximum displacement [mm]	111.1	111.1	0.00
Displacement at top [mm]	-24.8	-24.8	0.00
Displacement at bottom [mm]	-9.6	-9.6	0.00
Maximum shear force [kN]	6.8	6.8	0.00
Minimum shear force [kN]	-3.2	-3.2	0.00
Maximum bending moment [kNm]	10.7	10.7	0.00
Minimum bending moment [kNm]	-2.4	-2.4	0.00

Use D-Sheet Piling input file bm1-7.shi to run this benchmark.

1.8 Calculation of the K-ratios for a straight slip surface

1.8.1 Description

The Müller-Breslau formulas which assume a straight slip surface are given in Müller-Breslau (1906). For this problem the following values are chosen:

Friction angle	φ	25°
Delta friction angle	δ	15°
Shell factor	s	2.5
Overconsolidation ratio	OCR	1.2

1.8.2 Benchmark results

According to Müller-Breslau (1906), K-ratios are (including the arching effect):

$$K_a = \frac{\cos^2 \varphi}{s \left(1 + \sqrt{\frac{\sin\varphi \sin(\varphi + \delta)}{\cos\delta}}\right)^2} \tag{1.41}$$

$$K_p = \frac{s \times \cos^2 \varphi}{\left(1 - \sqrt{\frac{\sin\varphi \sin(\varphi + \delta)}{\cos\delta}}\right)^2} \tag{1.42}$$

And the neutral earth pressure ratio K_0 is:

$K_0 = \sqrt{OCR}\ (1 - \sin\varphi)$ for coarse grain

$K_0 = OCR^{\sin\varphi}\ (1 - \sin\varphi)$ for fine coarse

Those three formulas lead to:

- ◇ K_a = 0.1403
- ◇ K_p = 9.3086
- ◇ K_0 = 0.6236 for fine grain
- ◇ K_0 = 0.6325 for coarse grain

1.8.3 D-SHEET PILING results

In D-SHEET PILING, calculations are performed using the K_a, K_0, K_p method in the *Model* window and the *Straight slip surfaces* option in the *Soil Materials* window. The results of the D-SHEET PILING calculation and the analytical calculation are given in the following table.

Table 1.9: *Results of benchmark 1-8*

Earth pressure coefficient	Grain type	Benchmark	D-SHEET PILING	Relative error [%]
K_a [-]	-	0.14	0.14	0.00
K_p [-]	-	9.31	9.31	0.00
K_0 [-]	Fine	0.62	0.62	0.00
	Coarse	0.63	0.63	0.00

Use D-SHEET PILING input file bm1-8.shi to run this benchmark.

1.9 Calculation of the K-ratios for a curved slip surface

1.9.1 Description

The Kötter equations Kötter (1903) assume a curved slip surface (logarithmic spiral and straight part). For this problem the following values are chosen:

Friction angle	φ	25°
Delta friction angle	δ	15°
Shell factor	s	2
Overconsolidation ratio	OCR	1.2

1.9.2 Benchmark results

According to Kötter Kötter (1903), the K-ratios are (including the arching effect):

$$K_a = \frac{1 - \sin\varphi \sin(2\alpha + \varphi)}{s \times (1 + \sin\varphi)} \exp\{(-\frac{\pi}{2} + \varphi + 2\alpha) \tan\varphi\} \tag{1.43}$$

$$K_p = s \times \frac{1 + \sin\varphi \sin(2\alpha' - \varphi)}{(1 - \sin\varphi)} \exp\{(\frac{\pi}{2} + \varphi - 2\alpha') \tan\varphi\} \tag{1.44}$$

where α and α' are solutions of equations:

$$\cos(2\alpha + \varphi - \delta) = \frac{\sin\delta}{\sin\varphi}$$

$$\cos(2\alpha' - \varphi + \delta) = \frac{\sin\delta}{\sin\varphi}$$

And the neutral earth pressure ratio K_0 is:

$K_0 = \sqrt{OCR}\ (1 - \sin\varphi)$ for coarse grain

$K_0 = OCR^{\sin\varphi}\ (1 - \sin\varphi)$ for fine coarse

Those three formulas lead to:

- ◇ K_a = 0.1426
- ◇ K_p = 8.3535
- ◇ K_0 = 0.6236 for fine grain
- ◇ K_0 = 0.6325 for coarse grain

1.9.3 D-Sheet Piling results

In D-Sheet Piling, calculations are performed using the K_a, K_0, K_p method in the *Model* window and the *Curved slip surfaces* option in the *Soil Materials* window. The results of the D-Sheet Piling calculation and the analytical calculation are given in Table 1.10.

***Table 1.10:** Results of benchmark 1-9*

Earth pressure coefficient	Grain type	Benchmark	D-Sheet Piling	Relative error [%]
K_a [-]	-	0.14	0.14	0.00
K_p [-]	-	8.35	8.35	0.00
K_0 [-]	Fine	0.62	0.62	0.00
	Coarse	0.63	0.63	0.00

Use D-SHEET PILING input file bm1-9.shi to run this benchmark.

1.10 Modulus of subgrade reaction according to Ménard

1.10.1 Description

This benchmark checks the calculation of the modulus of subgrade reaction according to Ménard Ménard (1971). Five soil types (peat, clay, loam, sand and gravel) and two pile types (with diameters of 1 m and 0.4 m) are combined. The Ménard pressuremeter modulus is E_m = 5 kN/m^2.

1.10.2 Benchmark results

The modulus of subgrade reaction calculated according to Ménard is given in Ménard (1971):

$$\frac{1}{k_h} = \begin{cases} \frac{1}{3E_m}\left[1.3R_0\left(2.65\frac{R}{R_0}\right)^{\alpha} + \alpha R\right] & \text{if } R \geq R_0 \\ \frac{2R}{E_m}\cdot\frac{4(2.65)^{\alpha}+3\alpha}{18} & \text{if } R < R_0 \end{cases} \tag{1.45}$$

where:

k_h	is the modulus of horizontal subgrade reaction;
E_m	is the pressiometric modulus in kN/m^2;
R_0	is a constant: R_0 = 0.3 m;
R	is the half width of the pile in m;
α	is a rheological coefficient depending on the kind of the soil and the soil conditions.

Analytical results for the different soil and pile combinations are shown in Table 1.12.

Table 1.12: *Modulus of subgrade reaction acc. to Ménard formula*

Soil type	Pile diameter	Rheological coefficient	Half width of the pile	Modulus
	D	α	R	k
	[m]	[-]	[m]	[kN/m^3]
Peat	1	1	0.5	6.749
Clay	1	0.667	0.5	10.845
Loam	1	0.5	0.5	14.024
Sand	1	0.333	0.5	18.598
Gravel	1	0.25	0.5	21.727
Peat	0.4	1	0.2	16.544
Clay	0.4	0.667	0.2	23.292
Loam	0.4	0.5	0.2	28.085
Sand	0.4	0.333	0.2	34.428
Gravel	0.4	0.25	0.2	38.438

1.10.3 D-SHEET PILING results

Table 1.13: *Results of benchmark 1-10 – Modulus of subgrade reaction according to Ménard*

Pile diameter [m]	Soil type	Benchmark	D-SHEET PILING	Relative error [%]
1	Peat	6.75	6.75	0.00
1	Clay	10.84	10.84	0.00
1	Loam	14.02	14.02	0.00
1	Sand	18.60	18.60	0.00
1	Gravel	21.73	21.73	0.00
0.4	Peat	16.54	16.54	0.00
0.4	Clay	23.29	23.29	0.00
0.4	Loam	28.08	28.08	0.00
0.4	Sand	34.43	34.43	0.00
0.4	Gravel	38.44	38.44	0.00

Use D-SHEET PILING input file bm1-10.shi to run this benchmark.

1.11 Single pile loaded by horizontal force

1.11.1 Description

This benchmark is identical to benchmark bm1-1 (section 1.1) except that the sheet pile is replaced by a single pile loaded by a horizontal force.

1.11.2 Benchmark results

Benchmark results are the same as benchmark bm1-1 (section 1.1).

1.11.3 D-SHEET PILING results

Modeling this problem In D-SHEET PILING is straightforward. Plasticity is avoided by a proper choice of the active and passive earth pressure coefficients.To compare D-SHEET PILING results and benchmark results, the modulus of subgrade reaction of the soil In D-SHEET PILING must be divided by a factor 2 (k = 5 kN/m^3) as the soil is present on both sides of the beam. Results are compared in Table 1.14.

Table 1.14: *Results of benchmark 1-11*

	Benchmark	D-SHEET PILING	Relative error [%]
Maximum displacement [mm]	117.9	118.0	0.08
Maximum shear force at [kN]	5.0	5.0	0.00
Maximum bending moment [kNm]	11.6	11.6	0.00
Minimum bending moment [kNm]	-0.8	-0.8	0.00

Use D-SHEET PILING input file bm1-11.shi to run this benchmark.

1.12 Passive earth pressure coefficient acc. to Brinch-Hansen

1.12.1 Description

A single pile of length L = 5 m and diameter B = 0.6 m, in stratified soil, is loaded by a horizontal force F = 300 kN acting half way down the pile. As the pile is supposed to be rigid (stiffness EI = 10^{10} kNm^2), the distribution of the horizontal stresses along the pile is uniform and equal to $\sigma_H = F/(L \times B) = 100$ kN/m^2.

The passive earth pressure coefficient and the adapted cohesion are calculated according to Brinch-Hansen Brinch-Hansen and Christensen (1961).

1.12.2 Benchmark results

Factors K_q and K_c are calculated using the following equations:

$$K_q = \frac{K_q^0 + K_q^\infty \times \alpha_q \times \frac{D}{B}}{1 + \alpha_q \times \frac{D}{B}} \tag{1.46}$$

$$K_c = \frac{K_c^0 + K_c^\infty \times \alpha_c \times \frac{D}{B}}{1 + \alpha_c \times \frac{D}{B}} \tag{1.47}$$

where:

$$K_q^0 = e^{(\frac{\pi}{2}+\varphi)\times\tan\varphi} \times \cos\varphi \times \tan(\frac{\pi}{4} + \frac{\varphi}{2}) - e^{(-\frac{\pi}{2}+\varphi)\times\tan\varphi} \times \cos\varphi \times \tan(\frac{\pi}{4} - \frac{\varphi}{2}) \tag{1.48}$$

$$K_c^0 = [e^{(\frac{\pi}{2}+\varphi)\times\tan\varphi} \times \cos\varphi \times \tan(\frac{\pi}{4} + \frac{\varphi}{2}) - 1] \times \cot\varphi \tag{1.49}$$

$$K_q^\infty = K_c^\infty \times K_0 \times \tan\varphi \tag{1.50}$$

$$K_c^\infty = N_c \times d_c^\infty \tag{1.51}$$

$$d_c^\infty = 1.58 + 4.09 \times \tan^4\varphi \tag{1.52}$$

$$N_c = [e^{\pi\times\tan\varphi} \times \tan^2(\frac{\pi}{4} + \frac{\varphi}{2}) - 1] \times \cot\varphi \tag{1.53}$$

$$K_0 = 1 - \sin\varphi \quad \text{for OCR = 1} \tag{1.54}$$

$$\alpha_q = \frac{K_q^0}{K_q^\infty - K_q^0} \times \frac{K_0 \times \sin\varphi}{\sin(\frac{\pi}{4} + \frac{\varphi}{2})} \tag{1.55}$$

$$\alpha_c = \frac{K_c^0}{K_c^\infty - K_c^0} \times 2\sin(\frac{\pi}{4} + \frac{\varphi}{2}) \tag{1.56}$$

D is the average depth at the middle of the layer [m].
By identification with the usual formula for the calculation of the passive earth pressure $\sigma_p = K_p \times \sigma'_v + 2c^*\sqrt{K_p}$, it can be deduced:

$$K_p = K_q \quad \text{Passive earth pressure coefficient [-]} \tag{1.57}$$

$$c^* = \frac{c \times K_c}{2\sqrt{K_q}} \quad \text{Adapted cohesion [kN/m}^2\text{]} \tag{1.58}$$

Results for the different layers are given in Table 1.15.

Table 1.15: *Calculation of factors K_q and K_c according to Brinch-Hansen*

	Layer 1	**Layer 2**	**Layer 3**
Top level [m]	0	-2	-3.5
Depth *D* [m]	1	2.75	4.25
Saturated weight [kN/m^3]	15	20	15
Cohesion c [kN/m^2]	10	0	20
Friction angle [°]	20	32	25
Factor $K_q = K_p$ [-]	3.0855	10.6483	6.6222
Factor K_c [-]	12.4286	40.4978	26.9113
Adapted cohesion c^* [kN/m^2]	35.3777	0	104.5760

The effective vertical stress and the passive earth pressure are calculated for different depths. These results are given in Table 1.16.

Table 1.16: *Stresses according to Brinch-Hansen*

Depth	[m]	-0.44	-2.50	-4.14
σ_w	[kPa]	4.4	25.0	41.4
σ_v	[kPa]	6.6	40.0	69.6
σ'_v	[kPa]	2.2	15.0	28.2
σ_p	[kPa]	100	100	100
σ_H / σ_p	[%]	76.29	62.61	13.79

1.12.3 D-SHEET PILING results

The results of the D-SHEET PILING calculation and the benchmark are given in Table 1.17.

Table 1.17: *Results of benchmark 1-12 – Passive earth pressure coefficient and adapted cohesion according to Brinch-Hansen*

	Depth	**Benchmark**	**D-SHEET PILING**	**Relative error [%]**
Cohesion [kPa]	Layer 1	35.38	35.38	0.00
	Layer 2	0.00	0.00	0.00
	Layer 3	104.58	104.58	0.00
Passive earth pressure coefficient [-]	Layer 1	3.09	3.09	0.00
	Layer 2	10.65	10.65	0.00
	Layer 3	6.62	6.62	0.00
Mobilized passive resistance [%]	-0.44 m	76	76	0.00
	-2.50 m	63	63	0.00
	-4.14 m	14	14	0.00

Use D-SHEET PILING input file bm1-12.shi to run this benchmark.

2 Group 2: Benchmarks from literature (approximate solution)

This chapter contains benchmarks described in literature, for which an approximate solution is known (group 2).

2.1 Horizontal load due to different level of water table

2.1.1 Description

A sheet pile wall is loaded by hydrostatic water pressure, with (as far as is physically possible) stationary, but different, water table levels on either side of the wall. In D-SHEET PILING a sheet pile wall 12 m long is placed in homogeneous soil with the water table at the top of the wall. Thereafter, in succeeding stages, the water table on the left hand side of the wall is lowered to -2, -4 and -6 m respectively. The water pressures at the middle level and the toe level are compared.

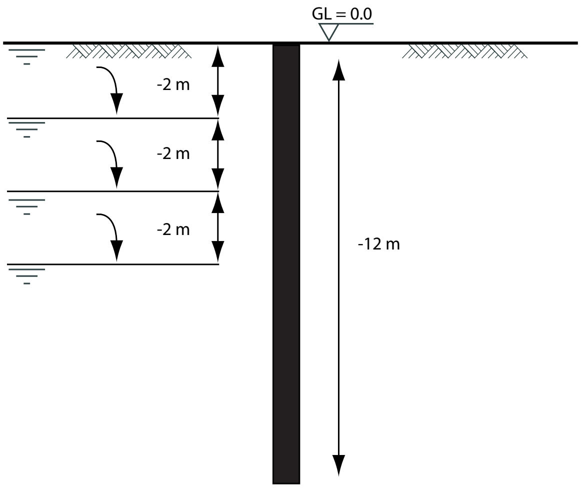


Figure 2.1: *Changing water levels (benchmark bm2-1)*

2.1.2 Benchmark results

On both sides the water pressure increases linearly with depth. The increase per meter depth equals the volumetric weight of the water.

2.1.3 D-SHEET PILING results

The calculations are carried out using the input file which is similar to that for benchmark 1-4 (section 1.4). The results of D-SHEET PILING and the benchmark are compared in Table 2.1.

Table 2.1: Results of benchmark 2-1 – Water pressures for different water levels

Water table lowering (left)	Depth	Benchmark [kN/m^2]	D-SHEET PILING [kN/m^2]	Relative error [%]
0 m	Middle	60	60	0.00
	Toe	120	120	0.00
2 m	Middle	40	40	0.00
	Toe	100	100	0.00
4 m	Middle	20	20	0.00
	Toe	80	80	0.00
6 m	Middle	0	0	0.00
	Toe	60	60	0.00

Use D-SHEET PILING input file bm2-1.shi to run this benchmark.

2.2 Fundamental solution according to Culmann

2.2.1 Description

At failure the equilibrium of a sliding soil mass must be insured. For a simple case the equilibrium can be calculated analytically.

A short sheet pile wall (length L = 2 m) is fixed at the toe. The soil is purely cohesive (c = 1 kN/m^2 and φ = 0°) and almost mass-less (γ_{soil} = 1 kN/m^3). In this case the shear force along a sliding surface is known (length of surface × cohesion) and the equilibrium can be calculated (Figure 2.2). A surcharge load of q = 2 kN/m^2 is applied; this value is the maximum force possible that insures stability.

2.2.2 Benchmark results

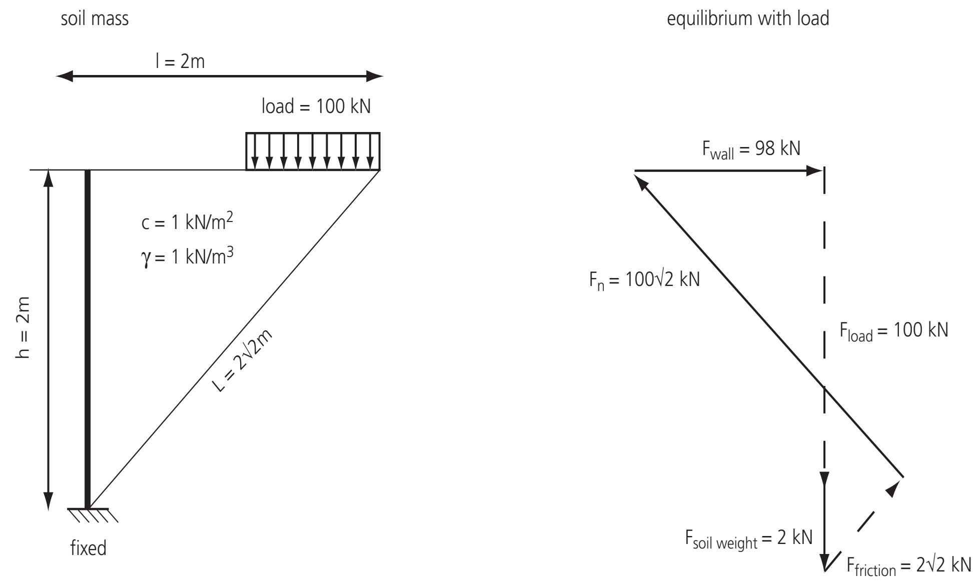


***Figure 2.2:** The force against the wall is calculated graphically*

2.2.3 D-SHEET PILING results

The results of D-SHEET PILING and the benchmark are shown in Table 2.2.

Table 2.2: *Results of benchmark 2-2*

	Benchmark	**D-SHEET PILING**	**Rel. error [%]**
Total force without surface load [kN]	2.0	2.0	0.00
Total force with surface load [kN]	98.0	98.0	0.00

Use D-SHEET PILING input file bm2-2.shi to run this benchmark.

3 Group 3: Benchmarks from spreadsheets

This chapter contains benchmarks which test program features specific to D-Sheet Piling using spreadsheets (group 3).

3.1 Anchor wall stability for a short anchorage in homogeneous soil

3.1.1 Description

A sheet pile H = 7 m long has a ground surface at 0 m on one side and -4.5 m on the other side. An anchor is attached at -2 m, at an angle β = 5 degrees to the horizontal axis. The anchor length is L = 5 m and the anchor wall is h = 1 m high. The soil is homogeneous (γ' = 5 kN/m^3, φ = 25°and c = 2 kPa). A uniform load of q = 6 kN/m^2 is applied on the right side.

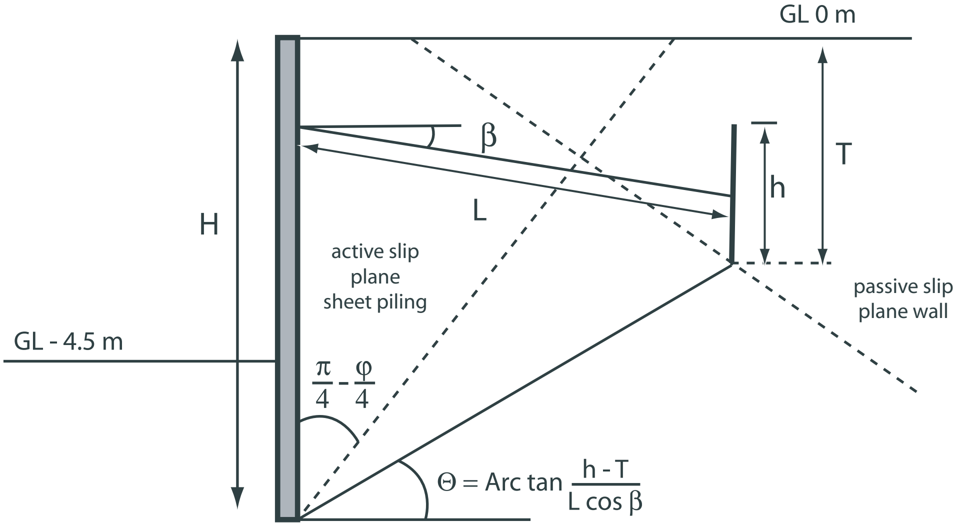


Figure 3.1: *Short anchor (bm3-1)*

3.1.2 Benchmark results

The allowable anchor force *P* according to Kranz method Kranz (1953) for a short anchorage is given by equation:

$$P = \frac{E_a - (E_0 + E_r) + E_c}{E_s} \tag{3.1}$$

where:

E_a is the active pressure on the sheet pile:
$E_a = \frac{1}{2} K_a \times \gamma \times H^2 - 2c\sqrt{K_a} \times H + K_a \times q \times H$

E_0 is the active pressure on the anchor wall:
$E_o = \frac{1}{2} K_a \times \gamma \times T^2 - 2c\sqrt{K_a} \times T + K_a \times q \times T$

E_r is the horizontal pressure on deep slide plane:
$$E_r = L \times \cos\beta \left(\gamma' \frac{H+T}{2} + q \right) \tan(\theta - \varphi)$$

E_c is the horizontal cohesive force along the slide plane:
$E_C = c \times L \times \cos\beta$

E_s is the factor due to the anchor inclination:
$E_S = \cos\beta - \sin\beta \times \tan(\theta - \varphi)$

K_a is the lateral earth pressure ratio at active yielding:
$K_a = \dfrac{1 - \sin\varphi}{1 + \sin\varphi}$
γ' is the effective soil unit weight in kN/m^3;
q is the surface load in kN/m^2;
H is the distance between the level of the top of the sheet pile wall and the level at which the maximum bending moment occurs.

Analytical solution is worked out in an Excel spreadsheet and leads to the following intermediate results:
$T = z + \frac{1}{2}h + L \times \sin\beta = 2.936$ m
K_a = 0.4059
θ = 39.213°
The final analytical results are given in Table 3.2.

3.1.3 D-SHEET PILING results

The "actual anchor forces" for "Representative" and "CUR" cases are deduced by performing two extra calculations with D-SHEET PILING:

- For *Representative* verification, a *Standard* calculation is performed and the resulting anchor force is 17.97194 kN;
- For *CUR* verification, a *Verify Sheet Piling* calculation is performed after selecting *CUR* as design code and entering 1.3 as *Anchor stiffness multiplication factor*. The maximum resulting anchor force is $F_{a;max}$ = 23.70871 kN therefore the actual anchor force is 1.5 $\times$ $F_{a;max}$ = 35.563 kN.

For the anchor stability check, the calculation is performed using the *Allowable Anchor Force* tab in the *Start Calculation* menu. the D-SHEET PILING results and the benchmark results are compared in Table 3.2.

Table 3.2: *Results of benchmark 3-1 – Short anchor stability*

Result	Unit	Benchmark	D-SHEET PILING	Error [%]
E_a (with loads)	[kN]	48.926	48.913	0.03
E_r (with loads)	[kN]	38.906	38.906	0.00
E_0	[kN]	8.413	8.410	0.04
E_c	[kN]	9.962	9.962	0.00
E_s	[-]	0.974	0.978	0.41
Allowable anchor force (with loads)	[kN]	11.877	11.821	0.47
Allowable anchor force (no loads)	[kN]	2.148	2.133	0.70
Actual anchor force (Rep.)	[kN]	17.972	17.972	0.00
Actual anchor force (CUR)	[kN]	35.563	35.563	0.00

Use D-SHEET PILING input file bm3-1.shi to run this benchmark.

3.2 Anchor wall stability for a long anchorage in homogeneous soil

3.2.1 Description

This benchmark has the same input as benchmark 3-1 (section 3.1) except for the anchor length, L = 10 m. Therefore, the anchorage is now a long anchorage.

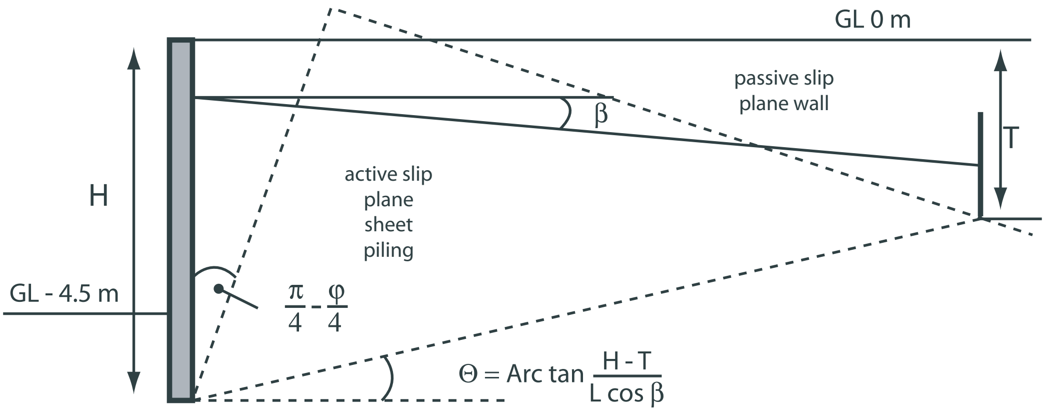


Figure 3.2: *Long anchor (bm3-2)*

3.2.2 Benchmark results

The allowable anchor force *P* according to Kranz method Kranz (1953) for a long anchorage is given by equation:

$$P = E_p - E_0 \tag{3.2}$$

where:

E_p Passive pressure on the anchor wall:
$E_p = \frac{1}{2} K_p \times \gamma \times T^2 + 2c\sqrt{K_p} \times T + K_p \times q \times T$

E_0 Active pressure on the anchor wall:
$E_0 = \frac{1}{2} K_a \times \gamma \times T^2 - 2c\sqrt{K_a} \times T$

K_a Lateral earth pressure ratio at active yielding:
$K_a = \dfrac{1 - \sin\varphi}{1 + \sin\varphi}$

K_p Lateral earth pressure ratio at passive yielding:
$K_p = \dfrac{1 + \sin\varphi}{1 - \sin\varphi}$

Analytical solution is worked out in an Excel spreadsheet and leads to the following intermediate results:
$T = z + \frac{1}{2}h + L \times \sin\beta$ = 3.372 m
K_a = 0.4059
K_p = 2.4639

The final analytical results are given in Table 3.4.

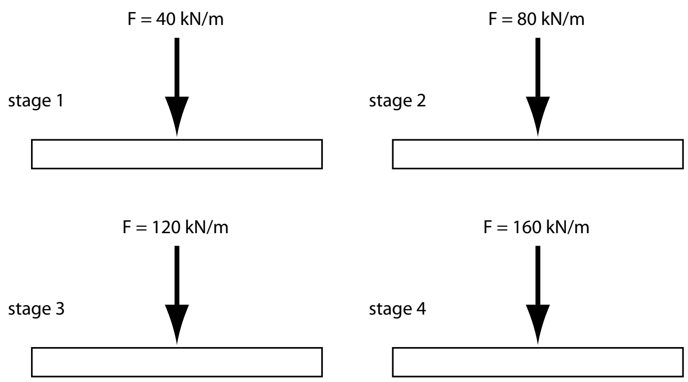


Figure 3.3: *Application of horizontal line loads for the four stages*

3.2.3 D-SHEET PILING results

The “actual anchor forces” for “Representative” and “CUR” cases are deduced by performing two extra calculations with D-Sheet Piling:

- ◇ For *Representative* verification, a *Standard* calculation is performed and the resulting anchor force is 15.03651 kN;
- ◇ For *CUR* verification, a *Verify Sheet Piling* calculation is performed after selecting *CUR* as design code and entering 1.3 as *Anchor stiffness multiplication factor*. The maximum resulting anchor force is $F_{a;max}$ = 19.06460 kN therefore the actual anchor force is 1.5 $\times$ $F_{a;max}$ = 28.597 kN.

For the anchor stability check, the calculation is performed using the *Allowable Anchor Force* tab from the *Start Calculation* menu. The D-SHEET PILING results and the benchmark results are compared in Table 3.4.

Table 3.4: *Results of benchmark 3-2 – Long anchor stability*

Result	Unit	Benchmark	D-SHEET PILING	Error [%]
E_p (without loads)	[kN]	91.190	91.206	0.02
E_p (with loads)	[kN]	141.033	141.058	0.03
E_0	[kN]	11.152	11.148	0.04
Allowable anchor force (no loads)	[kN]	80.037	80.058	0.03
Actual anchor force (Rep.)	[kN]	15.037	15.037	0.00
Actual anchor force (CUR)	[kN]	28.597	28.597	0.00

Use D-SHEET PILING input file bm3-2.shi to run this benchmark.

3.3 Displacement using several branches in the stress-displacement diagram

3.3.1 Description

This benchmark evaluates the horizontal displacement of a sheet pile wall (length L = 20 m) using four branches in the stress-displacement diagram. Four horizontal line loads of F = 40 kN/m are consecutively applied at four stages (Figure 3.3).

The four branches of the stress-displacement diagram have the following characteristics:

- ◇ Branch 1: k_1 = 100 kN/m^3 starting at σ_H = 0

◇ Branch 2: k_2 = 500 kN/m^3 starting at 25 % of ($\sigma_p - \sigma_a$)
◇ Branch 3: k_3 = 250 kN/m^3 starting at 50 % of ($\sigma_p - \sigma_a$)
◇ Branch 4: k_4 = 400 kN/m^3 starting at 75 % of ($\sigma_p - \sigma_a$)

For this problem, the following values are chosen:
γ = 0 kN/m^3
c = 2 kN/m^2
K_a = K_0 = 0
K_p = 4

As the pile is supposed to be rigid (EI = 9 108 kNm^2/m), the distribution of the horizontal stresses along the pile is uniform and equal to:
$\sigma_H = \frac{F}{L}$

3.3.2 Benchmark results

As the unit weight of the soil is zero, the initial vertical stress is nil. This leads to:

$$\sigma_a = K_a \times \sigma_v - 2c\sqrt{K_a} = 0 \tag{3.3}$$
$$\sigma_0 = K_0 \times \sigma_v = 0 \tag{3.4}$$
$$\sigma_p = K_p \times \sigma_v + 2c\sqrt{K_p} = 8 \text{ kN/m}^2 \tag{3.5}$$

According to the input percentage of stress variation, the four branches of the stress-displacement diagram start respectively at 0, 2, 4 and 6 kPa. Each new load step corresponds to the limit point of each branch. Then, the total displacement after each stage is:

$$w_1 = \frac{\sigma_1 - \sigma_0}{k_1} = \frac{F/L}{k_1} = \frac{40/20}{100} = 0.020 \text{ m}$$
$$w_2 = w_1 + \frac{\sigma_2 - \sigma_1}{k_2} = 0.020 + \frac{40/20}{500} = 0.02 \text{ m}$$
$$w_3 = w_2 + \frac{\sigma_3 - \sigma_2}{k_3} = 0.024 + \frac{40/20}{250} = 0.032 \text{ m}$$
$$w_4 = w_3 + \frac{\sigma_4 - \sigma_3}{k_4} = 0.032 + \frac{40/20}{400} = 0.037 \text{ m}$$

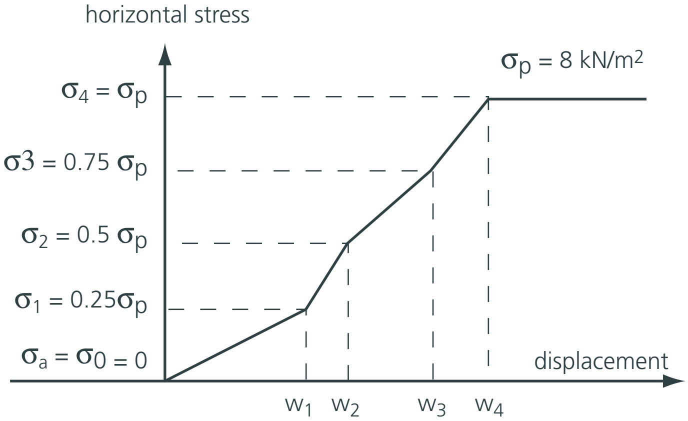


Figure 3.4: *Stress-displacement diagram*

3.3.3 D-SHEET PILING results

D-Sheet Piling calculations are performed using the K_a, K_0, K_p method in the *Model* window. The results of the D-SHEET PILING calculation and the benchmark are given in Table 3.5.

Table 3.5: *Results of benchmark 3-3 – Displacements*

Stage	Benchmark [mm]	D-SHEET PILING [mm]	Relative error [%]
Stage 1	20.0	20.0	0.00
Stage 2	24.0	24.0	0.00
Stage 3	32.0	32.0	0.00
Stage 4	37.0	37.0	0.00

Use D-SHEET PILING input file bm3-3.shi to run this benchmark.

3.4 Displacement during unloading/reloading steps

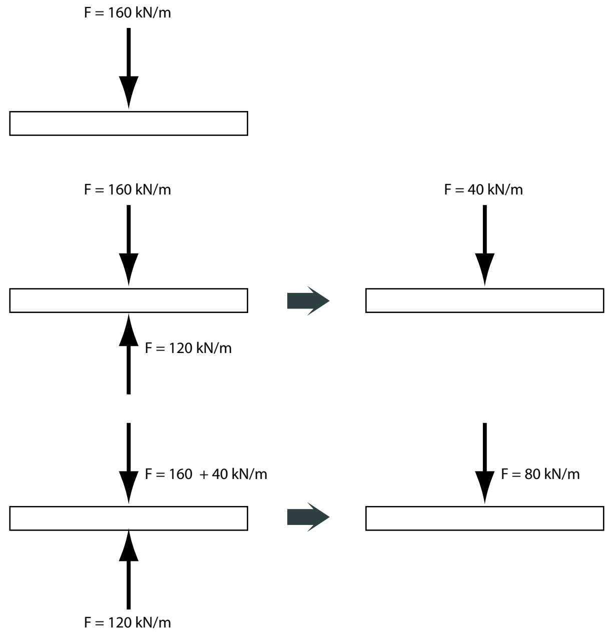


Figure 3.5: *Loads applied in each stage*

3.4.1 Description

This benchmark evaluates the horizontal displacement of a sheet pile wall (L = 20 m) loaded with a load of F_1 = 160 kN/m (stage 1), unloaded with a load of F_2 = –20 kN/m (stage 2) and reloaded with a load of F_3 = 40 kN/m (stage 3).

For this problem, the following values are used:
γ = 0 kN/m^3
c = 2 kN/m^2
K_a = K_0 = 0
K_p = 4
k_0 = 50 kN/m^3
k_1 = 100 kN/m^3

As the pile is supposed to be rigid (EI = 9 108 kNm^2/m), the distribution of the horizontal stresses along the pile is uniform and equal to $\sigma_H = F/L$.

3.4.2 Benchmark results

As the unit weight of the soil is zero, the initial vertical stress is also zero. This leads to:

$$\sigma_a = K_a \times \sigma_v - 2c\sqrt{K_a} = 0 \tag{3.6}$$

$$\sigma_0 = K_0 \times \sigma_v = 0 \tag{3.7}$$

$$\sigma_p = K_p \times \sigma_v + 2c\sqrt{K_p} = 8 \text{ kN/m}^2 \tag{3.8}$$

The first load step leads to a passive state. The following unloading step leads therefore to non-elastic soil behavior: that means the unloading subgrade reaction coefficient k_0 shall be used in the calculations for this stage. For the following reloading step, the soil is elastic: the subgrade reaction coefficient k_1 shall therefore be used in the calculations for this stage. The displacements for each stage are:

$$w_1 = \frac{\sigma_1}{k_1} = \frac{F_1}{L \times k_1} = 80 \text{ mm}$$

$$w_2 = w_1 + \frac{\sigma_2 - \sigma_1}{k_0} = w_1 + \frac{F_2}{k_0} = 40 \text{ mm}$$

$$w_3 = w_2 + \frac{\sigma_3 - \sigma_2}{k_1} = w_2 + \frac{F_3}{k_1} = 60 \text{ mm}$$

This is illustrated in Figure 3.6, below.

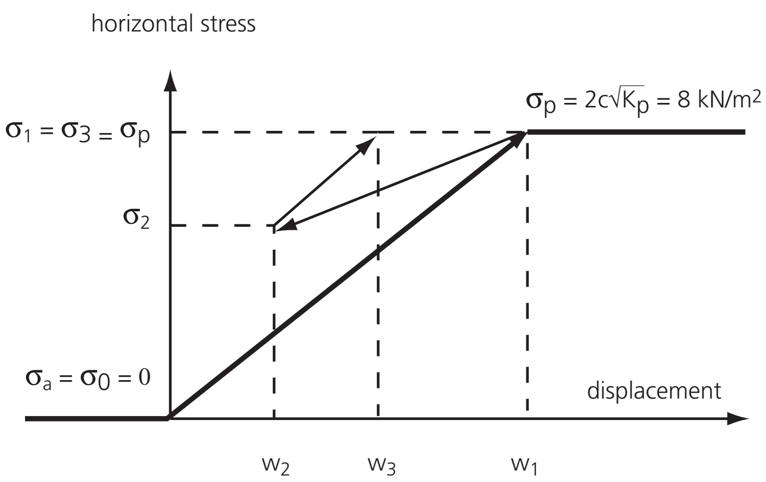


Figure 3.6: *Stress-displacement diagram for unloading*

3.4.3 D-SHEET PILING results

D-Sheet Piling calculations are performed using the K_a, K_0, K_p method in the *Model* window. The results of the D-SHEET PILING calculation and the benchmark are given in Table 3.6.

Table 3.6: *Results of benchmark 3-4 – Displacements*

Stage	**Benchmark [mm]**	**D-SHEET PILING [mm]**	**Relative error [%]**
Stage 1: loading	80.0	80.0	0.00
Stage 2: unloading	40.0	40.0	0.00
Stage 3: reloading	60.0	60.0	0.00

Use D-SHEET PILING input file bm3-4.shi to run this benchmark.

3.5 Functioning of anchors and struts

3.5.1 Description

The middle of a beam (length L = 20 m) is loaded with a horizontal force F = 20 kN/m and reinforced with an reinforcement (anchor or strut) inclined at β = 30°. See Figure 3.7. If the soil has no stiffness, then the applied force is completely transmitted to the reinforcement. Two types of reinforcements are considered: bm3-5a uses anchors whereas bm3-5b uses struts.

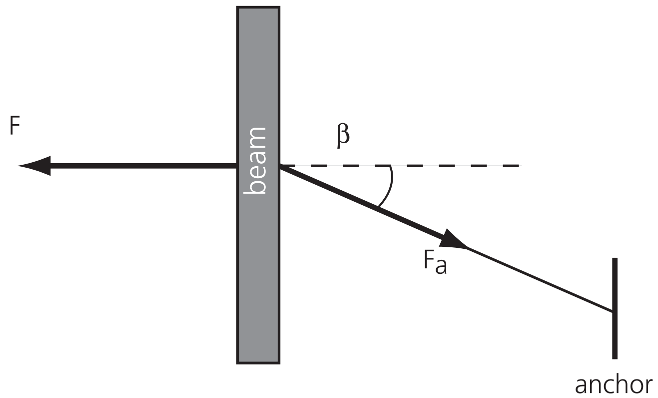


Figure 3.7: *Position of the anchor*

3.5.2 Benchmark results

According to Figure 3.7, equilibrium gives:

$$F_a = \frac{F}{\cos\beta} = \frac{20}{\cos 30°} = 23.09 \text{ kN/m} \quad (3.9)$$

For elastic behavior, the horizontal displacement at the middle of the beam is:

$$w = \frac{F_a \times l}{A_a \times E_a \times \cos\beta} = 12.698 \text{ mm} \quad (3.10)$$

where:

E_a = 2.1 $\times$ 10^8 kN/m^2
A_a = 10^{-4} m^2/m
l = 10 m

3.5.3 D-SHEET PILING results

In D-SHEET PILING, the modulus of subgrade reaction is set equal to its minimum (k = 0.01 kN/m^3) in order to neglect the stiffness of the soil.

Table 3.8: *Results of benchmark 3-5a – Anchor*

	Benchmark	D-SHEET PILING	Relative error [%]
Anchor force [kN]	23.09	23.09	0.00
Maximum displacement [mm]	12.7	12.7	0.00

Table 3.9: *Results of benchmark 3-5b – Strut*

	Benchmark	D-SHEET PILING	Relative error [%]
Strut force [kN]	23.09	23.09	0.00
Maximum displacement [mm]	12.7	12.7	0.00

Use D-SHEET PILING input files bm3-5a.shi and bm3-5b.shi to run this benchmark.

3.6 Additional horizontal pressure due to a uniform load

3.6.1 Description

This benchmark evaluates the horizontal stress distribution along the sheet piling due to a uniform load q = 20 kN/m^2. Calculations are performed with the K_a, K_0, K_p method with: $K_a = K_0 = K_p = 1$.

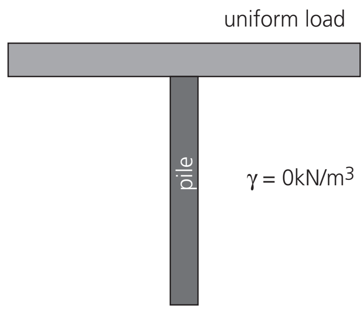


Figure 3.8: *Uniform distribution of the load*

3.6.2 Benchmark results

The soil weight γ is nil so that the horizontal stress along the pile due to the soil weight is nil. The horizontal stress along the sheet piling is therefore constant and equal to 20 kN/m^2 i.e. equal to the vertical stress since $K_a = K_0 = K_p = 1$.

3.6.3 D-SHEET PILING results

Table 3.10: *Results of benchmark 3-6 – Horizontal pressure along the sheet piling*

Benchmark [kN/m^2]	D-SHEET PILING [kN/m^2]	Relative error [%]
20	20	0.00

Use D-SHEET PILING input file bm3-6.shi to run this benchmark.

3.7 Additional horizontal pressure due to a surcharge load

3.7.1 Description

This benchmark evaluates the horizontal stress distribution along a pile due to a triangular surcharge load with $q_{max} = 20$ kN/m^2 at $x = 0$ m and $q_{min} = 0$ at $x = 5$ m. When using a surcharge load, calculations can be performed only using the Culmann method.

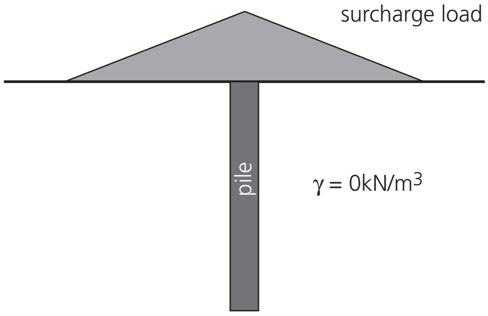


Figure 3.9: *Triangular distribution of the surcharge load*

Two cases are considered depending on the values of the K-ratios calculated with the Culmann method:

- ◇ Case A (benchmark 3-7a) with $K_a < K_0 < K_p$
- ◇ Case B (benchmark 3-7b) with $K_p = K_a = K_0 = 1$

3.7.2 Benchmark results

The horizontal stress distribution for both cases is calculated in a spreadsheet for both cases.

For case A ($K_a < K_0 < K_p$):

$$\sigma_H = f \frac{2P}{\pi} \frac{x^2 y}{\left(x^2 + y^2\right)^2} \tag{3.11}$$

For case B (K_p = K_a = K_0 = 1):

$$\sigma_H = \frac{K\ P}{\pi} \left[(\phi_1 - \phi_2) + \sin\phi_1 \cos\phi_1 - \sin\phi_2 \cos\phi_2\right] \tag{3.12}$$

where:

σ_H is the additional horizontal earth pressure due to line load, in kPa;

f is the multiplication factor (influence of the sheet pile wall):
$$f = \begin{cases} L & \text{if } x_i > L \\ 2 - x_i/L & \text{if } x_i \leq L \end{cases}$$
L is the length of the sheet pile, in m;
P is the line load, in kN/m;
x, y is the horizontal and vertical coordinates, in m.

The surcharge load is divided into 50 elements of 0.1 m. Results at different depths are presented in the tables below.

3.7.3 D-SHEET PILING results

The soil weight γ is nil so that the horizontal stress along the pile due to the soil weight is nil, only the horizontal stress due to the surcharge load is calculated by D-Sheet Piling. For benchmark 3-7a, the value of the cohesion is set to c = 100 kN/m^2 to get $K_a < K_0 < K_p$. For benchmark 3-7b, the earth pressure coefficients are set to 1 using the *Manual* option in the *Start Calculation* window. Results are found in the *Effective Stress* chart in the *Stress State Charts* window using the *View Data* option.

Table 3.12: *Results of benchmark 3-7a – Horizontal effective stress due to triangular surcharge ($K_a < K_0 < K_p$)*

Depth	Benchmark [kN/m^2]	D-SHEET PILING [kN/m^2]	Relative error [%]
–2 m	4.54	4.54	0.00
–4 m	1.59	1.59	0.00
–6 m	0.68	0.68	0.00
–8 m	0.34	0.34	0.00
–10 m	0.19	0.19	0.00

Table 3.13: *Results of benchmark 3-7b – Horizontal effective stress due to triangular surcharge (K_p = K_a = K_0 = 1)*

Depth	Benchmark [kN/m^2]	D-SHEET PILING [kN/m^2]	Relative error [%]
–4 m	11.41	11.41	0.00
–6 m	8.85	8.85	0.00
–8 m	7.11	7.11	0.00
–10 m	5.90	5.92	0.34

Use D-SHEET PILING input files bm3-7a.shi and bm3-7b.shi to run this benchmark.

3.8 Vertical force balance

3.8.1 Description

The vertical balance of a sheet pile wall loaded with a horizontal load F = 100 kN/m in the middle, loaded by a normal force of N = 40 kN over the entire sheet piling, and reinforced at the middle by an anchor with an inclination β = 15°is checked. The soil weight is γ = 15 kN/m^3, the angle of friction is δ = 20°, the neutral earth pressure coefficient is K_0 = 0.58 and the maximum point resistance is $p_{r;\max;point}$ = 6 MPa. The soil reaction is neglected as the modulus of subgrade reaction is equal to k = 0.01 kN/m^3. The pile is composed of two sections with the properties given in Table 3.14.

Table 3.14: *Properties of the sheet piling (benchmark 3-8)*

		Section 1 (top)	**Section 2 (bottom)**
Length L	[m]	6	4
Acting width b	[m]	2.5	1.5
Height h	[mm]	400	600
Coating area A_{coat}	[m^2/m^2 wall]	1.35	1.5
Steel section A_{steel}	[cm^2/m]	170	220

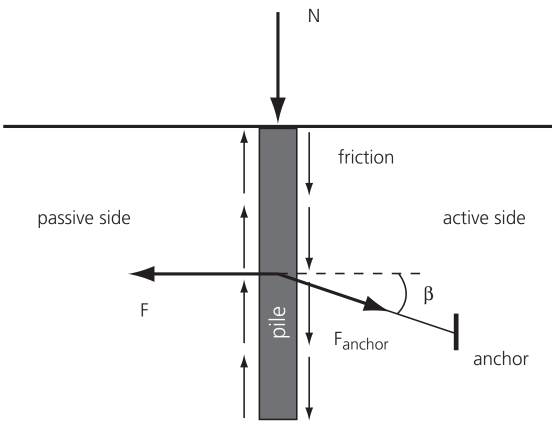


Figure 3.10: *Forces equilibrium in benchmark 3-8*

The vertical balance is checked for plugged and unplugged cases, using factors $\gamma_{m;b}$ = 1.2 and ξ = 1.5.

3.8.2 Benchmark results

For the calculation of the vertical force balance, four contributions must be considered:

$$F_{balance} = F_V^{active} + F_V^{passive} + N + F_V^{anchor} \tag{3.13}$$

with:

$$F_v^{passive} = -F_V^{active} \tag{3.14}$$

$$F_v^{passive} = \int_0^L K_0\ \gamma\ z \tan\delta\ b\ dz = \frac{K_0\ \gamma\ \tan\delta}{2}\left[L_1^2\, b_1 + \left((L_1+L_2)^2 - L_1^2\right)\ b_2\right]$$
(plugged) (3.15)

$$F_v^{passive} = \frac{K_0\ \gamma\ \tan\delta}{2}\left[L_1^2\, b_1\ A_{coat;1} + \left((L_1+L_2)^2 - L_1^2\right)\ b_2\ A_{coat;2}\right]$$
(unplugged) (3.16)

For vertical balance unplugged, a wall surface of 1m^2/m is used instead of the paint surface (A_{coat}) in accordance with CUR 166 CUR (2005) (Part 1, page 69, last alinea), leading therefore to the same results for both plugged and unplugged cases:

$$F_V^{passive} = -F_V^{active} = 142.49 + 151.99 = 294.49 \text{ kN (plugged and unplugged)} \tag{3.17}$$

$$F_V^{anchor} = -1.1 \times F \ \tan\beta \ b = -73.69 \text{ kN} \tag{3.18}$$

$$N = -40 \text{ kN} \tag{3.19}$$

The resulting vertical force is then equal to: $F_{balance} = 113.69$ kN

The vertical toe capacity is:

$$F_{toe;d} = \frac{p_{\text{r;point;max}} \ A_{steel} \ b}{\xi \times \gamma_{m,b}} = \frac{6000 \times 0.022 \times 1.5}{1.5 \times 1.2} = 110 \text{ kN} \quad \text{(unplugged)} \tag{3.20}$$

$$F_{toe,d} = \frac{p_{\text{r;point;max}} \ h \ b}{\xi \times \gamma_{m,b}} = \frac{6000 \times 0.6 \times 1.5}{1.5 \times 1.2} = 3000 \text{ kN} \quad \text{(plugged)} \tag{3.21}$$

The vertical toe capacity is sufficient in both cases (plugged and unplugged).

3.8.3 D-SHEET PILING results

The results of the benchmark are compared with those found by D-Sheet Piling in Table 3.15.

Table 3.15: Results of benchmark 3-8

	Benchmark [kN/m^2]	D-SHEET PILING [kN/m^2]	Relative error [%]
Unplugged:			
Vertical active force [kN]	-294.49	-294.48	0.00
Vertical passive force [kN]	294.49	294.49	0.00
Vertical anchor force [kN]	-73.69	-73.68	0.01
Normal force on sheet piling [kN]	-40.00	-40.00	0.00
Resulting vertical force [kN]	-113.69	-113.67	0.02
Vertical force capacity [kN]	110.00	110.00	0.00
Plugged:			
Vertical active force [kN]	-294.49	-294.48	0.00
Vertical passive force [kN]	294.49	294.49	0.00
Vertical anchor force [kN]	-73.69	-73.69	0.01
Normal force on sheet piling [kN]	-40.00	-40.00	0.00
Resulting vertical force [kN]	-113.69	-113.67	0.02
Vertical force capacity [kN]	3000.00	3000.00	0.00

Use D-SHEET PILING input file bm3-8.shi to run this benchmark.

3.9 Horizontal pressures in stratified soil with additional pore pressures

3.9.1 Description

The horizontal pressures along a pile (L = 16 m) in a stratified soil are calculated. The geometry is outlined in Figure 3.11. The characteristics of the layers are given in Table 3.16.

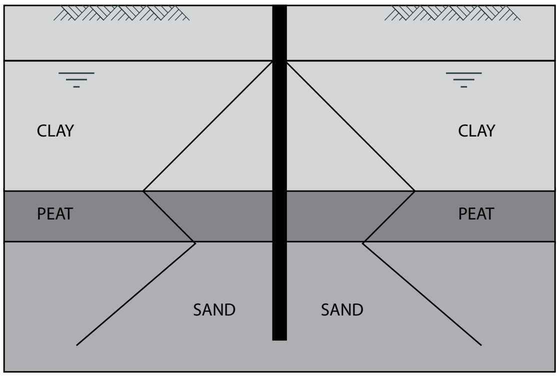


Figure 3.11: *Stratified soil with additional pore pressures (bm3-9)*

Table 3.16: *Properties of the layers (bm3-9)*

		Clay unsat.	**Clay sat.**	**Peat**	**Sand**
Depth top layer	[m NAP]	0	-1	-12	-13
γ	[kN/m^3]	14	16	11	20
K_0	[-]	0.61	0.61	0.69	0.43
Excess pore pressure (top)	[kPa]	0	0	-42	-80
Excess pore pressure (bottom)	[kPa]	0	-42	-80	-80

3.9.2 Benchmark results

Horizontal effective pressures along the sheet piling are calculated in an Excel spreadsheet using the following formulas:

$$\sigma'_H = K_0 \left(\gamma \times z - \sigma_w\right) \tag{3.22}$$

$$\sigma_w = \gamma_w \left(z_{water} - z\right) + \sigma_{w;excess} \tag{3.23}$$

3.9.3 D-SHEET PILING results

the D-SHEET PILING and spreadsheet results are compared in Table 3.17 for few depths. The maximum relative error along the sheet piling is also given.

Table 3.17: *Results of benchmark 3-9*

	Depth [m NAP]	Benchmark [kPa]	D-SHEET PILING [kPa]	Relative error [%]
Pore pressure	0	0.00	0.00	0.00
	-1	0.00	0.00	0.00
	-3.2	13.60	13.60	0.00
	-5.4	27.20	27.20	0.00
	-7.6	40.80	40.80	0.00
	-9.8	54.40	54.40	0.00
	-12	68.00	68.00	0.00
	-13	40.00	40.00	0.00
	-15.5	65.00	65.00	0.00
	-18	90.00	90.00	0.00
Horizontal stress	0	0.00	0.00	0.00
	-1	8.54	8.54	0.00
	-3.2	21.72	21.72	0.00
	-5.4	34.89	34.89	0.00
	-7.6	48.07	48.07	0.00
	-9.8	61.24	61.24	0.00
	-12	74.42	74.42	0.00
	-13	111.09	111.09	0.00
	-15.5	79.98	79.98	0.00
	-18	90.73	90.73	0.00

Use D-SHEET PILING input file bm3-9.shi to run this benchmark.

3.10 Flexural stiffness of a combined wall

3.10.1 Description

In this benchmark, the calculation of the flexural stiffness of the upper and lower parts of a combined wall is checked. The combined wall consists of three PU 12 sheet piling elements between each pair of King piles (HZ775C-12). The center-to-center distance between the King piles is 0.53 + 3 $\times$ 0.6 = 2.33 m. The length of the King piles is 10 m and the length of the sheet piling is 5 m. See Figure 3.12 for a graphic representation of the combined wall.

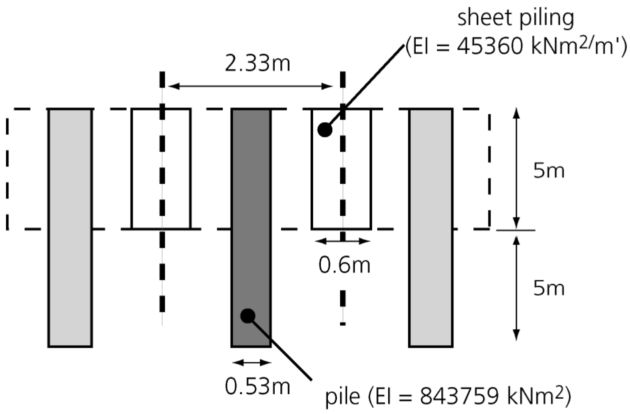


Figure 3.12: *Combined wall*

3.10.2 Benchmark results

For the upper part of the wall, the flexural stiffness of one PU 12 sheet piling is 45360 $\times$ 0.6 = 27216 kNm^2. The flexural stiffness of one King pile is 843759 kNm^2. The flexural stiffness of the considered 2.33 m section of the wall (1 pile + 3 sheet-piling parts) is 843759 + 3 $\times$ 27216 = 925407 kNm^2. The corresponding value per running meter is EI = 925407 / 2.33 = 397170.386 kNm^2/m'.

For the lower part of the wall, the flexural stiffness of one steel pile is 843759 kNm^2. As the acting width of the pile is 0.53 m, the corresponding value per running meter is EI = 843759 / 0.53 = 1591998.11 kNm^2/m.

3.10.3 D-SHEET PILING results

In the *Sheet Piling* window of the *Construction* menu of D-SHEET PILING, the *Combined Wall* option is used: for the *Sheet pile*, type PU 12 is selected from the library and for the *Pile*, type HZ775C-12 is selected. The results of the D-SHEET PILING calculation and the benchmark are given in the following table.

Table 3.18: *Results of benchmark 3-10*

	Benchmark	**D-SHEET PILING**	**Relative error [%]**
Stiffness upper part [kNm^2/m']	3.9717 $\times$ 10^5	3.9717 $\times$ 10^5	0.00
Stiffness lower part [kNm^2/m']	1.5920 $\times$ 10^6	1.5920 $\times$ 10^6	0.00
Stiffness upper part [kNm^2]	9.2540 $\times$ 10^5	9.2540 $\times$ 10^5	0.00
Stiffness lower part [kNm^2]	8.4380 $\times$ 10^5	8.4380 $\times$ 10^5	0.00

Use D-SHEET PILING input file bm3-10.shi to run this benchmark.

3.11 Interpretation of a CPT GEF file generated manually

3.11.1 Description

Two CPT-GEF files are generated manually using the GEFPlotTool program every 0.1 m depth. Within each layer, the cone resistance and the friction ratio are set constant and equal to the values given in Table 3.19.

Table 3.19: *CPT-GEF files – Values of the cone resistance and the friction ratio*

	Top level [m]	q_c [MPa]	Friction ratio [%]
CPT-GEF file "bm3-11a"	1	10	1.212
	-5	2	0.928
	-7	2	2.507
	-10.5	1	3.323
	-13.5	0.1	4.417
	-19.5	0.07	7.791
CPT-GEF file "bm3-11b"	4	70	1.065
	2	45	1.272
	0	25	1.101
	-2	35	2.092
	-4	8	1.201
	-6	20	2.969
	-8	30	4.19
	-10	2	1.984
	-12	0.5	1.32
	-14	1.5	3.197
	-16	2	4.745
	-18	3	6.839
	-20	1	10.062
	-22	0.05	9.015

3.11.2 Benchmark results

Using respectively the *CUR* and *NEN (Stress dependent)* rules and a minimum layer thickness of 0.6 m, the interpretation of both CPT bm3-11a and bm3-11b leads to the soil profiles given in Table 3.20 and Table 3.21.

Table 3.20: *Interpretation of CPT-GEF file "bm3-11a"using CUR rule*

Top level [m NAP]	Material name
1	Sand, slightly silty, moderate
-5	Sand, very silty, loose
-6.8	Loam, very sandy, stiff
-10.4	Clay, slightly sandy, moderate
-13.4	Clay, clean, weak
-19.4	Peat, moderate preloaded, moderate

Table 3.21: *Interpretation of CPT-GEF file "bm3-11b"using NEN (Stress dep.) rule*

Interpretation without stress dependency				**Interpretation with stress dep.**	
Top level [m]	γ_{unsat} [kN/m^3]	γ_{sat} [kN/m^3]	σ_v' [kN/m^2]	Top level [m NAP]	Material name
4	18	20	0.00	4	Gravel, sl sil, moderate
2.2	19	21	32.40	1.6	Sand, clean, stiff
0.4	18	20	66.60	-0.2	Sand, sl sil, moderate
-2	18	20	94.18	-2	Sand, ve sil, loose
-3.8	19	19	112.52	-3.8	Loam, ve san, stiff
-5.6	19	19	129.06	-5.6	Loam, sl san, weak
-8	18	18	151.12	-8	Clay, ve san, stiff
-10.4	18	18	170.78	-10.4	Clay, sl san, moderate
-12.2	19	19	185.52	-12.2	Clay, clean, stiff
-14	14	14	202.06	-14	Clay, clean, weak
-15.8	15	15	209.60	-15.8	Clay, organ, moderate
-17.6	13	13	218.94	-17.6	Clay, organ, weak
-20	12	12	226.60	-20	Peat, mod pl, moderate
-22.4	10	10	231.86	-22.4	Peat, not pl, weak

3.11.3 D-SHEET PILING results

When importing CPT "bm3-11a", the *CUR* rule must be selected whereas when importing CPT "bm3-11b", the *NEN (Stress dep.)* rule must be selected. For both, a *Minimum layer thickness* of 0.6 m is used. D-Sheet Piling results are given in Figure 3.13 and Figure 3.14. Results coincide perfectly with the expected results given in Table 3.20 and Table 3.21.

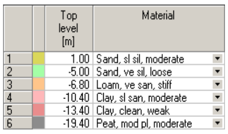


Figure 3.13: *D-Sheet Piling results: Soil Profiles window after interpretation of CPT-GEF file "bm3-11a" with CUR rule*

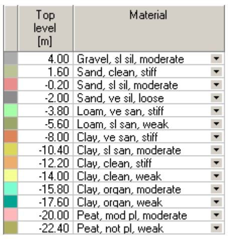


Figure 3.14: *D-Sheet Piling results: Soil Profiles window after interpretation of CPT-GEF file "bm3-11b" with NEN (Stress dependent) rule*

Use CPT-GEF files bm3-11a.gef and bm3-11b.gef to run this benchmark.

4 Group 4: Benchmarks generated by D-Sheet Piling

This chapter contains benchmarks for which the reference results are generated using D-Sheet Piling.

4.1 Comparison of the c, φ, δ and K_a, K_0, K_p methods: uniform load on lower side

4.1.1 Description

To check that the results of the c, φ, δ method will not deviate very much from the K_a, K_0, K_p method, a calculation is performed using both methods. A sheet pile wall, of length 7.0 m and EI = 8700 kNm^2/m' is retains sand with a height difference of 2 m from one side of the wall to the other. The surface on the lower (right) side of a sheet pile wall is loaded with a uniform load of 25 kN/m^2.

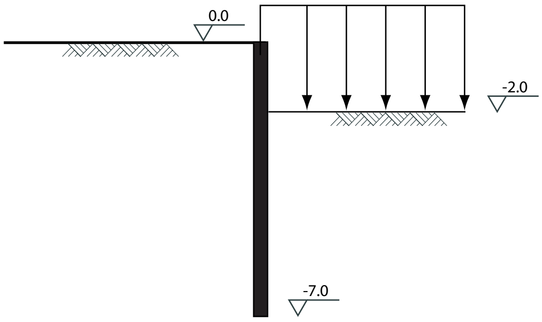


Figure 4.1: *Geometry of bm4-1*

4.1.2 D-SHEET PILING results

In Table 4.1 the results found using the K_a, K_0, K_p method and the c, φ, δ method are presented and compared.

Table 4.1: *Results of benchmark 4-1*

	D-SHEET PILING (bm4-1a)	**D-SHEET PILING (bm4-1b)**	**Relative error [%]**
Calculation method	K_a, K_0, K_p method	c, φ, δ method	
Maximum displacement [mm]	7.1	7.2	1.39
Maximum moment [kNm]	10.3	10.4	0.96
Maximum shear force [kN]	10.6	10.7	0.93

Use D-SHEET PILING input files bm4-1a.shi and bm4-1b.shi to run this benchmark.

4.2 Comparison of the c, φ, δ and K_a, K_0, K_p methods: uniform load on higher side

4.2.1 Description

The calculation method is the same as in section 4.1, but now the surface on the higher (left) side of the wall is loaded instead.

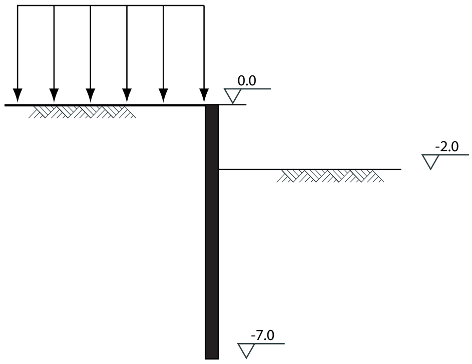


Figure 4.2: *Geometry for bm4-2*

4.2.2 D-SHEET PILING results

In Table 4.2 the results of the K_a, K_0, K_p method and the c, φ, δ method are presented and compared.

Table 4.2: *Results of benchmark 4-2*

	D-Sheet Piling (bm4-2a)	**D-Sheet Piling (bm4-2b)**	**Rel. error [%]**
Calculation method	K_a, K_0, K_p method	c, φ, δ method	
Maximum displacement [mm]	70.6	72.1	2.08
Maximum moment [kNm]	61.8	62.8	1.59
Maximum shear force [kN]	32.5	33.0	1.52

Use D-SHEET PILING input files bm4-2a.shi and bm4-2b.shi to run this benchmark.

4.3 Influence of the load distance to sheet pile: load of 25 kN/m^2 on high side

4.3.1 Description

To verify the influence on the results of the exact starting point of a surcharge load, the geometry show in Figure 4.3 is loaded by a uniform surcharge of 25 kN/m^2 starting near the wall and ending at 50 m from the wall. The distance between the load and the sheet pile wall is varied from 0 m, 0.01 m, to 0.1 m.

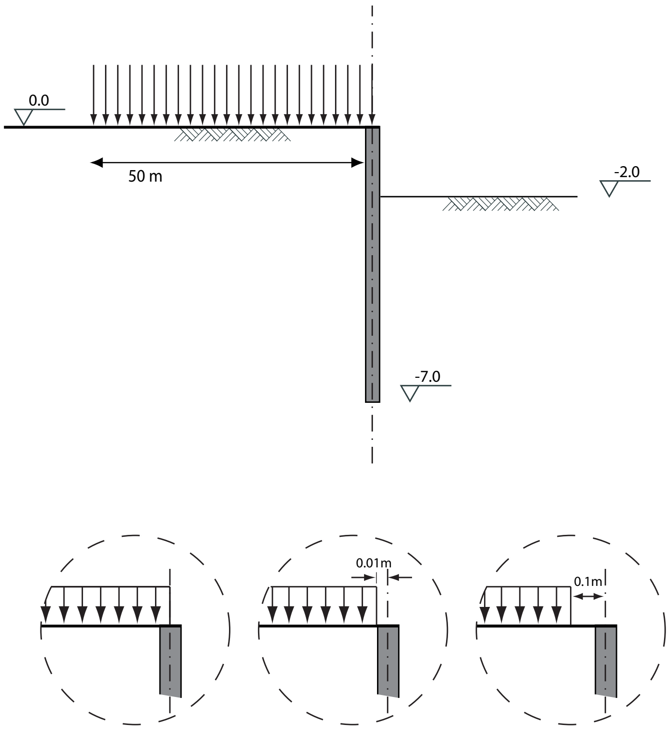


Figure 4.3: *Geometry for bm4-3*

4.3.2 D-SHEET PILING results

In Table 4.3 the results for different distances between the load and the sheet pile wall are presented for comparison. Calculations are performed with the *Fine* earth pressure coefficients option from the *Calculation Options* window.

Table 4.3: *Results of benchmark 4-3*

	D-SHEET PILING (bm4-3a)	**D-SHEET PILING (bm4-3b)**	**D-SHEET PILING (bm4-3c)**
Dist. load/sheet piling [m]	0	0.01	0.1
Max. displacement [mm]	70.9	70.7	65.6
Max. moment [kNm]	61.8	61.7	57.9
Max. shear force [kN]	32.4	32.3	30.3

Use D-SHEET PILING input files bm4-3a.shi, bm4-3b.shi and bm4-3c.shi to run this benchmark.

4.4 Influence of soil against sheet pile wall for an excavation

4.4.1 Description

Three cases are compared to verify if an excavation where a small part of soil has been left against the sheet pile wall can be schematized by putting a load of same size and weight on the surface behind the sheet pile. These cases are outlined below and shown in Figure 4.4:

- ◇ Case A (bm4-4a): An initial situation with different horizontal levels at each side of the sheet pile without any load or excavation;
- ◇ Case B (bm4-4b): A small part of soil is added on a horizontal surface. This calculation is performed by means of partly excavating a higher surface level;

◇ Case C (bm4-4c): A load is put on the surface to schematize the effect of case B.

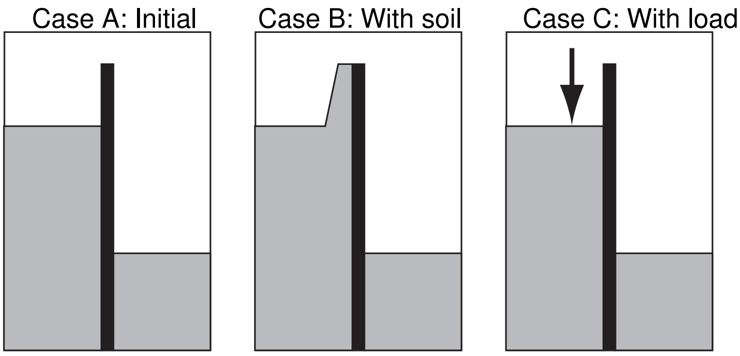


Figure 4.4: *Schematization of the three situations of bm4-4*

4.4.2 D-SHEET PILING results

In Table 4.4 the results of the different calculations are presented for comparison.

Table 4.4: *Results of benchmark 4-4*

	D-SHEET PILING (bm4-4a)	**D-SHEET PILING (bm4-4b)**	**D-SHEET PILING (bm4-4c)**
Situation	Without soil	With soil	With load
Maximum displacement [mm]	19.2	33.4	29.9
Maximum moment [kNm]	16.2	26.9	24.6
Maximum shear force [kN]	12.0	15.1	14.9

Use D-SHEET PILING input files bm4-4a.shi, bm4-4b.shi and bm4-4c.shi to run this benchmark.

4.5 Equilibrium of initially unequal surfaces and surcharges

4.5.1 Description

The option *First stage represents initial situation* from the *Calculation Options* window allows modeling of initially non-horizontal surfaces, or initial loads that already exist before installation of the sheet piling. Two D-Sheet Piling calculations are performed:

◇ Case A (bm4-5a): option *First stage represents initial situation* selected;
◇ Case B (bm4-5b): option First stage represents initial situation unselected;

This benchmark verifies that a combination of initially unequal surfaces and surcharges does not result in any displacement and moments during the first phase (bm4-5a with option *First stage represents initial situation* selected) provided that no active or passive soil yielding occurs. It is also checked if the incremental displacements and moments during subsequent stages are the same as the incremental results from a standard D-Sheet Piling analysis (bm4-5b without option *First stage represents initial situation* selected), again provided that no soil yielding occurs. The input data is summarized below:

◇ homogeneous soil, unit weight = 10 kN/m^3
◇ modulus of subgrade reaction = 1000 kPa/m
◇ c, φ, δ method
◇ cohesion = 0 kN/m^2

◇ friction angle = 30°
◇ sheet piling length = 21 m
◇ flexural stiffness of sheet piling = 4.1370×10^8 kNm^2/m'
◇ phreatic surface located at -100 m

The loading is modeled as follows:

◇ Phase 1: On the left of the sheet pile wall is a surface higher than the top of the wall, comparable to a surcharge of 10 kN/m. On the right hand side of the sheet pile wall an initial surcharge of 20 kN/m.
◇ Phase 2: The surcharge on the right hand side is reduced to 10 kN/m. The non-horizontal surface on the left-hand side is replaced by a surface load with equal weight.
◇ Phase 3: An excavation of 1 m on the right hand side.

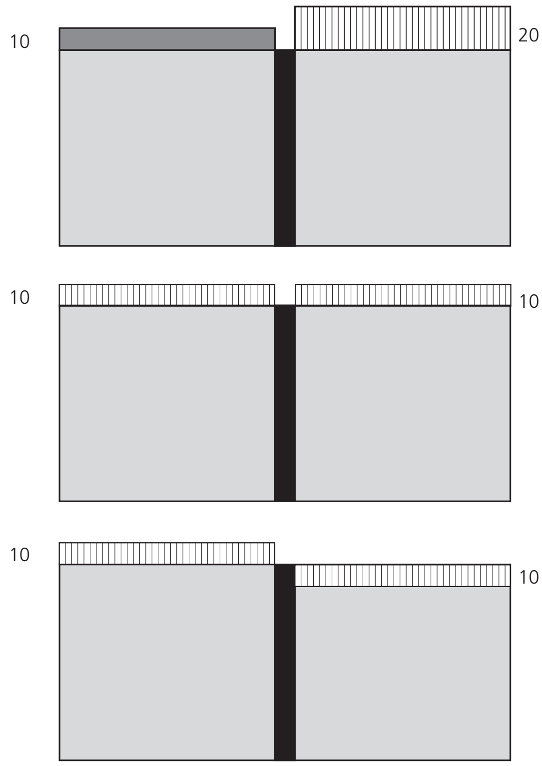


Figure 4.5: *Loading during phases 1, 2 and 3*

4.5.2 D-Sheet Piling results

The results of Table 4.5 show that no displacement occurs during the initial stage of bm4-3a. Moreover displacements and moments calculated using the option *First stage represents initial situation* (bm4-5b) are equal to the incremental displacements and moments calculated from a standard D-Sheet Piling calculation (bm4-5a), i.e. without option *First stage represents initial situation*.

Table 4.5: Results of benchmark 4-5 – Maximum displacements

	D-SHEET PILING (bm4-5a)	D-Sheet Piling (bm4-5b)		Rel. error
	[mm]	Brut [mm]	Incremental [mm]	[%]
Phase 1	0	-4.1	-4.1 –(-4.1) = 0	0.00
Phase 2	4.1	0	0 –(-4.1) = 4.1	0.00
Phase 3	7.8	3.2	3.2 –(-4.1) = 7.3	6.41

Use D-SHEET PILING input files bm4-5a.shi and bm4-5b.shi to run this benchmark

4.6 Comparison of secant and tangent modulus of subgrade reaction

4.6.1 Description

This benchmark evaluates the horizontal displacement of a rigid sheet pile wall (length L = 20 m, stiffness EI = 9 $\times$ 10^8 kNm^2/m) loaded with a horizontal line load of F = 160 kN/m applied to the centre of the wall. The stress-displacement diagram used has three branches, with intersections at 50 %, 80 % and 100 % of (K_p - K_a) $\times$ σ_V as illustrated in Figure 4.6. The stiffness of the different branches is defined employing two kinds of modulus of subgrade reaction:

◇ secant modulus (from CUR 166) in benchmark bm4-6a,
◇ tangent modulus (D-Sheet Piling Classic) in benchmark bm4-6b.

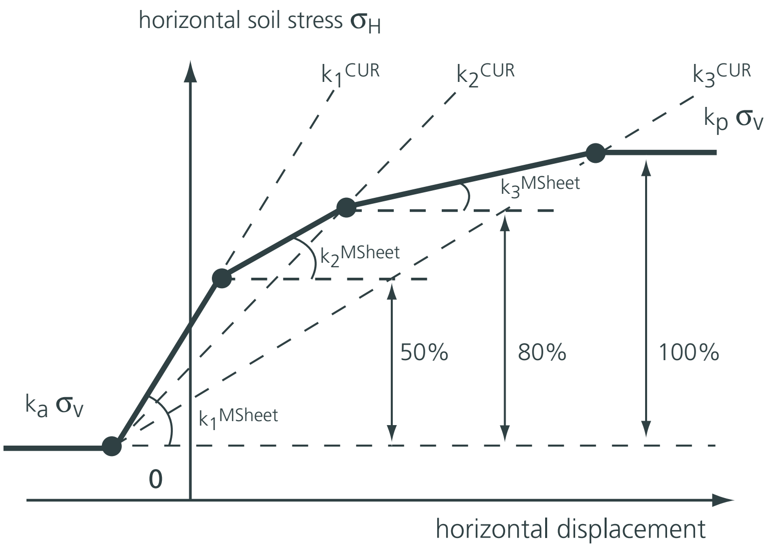


Figure 4.6: Stress-displacement diagram with three branches according to CUR 166 and D-Sheet Piling Classic

According to Figure 4.6, the relations that link the secant moduli k_1, k_2 and k_3 from CUR 166 to the tangent moduli as used In D-SHEET PILING are:

$$k_1^{D-Sheet\ Piling} = k_1^{CUR} \tag{4.1}$$
$$k_2^{D-Sheet\ Piling} = \frac{0.8 - 0.5}{\frac{0.8}{k_2^{CUR}} - \frac{0.5}{k_1^{CUR}}} \tag{4.2}$$
$$k_3^{D-Sheet\ Piling} = \frac{1 - 0.8}{\frac{1}{k_3^{CUR}} - \frac{0.8}{k_2^{CUR}}} \tag{4.3}$$

According to Table 3.3 of CUR 166 procedure CUR (2005), the stress-displacement diagram of a soft peat is defined with the following lowest values of modulus of subgrade reaction:

- ◇ k_1^{CUR} = 1000 kN/m^3
- ◇ k_2^{CUR} = 500 kN/m^3
- ◇ k_3^{CUR} = 250 kN/m^3

So, the conversion to tangent moduli as used by D-Sheet Piling leads to:

- ◇ $k_1^{D-Sheet\ Piling}$ = 1000 kN/m^3
- ◇ $k_2^{D-Sheet\ Piling}$ = 272.727272… kN/m^3
- ◇ $k_3^{D-Sheet\ Piling}$ = 83.333333… kN/m^3

The following values are chosen:

- ◇ $\gamma = 0$ kN/m^3 $c = 2$ kN/m^2
- ◇ $K_a = K_0 = 0$ and $K_p = 4$

As the pile is supposed to be rigid, the distribution of the horizontal stresses along the pile is uniform and equal to:

$$\sigma_H = F/L = 160/20 = 8\ \mathrm{kN/m^2} \tag{4.4}$$

As the unit weight of the soil is zero, the initial vertical stress is nil. This leads to:

$$\sigma_a = K_a\sigma_v - 2c\sqrt{K_a} = 0 \tag{4.5}$$
$$\sigma_0 = K_0\sigma_v = 0 \tag{4.6}$$
$$\sigma_p = K_p\sigma_v + 2c\sqrt{K_p} = \ 8\ \mathrm{kN/m^2}. \tag{4.7}$$

As the initial horizontal stress is equal to the active stress and the final horizontal stress is equal to the passive stress, the three branches in the stress-displacement diagram are used in the calculations.

4.6.2 D-SHEET PILING results

For D-Sheet Piling calculation with secant moduli (bm4-6a), the option *Secant (CUR 166)* must be selected in the *Soil Materials* window. From Table 3.3 of CUR 166, the soft peat is selected. For D-Sheet Piling calculation with tangent moduli (bm4-6b), the option *Tangent (D-Sheet Piling Classic)* must be selected in the *Soil Materials* window.

Table 4.6: Results of benchmark 4-6

	D-SHEET PILING (bm4-6a)	D-SHEET PILING (bm4-6b)	Relative error [%]
Modulus type	Secant modulus	Tangent modulus	
Max. displacement [m]	32.0	32.0	0.00
Max. moment [kNm]	400.0	400.0	0.00
Max. shear force [kN]	80.0	80.0	0.00

Use D-SHEET PILING input file bm4-6a.shi and bm4-6b.shi to run this benchmark.

4.7 Non-horizontal surface

4.7.1 Description

In D-SHEET PILING, a non-horizontal soil surface (bm4-7a) is alternatively modelled as a horizontal surface with additional surcharge loads (bm4-7b). This benchmark compares the results of both configurations calculated with D-Sheet Piling. The Culmann method is used.

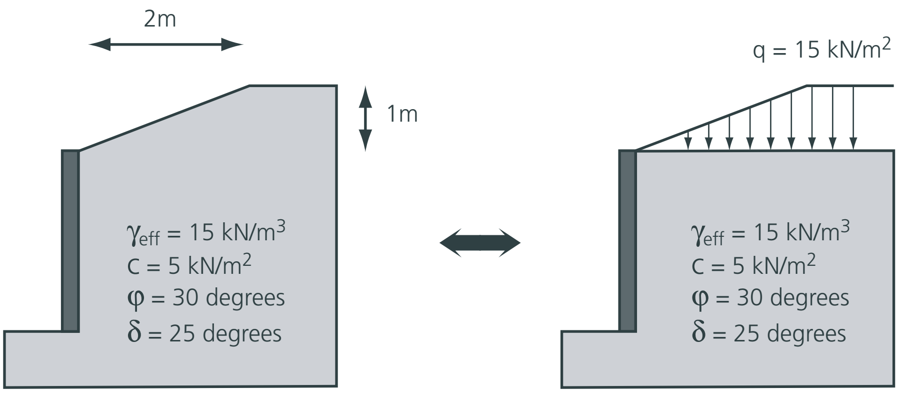


Figure 4.7: *Non-horizontal soil surface modeled as a horizontal surface with an additional trapezoidal surcharge*

4.7.2 D-SHEET PILING results

The results of both configurations are compared in Table 4.7.

Table 4.7: Results of benchmark 4-7

	D-SHEET PILING (bm4-7a)	D-SHEET PILING (bm4-7b)	Rel. error [%]
Maximum moment [kNm]	19.3	19.3	0.00
Maximum shear stress [kN]	25.2	25.2	0.00
Max. displacement [mm]	0.0167	0.0167	0.00

Use D-SHEET PILING input files bm4-7a.shi and bm4-7b.shi to run this benchmark.

4.8 Symmetry of a problem

4.8.1 Description

The symmetry of a problem In D-SHEET PILING is checked. Calculations are performed using the Culmann method.

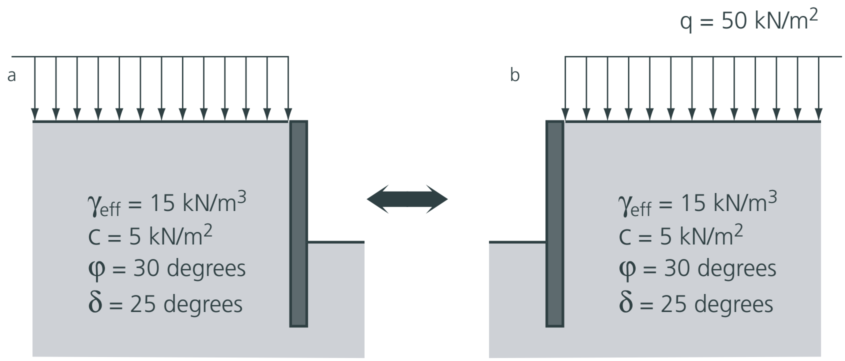


Figure 4.8: *Symmetry of the problem*

4.8.2 D-SHEET PILING results

Two calculations are performed with D-Sheet Piling:

- ◇ with the upper side on the left (bm4-8a);
- ◇ with the upper side on the right (bm4-8b).

The results of the two calculations are compared in Table 4.8.

Table 4.8: *Results of benchmark 4-8*

	D-SHEET PILING (bm4-8a)	**D-SHEET PILING (bm4-8b)**	**Relative error [%]**
Active side	Left	Right	
Max. moment [kNm]	-37.8	37.8	0.00
Max. shear force [kN]	-26.3	26.3	0.00
Max. displacement [mm]	67.5	-67.5	0.00

Use D-SHEET PILING input files bm4-8a.shi and bm4-8b.shi to run this benchmark.

4.9 Effect of the acting width

4.9.1 Description

The effect of the acting width is checked in this benchmark. The same problem is considered for two values of the acting width: 1 m and 2 m. This benchmark checks that output pressures and moments are multiplied by a factor 2 when the acting width is 2 m.

4.9.2 D-SHEET PILING results

The normal force must be entered as a total force (in kN). As the normal force per running meter is set equal to 5 kN/m', then the input normal forces are 5 kN and 10 kN respectively for the benchmarks with an acting width of 1 and 2 m. The results of these two analyses are compared in Table 4.9.

Table 4.9: *Results of benchmark 4-9*

	D-SHEET PILING (bm4-9a)	D-SHEET PILING (bm4-9b)	Factor
Acting width [m]	1	2	
Maximum displacement [mm]	-4.3	-4.3	1.00
Maximum moment [kNm]	-29.6	-59.1	2.00
Maximum shear force [kN]	-27.3	-54.5	2.00
Vertical force balance results:			
Vertical force active [kN]	-44.94	-89.87	2.00
Vertical force passive [kN]	28.65	57.31	2.00
Vertical anchor force [kN]	-2.90	-5.80	2.00
Normal force on sheet piling [kN]	-5.00	-10.00	2.00
Resulting vertical force [kN]	-24.19	-48.36	2.00
Vertical force capacity [kN]	102.00	102.00	1.00
Soil collapse results:			
Horizontal effective pressure (left) [kN]	58.3	116.6	2.00
Horizontal effective pressure (right) [kN]	91.5	182.9	2.00
Maximum passive effective resistance [kN]	77.31	154.63	2.00
Mobilized passive effective resistance [kN]	58.32	116.63	2.00
Percentage mobilized resistance [%]	75.4	75.4	1.00
Maximum passive moment [kNm]	308.19	616.38	2.00
Mobilized passive moment [kNm]	227.83	455.66	2.00
Percentage mobilized moment [%]	73.9	73.9	1.00
"Allowable Anchor Force" results [kN]			
E_a: active pressure sheet pile (with loads)	91.438	182.876	2.00
E_a: active pressure sheet pile (no loads)	87.410	174.819	2.00
E_r: horiz. pressure slide plane (with loads)	10.735	21.470	2.00
E_r: horiz. pressure slide plane (no loads)	10.427	20.854	2.00
E_0: active pressure anchor wall	23.410	46.820	2.00
E_c: cohesion along slide plane	2.989	5.977	2.00
Allowable anchor force (with loads)	60.417	120.835	2.00
Allowable anchor force (no loads)	56.689	113.378	2.00
Calculated anchor force	33.262	66.525	2.00

Use D-SHEET PILING input files bm4-9a.shi and bm4-9b.shi to run this benchmark.

4.10 Effect of the shell factor

4.10.1 Description

The effect of the shell factor inputted in the *Soil Materials* window is checked in this benchmark. Verification is made on a 3-layered soil profile. Two D-Sheet Piling files are used:

- ◇ bm4-10a: a shell factor is inputted (see Table 4.10);
- ◇ bm4-10b: no shell factor used but the soil properties (K and k) are modified (see Ta-

ble 4.11)

Benchmarks 4-10a and 4-10b should give the same results.

Table 4.10: *Soil properties for bm4-10a*

Soil parameter		Layer 1	Layer 2	Layer 3
Unsaturated weight [kN/m^3]	γ_{unsat}	14	15	17
Saturated weight [kN/m^3]	γ_{sat}	14	15	20
Cohesion [kN/m^2]	c	2	5	0
Friction angle [°]	φ	30	30	30
Delta friction angle [°]	δ	0	0	0
Shell factor [-]	s	1.5	2	2.5
Earth pressure coefficients acc. to Müller-Breslau [-]	K_a	0.333	0.333	0.333
	K_0	0.5	0.5	0.5
	K_p	3	3	3
Modulus of subgrade reaction [kN/m^3]	$k_{h;0}$	5000	10000	15000
	$k_{h;1}$	2000	6000	12000
	$k_{h;2}$	800	4000	6000
	$k_{h;3}$	500	2000	3000
	$k_{h;4}$	100	1000	1800

Table 4.11: *Modified soil properties for bm4-10b*

Soil parameter		Layer 1	Layer 2	Layer 3
Earth pressure coefficients acc. to Müller-Breslau [-]	K_a	0.222	0.167	0.133
	K_0	0.5	0.5	0.5
	K_p	4.5	6	7.5
Modulus of subgrade reaction [kN/m^3]	$k_{h;0}$	7500	20000	37500
	$k_{h;1}$	3000	12000	30000
	$k_{h;2}$	1200	8000	15000
	$k_{h;3}$	750	4000	7500
	$k_{h;4}$	150	2000	4500

4.10.2 D-SHEET PILING results

Benchmarks 4-10a and 4-10b give almost the same results (see Table 4.12).

Table 4.12: *Results of benchmark 4-10*

Stage		D-SHEET PILING (bm4-10a)	D-SHEET PILING (bm4-10b)	Rel. error [%]
1	Max. displacement [mm]	10.7	10.6	0.94
	Max. moment [kNm]	27.6	27.4	0.73
	Max. shear force [kN]	14.5	14.4	0.69
2	Max. displacement [mm]	492.9	482.3	2.20
	Max. moment [kNm]	321.3	320.5	0.25
	Max. shear force [kN]	253.1	251.9	0.48
3	Max. displacement [mm]	493.1	482.6	2.18
	Max. moment [kNm]	319.7	319.0	0.22
	Max. shear force [kN]	251.3	250.0	0.52

Use D-SHEET PILING input files bm4-10a.shi and bm4-10b.shi to run this benchmark.

4.11 Functioning of pre-tensioned anchors

4.11.1 Description

The functioning of a pre-tensioned anchor is checked by comparing the results of two cases:

- Case A: a beam is reinforced with an anchor at the middle, pre-tensioned with a force $F_{pt} =$ 200 kN/m and inclined with an angle of β = 60°(Figure 4.9).
- Case B: the same beam without reinforcement is loaded with an horizontal force of $F = F_{PT} \times \cos\beta =$ 100 kN/m to model the pre-tensioning (Figure 4.9).

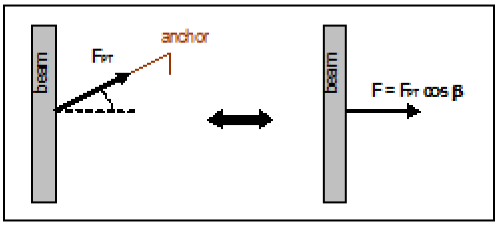


Figure 4.9: *Anchor with pre-tensioning*

In both cases, three horizontal loads of respectively 50, 100 and 200 kN are applied at three consecutive stages, at the middle of the beam.

4.11.2 D-SHEET PILING results

Both benchmarks give exactly the same results as shown in Table 4.13.

Table 4.13: Results of benchmark 4-11

Stage			D-SHEET PILING (bm4-11a)	D-SHEET PILING (bm4-11b)	Relative error [%]
1	Displacement	[mm]	-20.8	-20.8	0.00
	Moment	[kNm]	-30.0	-30.0	0.00
	Shear force	[kN]	50.0	50.0	0.00
	Mob. perc. resistance	[%]	49.7	49.7	0.00
2	Displacement	[mm]	-10.4	-10.4	0.00
	Moment	[kNm]	-15.0	-15.0	0.00
	Shear force	[kN]	25.0	25.0	0.00
	Mob. perc. resistance	[%]	49.4	49.4	0.00
3	Displacement	[mm]	0.0	0.0	0.00
	Moment	[kNm]	0.0	0.0	0.00
	Shear force	[kN]	0.0	0.0	0.00
	Mob. perc. resistance	[%]	49.1	49.1	0.00
4	Displacement	[mm]	20.8	20.8	0.00
	Moment	[kNm]	30.0	30.0	0.00
	Shear force	[kN]	-50.0	-50.0	0.00
	Mob. perc. resistance	[%]	49.7	49.7	0.00

Use D-SHEET PILING input files bm4-11a.shi and bm4-11b.shi to run this benchmark.

4.12 Functioning of pre-compressed strut

4.12.1 Description

The data for this problem are the same as given in section 4.11, but the anchor is replaced by a strut (with the same characteristics).

4.12.2 D-SHEET PILING results

The results of both D-Sheet Piling calculations are the same as shown in Table 4.14.

Table 4.14: *Results of benchmark 4-12*

Stage			D-SHEET PILING (bm4-12a)	D-SHEET PILING (bm4-12b)	Rel. error [%]
1	Displacement	[mm]	-20.8	-20.8	0.00
	Moment	[kNm]	-30.0	-30.0	0.00
	Shear force	[kN]	50.0	50.0	0.00
	Mob. perc. resist.	[%]	49.7	49.7	0.00
2	Displacement	[mm]	-10.4	-10.4	0.00
	Moment	[kNm]	-15.0	-15.0	0.00
	Shear force	[kN]	25.0	25.0	0.00
	Mob. perc. resist.	[%]	49.4	49.4	0.00
3	Displacement	[mm]	0.0	0.0	0.00
	Moment	[kNm]	0.0	0.0	0.00
	Shear force	[kN]	0.0	0.0	0.00
	Mob. perc. resist.	[%]	49.1	49.1	0.00
4	Displacement	[mm]	20.8	20.8	0.00
	Moment	[kNm]	30.0	30.0	0.00
	Shear force	[kN]	-50.0	-50.0	0.00
	Mob. perc. resist.	[%]	49.7	49.7	0.00

Use D-SHEET PILING input files bm4-12a.shi and bm4-12b.shi to run this benchmark.

4.13 Reduction of delta friction angles according to CUR 166

4.13.1 Description

The functioning of the option "Reduce delta friction angles according to CUR" available in the *Calculation Options* window is checked in this benchmark. Verification is made on a 3-layered soil profile. The soil properties are given in Table 4.15. Three D-SHEET PILING files are used:

- ◇ bm4-13a: the option is marked;
- ◇ bm4-13b: the option is unmarked and the inputted delta friction angles are from reduced manually (see last row of Table 4.15);
- ◇ bm4-13c: the option is unmarked.

Benchmarks 4-13a and 4-13b should give the same results but different from bm4-13c.

Table 4.15: *Soil properties (bm4-13)*

	Layer 1	Layer 2	Layer 3
Unsaturated weight [kN/m^3]	15	15	15
Saturated weight [kN/m^3]	15	15	15
Cohesion [kN/m^2]	15	15	15
Friction angle [$^\circ$]	30	35	38
Delta friction angle [$^\circ$]	24	33	36
Reduced delta friction angle [$^\circ$]	24	16.6	17.2

For benchmark 4-15b, the inputted delta friction angles are reduced according to CUR:

- ◇ For layer 1, as φ = 30°, no change is made to δ;
- ◇ For layer 2, as 30$< \varphi = $ 35°, δ is reduced to 16.6°;

◇ For layer 3, as $\varphi > 35°$, δ is reduced to 17.2°;

Results are given in Table 4.16 below.

4.13.2 D-SHEET PILING results

As expected, benchmarks 4-13a and 4-13b give the same results (see Table 4.16) but different from bm4-13c (max. moment 142.7 kNm, max. shear force 80.0 kN and max. displacement 56.7 mm).

Table 4.16: *Results of benchmark 4-13*

	D-SHEET PILING (bm4-13b)	**D-SHEET PILING (bm4-13a)**	**Rel. error [%]**
Max. moment [kNm]	152.1	152.1	0.00
Max. shear force [kN]	81.3	81.3	0.00
Max. displacement [mm]	61.4	61.4	0.00

Use D-SHEET PILING input files bm4-13a.shi to bm4-13c.shi to run this benchmark.

4.14 Pile loaded by calculated and user-defined soil displacements

4.14.1 Description

The calculated soil displacements due to a surcharge (magnitude 10 kN/m^2, width 10 m, distance to sheet piling: 2 m) are checked in this benchmark by comparing the final results of two calculations:

◇ Soil displacements are automatically calculated by D-SHEET PILING using De Leeuw tables;
◇ Soil displacements are user-defined: the

Two cases are considered:

◇ Case 1: a stiff top layer of 1 m thickness and an elastic layer of 5 m thickness with a Young's modulus of $E = 1500$ kN/m^2 (i.e. γ_{unsat} = 18 kN/m^3);
◇ Case 2: Without stiff top layer and with a layered elastic cluster: top layer of 1 m thick with a Young's modulus of $E = 1500$ kN/m^2 (i.e. γ_{unsat} = 18 kN/m^3) and a bottom layer of 4 m thick with $E = 1000$ kN/m^2 (i.e. γ_{unsat} = 13 kN/m^3).

Case 1 Case 2

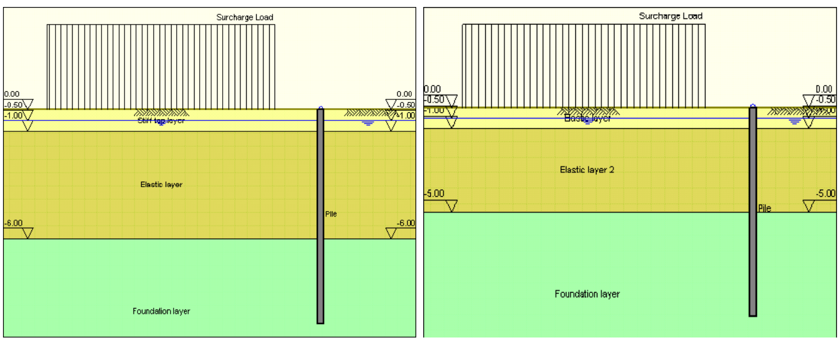


Figure 4.10: *Geometry overview (bm4-14)*

4.14.2 D-SHEET PILING results (Calculated soil displacements)

Two D-SHEET PILING calculations corresponding to both cases are performed:

- ◇ bm4-14a modelled case 1;
- ◇ bm4-14b modelled case 2.

The soil properties are given in Table 4.17. The earth pressure coefficients are automatically calculated by D-SHEET PILING using Brinch-Hansen theory, at different depths. The output values of the passive earth pressure coefficient and the fictive cohesion are given in Table 4.18 for case 1 and Table 4.19 for case 2 and are used as input values for the calculation using *User-defined soil displacements* (see below).

Table 4.17: *Soil properties for bm4-14a and bm4-14b using Calculated soil displacements option*

	Stiff	Elastic	Elastic 2	Foundation
Unsaturated weight [kN/m^3]	18.5	18	13	17
Saturated weight [kN/m^3]	20	18	13	20
Cohesion [kN/m^2]	0	10	5	5
Friction angle [°]	30	25	20	25

4.14.3 D-SHEET PILING results (User-defined soil displacements)

Two D-SHEET PILING calculations (bm4-14c and bm4-14d) corresponding to both cases (respectively case 1 and case 2) are performed. The soil properties are given in both tables below. Elastic layer is divided into sub-layers of 1 m thickness.

Table 4.18: *Input values for bm4-14c using User-defined soil displacements option (= output values of bm4-14a)*

Layer	Top level	Soil displac.	Horiz. modulus		Fictive cohesion	K_p
			Top	Bottom		
	[m NAP]	[mm]	[kN/m^3]	[kN/m^3]	[kN/m^2]	[-]
Stiff	0	0	10^5	10^5	0.00	4.75
Elastic	-1	0	10^5	1985.40	42.57	5.04
Elastic	-2	190.3	1985.40	1817.97	49.66	6.05
Elastic	-3	295.2	1817.97	1839.87	52.65	6.72
Elastic	-4	298.6	1839.87	2319.19	54.23	7.19
Elastic	-5	202.7	2319.19	10^5	55.18	7.53
Foundation	-6	0	10^5	10^5	27.90	7.80
Foundation	-10	0	10^5	10^5	28.49	8.46

Table 4.19: *Input values for bm4-14d using User-defined soil displacements option (= output values of bm4-14b)*

Layer	**Top level**	**Soil displac.**	**Horiz. modulus**		**Fictive cohesion**	K_p
			Top	**Bottom**		
	[m NAP]	[mm]	[kN/m^3]	[kN/m^3]	[kN/m^2]	[-]
Elastic	0	622.4	131.98	567.90	15.54	3.29
Elastic 2	-1	664.8	567.90	783.90	19.63	3.37
Elastic 2	-2	649.8	783.90	960.47	22.30	3.95
Elastic 2	-3	539.6	960.47	1379.20	23.37	4.31
Elastic 2	-4	328.1	1379.20	10^5	23.91	4.56
Foundation	-5	0	10^5	10^5	27.59	7.53
Foundation	-10	0	10^5	10^5	28.49	8.46

Results of the comparison are given in Table 4.20. Correlation is very good.

Table 4.20: *Results of benchmark 4-14*

Case		**D-SHEET PILING (*Calculated displacements*)**		**D-SHEET PILING (*User-defined displacements.*)**		**Rel. error**
		File	**Result**	**File**	**Result**	**[%]**
1	Max. moment [kNm]	bm4-14a	525.13	bm4-14c	524.79	0.06
	Max. shear force [kN]		383.04		383.17	0.05
	Max. displac. [mm]		217.14		217.04	0.05
2	Max. moment [kNm]	bm4-14b	740.53	bm4-14d	740.42	0.01
	Max. shear force [kN]		385.51		385.44	0.03
	Max. displac. [mm]		455.13		455.16	0.02

Use D-SHEET PILING input files bm4-14a.shi to bm4-14d.shi to run this benchmark.

4.15 Loading by soil displacements – Comparison between single pile and sheet piling

4.15.1 Description

The functioning of a sheet piling loaded by user-defined soil displacements is checked by comparing the results with those obtained in benchmark 4-14 (section 4.14) for a single pile. Two cases are considered (1 and 2) as described in section 4.14.

4.15.2 D-SHEET PILING results

Results of the comparison are excellent as expected.

Table 4.21: *Results of benchmark 4-15 – Loading by soil displacements*

Case		D-SHEET PILING (*Calculated displacements*)		D-SHEET PILING (*User-defined displac.*)		Rel. error
		File	Result	File	Result	[%]
1	Max. moment [kNm]	bm4-14c	524.8	bm4-15a	524.8	0.00
	Max. shear force [kN]		383.2		383.2	0.00
	Max. displac. [mm]		217.0		217.0	0.00
2	Max. moment [kNm]	bm4-14d	740.4	bm4-15b	740.4	0.00
	Max. shear force [kN]		385.4		385.4	0.00
	Max. displac. [mm]		455.2		455.2	0.00

Use D-SHEET PILING input files bm4-15a.shi and bm4-15b.shi to run this benchmark.

4.16 Automatic determination of the favorable/unfavorable effect of loads

4.16.1 Description

The automatic determination of the favorable/unfavorable effect of loads (in case of verification calculation using partial factors) is checked in this benchmark. The same geometry and loading as benchmark 4-17a is used (section 4.17) except that the left side is always the passive side. Moreover, the favorable/unfavorable effect of loads is different:

- ◇ Case A (bm4-16a): the option *D-Sheet Piling determined* is used in the different loads windows;
- ◇ Case B (bm4-16b): loads on passive side are inputted as *Favorable* whereas loads on active side are inputted as *Unfavorable*;

A verification calculation acc. to Eurocode is performed for DA 2 for both benchmarks 4-16a and 4-16b. Results are expected to be the same.

4.16.2 D-SHEET PILING results

Table 4.22: *Results of benchmark 4-16*

Stage	Results	D-SHEET PILING (bm4-16a)	D-SHEET PILING (bm4-16b)	Rel. error [%]
1	Max. moment [kNm]	34.60	34.60	0.00
	Max. shear force [kN]	43.94	43.94	0.00
	Max. displac. [mm]	19.20	19.20	0.00
	Perc. mob. moment [%]	0.00	0.00	0.00
	Perc. mob. resist. [%]	14.96	14.96	0.00
2	Max. moment [kNm]	903.21	903.21	0.00
	Max. shear force [kN]	445.49	445.49	0.00
	Max. displac. [mm]	383.67	383.67	0.00
	Perc. mob. moment [%]	12.33	12.33	0.00
	Perc. mob. resist. [%]	22.33	22.33	0.00
	Anchor force [kN]	108.00	108.00	0.00
3	Max. moment [kNm]	513.73	513.73	0.00
	Max. shear force [kN]	260.02	260.02	0.00
	Max. displac. [mm]	298.37	298.37	0.00
	Perc. mob. moment [%]	58.45	58.45	0.00
	Perc. mob. resist. [%]	62.55	62.55	0.00
	Anchor force [kN]	61.79	61.79	0.00

Use D-SHEET PILING input files bm4-16a.shi and bm4-16b.shi to run this benchmark.

4.17 Verify Sheet Piling calculation acc. CUR 166 Method B (only last stage verified)

4.17.1 Description

The verification is made on an anchored sheet pile wall of 14 m using three stages. Temporary and permanent loads are applied on left and right sides as shown in Table 4.23. The anchor modulus is E_{anchor} = 2.1 $\times$ 10^8 kPa.

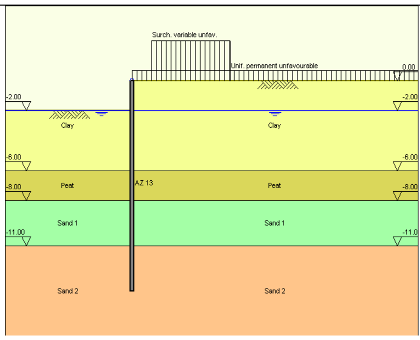
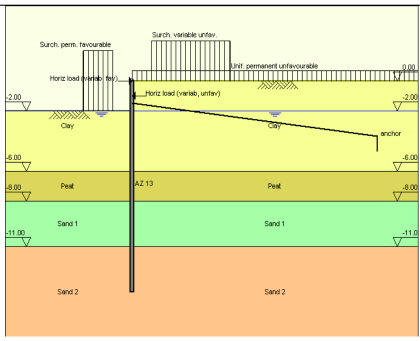
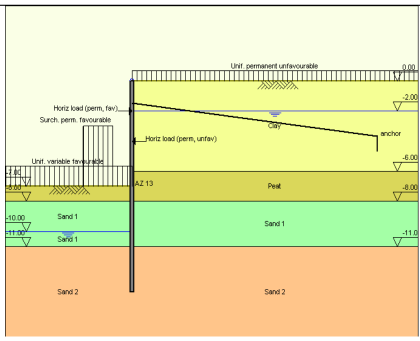
Stage 1:	
Stage 2:	
Stage 3:	

Figure 4.11: *Stages overview (bm4-17)*

Note: Loads applied on the active side should normally be considered as unfavorable and loads applied on the passive side as favorable. However, in order to check the correct functioning of the option Favorable/Unfavorable in the loads windows, this is not always the case.

The magnitude of the different applied loads in given in Table 4.23.

Table 4.23: *Loads (bm4-17)*

Type of load			**Magnitude**	**Distance or Level**	**Length**	**Present in stage...**		
			[kN/m^2]	**[m]**	**[m]**	**1**	**2**	**3**
Uniform	Variable	Fav.	20 (left)					x
	Perm.	Unfav.	10 (right)			x	x	x
Surcharge	Variable	Unfav.	40	2	8	x	x	
	Perm.	Fav.	60	2	3		x	x
Horiz. line	Perm.	Fav.	200	-2				x
	Perm.	Unfav.	-100	-4				x
	Variable	Fav.	150	0			x	
	Variable	Unfav.	-300	-1			x	

The ground and water levels of the different stages are given in Table 4.24. For stages 1 and 3 the left side is inputted as passive side whereas for stage 2 it is the right side, in order to check the correct functioning of the changes of the water and ground levels.

Table 4.24: *Ground and water levels (bm4-17)*

		Stage 1	**Stage 2**	**Stage 3**
Ground level at left side	GL_{left}	-2	-2	-7
Ground level at right side	GL_{right}	0	0	0
Phreatic line at left side	WL_{left}	-2	-2	-10
Phreatic line at right side	WL_{right}	-2	-2	-2
Passive side		Right	Left	Left

The low representative values given in Table 4.25 are used as soil inputs.

Table 4.25: *Soil properties for all stages (bm4-17)*

		Clay	**Peat**	**Sand 1**	**Sand 2**
Top level	[m NAP]	0	-6	-8	-11
Unsaturated total unit weight	[kN/m^3]	15	10	17	17
Saturated total unit weight	[kN/m^3]	16	11	19	19
Cohesion	[kN/m^2]	12.5	5	0	0
Friction angle	[deg]	21	24.5	31	37
Delta Friction angle	[deg]	14	18	24	24
Shell factor	[-]	1	1	1	1
Over-consolidation ratio (OCR)	[-]	1	1	1	1
Grain type		Fine	Fine	Fine	Fine
Modulus of subgrade reaction	[kN/m^3]	2000	800	10000	10000

Verification is performed for the three safety classes (I, II, III) applying the partial factors and level variations defined in the *User Defined Partial Factors* window (see Figure 4.12) on soil strength (c, φ, δ and k), ground level, phreatic surface and the loads, only during the last stage. The multiplication factor for the anchor stiffness is 1.2.

Table 4.26: Design values for loads (steps 6.1 to 6.4)

Type of load			Magnitude [kN/m^2]		
			Stage 1	Stage 2	Stage 3
Uniform	Variable	Fav.			0
	Perm.	Unfav.	10	10	9
Surcharge	Variable	Unfav.	40	40	
	Perm.	Fav.		60	66
Horiz. line	Perm.	Fav.			220
	Perm.	Unfav.			-90
	Variable	Fav.		150	
	Variable	Unfav.		-300	

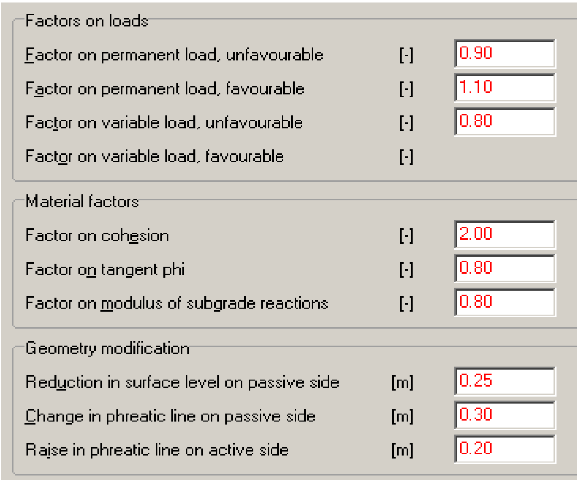


Figure 4.12: *Partial safety factors and geometry variations (bm4-17)*

Two types of calculation results are compared:

- ◇ a verification calculation acc. to CUR 166 using representative input values;
- ◇ a standard calculation using design input values.

4.17.2 D-SHEET PILING results (standard calculation using design input values)

A CUR 166 verification consists on the execution of six analyses (steps 6.1 to 6.5 and 9.1) using different design values:

- ◇ Steps 6.1 to 6.4 uses the design values given in Table 4.26, Table 4.27 and Table 4.28 respectively for loads, materials and geometric levels;
- ◇ Steps 6.5 uses the representative values as input (no partial factors);
- ◇ Step 9.1 uses the same inputs as the step that gives the maximum anchor force between the six following sub-steps: 6.1, 6.2, 6.3, 6.4, 6.5 and 6.5 $\times$ 1.2, except for the anchor stiffness which is multiplied by the multiplication factor. In this project, it corresponds to step 6.2.

Table 4.27: *Design values for soil properties in the last stage (steps 6.1 to 6.4)*

Layer	Parameter	Unit	Steps 6.1 and 6.3	Steps 6.2 and 6.4
Clay	c	[kPa]	6.25	6.25
	φ	[°]	25.63	25.63
	δ	[°]	17.09	17.09
	k	[kN/m^3]	2500	4500
Peat	c	[kPa]	2.5	2.5
	φ	[°]	29.67	29.67
	δ	[°]	21.80	21.80
	k	[kN/m^3]	1000	1800
Sand 1	c	[kPa]	0	0
	φ	[°]	36.91	36.91
	δ	[°]	28.57	28.57
	k	[kN/m^3]	12500	22500
Sand 2	c	[kPa]	0	0
	φ	[°]	43.29	43.29
	δ	[°]	28.08	28.08
	k	[kN/m^3]	12500	22500

Table 4.28: *Design values for geometric levels in the last stage (steps 6.1 to 6.4)*

Level [m NAP]	Steps 6.1 and 6.2	Steps 6.3 and 6.4
GL_{left}	-7.25	-7.25
GL_{right}	0	0
WL_{left}	-9.7	-10.3
WL_{right}	-1.8	-1.8

Results of those different calculations are given in Table 4.29.

4.17.3 D-SHEET PILING results (CUR 166 verification calculation using representative input values)

D-SHEET PILING results are obtained using the option *Partial factors in verified stage only (method B)* and selecting the last stage in the *Verify Sheet Piling* tab of the *Start Calculation* window with an *Anchor stiffness multiplication factor* of 1.2. The results obtained from the *Moment/Force/Displacement Charts* window are compared in the tables below. As expected, the three Verification calculations with the three different classes give the same results.Relative differences between the Verification and the Standard calculations come from the number of nodes along the wall which is different.

Table 4.29: Results of benchmark 4-17a – Stage 3

Step	Result	D-SHEET PILING (Standard)		D-SHEET PILING (Verify)	Error [%]
Step 6.1	Max. moment [kNm]	bm4-17d	-224.44	-224.22	0.10
	Max. shear force [kN]		-166.01	-165.96	0.03
	Max. displac. [mm]		-37.11	-37.05	0.16
	Perc. mob. moment [%]		33.11	33.17	0.18
	Perc. mob. resist. [%]		35.36	35.41	0.14
	Anchor force [kN]		37.83	37.79	0.11
Step 6.2	Max. moment [kNm]	bm4-17e	-202.01	-201.59	0.21
	Max. shear force [kN]		164.23	164.46	0.14
	Max. displac. [mm]		-33.28	-33.17	0.33
	Perc. mob. moment [%]		32.48	32.54	0.18
	Perc. mob. resist. [%]		35.14	35.19	0.14
	Anchor force [kN]		51.59	51.54	0.10
Step 6.3	Max. moment [kNm]	bm4-17f	-223.82	-223.81	0.00
	Max. shear force [kN]		-165.87	-165.87	0.00
	Max. displac. [mm]		-37.01	-37.01	0.00
	Perc. mob. moment [%]		29.90	29.90	0.00
	Perc. mob. resist. [%]		32.41	32.41	0.00
	Anchor force [kN]		37.74	37.74	0.00
Step 6.4	Max. moment [kNm]	bm4-17g	-201.31	-201.31	0.00
	Max. shear force [kN]		164.55	164.55	0.00
	Max. displac. [mm]		-33.14	-33.14	0.00
	Perc. mob. moment [%]		29.56	29.56	0.00
	Perc. mob. resist. [%]		32.36	32.37	0.03
	Anchor force [kN]		51.51	51.51	0.00
Step 6.5	Max. moment [kNm]	bm4-17h	-216.56	-216.56	0.00
	Max. shear force [kN]		-153.80	-153.80	0.00
	Max. displac. [mm]		-35.64	-35.64	0.00
	Perc. mob. moment [%]		25.75	25.75	0.00
	Perc. mob. resist. [%]		28.15	28.15	0.00
	Anchor force [kN]		32.12		
Step 6.5$\times$ 1.2	Max. moment [kNm]	bm4-17h ($\times$ 1.2)	-259.87	-259.87	0.00
	Max. shear force [kN]		-184.56	-184.56	0.00
	Anchor force [kN]		38.54	38.55	0.03
Step 9.1	Anchor force [kN]	bm4-17i	47.55	47.48	0.15

Use D-SHEET PILING input files bm4-17a.shi till bm4-17i.shi to run this benchmark.

4.18 Verify Sheet Piling calculation acc. CUR 166 Method B (all stages verified)

4.18.1 Description

The same benchmark as the previous benchmark is used (section 4.17) except that method B is applied on all stages which means that all stages are checked as a “final” stage (i.e. representative values, with no partial factors, are assumed for all stages apart from the “final” stage being checked). The partial factors corresponding to the selected safety class are only applied to the “final” stage.

Two types of calculation results are compared:

- ◇ (bm4-18a) A verification calculation acc. to CUR 166 with method B with all stages verified. Safety classes I, II and III and an anchor stiffness multiplication factor of 1, 1.2 and 1.4 respectively for stages 1, 2 and 3 are used;
- ◇ A verification calculation acc. to CUR 166 with method B with only one stage verified:
- ◇ (bm4-18b) Stage 1 is verified with safety class I and an anchor stiffness multiplication factor of 1;
- ◇ (bm4-18c) Stage 2 is verified with safety class II and an anchor stiffness multiplication factor of 1.2;
- ◇ (bm4-18d) Stage 3 is verified with safety class III and an anchor stiffness multiplication factor of 1.4.

Results of bm4-18a should be the same as bm4-18b, 4-18c and bm4-18d respectively for stages 1, 2 and 3.

4.18.2 D-SHEET PILING results

Table 4.30: *Results of benchmark 4-18 – Stage 1*

Step	**Result**	**D-SHEET PILING (bm4-18b)**	**D-SHEET PILING (bm4-18a)**	**Error [%]**
Step 6.1	Max. moment [kNm]	19.12	19.12	0.00
	Max. shear force [kN]	25.02	25.02	0.00
	Max. displac. [mm]	10.37	10.37	0.00
	perc. mob. moment [%]	0.00	0.00	0.00
	Perc. mob. resist. [%]	6.75	6.75	0.00
Step 6.2	Max. moment [kNm]	14.56	14.56	0.00
	Max. shear force [kN]	22.89	22.89	0.00
	Max. displac. [mm]	5.75	5.75	0.00
	perc. mob. moment [%]	0.00	0.00	0.00
	Perc. mob. resist. [%]	6.74	6.74	0.00
Step 6.3	Max. moment [kNm]	18.34	18.34	0.00
	Max. shear force [kN]	22.46	22.46	0.00
	Max. displac. [mm]	10.19	10.19	0.00
	perc. mob. moment [%]	0.00	0.00	0.00
	Perc. mob. resist. [%]	6.18	6.18	0.00
Step 6.4	Max. moment [kNm]	13.86	13.86	0.00
	Max. shear force [kN]	20.56	20.56	0.00
	Max. displac. [mm]	5.71	5.71	0.00
	perc. mob. moment [%]	0.00	0.00	0.00
	Perc. mob. resist. [%]	6.17	6.17	0.00
Step 6.5	Max. moment [kNm]	24.92	24.92	0.00
	Max. shear force [kN]	31.96	31.96	0.00
	Max. displac. [mm]	17.01	17.01	0.00
	perc. mob. moment [%]	0.00	0.00	0.00
	Perc. mob. resist. [%]	14.46	14.46	0.00
Step 6.5 $\times$ 1.2	Max. moment [kNm]	29.90	29.90	0.00
	Max. shear force [kN]	38.35	38.35	0.00

__Table 4.31:__ Results of benchmark 4-18 – Stage 2

Step	Result	D-SHEET PILING (bm4-18c)	D-SHEET PILING (bm4-18a)	Error [%]
Step 6.3	Max. moment [kNm]	465.89	465.89	0.00
	Max. shear force [kN]	240.19	240.19	0.00
	Max. displac. [mm]	246.09	246.09	0.00
	perc. mob. moment [%]	7.32	7.32	0.00
	Perc. mob. resist. [%]	13.22	13.22	0.00
	Anchor force [kN]	80.00	80.00	0.00
Step 6.4	Max. moment [kNm]	457.59	457.59	0.00
	Max. shear force [kN]	240.19	240.19	0.00
	Max. displac. [mm]	208.85	208.85	0.00
	perc. mob. moment [%]	7.53	7.53	0.00
	Perc. mob. resist. [%]	13.62	13.62	0.00
	Anchor force [kN]	80.00	80.00	0.00
Step 6.5	Max. moment [kNm]	150.00	150.00	0.00
	Max. shear force [kN]	150.00	150.00	0.00
	Max. displac. [mm]	24.57	24.57	0.00
	perc. mob. moment [%]	11.07	11.07	0.00
	Perc. mob. resist. [%]	14.91	14.91	0.00
Step 6.5×1.2	Max. moment [kNm]	180.00	180.00	0.00
	Max. shear force [kN]	180.00	180.00	0.00
	Anchor force [kN]	96.00	96.00	0.00
Step 9.1	Anchor force [kN]	96.00	96.00	0.00

Table 4.32: Results of benchmark 4-18 – Stage 3

Step	Result	D-SHEET PILING (bm4-18d)	D-SHEET PILING (bm4-18a)	Error [%]
Step 6.1	Max. moment [kNm]	224.22	224.22	0.00
	Max. shear force [kN]	165.96	165.96	0.00
	Max. displac. [mm]	37.05	37.05	0.00
	perc. mob. moment [%]	33.17	33.17	0.00
	Perc. mob. resist. [%]	35.41	35.41	0.00
	Anchor force [kN]	37.79	37.79	0.00
Step 6.2	Max. moment [kNm]	201.59	201.59	0.00
	Max. shear force [kN]	164.46	164.46	0.00
	Max. displac. [mm]	33.17	33.17	0.00
	perc. mob. moment [%]	32.54	32.54	0.00
	Perc. mob. resist. [%]	35.19	35.19	0.00
	Anchor force [kN]	51.54	51.54	0.00
Step 6.3	Max. moment [kNm]	223.81	223.81	0.00
	Max. shear force [kN]	165.87	165.87	0.00
	Max. displac. [mm]	37.01	37.01	0.00
	perc. mob. moment [%]	29.90	29.90	0.00
	Perc. mob. resist. [%]	32.41	32.41	0.00
	Anchor force [kN]	37.74	37.74	0.00
Step 6.4	Max. moment [kNm]	201.31	201.31	0.00
	Max. shear force [kN]	164.55	164.55	0.00
	Max. displac. [mm]	33.14	33.14	0.00
	perc. mob. moment [%]	29.56	29.56	0.00
	Perc. mob. resist. [%]	32.37	32.37	0.00
	Anchor force [kN]	51.51	51.51	0.00
Step 6.5	Max. moment [kNm]	216.56	216.56	0.00
	Max. shear force [kN]	153.80	153.80	0.00
	Max. displac. [mm]	35.64	35.64	0.00
	perc. mob. moment [%]	25.75	25.75	0.00
	Perc. mob. resist. [%]	28.15	28.15	0.00
Step 6.5 $\times$ 1.2	Max. moment [kNm]	259.87	259.87	0.00
	Max. shear force [kN]	184.56	184.56	0.00
	Anchor force [kN]	38.55	38.55	0.00
Step 9.1	Anchor force [kN]	43.85	43.85	0.00

Use D-SHEET PILING input files bm4-18a.shi till bm4-18d.shi to run this benchmark.

4.19 Verify Sheet Piling calculation acc. CUR 166 Method A

4.19.1 Description

The same benchmark as benchmark 4-17 is used (section 4.17) except that method A instead of method B is used, which means that partial factors are applied on all stages.

4.19.2 D-SHEET PILING results (standard calculation using design input values)

The same design values for soil properties as benchmark 4-17 (section 4.17) are used in all stages. For steps 6.1 to 6.4, design values given in Table 4.33 and Table 4.35 respectively for loads and geometric levels are used.

Table 4.33: *Design values for loads (steps 6.1 to 6.4)*

Type of load			Magnitude [kN/m^2]		
			Stage 1	Stage 2	Stage 3
Uniform	Variable	Fav.			0
Uniform	Perm.	Unfav.	9	9	9
Surcharge	Variable	Unfav.	32	32	
Surcharge	Perm.	Fav.		66	66
Horiz. line	Perm.	Fav.			220
Horiz. line	Perm.	Unfav.			-90
Horiz. line	Variable	Fav.		0	
Horiz. line	Variable	Unfav.		-240	

Table 4.34: *Design values for soil properties in the last stage (steps 6.1 to 6.4)*

Layer	Parameter	Unit	Steps 6.1 and 6.3	Steps 6.2 and 6.4
Clay	c	[kPa]	6.25	6.25
	φ	[°]	25.63	25.63
	δ	[°]	17.09	17.09
	k	[kN/m^3]	2500	4500
Peat	c	[kPa]	2.5	2.5
	φ	[°]	29.67	29.67
	δ	[°]	21.80	21.80
	k	[kN/m^3]	1000	1800
Sand 1	c	[kPa]	0	0
	φ	[°]	36.91	36.91
	δ	[°]	28.57	28.57
	k	[kN/m^3]	12500	22500
Sand 2	c	[kPa]	0	0
	φ	[°]	43.29	43.29
	δ	[°]	28.08	28.08
	k	[kN/m^3]	12500	22500

Table 4.35: *Design values for geometric levels (steps 6.1 to 6.4)*

Level [m NAP]	Stage 1		Stage 2		Stage 3	
	6.1/6.2	6.3/6.4	6.1/6.2	6.3/6.4	6.1/6.2	6.3/6.4
GL_{left}	-2	-2	-2.25	-2.25	-7.25	-7.25
GL_{right}	-0.25	-0.25	0	0	0	0
WL_{left}	-1.8	-1.8	-2[a]	-2[a]	-9.7	-10.3
WL_{right}	-1.7	-2.3	-1.8	-1.8	-1.8	-1.8

[a] No increase of the water level because the water level is above the ground level

Results of those different calculations are given in section 4.19.3.

4.19.3 D-SHEET PILING results (CUR 166 verification calculation using representative input values)

D-SHEET PILING results are obtained using the option *Partial factors in verified stage only (method A)* with an *Anchor stiffness multiplication factor* of 1.2. The results obtained from the *Moment/Force/Displacement Charts* window are compared in the tables below. Relative differences come from the number of decimals used for the input values limited to 2.

Table 4.36: *Results of benchmark 4-19a – CUR method A, Class I, Stage 1*

Step	**Result**	**File**	**D-Sheet Piling**	**D-Sheet Piling (bm4-19a)**	**Error [%]**
6.1	Max. moment [kNm]	bm4-19d	19.17	19.13	0.21
	Max. shear force [kN]		25.07	25.02	0.20
	Max. displac. [mm]		10.39	10.37	0.19
	Perc. mob. moment [%]		0.00	0.00	0.00
	Perc. mob. resist. [%]		6.76	6.75	0.15
6.2	Max. moment [kNm]	bm4-19e	14.58	14.56	0.14
	Max. shear force [kN]		22.94	22.89	0.22
	Max. displac. [mm]		5.76	5.75	0.17
	Perc. mob. moment [%]		0.00	0.00	0.00
	Perc. mob. resist. [%]		6.74	6.74	0.00
6.3	Max. moment [kNm]	bm4-19f	18.34	18.34	0.00
	Max. shear force [kN]		22.46	22.46	0.00
	Max. displac. [mm]		10.19	10.19	0.00
	perc. mob. moment [%]		0.00	0.00	0.00
	Perc. mob. resist. [%]		6.18	6.18	0.00
6.4	Max. moment [kNm]	bm4-19g	13.86	13.86	0.00
	Max. shear force [kN]		20.57	20.56	0.05
	Max. displac. [mm]		5.71	5.71	0.00
	Perc. mob. moment [%]		0.00	0.00	0.00
	Perc. mob. resist. [%]		6.17	6.17	0.00
6.5	Max. moment [kNm]	bm4-17h	24.92	24.92	0.00
	Max. shear force [kN]		31.96	31.96	0.00
	Max. displac. [mm]		17.01	17.01	0.00
	Perc. mob. moment [%]		0.00	0.00	0.00
	Perc. mob. resist. [%]		14.46	14.46	0.00
6.5×1.2	Max. moment [kNm]		29.90	29.90	0.00
	Max. shear force [kN]		38.35	38.35	0.00

Table 4.37: *Results of benchmark 4-19a/b/c – Stage 2*

Step	Result	File	D-Sheet Piling	D-Sheet Piling	Error [%]
Step 6.1	Max. moment [kNm]	bm4-19d	463.69	464.33	0.14
	Max. shear force [kN]		240.19	240.19	0.00
	Max. displac. [mm]		238.89	239.79	0.38
	Perc. mob. moment [%]		6.93	6.94	0.14
	Perc. mob. resist. [%]		12.68	12.69	0.08
	Anchor force [kN]		80.00	80.00	0.00
Step 6.2	Max. moment [kNm]	bm4-19e	456.18	456.49	0.07
	Max. shear force [kN]		240.19	240.19	0.00
	Max. displac. [mm]		197.01	197.45	0.22
	Perc. mob. moment [%]		7.15	7.15	0.00
	Perc. mob. resist. [%]		13.10	13.10	0.00
	Anchor force [kN]		80.00	80.00	0.00
Step 6.3	Max. moment [kNm]	bm4-19f	464.35	465.96	0.35
	Max. shear force [kN]		240.19	240.19	0.00
	Max. displac. [mm]		240.12	243.30	1.31
	perc. mob. moment [%]		6.89	7.10	2.96
	Perc. mob. resist. [%]		12.63	12.95	2.47
	Anchor force [kN]		80.00	80.00	0.00
Step 6.4	Max. moment [kNm]	bm4-19g	456.49	457.73	0.27
	Max. shear force [kN]		240.19	240.19	0.00
	Max. displac. [mm]		197.70	199.36	0.83
	Perc. mob. moment [%]		7.11	7.32	2.87
	Perc. mob. resist. [%]		13.05	13.37	2.39
	Anchor force [kN]		80.00	80.00	0.00
Step 6.5	Max. moment [kNm]	bm4-17h	150.00	150.00	0.00
	Max. shear force [kN]		150.00	150.00	0.00
	Max. displac. [mm]		24.57	24.57	0.00
	perc. mob. moment [%]		11.07	11.07	0.00
	Perc. mob. resist. [%]		14.91	14.91	0.00
	Anchor force [kN]		80.00		
Step 6.5 $\times$ 1.2	Max. moment [kNm]		180.00	180.00	0.00
	Max. shear force [kN]		180.00	180.00	0.00
	Anchor force [kN]		96.00	96.00	0.00
Step 9.1	Anchor force $\times$ 1.2 [kN]	bm4-19h	96.00	96.00	0.00
	Anchor force [kN]		80.00		

Table 4.38: *Results of benchmark 4-19a/b/c – Stage 3*

Step	Result	File	D-Sheet Piling	D-Sheet Piling	Error [%]
Step 6.1	Max. moment [kNm]	bm4-19d	283.74	284.71	0.34
	Max. shear force [kN]		182.24	182.83	0.32
	Max. displac. [mm]		176.46	177.41	0.54
	Perc. mob. moment [%]		33.95	34.00	0.15
	Perc. mob. resist. [%]		37.61	37.68	0.19
	Anchor force [kN]		38.32	38.13	0.50
Step 6.2	Max. moment [kNm]	bm4-19e	278.84	279.24	0.14
	Max. shear force [kN]		179.15	179.79	0.36
	Max. displac. [mm]		144.56	145.09	0.37
	Perc. mob. moment [%]		33.17	33.16	0.03
	Perc. mob. resist. [%]		37.12	37.13	0.03
	Anchor force [kN]		53.77	53.47	0.56
Step 6.3	Max. moment [kNm]	bm4-19f	286.75	288.57	0.63
	Max. shear force [kN]		183.14	183.33	0.10
	Max. displac. [mm]		177.72	180.83	1.72
	Perc. mob. moment [%]		30.42	30.45	0.10
	Perc. mob. resist. [%]		34.26	34.30	0.12
	Anchor force [kN]		37.95	37.82	0.34
Step 6.4	Max. moment [kNm]	bm4-19g	280.71	281.57	0.31
	Max. shear force [kN]		180.01	180.12	0.06
	Max. displac. [mm]		145.33	146.95	1.10
	Perc. mob. moment [%]		30.06	30.07	0.03
	Perc. mob. resist. [%]		34.04	34.05	0.03
	Anchor force [kN]		53.37	53.31	0.11
Step 6.5	Max. moment [kNm]	bm4-17h	216.56	216.56	0.00
	Max. shear force [kN]		153.80	153.80	0.00
	Max. displac. [mm]		35.64	35.64	0.00
	Perc. mob. moment [%]		25.75	25.75	0.00
	Perc. mob. resist. [%]		28.15	28.15	0.00
	Anchor force [kN]		32.12		
Step 6.5 $\times$ 1.2	Max. moment [kNm]		259.87	259.87	0.00
	Max. shear force [kN]		184.56	184.56	0.00
	Anchor force [kN]		38.54	38.55	0.03
Step 9.1	Anchor force $\times$ 1.2 [kN]	bm4-19h	31.90	31.89	0.03
	Anchor force [kN]		26.58		

Use D-SHEET PILING input files bm4-19a.shi till bm4-19h.shi to run this benchmark.

4.20 Design Sheet Piling Length acc. CUR 166

4.20.1 Description

The same problem as in section 4.17 is considered. For the *Design Sheet Piling Length* option, D-SHEET PILING applies the same partial factors and geometric variations as for step 6.3 of the *Verify Sheet Piling* option. Therefore, the results of the *Design Sheet Piling Length* calculation (for a length of 14 m) should be the same as:

- results of benchmark 4-19a/b/c (step 6.3) (section 4.19) for method A;
- results of benchmark 4-18b (step 6.3) (section 4.18) for method B with stage 1 selected;
- results of benchmark 4-18c (step 6.3) (section 4.18) for method B with stage 2 selected;
- results of benchmark 4-18d (step 6.3) (section 4.18) for method B with stage 3 selected;

4.20.2 D-SHEET PILING results

D-SHEET PILING results are obtained using the *Design Sheet Piling Length* tab and selecting a sheet piling length of 14 m.

Table 4.39: *Results of benchmark 4-20 – Method A, stage 3*

Safety class	Results	D-SHEET PILING "Verify" (step 6.3)		D-SHEET PILING "Design" (14 m length)		Error [%]
I	Max. displac. [mm]	bm4-19a	180.83	bm4-20a	180.83	0.00
	Max. moment [kNm]		288.57		288.57	0.00
	Anchor force [kN]		37.82		37.82	0.00
	Mob. resistance [%]		34.30		34.30	0.00
II	Max. displac. [mm]	bm4-19b	180.83	bm4-20b	180.83	0.00
	Max. moment [kNm]		288.57		288.57	0.00
	Anchor force [kN]		37.82		37.82	0.00
	Mob. resistance [%]		34.30		34.30	0.00
III	Max. displac. [mm]	bm4-19c	180.83	bm4-20c	180.83	0.00
	Max. moment [kNm]		288.57		288.57	0.00
	Anchor force [kN]		37.82		37.82	0.00
	Mob. resistance [%]		34.30		34.30	0.00

Table 4.40: Results of benchmark 4-20 – Method B

Safety class	Results	D-SHEET PILING "Verify" (step 6.3)		D-SHEET PILING "Design" (14 m length)		Error [%]
Stage 1	Max. displac. [mm]	bm4-18b	10.19	bm4-20d	10.19	0.00
	Max. moment [kNm]		18.34		18.34	0.00
	Anchor force [kN]		0.00		0.00	0.00
	Mob. resistance [%]		6.18		6.18	0.00
Stage 2	Max. displac. [mm]	bm4-18c	246.09	bm4-20e	246.09	0.00
	Max. moment [kNm]		465.89		465.89	0.00
	Anchor force [kN]		80.00		80.00	0.00
	Mob. resistance [%]		13.22		13.22	0.00
Stage 3	Max. displac. [mm]	bm4-18d	37.01	bm4-20f	37.01	0.00
	Max. moment [kNm]		223.81		223.81	0.00
	Anchor force [kN]		37.74		37.74	0.00
	Mob. resistance [%]		32.41		32.41	0.00

Use D-SHEET PILING input files bm4-20a.shi to bm4-20f.shi to run this benchmark.

4.21 Verify Sheet Piling acc. Eurocode 7 – General

4.21.1 Description

The verification is made using the same input as benchmark 4-17 (section 4.17). The representative values of the loads, geometric levels and soil inputs are respectively given in Table 4.23, Table 4.24 and Table 4.25.

Verification is performed for both types of design approach:

- ◇ partial factors applied on loads
- ◇ partial factors applied on effect of loads.

The partial factors and level variations used are given in Figure 4.13.

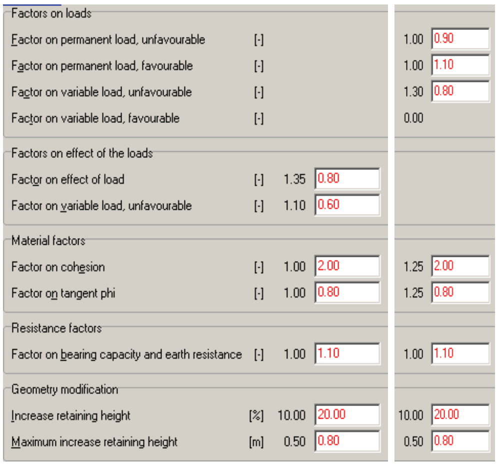


Figure 4.13: *Partial safety factors and geometry variations for the different design approaches (bm4-21)*

Note: In Figure 4.13, values in red color are different from the default values prescribed by Eurocode **?**.

Two types of calculation results are compared for each design approach:

- a Eurocode verification calculation using representative input values;
- a standard calculation using design input values.

4.21.2 D-SHEET PILING results (standard calculation using design input values)

A standard calculation is performed using design input values determined by applying the partial factors of Figure 4.13. Results are given in Table 4.41, Table 4.42 and Table 4.43 respectively for loads, materials and ground levels.

Table 4.41: *Design values for loads (bm4-21)*

Type of load			**Magnitude [kN/m^2]**		
			Stage 1	**Stage 2**	**Stage 3**
Uniform	Variable	Fav.			0
Uniform	Perm.	Unfav.	9	9	9
Surcharge	Variable	Unfav.	32	32	
Surcharge	Perm.	Fav.		66	66
Horiz. line	Perm.	Fav.			220
Horiz. line	Perm.	Unfav.			-90
Horiz. line	Variable	Fav.		0	
Horiz. line	Variable	Unfav.		-240	

Table 4.42: *Design values for soil parameters (bm4-21)*

Parameter	**Unit**	**Clay**	**Peat**	**Sand 1**	**Sand 2**
Cohesion	[kPa]	6.25	2.5	0	0
Friction angle	[°]	25.63	29.67	36.91	43.29
Delta friction angle	[°]	17.09	21.80	28.57	28.08

Table 4.43: Design values for ground level at both sides (bm4-21)

Level [m NAP]	Stage 1	Stage 2	Stage 3
GL_{left}	-2	-2.1	-7.8
GL_{right}	-0.4	0	0
WL_{left}	-2	-2	-10
WL_{right}	-2	-2	-2

Results of those different calculations are given in Table 4.44 and Table 4.45 for the different design approaches.

4.21.3 D-SHEET PILING results (Eurocode verification calculation using representative input values)

D-SHEET PILING calculations are performed in the *Verify Sheet Piling* tab of the *Start Calculation* window selecting *EuroCode*. D-SHEET PILING results are found in the *Report* window.For design approaches DA 1 set 1 and DA 3, D-SHEET PILING multiplies the moments and the shear forces with the user-defined partial factor applied on the effect of the loads. Therefore, to compare the D-SHEET PILING and the benchmark results, the moments and the shear forces from the benchmark results are multiplied by 0.8 (see Table 4.44 and Table 4.45). Relative differences come from the number of decimals used for the input values limited to 2.

Table 4.44: Results of benchmark 4-21a/c – Design approach with partial factors on effect of loads

Stage	Result	D-SHEET PILING (Standard)		D-SHEET PILING (Verify)	Relative error
		(bm4-21e)	× 0.8	(bm4-21a/c)	[%]
1	Max. moment [kNm]	20.43	16.35	16.35	0.00
	Max. shear force [kN]	24.77	19.82	19.81	0.05
	Max. displac. [mm]	11.22		11.22	0.00
	Perc. mob. moment [%]	0.00		0.00	0.00
	Perc. mob. resist. [%]	6.39		6.39	0.00
2	Max. moment [kNm]	270.88	216.70	216.69	0.00
	Max. shear force [kN]	180.69	144.55	144.55	0.00
	Max. displac. [mm]	135.70		135.69	0.01
	Perc. mob. moment [%]	6.00		6.00	0.00
	Perc. mob. resist. [%]	9.99		10.00	0.10
	Anchor force [kN]	80.00	64.00	64.00	0.00
3	Max. moment [kNm]	236.98	189.59	189.59	0.00
	Max. shear force [kN]	189.44	151.55	151.55	0.00
	Max. displac. [mm]	88.86		88.85	0.01
	Perc. mob. moment [%]	42.62		42.62	0.00
	Perc. mob. resist. [%]	44.89		44.89	0.00
	Anchor force [kN]	58.12	46.50	46.50	0.00

Table 4.45: Results of benchmark 4-21b/d – Design approach with partial factors on loads

Stage	Result	D-SHEET PILING (Standard)	D-Sheet Piling (Verify)	Relative error
		(bm4-21f)	(bm4-21b/d)	[%]
1	Max. moment [kNm]	21.36	21.37	0.05
	Max. shear force [kN]	25.80	25.79	0.04
	Max. displac. [mm]	12.41	12.41	0.00
	Perc. mob. moment [%]	0.00	0.00	0.00
	Perc. mob. resist. [%]	6.65	6.65	0.00
2	Max. moment [kNm]	440.87	440.86	0.00
	Max. shear force [kN]	240.19	240.19	0.00
	Max. displac. [mm]	239.51	239.49	0.01
	Perc. mob. moment [%]	6.54	6.54	0.00
	Perc. mob. resist. [%]	11.99	11.99	0.00
	Anchor force [kN]	80.00	80.00	0.00
3	Max. moment [kNm]	282.33	282.32	0.00
	Max. shear force [kN]	192.46	192.46	0.00
	Max. displac. [mm]	170.04	170.03	0.01
	Perc. mob. moment [%]	41.88	41.88	0.00
	Perc. mob. resist. [%]	44.41	44.41	0.00
	Anchor force [kN]	41.67	41.64	0.07

Use D-SHEET PILING input files bm4-21a.shi to bm4-21f.shi to run this benchmark.

4.22 Design Sheet Piling Length acc. Eurocode 7 – General

4.22.1 Description

The same problem as benchmark 4-21 (section 4.21) is considered. For the *Design Sheet Piling Length* option, D-SHEET PILING applies the same partial factors and geometric variations as for the *Verify Sheet Piling* option. Therefore, the results of the *Design Sheet Piling Length* calculation (for a length of 14 m) should be the same as the results of benchmark 4-21 (section 4.21).

4.22.2 D-SHEET PILING results

D-SHEET PILING results are obtained using the *Design Sheet Piling Length* tab and selecting a sheet piling length of 14 m.

Table 4.46: Results of benchmark 4-22 – Stage 3

DA	Results for stage 3	D-SHEET PILING "Verify" (step 6.3)		D-SHEET PILING "Design" (length = 14 m)		Relative error [%]
1 set 1	Max. displac. [mm]	bm4-21a	88.85	bm4-22a	88.85	0.00
	Max. moment [kNm]		189.59		189.59	0.00
	Anchor force [kN]		46.50		46.50	0.00
	Mob. resistance [%]		44.89		44.89	0.00
1 set 2	Max. displac. [mm]	bm4-21b	170.03	bm4-22b	170.03	0.00
	Max. moment [kNm]		282.32		282.32	0.00
	Anchor force [kN]		41.64		41.67	0.07
	Mob. resistance [%]		44.41		44.41	0.00
2	Max. displac. [mm]	bm4-21c	88.85	bm4-22c	88.85	0.00
	Max. moment [kNm]		189.59		189.59	0.00
	Anchor force [kN]		46.50		46.50	0.00
	Mob. resistance [%]		44.89		44.89	0.00
3	Max. displac. [mm]	bm4-21d	170.03	bm4-22d	170.03	0.00
	Max. moment [kNm]		282.32		282.32	0.00
	Anchor force [kN]		41.64		41.67	0.07
	Mob. resistance [%]		44.41		44.41	0.00

Use D-SHEET PILING input files bm4-22a.shi to bm4-22d.shi to run this benchmark.

4.23 Verify Sheet Piling calculation acc. Eurocode 7 - NL annex

4.23.1 Description

The verification is made using the same input as benchmark 4-17 (section 4.17). The Dutch Annex of Eurocode 7 prescribes the same step-by-step procedure as the CUR 166 recommendations only the partial factors of the three safety classes are different. However, to check the correctness of a verification calculation acc. to NL Annex of Eurocode 7, the same user-defined partial factors as for benchmarks for CUR 166 (benchmarks 4-17, 4-18 and 4-19) are used, except that they are inputted in the *EC7 NL* tab of the *User Defined Partial Factors* window instead of the *CUR* tab. Then, a simple comparison with the results of benchmarks 4-17, 4-18 and 4-19 is performed (see Table 4.47).

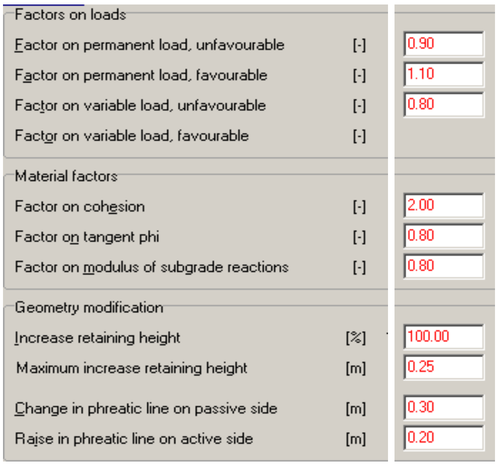


Figure 4.14: *Partial safety factors and geometry variations for the different classes of Eurocode 7 with NL Annex (bm4-23)*

Table 4.47: *Verification calculations performed for benchmark 4-23*

Method	**Verified stage**	**CUR 166**		**EC 7 NL annex**	
		Class	File name	RC	File name
A		I	bm4-19a	1	bm4-23a
A		II	bm4-19b	2	bm4-23b
A		III	bm4-19c	3	bm4-23c
B	Stage 1	I	bm4-18b	1	bm4-23d
B	Stage 2	II	bm4-18c	2	bm4-23e
B	Stage 3	III	bm4-18d	3	bm4-23f
B	All	I, II, III	bm4-18a	1, 2, 3	bm4-23g

4.23.2 D-Sheet Piling results

Table 4.48: *Results of benchmark 4-23a/b/c – Method A*

Step	**Result**	**D-SHEET PILING CUR 166 (bm4-19a/b/c)**	**D-SHEET PILING EC7-NL (bm4-23a/b/c)**	**Error [%]**
Step 6.1	Max. moment [kNm]	284.71	284.71	0.00
	Max. shear force [kN]	182.83	182.83	0.00
	Max. displac. [mm]	177.41	177.41	0.00
	Perc. mob. moment [%]	34.00	34.00	0.00
	Perc. mob. resist. [%]	37.68	37.68	0.00
	Anchor force [kN]	38.13	38.13	0.00
Step 6.2	Max. moment [kNm]	279.24	279.24	0.00
	Max. shear force [kN]	179.79	179.79	0.00
	Max. displac. [mm]	145.09	145.09	0.00
	Perc. mob. moment [%]	33.16	33.16	0.00
	Perc. mob. resist. [%]	37.13	37.13	0.00
	Anchor force [kN]	53.47	53.47	0.00
Step 6.3	Max. moment [kNm]	288.57	288.57	0.00
	Max. shear force [kN]	183.33	183.33	0.00
	Max. displac. [mm]	180.83	180.83	0.00
	Perc. mob. moment [%]	30.45	30.45	0.00
	Perc. mob. resist. [%]	34.30	34.30	0.00
	Anchor force [kN]	37.82	37.82	0.00
Step 6.4	Max. moment [kNm]	281.57	281.57	0.00
	Max. shear force [kN]	180.12	180.12	0.00
	Max. displac. [mm]	146.95	146.95	0.00
	Perc. mob. moment [%]	30.07	30.07	0.00
	Perc. mob. resist. [%]	34.05	34.05	0.00
	Anchor force [kN]	53.31	53.31	0.00
Step 6.5	Max. moment [kNm]	216.56	216.56	0.00
	Max. shear force [kN]	153.80	153.80	0.00
	Max. displac. [mm]	35.64	35.64	0.00
	Perc. mob. moment [%]	25.75	25.75	0.00
	Perc. mob. resist. [%]	28.15	28.15	0.00
Step 6.5 $\times$ 1.2	Max. moment [kNm]	259.87	259.87	0.00
	Max. shear force [kN]	184.56	184.56	0.00
	Anchor force [kN]	38.55	38.55	0.00
Step 9.1	Anchor force $\times$ 1.2 [kN]	31.89	31.89	0.00

Table 4.49: *Results of benchmark 4-23d – Method B (only stage 1 verified)*

Step	**Result**	**D-SHEET PILING CUR 166 (bm4-18b)**	**D-SHEET PILING EC7-NL (bm4-23d)**	**Error [%]**
Step 6.1	Max. moment [kNm]	19.12	19.12	0.00
	Max. shear force [kN]	25.02	25.02	0.00
	Max. displac. [mm]	10.37	10.37	0.00
	Perc. mob. moment [%]	0.00	0.00	0.00
	Perc. mob. resist. [%]	6.75	6.75	0.00
Step 6.2	Max. moment [kNm]	14.56	14.56	0.00
	Max. shear force [kN]	22.89	22.89	0.00
	Max. displac. [mm]	5.75	5.75	0.00
	Perc. mob. moment [%]	0.00	0.00	0.00
	Perc. mob. resist. [%]	6.74	6.74	0.00
Step 6.3	Max. moment [kNm]	18.34	18.34	0.00
	Max. shear force [kN]	22.46	22.46	0.00
	Max. displac. [mm]	10.19	10.19	0.00
	Perc. mob. moment [%]	0.00	0.00	0.00
	Perc. mob. resist. [%]	6.18	6.18	0.00
Step 6.4	Max. moment [kNm]	13.86	13.86	0.00
	Max. shear force [kN]	20.56	20.56	0.00
	Max. displac. [mm]	5.71	5.71	0.00
	Perc. mob. moment [%]	0.00	0.00	0.00
	Perc. mob. resist. [%]	6.17	6.17	0.00
Step 6.5	Max. moment [kNm]	24.92	24.92	0.00
	Max. shear force [kN]	31.96	31.96	0.00
	Max. displac. [mm]	17.01	17.01	0.00
	Perc. mob. moment [%]	0.00	0.00	0.00
	Perc. mob. resist. [%]	14.46	14.46	0.00
Step 6.5 $\times$ 1.2	Max. moment [kNm]	29.90	29.90	0.00
	Max. shear force [kN]	38.35	38.35	0.00

Table 4.50: *Results of benchmark 4-23e– Method B (only stage 2 verified)*

Step	**Result**	**D-SHEET PILING CUR 166 (bm4-18c)**	**D-SHEET PILING EC7-NL (bm4-23e)**	**Error [%]**
Step 6.3	Max. moment [kNm]	465.89	465.89	0.00
	Max. shear force [kN]	240.19	240.19	0.00
	Max. displac. [mm]	246.09	246.09	0.00
	Perc. mob. moment [%]	7.32	7.32	0.00
	Perc. mob. resist. [%]	13.22	13.22	0.00
	Anchor force [kN]	80.00	80.00	0.00
Step 6.4	Max. moment [kNm]	457.59	457.59	0.00
	Max. shear force [kN]	240.19	240.19	0.00
	Max. displac. [mm]	208.85	208.85	0.00
	Perc. mob. moment [%]	7.53	7.53	0.00
	Perc. mob. resist. [%]	13.62	13.62	0.00
	Anchor force [kN]	80.00	80.00	0.00
Step 6.5	Max. moment [kNm]	150.00	150.00	0.00
	Max. shear force [kN]	150.00	150.00	0.00
	Max. displac. [mm]	24.57	24.57	0.00
	Perc. mob. moment [%]	11.07	11.07	0.00
	Perc. mob. resist. [%]	14.91	14.91	0.00
Step 6.5 $\times$ 1.2	Max. moment [kNm]	180.00	180.00	0.00
	Max. shear force [kN]	180.00	180.00	0.00
	Anchor force [kN]	96.00	96.00	0.00
Step 9.1	Anchor force [kN]	96.00	96.00	0.00

Table 4.51: *Results of benchmark 4-23f – Method B (only stage 3 verified)*

Step	**Result**	**D-SHEET PILING CUR 166 (bm4-18d)**	**D-SHEET PILING EC7-NL (bm4-23f)**	**Error [%]**
Step 6.1	Max. moment [kNm]	224.22	224.22	0.00
	Max. shear force [kN]	165.96	165.96	0.00
	Max. displac. [mm]	37.05	37.05	0.00
	Perc. mob. moment [%]	33.17	33.17	0.00
	Perc. mob. resist. [%]	35.41	35.41	0.00
	Anchor force [kN]	37.79	37.79	0.00
Step 6.2	Max. moment [kNm]	201.59	201.59	0.00
	Max. shear force [kN]	164.46	164.46	0.00
	Max. displac. [mm]	33.17	33.17	0.00
	Perc. mob. moment [%]	32.54	32.54	0.00
	Perc. mob. resist. [%]	35.19	35.19	0.00
	Anchor force [kN]	51.54	51.54	0.00
Step 6.3	Max. moment [kNm]	223.81	223.81	0.00
	Max. shear force [kN]	165.87	165.87	0.00
	Max. displac. [mm]	37.01	37.01	0.00
	Perc. mob. moment [%]	29.90	29.90	0.00
	Perc. mob. resist. [%]	32.41	32.41	0.00
	Anchor force [kN]	37.74	37.74	0.00
Step 6.4	Max. moment [kNm]	201.31	201.31	0.00
	Max. shear force [kN]	164.55	164.55	0.00
	Max. displac. [mm]	33.14	33.14	0.00
	Perc. mob. moment [%]	29.56	29.56	0.00
	Perc. mob. resist. [%]	32.37	32.37	0.00
	Anchor force [kN]	51.51	51.51	0.00
Step 6.5	Max. moment [kNm]	216.56	216.56	0.00
	Max. shear force [kN]	153.80	153.80	0.00
	Max. displac. [mm]	35.64	35.64	0.00
	Perc. mob. moment [%]	25.75	25.75	0.00
	Perc. mob. resist. [%]	28.15	28.15	0.00
Step 6.5 $\times$ 1.2	Max. moment [kNm]	259.87	259.87	0.00
	Max. shear force [kN]	184.56	184.56	0.00
	Anchor force [kN]	38.55	38.55	0.00
Step 9.1	Anchor force [kN]	43.85	43.85	0.00

Table 4.52: Results of benchmark 4-23g – Method B (All stages verified)

Step	Result for stage 3	D-SHEET PILING CUR 166 (bm4-18d)	D-SHEET PILING EC7-NL (bm4-23g)	Error [%]
Step 6.1	Max. moment [kNm]	224.22	224.22	0.00
	Max. shear force [kN]	165.96	165.96	0.00
	Max. displac. [mm]	37.05	37.05	0.00
	Perc. mob. moment [%]	33.17	33.17	0.00
	Perc. mob. resist. [%]	35.41	35.41	0.00
	Anchor force [kN]	37.79	37.79	0.00
Step 6.2	Max. moment [kNm]	201.59	201.59	0.00
	Max. shear force [kN]	164.46	164.46	0.00
	Max. displac. [mm]	33.17	33.17	0.00
	Perc. mob. moment [%]	32.54	32.54	0.00
	Perc. mob. resist. [%]	35.19	35.19	0.00
	Anchor force [kN]	51.54	51.54	0.00
Step 6.3	Max. moment [kNm]	223.81	223.81	0.00
	Max. shear force [kN]	165.87	165.87	0.00
	Max. displac. [mm]	37.01	37.01	0.00
	Perc. mob. moment [%]	29.90	29.90	0.00
	Perc. mob. resist. [%]	32.41	32.41	0.00
	Anchor force [kN]	37.74	37.74	0.00
Step 6.4	Max. moment [kNm]	201.31	201.31	0.00
	Max. shear force [kN]	164.55	164.55	0.00
	Max. displac. [mm]	33.14	33.14	0.00
	Perc. mob. moment [%]	29.56	29.56	0.00
	Perc. mob. resist. [%]	32.37	32.37	0.00
	Anchor force [kN]	51.51	51.51	0.00
Step 6.5	Max. moment [kNm]	216.56	216.56	0.00
	Max. shear force [kN]	153.80	153.80	0.00
	Max. displac. [mm]	35.64	35.64	0.00
	Perc. mob. moment [%]	25.75	25.75	0.00
	Perc. mob. resist. [%]	28.15	28.15	0.00
Step 6.5 $\times$ 1.2	Max. moment [kNm]	259.87	259.87	0.00
	Max. shear force [kN]	184.56	184.56	0.00
	Anchor force [kN]	38.55	38.55	0.00
Step 9.1	Anchor force [kN]	43.85	43.85	0.00

Use D-SHEET PILING input files bm4-23a.shi till bm4-23g.shi to run this benchmark.

4.24 Design Sheet Piling Length acc. Eurocode 7 – NL annex

4.24.1 Description

The same problem as in section 4.17 is considered. For the *Design Sheet Piling Length* option, D-SHEET PILING applies the same partial factors and geometric variations as for step 6.3 of the *Verify Sheet Piling* option. Therefore, the results of the *Design Sheet Piling Length* calculation (for a length of 14 m) should be the same as:

- results of benchmark 4-23a/b/c (step 6.3) (section 4.23) for method A;
- results of benchmark 4-23d (step 6.3) (section 4.23) for method B with stage 1 selected;
- results of benchmark 4-23e (step 6.3) (section 4.23) for method B with stage 2 selected;
- results of benchmark 4-23f (step 6.3) (section 4.23) for method B with stage 3 selected.

4.24.2 D-SHEET PILING results

D-SHEET PILING results are obtained using the *Design Sheet Piling Length* tab and selecting a sheet piling length of 14 m.

Table 4.53: *Results of benchmark 4-24 – Method A*

Class	**Result for stage 3**	**D-SHEET PILING "Verify" (step 6.3)**		**D-SHEET PILING "Design" (14 m length)**		**Error [%]**
RC1	Max. displac. [mm]	bm4-23a	180.83	bm4-24a	180.83	0.00
	Max. moment [kNm]		288.57		288.57	0.00
	Anchor force [kN]		37.82		37.82	0.00
	Mob. resistance [%]		34.30		34.30	0.00
RC2	Max. displac. [mm]	bm4-23b	180.83	bm4-24b	180.83	0.00
	Max. moment [kNm]		288.57		288.57	0.00
	Anchor force [kN]		37.82		37.82	0.00
	Mob. resistance [%]		34.30		34.30	0.00
RC3	Max. displac. [mm]	bm4-23c	180.83	bm4-24c	180.83	0.00
	Max. moment [kNm]		288.57		288.57	0.00
	Anchor force [kN]		37.82		37.82	0.00
	Mob. resistance [%]		34.30		34.30	0.00

Table 4.54: *Results of benchmark 4-24 – Method B*

Stage	**Results**	**D-SHEET PILING "Verify" (step 6.3)**		**D-SHEET PILING "Design" (14 m length)**		**Error [%]**
1	Max. displac. [mm]	bm4-23d	10.19	bm4-24d	10.19	0.00
	Max. moment [kNm]		18.34		18.34	0.00
	Anchor force [kN]		0.00		0.00	0.00
	Mob. resistance [%]		6.18		6.18	0.00
2	Max. displac. [mm]	bm4-23e	246.09	bm4-24e	246.09	0.00
	Max. moment [kNm]		465.89		465.89	0.00
	Anchor force [kN]		80.00		80.00	0.00
	Mob. resistance [%]		13.22		13.22	0.00
3	Max. moment [kNm]	bm4-23f	37.01	bm4-24f	37.01	0.00
	Mob. resistance [%]		223.81		223.81	0.00
	Max. displac. [mm]		37.74		37.74	0.00
	Anchor force [kN]		32.41		32.41	0.00

Use D-SHEET PILING input files bm4-24a.shi to bm4-24f.shi to run this benchmark.

4.25 Verify Sheet Piling calculation acc. Eurocode 7 – Belgian annex and method A

The verification is made using the same input as benchmark 4-17 (section 4.17). Two types of calculation results are compared for each sets of DA 1:

- a *Verification* calculation with EC7-B – method A using:
  - representative input values and partial safety factor for set 1 (bm4-25a);
  - representative input values and partial safety factor for set 2 (bm4-25b);
- a *Standard* calculation using:
  - design input values calculated using the partial safety factor of set 1 (bm4-25c);
  - design input values calculated using the partial safety factor of set 2 (bm4-25d);

The representative values of the loads, geometric levels and soil inputs are respectively given in Table 4.23, Table 4.24 and Table 4.25. The partial factors and level variations used are given in Figure 4.15.

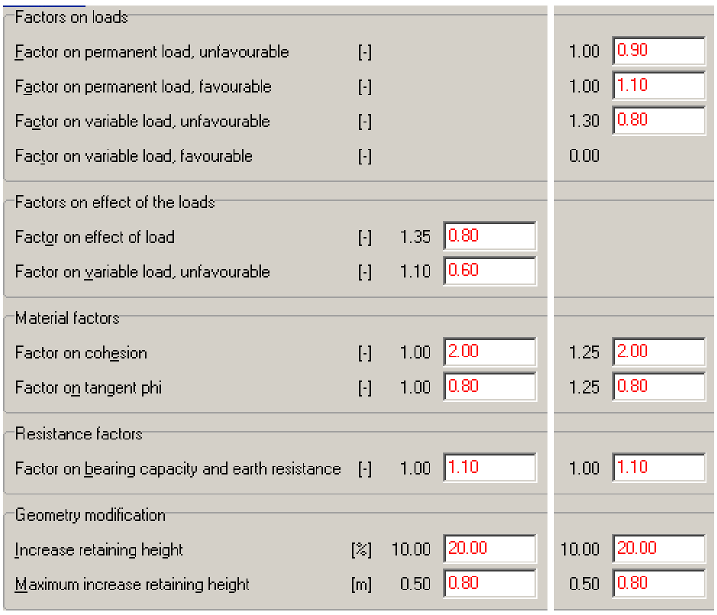


Figure 4.15: *Partial safety factors and geometry variations for the different design approaches (bm4-25)*

4.25.1 D-SHEET PILING results (standard calculation using design input values)

A standard calculation is performed using design input values determined by applying the partial factors of Figure 4.13. Results are given in Table 4.67, Table 4.68, Table 4.69 and Table 4.70 respectively for loads, materials and ground levels.

Table 4.55: *Design values for loads for set 1 (bm4-25c)*

Type of load			**Magnitude [kN/m^2]**		
			Stage 1	**Stage 2**	**Stage 3**
Uniform	Variable	Fav.			20
Uniform	Perm.	Unfav.	10	10	10
Surcharge	Variable	Unfav.	40 × 1.2 = 48	40 × 1.2 = 48	
Surcharge	Perm.	Fav.		60	60
Horiz. line	Perm.	Fav.			200
Horiz. line	Perm.	Unfav.			-100
Horiz. line	Variable	Fav.		150	
Horiz. line	Variable	Unfav.		-300 × 1.2 = -360	

Table 4.56: *Design values for loads for set 2 (bm4-25d)*

Type of load			**Magnitude [kN/m^2]**		
			Stage 1	**Stage 2**	**Stage 3**
Uniform	Variable	Fav.			20 × 0 = 0
Uniform	Perm.	Unfav.	10 × 0.9 = 9	10 × 0.9 = 9	10 × 0.9 = 9
Surcharge	Variable	Unfav.	40 × 0.8 = 32	40 × 0.8 = 32	
Surcharge	Perm.	Fav.		60 × 1.1 = 66	60 × 1.1 = 66
Horiz. line	Perm.	Fav.			200 × 1.1 = 220
Horiz. line	Perm.	Unfav.			-100 × 0.9 = -90
Horiz. line	Variable	Fav.		150 × 0 = 0	
Horiz. line	Variable	Unfav.		-300 × 0.8 = -240	

Table 4.57: *Design values for soil parameters (bm4-25)*

Parameter	**Unit**	**Clay**	**Peat**	**Sand 1**	**Sand 2**
Set 1 (bm4-25b):					
Cohesion	[kPa]	6.25	2.5	0	0
Friction angle	[°]	25.63	29.67	36.91	43.29
Delta friction angle	[°]	17.09	21.80	28.57	28.08
Set 2 (bm4-25c):					
Cohesion	[kPa]	6.25	2.5	0	0
Friction angle	[°]	25.63	29.67	36.91	43.29
Delta friction angle	[°]	17.09	21.80	28.57	28.08

Table 4.58: Design values for ground level at both sides (bm4-25)

Level [m NAP]	Stage 1	Stage 2	Stage 3
GL_{left}	-2	-2.1	-7.8
$GL_{left right}$	-0.4	0	0
$WL_{left left}$	-2	-2	-10
$WL_{left right}$	-2	-2	-2

Results of those different calculations are given in Table 4.59 and Table 4.61 for both sets.

4.25.2 D-SHEET PILING results (Eurocode verification calculation using representative input values)

D-SHEET PILING calculations are performed in the *Verify Sheet Piling* tab of the *Start Calculation* window selecting *EuroCode*. D-SHEET PILING results are found in the *Report* window. For design approaches DA 1 set 1 and DA 3, D-SHEET PILING multiplies the moments and the shear forces with the user-defined partial factor applied on the effect of the loads. Therefore, to compare the D-SHEET PILING and the benchmark results, the moments and the shear forces from the benchmark results are multiplied by 0.8 (see Table 4.44 and Table 4.45). Relative differences come from the number of decimals used for the input values limited to 2.

Table 4.59: Results of benchmark 4-25a – EC7-B method A, set 1

Stage	Result	D-SHEET PILING (Standard)		D-SHEET PILING (Verify)	Relative error
		(bm4-25c)	× 0.8	(bm4-25a)	[%]
1	Max. moment [kNm]	20.26	16.20	16.21	0.06
	Max. shear force [kN]	24.25	19.40	19.40	0.00
	Max. displac. [mm]	12.33		12.33	0.00
	Perc. mob. moment [%]	0.00		0.00	0.00
	Perc. mob. resist. [%]	6.40		6.40	0.00
2	Max. moment [kNm]	295.25.88	236.20	236.28	0.03
	Max. shear force [kN]	180.69	144.55	144.55	0.00
	Max. displac. [mm]	154.62		154.69	0.05
	Perc. mob. moment [%]	6.04		6.04	0.00
	Perc. mob. resist. [%]	10.05		10.05	0.00
	Anchor force [kN]	80.00	64.00	64.00	0.00
3	Max. moment [kNm]	234.69	187.75	187.79	0.02
	Max. shear force [kN]	194.33	155.47	155.47.55	0.00
	Max. displac. [mm]	100.03		100.09	0.06
	Perc. mob. moment [%]	42.99		43.00	0.02
	Perc. mob. resist. [%]	45.36		45.36	0.00
	Anchor force [kN]	57.99	46.39	46.39	0.00

Table 4.60: *Results of benchmark 4-25b – EC7-B method A, set 2*

Stage	Result	D-SHEET PILING (Standard)	D-Sheet Piling (Verify)	Relative error
		(bm4-25d)	(bm4-25b)	[%]
1	Max. moment [kNm]	21.21	21.22	0.05
	Max. shear force [kN]	25.37	25.37	0.00
	Max. displac. [mm]	13.34	13.34	0.00
	Perc. mob. moment [%]	0.00	0.00	0.00
	Perc. mob. resist. [%]	6.66	6.66	0.00
2	Max. moment [kNm]	467.26	467.20	0.01
	Max. shear force [kN]	240.19	240.19	0.00
	Max. displac. [mm]	259.89	259.76	0.05
	Perc. mob. moment [%]	6.63	6.63	0.00
	Perc. mob. resist. [%]	12.11	12.12	0.08
	Anchor force [kN]	80.00	80.00	0.00
3	Max. moment [kNm]	299.92	299.81	0.04
	Max. shear force [kN]	197.72	197.70	0.01
	Max. displac. [mm]	188.63	188.51	0.06
	Perc. mob. moment [%]	42.30	42.30	0.00
	Perc. mob. resist. [%]	44.93	44.94	0.02
	Anchor force [kN]	41.03	41.04	0.02

Table 4.61: *Results of benchmark 4-25b – EC7-B method A, set 2*

Stage	Result	D-SHEET PILING (Standard)	D-Sheet Piling (Verify)	Relative error
		(bm4-17h)	(bm4-25a/b)	[%]
1	Max. moment [kNm]	24.92	24.92	0.05
	Max. shear force [kN]	31.96	31.96	0.00
	Max. displac. [mm]	17.01	17.01	0.00
	Perc. mob. moment [%]	0.00	0.00	0.00
	Perc. mob. resist. [%]	14.46	14.46	0.00
2	Max. moment [kNm]	150.00	150.00	0.00
	Max. shear force [kN]	150.00	150.00	0.00
	Max. displac. [mm]	24.57	24.57	0.00
	Perc. mob. moment [%]	11.07	11.07	0.00
	Perc. mob. resist. [%]	14.91	14.91	0.00
	Anchor force [kN]	80.00	-	-
3	Max. moment [kNm]	216.56	216.56	0.00
	Max. shear force [kN]	153.80	153.80	0.00
	Max. displac. [mm]	35.64	35.64	0.00
	Perc. mob. moment [%]	25.75	25.75	0.00
	Perc. mob. resist. [%]	28.15	28.15	0.00
	Anchor force [kN]	41.03	-	-

Use D-SHEET PILING input files bm4-25a.shi to bm4-25d.shi to run this benchmark.

4.26 Design Sheet Piling Length acc. Eurocode 7 – Belgian annex and method A

4.26.1 Description

The same problem as benchmark 4-25 (section 4.25) is considered. For the *Design Sheet Piling Length* option, D-SHEET PILING applies the same partial factors and geometric variations as for the *Verify Sheet Piling* option. Therefore, the results of the *Design Sheet Piling Length* calculation (for a length of 14 m) should be the same as the results of benchmark 4-25 (section 4.25).

4.26.2 D-SHEET PILING results

D-SHEET PILING results are obtained using the *Design Sheet Piling Length* tab and selecting a sheet piling length of 14 m.

Table 4.62: *Results of benchmark 4-26 – EC7-B method A, stage 3*

DA	**Results for stage 3**	**D-SHEET PILING "Verify"**		**D-SHEET PILING "Design" (length = 14 m)**		**Rel. error [%]**
set 1	Max. displac. [mm]	bm4-25a	100.09	bm4-26a	100.09	0.00
	Max. moment [kNm]		187.79		187.79	0.00
	Anchor force [kN]		46.39		46.39	0.00
	Mob. resistance [%]		45.36		45.36	0.00
set 2	Max. displac. [mm]	bm4-25b	188.81	bm4-26b	188.51	0.00
	Max. moment [kNm]		299.81		299.81	0.00
	Anchor force [kN]		41.04		41.04	0.00
	Mob. resistance [%]		44.94		44.94	0.00

Use D-SHEET PILING input files bm4-26a.shi and bm4-26b.shi to run this benchmark.

4.27 Verify Sheet Piling calculation acc. Eurocode 7 – Belgian annex and method B (only last stage verified)

4.27.1 Description

The verification is made using the same input as benchmark 4-17 (section 4.17). Two types of calculation results are compared for each sets of DA 1:

- a *Verification* calculation with EC7-B – method A using:
  - representative input values and partial safety factor for set 1 (bm4-27a);
  - representative input values and partial safety factor for set 2 (bm4-27b);
- a *Standard* calculation using:
  - representative input values for stages 1 and 2 and design input values calculated using the partial safety factor of set 1 for stage 3 (bm4-27c);
  - representative input values for stages 1 and 2 and design input values calculated using the partial safety factor of set 2 for stage 3 (bm4-27d);

4.27.2 D-SHEET PILING results

D-SHEET PILING calculations are performed in the *Verify Sheet Piling* tab of the *Start Calculation* window selecting *EC7-B*. D-SHEET PILING results are found in the *Report* window. For design approaches DA 1 set 1, D-SHEET PILING multiplies the moments and the shear forces with the user-defined partial factor applied on the effect of the loads. Therefore, to compare the D-SHEET PILING and the benchmark results, the moments and the shear forces from the benchmark results are multiplied by 0.8. Relative differences come from the number of decimals used for the input values limited to 2.

Table 4.63: *Results of benchmark 4-27a – EC7-B method B (only last stage verified), set 1*

Stage	Result	D-SHEET PILING (Standard)		D-SHEET PILING (Verify)	Relative error
		(bm4-27c)	$\times$ 0.8	(bm4-27a)	[%]
3	Max. moment [kNm]	286.88	229.51	229.35	0.07
	Max. shear force [kN]	184.39	147.52	147.53	0.01
	Max. displac. [mm]	55.13		55.22	0.16
	Perc. mob. moment [%]	41.91		41.92	0.02
	Perc. mob. resist. [%]	43.67		43.68	0.02
	Anchor force [kN]	49.50	39.60	39.61	0.03

Table 4.64: *Results of benchmark 4-27b – EC7-B method B (only last stage verified), set 2*

Stage	Result	D-SHEET PILING (Standard)	D-Sheet Piling (Verify)	Relative error
		(bm4-27d)	(bm4-27b)	[%]
3	Max. moment [kNm]	271.10	270.93	0.06
	Max. shear force [kN]	176.67	176.71	0.02
	Max. displac. [mm]	50.68	50.77	0.18
	Perc. mob. moment [%]	40.07	40.08	0.02
	Perc. mob. resist. [%]	41.58	41.59	0.02
	Anchor force [kN]	37.55	37.56	0.03

Table 4.65: *Results of benchmark 4-27b – EC7-B method B (only last stage verified), Deformation*

Stage	Result	D-SHEET PILING (Standard)	D-Sheet Piling (Verify)	Relative error
		(bm4-17h)	(bm4-27a/b)	[%]
3	Max. moment [kNm]	216.56	216.56	0.00
	Max. shear force [kN]	153.80	153.80	0.00
	Max. displac. [mm]	35.64	35.64	0.00
	Perc. mob. moment [%]	25.75	25.75	0.00
	Perc. mob. resist. [%]	28.15	28.15	0.00
	Anchor force [kN]	32.12	-	-

Use D-SHEET PILING input files bm4-27a.shi to bm4-27d.shi to run this benchmark.

4.28 Design Sheet Piling Length acc. Eurocode 7 – Belgian annex and method B (only last stage verified)

4.28.1 Description

The same problem as benchmark 4-27 (section 4.27) is considered. For the *Design Sheet Piling Length* option, D-SHEET PILING applies the same partial factors and geometric variations as for the *Verify Sheet Piling* option. Therefore, the results of the Design Sheet Piling Length calculation (for a length of 14 m) should be the same as the results of benchmark 4-25 (section 4.27).

4.28.2 D-SHEET PILING results

D-SHEET PILING results are obtained using the *Design Sheet Piling Length* tab and selecting a sheet piling length of 14 m.

Table 4.66: *Results of benchmark 4-28 – EC7-B method B, stage 3*

DA	Results for stage 3	D-SHEET PILING "Verify"		D-SHEET PILING "Design" (length = 14 m)		Rel. error [%]
set 1	Max. displac. [mm]	bm4-27a	55.22	bm4-28a	55.22	0.00
	Max. moment [kNm]		229.35		229.35	0.00
	Anchor force [kN]		39.61		39.61	0.00
	Mob. resistance [%]		43.68		43.68	0.00
set 2	Max. displac. [mm]	bm4-27b	50.77	bm4-28b	50.77	0.00
	Max. moment [kNm]		270.93		270.93	0.00
	Anchor force [kN]		37.56		37.56	0.00
	Mob. resistance [%]		41.59		41.59	0.00

4.29 Total settlement by vibration

4.29.1 Description

For this benchmark, the D-SHEET PILING results of benchmark 5-6 (section 5.6) during the installation of the sheet piling are used to deduce the settlements during removal of the sheet piling and during "installation + removal" using the following formulas:

$$\Delta z\left(r\right) = 0.2 \times \Delta z_{\text{densification}}\left(r\right) + \Delta z_{\text{sheet volume}}\left(r\right) \text{ during removal} \tag{4.8}$$

$$\Delta z\left(r\right) = 1.2 \times \Delta z_{\text{densification}}\left(r\right) \text{ during installation and removal} \tag{4.9}$$

4.29.2 Benchmark results

The benchmark results are given in the tables below using the above formulas.

Table 4.67: *Total settlements during removal of sheet piling deduced from the settlements during installation calculated with* D-SHEET PILING

Distance to sheet pile	**During installation (D-SHEET PILING)**		**During removal**
	$\Delta z_{densification}$	$-\Delta z_{sheetvolume}$	Total settlements $\Delta z = 0.2 \times \Delta z_{densification} + \Delta z_{sheetvolume}$
[m]	[mm]	[mm]	[mm]
0.191	-197.67	58.28	0.2 x (-197.67) - 58.28 = -97.814
0.627	-149.16	46.73	0.2 x (-149.16) - 46.73 = -76.562
1.118	-126.77	34.86	0.2 x (-126.77) - 34.86 = -60.214
1.608	-109.19	27.86	0.2 x (-109.19) - 27.86 = -49.698
2.099	-91.99	25.19	0.2 x (-91.99) - 25.19 = -43.588
2.589	-79.44	20.85	0.2 x (-79.44) - 20.85 = -36.738
3.079	-69.12	17.37	0.2 x (-69.12) - 17.37 = -31.194
3.57	-57.91	15.87	0.2 x (-57.91) - 15.87 = -27.452
4.06	-49.41	13.20	0.2 x (-49.41) - 13.2 = -23.082
4.551	-41.15	10.89	0.2 x (-41.15) - 10.89 = -19.12
5.041	-33.66	9.84	0.2 x (-33.66) - 9.84 = -16.572
5.532	-26.98	7.91	0.2 x (-26.98) - 7.91 = -13.306
6.022	-21.17	6.18	0.2 x (-21.17) - 6.18 = -10.414
6.513	-16.39	4.60	0.2 x (-16.39) - 4.6 = -7.878
7.003	-11.46	3.86	0.2 x (-11.46) - 3.86 = -6.152
7.494	-7.49	2.48	0.2 x (-7.49) - 2.48 = -3.978
7.984	-4.46	1.19	0.2 x (-4.46) - 1.19 = -2.082
8.474	-1.58	0.59	0.2 x (-1.58) - 0.59 = -0.906
8.965	-0.42	0.00	0.2 x (-0.42) - 0 = -0.084
9.455	-0.08	0.00	0.2 x (-0.08) - 0 = -0.016
9.946	0.00	0.00	0.2 x (0) - 0 = 0
10.436	0.00	0.00	0.2 x (0) - 0 = 0

Table 4.68: Total settlements during removal of sheet piling deduced from the settlements during installation calculated with D-SHEET PILING

Distance to sheet pile	**During installation (D-SHEET PILING)**	**During installation and removal**
	$\Delta z_{densification}$	Total settlements: $\Delta z = 1.2 \times \Delta z_{densification}$
[m]	[mm]	[mm]
0.191	-197.67	1.2 × (-197.67) = -237.204
0.627	-149.16	1.2 × (-149.16) = -178.992
1.118	-126.77	1.2 × (-126.77) = -152.124
1.608	-109.19	1.2 × (-109.19) = -131.028
2.099	-91.99	1.2 × (-91.99) = -110.388
2.589	-79.44	1.2 × (-79.44) = -95.328
3.079	-69.12	1.2 × (-69.12) = -82.944
3.57	-57.91	1.2 × (-57.91) = -69.492
4.06	-49.41	1.2 × (-49.41) = -59.292
4.551	-41.15	1.2 × (-41.15) = -49.38
5.041	-33.66	1.2 × (-33.66) = -40.392
5.532	-26.98	1.2 × (-26.98) = -32.376
6.022	-21.17	1.2 × (-21.17) = -25.404
6.513	-16.39	1.2 × (-16.39) = -19.668
7.003	-11.46	1.2 × (-11.46) = -13.752
7.494	-7.49	1.2 × (-7.49) = -8.988
7.984	-4.46	1.2 × (-4.46) = -5.352
8.474	-1.58	1.2 × (-1.58) = -1.896
8.965	-0.42	1.2 × (-0.42) = -0.504
9.455	-0.08	1.2 × (-0.08) = -0.096
9.946	0.00	1.2 × 0 = 0
10.436	0.00	1.2 × 0 = 0

4.29.3 D-SHEET PILING results

The D-SHEET PILING results are compared in the tables below. Correlation is excellent.

Table 4.69: *Results of benchmark 4-25 – Total settlements during removal*

Distance to sheet pile	**Benchmark**	**D-SHEET PILING**	**Relative error**
[m]	[mm]	[mm]	[%]
0.191	-97.81	-97.81	0.00
0.627	-76.56	-76.56	0.00
1.118	-60.21	-60.21	0.00
1.608	-49.70	-49.70	0.00
2.099	-43.59	-43.59	0.00
2.589	-36.74	-36.74	0.00
3.079	-31.19	-31.19	0.00
3.57	-27.45	-27.45	0.00
4.06	-23.08	-23.08	0.00
4.551	-19.12	-19.12	0.00
5.041	-16.57	-16.57	0.00
5.532	-13.31	-13.31	0.00
6.022	-10.41	-10.41	0.00
6.513	-7.88	-7.88	0.00
7.003	-6.15	-6.15	0.00
7.494	-3.98	-3.98	0.00
7.984	-2.08	-2.08	0.00
8.474	-0.91	-0.91	0.00
8.965	-0.08	-0.08	0.00
9.455	-0.02	-0.02	0.00
9.946	0.00	0.00	0.00
10.436	0.00	0.00	0.00

Table 4.70: Results of benchmark 4-25 – Total settlements during installation and removal

Distance to sheet pile	Benchmark	D-SHEET PILING	Relative error
[m]	[mm]	[mm]	[%]
0.191	-237.20	-237.20	0.00
0.627	-178.99	-178.99	0.00
1.118	-152.12	-152.12	0.00
1.608	-131.03	-131.03	0.00
2.099	-110.39	-110.39	0.00
2.589	-95.33	-95.33	0.00
3.079	-82.94	-82.94	0.00
3.57	-69.49	-69.49	0.00
4.06	-59.29	-59.29	0.00
4.551	-49.38	-49.38	0.00
5.041	-40.39	-40.39	0.00
5.532	-32.38	-32.38	0.00
6.022	-25.40	-25.40	0.00
6.513	-19.67	-19.67	0.00
7.003	-13.75	-13.75	0.00
7.494	-8.99	-8.99	0.00
7.984	-5.35	-5.35	0.00
8.474	-1.90	-1.90	0.00
8.965	-0.50	-0.50	0.00
9.455	-0.10	-0.10	0.00
9.946	0.00	0.00	0.00
10.436	0.00	0.00	0.00

Use D-SHEET PILING input file bm4-25.shi to run this benchmark.

4.30 Elasto-plastic behaviour of a single pile loaded by soil displacements

4.30.1 Description

For this benchmark, the same input as Tutorial 19 of the User Manual of D-SHEET PILING is used (Figure 4.16) except that the bottom level of the top section is at -5 m instead of -2.05 m.

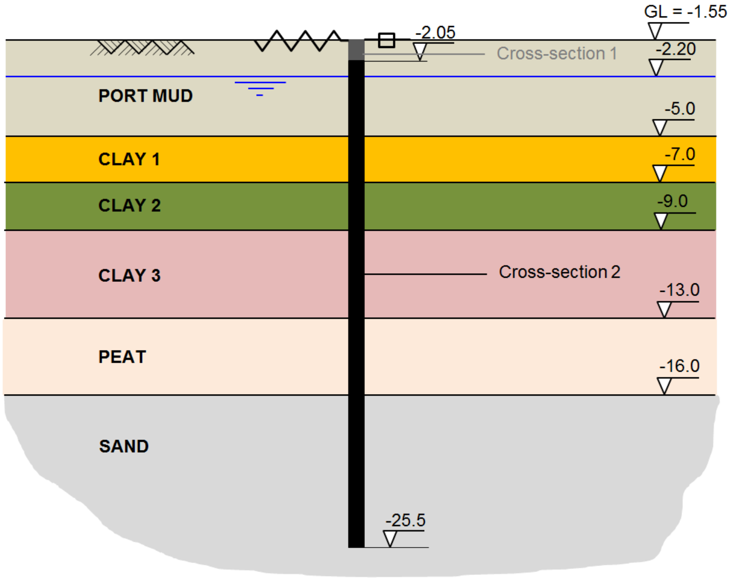


Figure 4.16: *Geometry of bm4-30*

The M-N-Kappa diagram of both sections is shown in Figure 4.17.

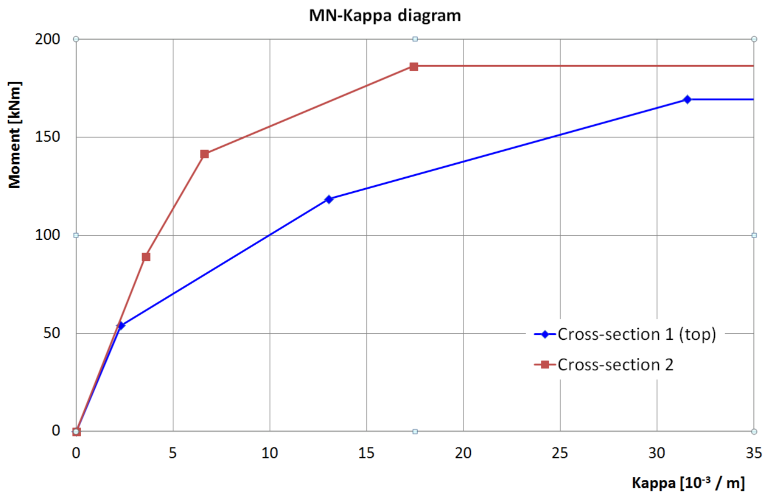


Figure 4.17: *M-N-Kappa diagrams of both sections of bm4-30*

Different calculations are performed:

- **Case A (bm4-30a) – Elasto-plastic calculation with the *Plastic* module, for which plasticity is not reached:**
  a *Plastic* calculation is performed using:
  - a Plastic moment equal to the moment of the 2nd point (i.e. xxx kNm for section 1);
  - a Plastic moment equal to the moment of the 2nd point (i.e. xxx kNm for section 2);
- **Case B (bm4-30b) – Elastic calculation:**
  an *Elastic* calculation is performed using only the elastic flexural stiffness; the calculated moments in case B (elastic) are expected to be much more larger than the calculated moments in case A (elasto-plastic);
- **Case C (bm4-30c) – Elasto-plastic calculation with manual input of the adapted flex-**

ural stiffness:
an *Elastic* calculation is performed using several pile sections with an adapted flexural stiffness deduced from the calculated Moment chart of the Plastic calculation (bm4-30a); the calculated moments in case C are expected to be close to the calculated moments in case A (elasto-plastic);

◇ **Case D (bm4-30d) – Elasto-plastic calculation with the *Plastic* module, for which plasticity is reached:**
a *Plastic* calculation is performed using the Plastic moments given in Figure 4.17; the calculated moments in case D are expected to reach the Plastic moment for some points along the pile without exceeding it;

◇ **Case E (bm4-30e) – Elastic calculation with the *Plastic* module:**
a *Plastic* calculation is performed using the elastic stiffness for all the branches of the M-N-Kappa diagram; the calculated moments in case E are expected to be equal to the calculated moments in case B.

4.30.2 D-SHEET PILING results

The results of bm4-30a are shown in Figure 4.22. The calculated moments in bm4-30a are used to deduce the manual inputted flexural stiffness used in bm4-30c by dividing the pile into 20 sections and by calculating an average flexural stiffness for each section. The values of the calculated moments and the deduced flexural stiffness are given in Table 4.71. Figure 4.22 shows the effect of a plastic calculation compare to an elastic calculation and shows that an elastic calculation (bm4-30b) and a plastic calculation with an elastic behaviour (bm4-30e) give the same results, so as expected.

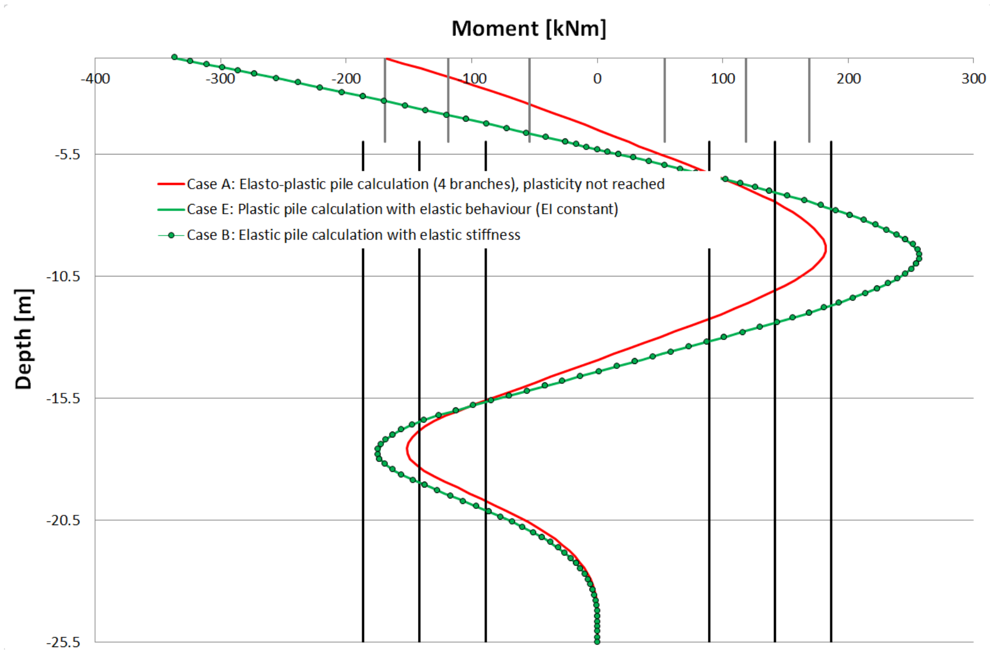


Figure 4.18: *Comparison of the results of benchmarks bm4-30a, bm4-30b and bm4-30e*

Table 4.71: *Moments calculated for benchmark 4-30a and input values of EI for benchmark 4-30c*

Level [m]	Calculated moment (bm4-30a) [kNm]	Branch of the M-N-Kappa diagram	Corresponding EI per point acc. to M-N-Kappa diagram [kNm^2]	Average EI per section [kNm^2]

-1.55	-169.2	Section 1 - Branch 3	5361.57	
-1.77	-154.79	Section 1 - Branch 3	6419.048	
-1.98	-140.57	Section 1 - Branch 3	7462.582	6403.347
-2.2	-126.71	Section 1 - Branch 3	8479.698	
-2.33	-118.5	Section 1 - Branch 3	9082.189	8272.778
-2.43	-112.25	Section 1 - Branch 2	10481.396	
-2.67	-98.24	Section 1 - Branch 2	13617.857	
-2.9	-84.67	Section 1 - Branch 2	16655.814	12900.693
-3.13	-71.48	Section 1 - Branch 2	19608.699	
-3.37	-58.65	Section 1 - Branch 2	22480.99	
-3.46	-54	Section 1 - Branch 2	23522	20139.325
-3.6	-46.12	Section 1 - Branch 1	23522	
-3.83	-33.86	Section 1 - Branch 1	23522	
-4.07	-21.82	Section 1 - Branch 1	23522	
-4.3	-9.95	Section 1 - Branch 1	23522	
-4.53	1.8	Section 1 - Branch 1	23522	
-4.77	13.47	Section 1 - Branch 1	23522	
-5	25.12	Section 1 - Branch 1	23522	23522
-5.17	33.44	Section 2 - Branch 1	24929	
-5.33	41.78	Section 2 - Branch 1	24929	
-5.5	50.13	Section 2 - Branch 1	24929	
-5.71	60.91	Section 2 - Branch 1	24929	
-5.93	71.68	Section 2 - Branch 1	24929	
-6.14	82.37	Section 2 - Branch 1	24929	
-6.28	89.1	Section 2 - Branch 2	24929	24835.591
-6.36	92.92	Section 2 - Branch 2	24667.911	
-6.57	103.26	Section 2 - Branch 2	23961.195	
-6.79	113.33	Section 2 - Branch 2	23272.932	24089.107
-7	123.06	Section 2 - Branch 2	22607.908	
-7.22	132.52	Section 2 - Branch 2	21961.337	
-7.44	141.15	Section 2 - Branch 2	21371.496	
-7.45	141.6	Section 2 - Branch 3	21340.739	22268.698
-7.67	148.98	Section 2 - Branch 3	19581.545	
-7.89	156.02	Section 2 - Branch 3	17903.399	
-8.11	162.3	Section 2 - Branch 3	16406.415	
-8.33	167.84	Section 2 - Branch 3	15085.828	18017.223
-8.56	172.65	Section 2 - Branch 3	13939.253	
-8.78	176.74	Section 2 - Branch 3	12964.307	
-9	180.11	Section 2 - Branch 3	12160.99	
-9.24	182.13	Section 2 - Branch 3	11679.476	13101.005
-9.47	182.01	Section 2 - Branch 3	11708.081	
-9.71	180.02	Section 2 - Branch 3	12182.443	
-9.94	176.41	Section 2 - Branch 3	13042.97	
-10.18	171.39	Section 2 - Branch 3	14239.604	12480.067
-10.41	165.15	Section 2 - Branch 3	15727.052	
-10.65	157.84	Section 2 - Branch 3	17469.56	
-10.88	149.62	Section 2 - Branch 3	19428.987	
-11.09	141.6	Section 2 - Branch 3	21340.739	17542.369
-11.12	140.6	Section 2 - Branch 2	21409.087	
-11.35	130.88	Section 2 - Branch 2	22073.428	
-11.59	120.58	Section 2 - Branch 2	22777.41	22052.27
-11.82	109.75	Section 2 - Branch 2	23517.617	
-12.06	98.48	Section 2 - Branch 2	24287.897	

-12.25	89.1	Section 2 - Branch 2	24929	23837.279
-12.29	86.84	Section 2 - Branch 1	24929	
-12.53	74.88	Section 2 - Branch 1	24929	
-12.76	62.65	Section 2 - Branch 1	24929	
-13	50.2	Section 2 - Branch 1	24929	
-13.23	37.89	Section 2 - Branch 1	24929	
-13.46	25.55	Section 2 - Branch 1	24929	
-13.69	13.19	Section 2 - Branch 1	24929	
-13.92	0.82	Section 2 - Branch 1	24929	
-14.15	-11.55	Section 2 - Branch 1	24929	
-14.38	-23.93	Section 2 - Branch 1	24929	
-14.62	-36.3	Section 2 - Branch 1	24929	
-14.85	-48.66	Section 2 - Branch 1	24929	
-15.08	-61	Section 2 - Branch 1	24929	
-15.31	-73.32	Section 2 - Branch 1	24929	
-15.54	-85.61	Section 2 - Branch 1	24929	
-15.61	-89.1	Section 2 - Branch 2	24929	24929
-15.77	-97.86	Section 2 - Branch 2	24330.273	
-16	-110.06	Section 2 - Branch 2	23496.43	
-16.22	-120.83	Section 2 - Branch 2	22760.324	
-16.44	-129.82	Section 2 - Branch 2	22145.877	
-16.67	-137.19	Section 2 - Branch 2	21642.153	
-16.84	-141.6	Section 2 - Branch 3	21340.739	22903.654
-16.89	-143.04	Section 2 - Branch 3	20997.482	
-17.11	-147.42	Section 2 - Branch 3	19953.408	
-17.33	-150.31	Section 2 - Branch 3	19264.509	
-17.56	-151.65	Section 2 - Branch 3	18945.089	19828.744
-17.78	-151.3	Section 2 - Branch 3	19028.52	
-18	-149.02	Section 2 - Branch 3	19572.011	
-18.23	-144.38	Section 2 - Branch 3	20678.062	
-18.33	-141.6	Section 2 - Branch 3	21340.739	19682.777
-18.47	-137.85	Section 2 - Branch 2	21597.044	
-18.7	-129.93	Section 2 - Branch 2	22138.358	
-18.94	-121.04	Section 2 - Branch 2	22745.97	
-19.17	-111.54	Section 2 - Branch 2	23395.275	
-19.41	-101.73	Section 2 - Branch 2	24065.767	
-19.64	-91.85	Section 2 - Branch 2	24741.043	
-19.71	-89.1	Section 2 - Branch 2	24929	23024.252
-19.88	-82.11	Section 2 - Branch 1	24929	
-20.11	-72.67	Section 2 - Branch 1	24929	
-20.34	-63.66	Section 2 - Branch 1	24929	
-20.58	-55.18	Section 2 - Branch 1	24929	
-20.81	-47.29	Section 2 - Branch 1	24929	
-21.05	-40.04	Section 2 - Branch 1	24929	
-21.28	-33.46	Section 2 - Branch 1	24929	
-21.52	-27.55	Section 2 - Branch 1	24929	
-21.75	-22.32	Section 2 - Branch 1	24929	
-21.98	-17.75	Section 2 - Branch 1	24929	
-22.22	-13.8	Section 2 - Branch 1	24929	
-22.45	-10.46	Section 2 - Branch 1	24929	
-22.69	-7.67	Section 2 - Branch 1	24929	
-22.92	-5.4	Section 2 - Branch 1	24929	
-23.16	-3.59	Section 2 - Branch 1	24929	

-23.39	-2.2	Section 2 - Branch 1	24929	
-23.63	-1.18	Section 2 - Branch 1	24929	
-23.86	-0.48	Section 2 - Branch 1	24929	
-24.09	-0.04	Section 2 - Branch 1	24929	
-24.33	0.19	Section 2 - Branch 1	24929	
-24.56	0.26	Section 2 - Branch 1	24929	
-24.8	0.23	Section 2 - Branch 1	24929	
-25.03	0.14	Section 2 - Branch 1	24929	
-25.27	0.04	Section 2 - Branch 1	24929	
-25.5	0	Section 2 - Branch 1	24929	24929

Figure 4.23 shows that a calculation with the *Plastic* module (bm4-30a) and a calculation with the *Elastic* module with adapted stiffness *EI* (bm4-30c) give very close results, so as expected, allowing to conclude that the *Plastic* module with *Single Pile* is working correctly.

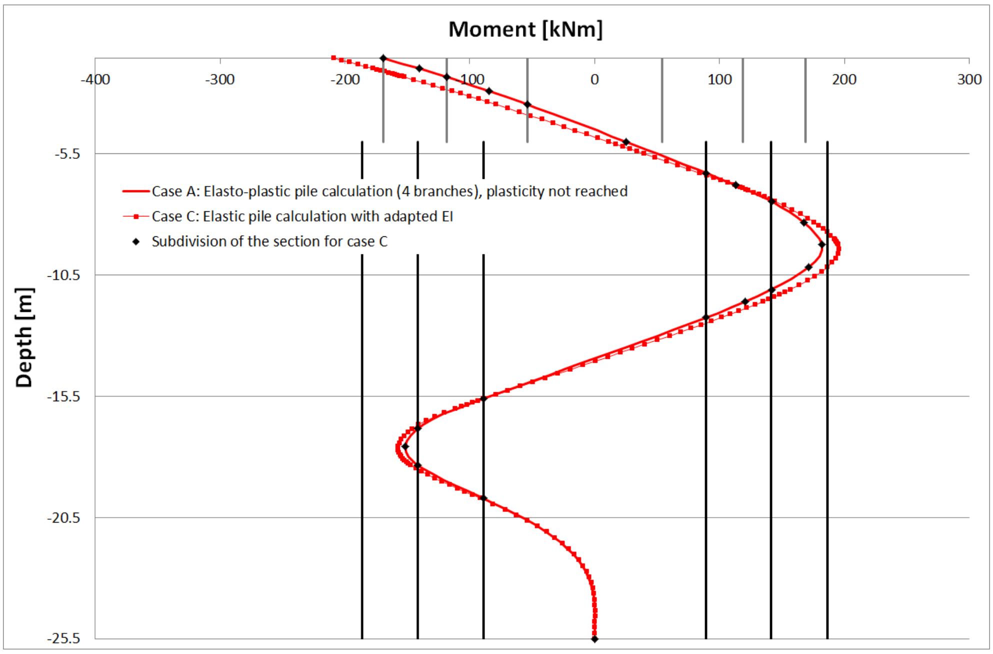


Figure 4.19: *Comparison of the results of benchmarks bm4-30a and bm4-30c*

So as expected, the moment chart of benchmark 4-30d (Figure 4.24) shows that the moment is limited by the plastic moment.

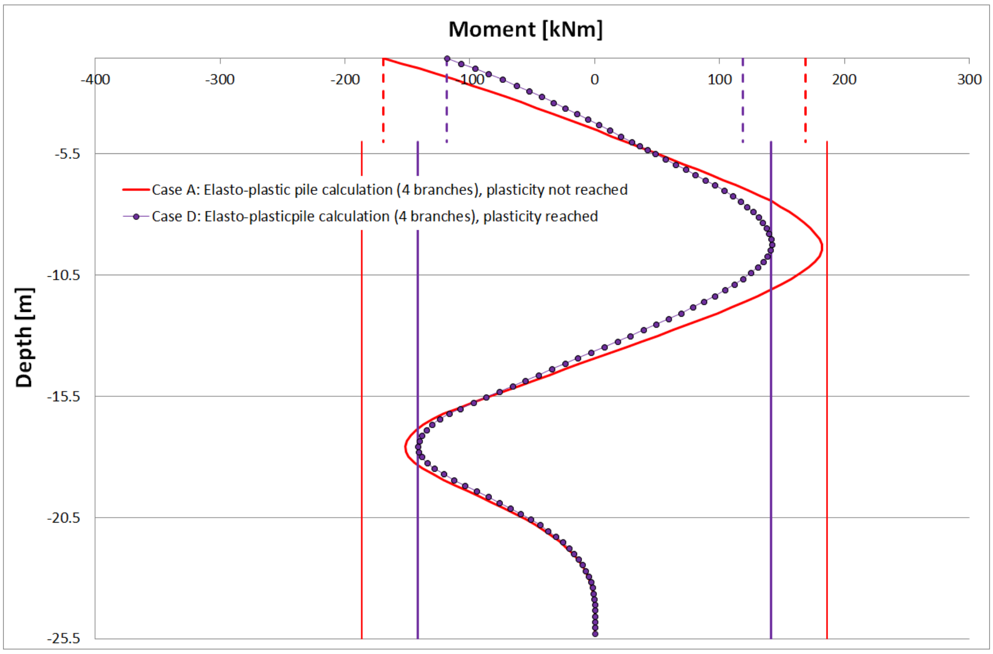


Figure 4.20: *Comparison of the results of benchmarks bm4-30a and bm4-30d*

Use D-SHEET PILING input file bm4-30a.shi until bm4-30f.shi to run this benchmark.

4.31 Elasto-plastic behaviour of a diaphragm wall

4.31.1 Description

For this benchmark, the same soil profile as benchmark 4-30 is used (Figure 4.21). At the right side, the soil is excavated until level

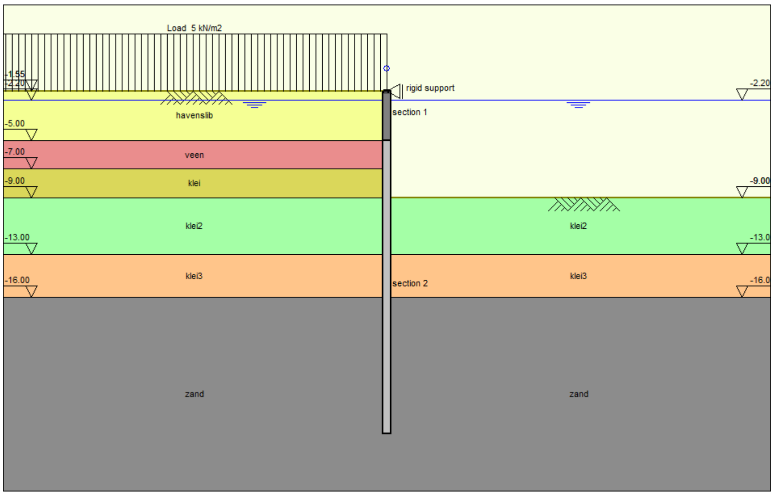


Figure 4.21: *Geometry of bm4-31*

Different calculations are performed:

◇ **Case A (bm4-31a) – Elasto-plastic calculation with the *Plastic* module, for which plasticity is not reached:**
a *Plastic* calculation is performed using:

- a Plastic moment equal to the moment of the 2nd point (i.e. xxx kNm for section 1);
- a Plastic moment equal to the moment of the 2nd point (i.e. xxx kNm for section 2);

◇ **Case B (bm4-31b) – Elastic calculation:**
an *Elastic* calculation is performed using only the elastic flexural stiffness; the calculated moments in case B (elastic) are expected to be much more larger than the calculated moments in case A (elasto-plastic);

◇ **Case C (bm4-31c) – Elasto-plastic calculation with manual input of the adapted flexural stiffness:**
an *Elastic* calculation is performed using several pile sections with an adapted flexural stiffness deduced from the calculated Moment chart of the Plastic calculation (bm4-30a); the calculated moments in case C are expected to be close to the calculated moments in case A (elasto-plastic);

◇ **Case D (bm4-31d) – Elasto-plastic calculation with the *Plastic* module, for which plasticity is reached:**
a *Plastic* calculation is performed using the Plastic moments given in Figure 4.17; the calculated moments in case D are expected to reach the Plastic moment for some points along the pile without exceeding it;

◇ **Case E (bm4-31e) – Elastic calculation with the *Plastic* module:**
a *Plastic* calculation is performed using the elastic stiffness for all the branches of the M-N-Kappa diagram; the calculated moments in case E are expected to be equal to the calculated moments in case B.

4.31.2 D-Sheet Piling results

The results of bm4-31a are shown in Figure 4.22. The calculated moments in bm4-30a are used to deduce the manual inputted flexural stiffness used in bm4-30c by dividing the pile into 20 sections and by calculating an average flexural stiffness for each section.

Figure 4.22 shows the effect of a plastic calculation compare to an elastic calculation and shows that an elastic calculation (bm4-30b) and a plastic calculation with an elastic behaviour (bm4-30e) give the same results, so as expected.

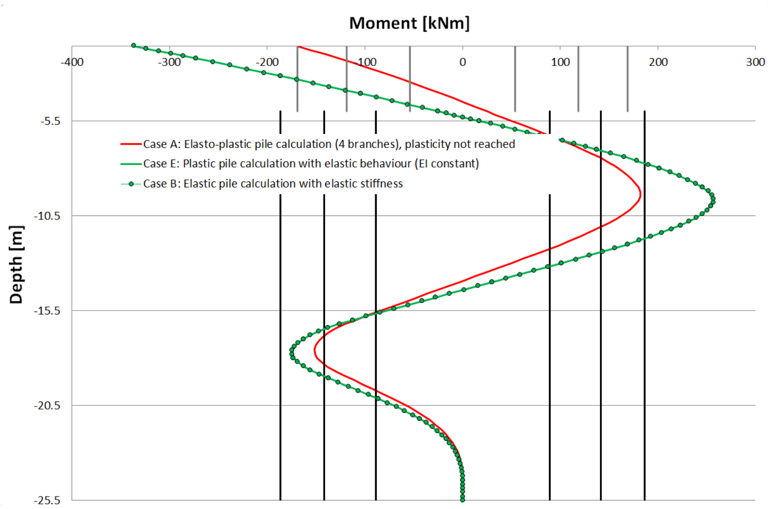


Figure 4.22: *Comparison of the results of benchmarks bm4-31a, bm4-31b and bm4-31e*

Figure 4.23 shows that a calculation with the *Plastic* module (bm4-30a) and a calculation with the *Elastic* module with adapted stiffness *EI* (bm4-30c) give very close results, so as expected, allowing to conclude that the *Plastic* module with *Single Pile* is working correctly.

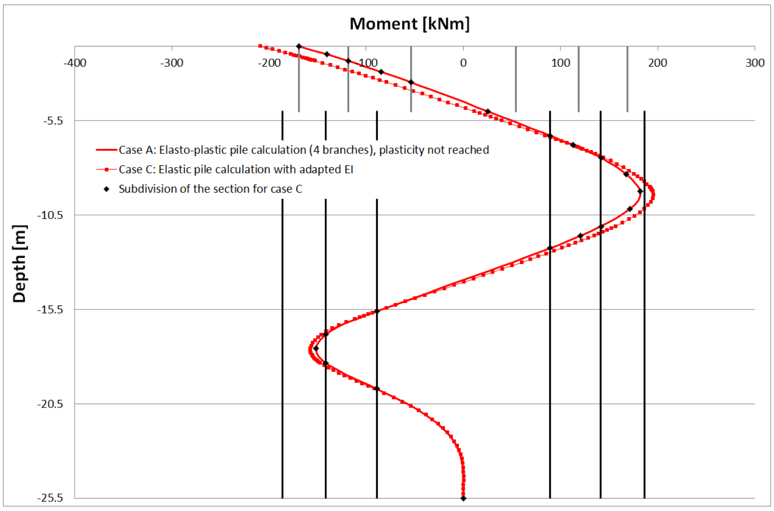


Figure 4.23: *Comparison of the results of benchmarks bm4-31a, bm4-31b and bm4-31c*

So as expected, the moment chart of benchmark 4-31d (Figure 4.24) shows that the moment is limited by the plastic moment.

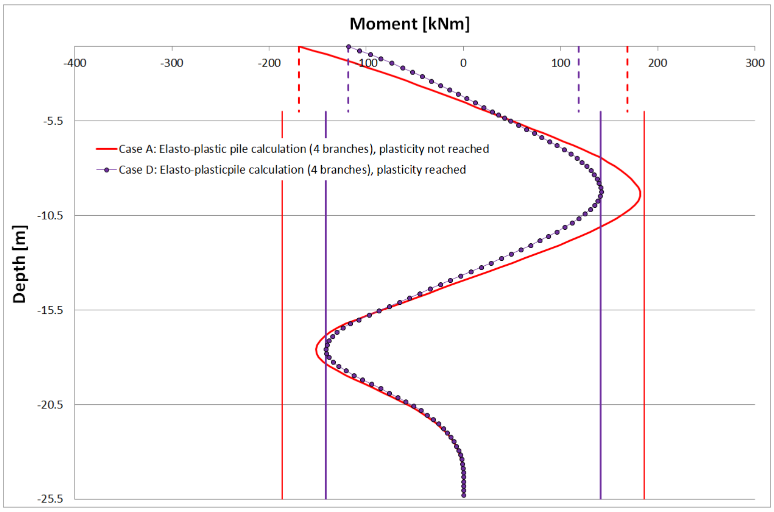


Figure 4.24: *Comparison of the results of benchmarks bm4-31a and bm4-31d*

Use D-SHEET PILING input file bm4-31a.shi until bm4-31e.shi to run this benchmark.

4.32 Functioning of the reduction factor on the stiffness

4.32.1 Description

To check that the reduction factor on *EI* is correctly applied, different calculations are compared:

◇ an Elastic Sheet Piling calculation (same input as Tutorial 1) with the following input is performed and should gives the same output:
  - Case A (bm4-32a): EI = 41370 kNm^2/m and f_{EI} = 0.6;
    the corrected stiffness is then EI_{corr} = 24822 kNm^2/m
  - Case B (bm4-32b): EI = 24822 kNm^2/m and f_{EI} = 1;

◇ an Plastic Sheet Piling calculation with a plastic moment of 160 kNm/m (same input as Tutorial 1) with the following input is performed and should gives the same output:

- Case C (bm4-32c): EI = 41370 kNm^2/m and f_{EI} = 0.6;
  the corrected stiffness is then EI_{corr} = 24822 kNm^2/m
- Case D (bm4-32d): EI = 24822 kNm^2/m and f_{EI} = 1;

4.32.2 D-SHEET PILING results

Table 4.72: *Results of benchmark 4-32 – Elastic Sheet Piling*

Result	**D-SHEET PILING (bm4-32a)**	**D-SHEET PILING (bm4-32b)**	**Error [%]**
Stiffness [kNm^2/m]	41370	24822	-
Reduction factor on EI [-]	0.6	1	-
Corrected stiffness [kNm^2/m]	24822	24822	0.00
Max. displac. [mm]	288.8	288.8	0.00
Max. moment [kNm]	158.73	158.73	0.00
Max. shear force [kN]	53.65	53.65	0.00
Perc. mob. resist. [%]	22.2	22.2	0.00

Table 4.73: *Results of benchmark 4-32 – Plastic Sheet Piling*

Result	**D-SHEET PILING (bm4-32c)**	**D-SHEET PILING (bm4-32d)**	**Error [%]**
Stiffness [kNm^2/m]	41370	24822	-
Reduction factor on EI [-]	0.6	1	-
Corrected stiffness [kNm^2/m]	24822	24822	0.00
Max. displac. [mm]	294.3	294.3	0.00
Max. moment [kNm]	159.79	159.79	0.00
Max. shear force [kN]	53.70	53.70	0.00
Perc. mob. resist. [%]	22.3	22.3	0.00

Use D-SHEET PILING input file bm4-32a.shi until bm4-32d.shi to run this benchmark.

5 Group 5: Benchmarks compared with other programs

This chapter contains benchmarks for which the results of D-SHEET PILING are compared with the results of other programs.

5.1 Overall Stability

5.1.1 Description

The *Overall Stability* option checks overall sheet piling stability using the Bishop method with circular slip planes. The same input as benchmark 4-17 (section 4.17) is used except that the additional pore pressures in the last stage are removed. The verification is made for the last stage, for different Design Codes:

- ◇ For representative verification, no partial factor is applied;
- ◇ For CUR verification, partial factors given in Figure 5.1 are applied on strength parameters (c and tan φ) and driving moment, for safety classes I, II and III;
- ◇ For Eurocode verification (General, Dutch Annex and Belgian annex), partial factors given in Figure 5.1 are applied on soil parameters (c, tan φ and γ) for all design approaches.

CUR 166

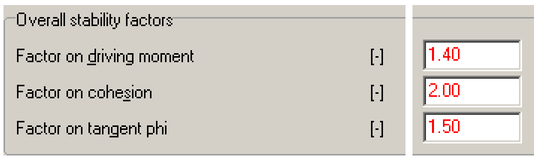


Figure 5.1: *todo*

Eurocode 7

Figure 5.2: *Partial factors for Overall Stability*

5.1.2 D-Geo Stability results

Calculations are performed using the Deltares Systems program D-Geo Stability (formerly known as MStab) with the Bishop method and the c-φ parameters. For Design Code check, the design input values of soil parameters are given in the tables below. For Eurocode 7, two calculations using low and high values of the unit weight (i.e. respectively divided and multiplied by the partial factor) are performed and the minimum resulting safety factor is taken.

Table 5.1: *Design values of soil properties acc. to CUR verification*

		Clay	**Peat**	**Sand 1**	**Sand 2**
Cohesion	[kPa]	6.25	2.50	0.00	0.00
Friction angle	[°]	14.35	16.90	21.83	26.67

Table 5.2: *Design values of soil properties acc. to Eurocode 7 verification*

		Clay	Peat	Sand 1	Sand 2
Cohesion	[kPa]	6.25	2.50	0.00	0.00
Friction angle	[°]	13.42	15.43	18.94	21.90
Unsaturated unit weight, low	[kN/m^3]	18.75	12.50	21.25	21.25
Saturated unit weight, low	[kN/m^3]	12.00	8.00	13.60	13.60
Unsaturated unit weight, high	[kN/m^3]	20.00	13.75	23.75	23.75
Saturated unit weight, high	[kN/m^3]	12.80	8.80	15.20	15.20

D-Geo Stability results are given in Table 5.3. For CUR verification, brut results must be corrected (i.e. divided by the partial factor on the driving moment) for comparison with D-SHEET PILING results.

Table 5.3: *D-Geo Stability results for benchmark 5-1 – Safety factor*

Design Code	Unit weight	Brut (3 decimals)	Corrected (2 decimals)
Representative		3.256	2.13
CUR		2.151	2.151/1.4 = 1.54
Eurocode 7	Low	2.242	2.03
	High	2.034	

5.1.3 D-SHEET PILING results

the D-SHEET PILING and D-Geo Stability results are compared in Table 5.4.

Table 5.4: *Results of benchmark 5-1 – Safety factor*

Design Code and class	File	D-Geo Stability (corrected)	D-SHEET PILING	Relative error [%]
Representative	bm5-1a	3.26	3.25	0.31
CUR – Safety class I	bm5-1b	1.54	1.53	0.65
CUR – Safety class II	bm5-1c	1.54	1.53	0.65
CUR – Safety class III	bm5-1d	1.54	1.53	0.65
EC7 (General) – DA 1 set 1	bm5-1e	2.03	2.03	0.00
EC7 (General) – DA 1 set 2	bm5-1f	2.03	2.03	0.00
EC7 (General) – DA 2	bm5-1g	2.03	2.03	0.00
EC7 (General) – DA 3	bm5-1h	2.03	2.03	0.00
EC7 (NL Annex) – RC 1	bm5-1i	2.03	2.03	0.00
EC7 (NL Annex) – RC 2	bm5-1j	2.03	2.03	0.00
EC7 (NL Annex) – RC 3	bm5-1k	2.03	2.03	0.00
EC7 (B Annex) – Set 1	bm5-1l	2.03	2.03	0.00
EC7 (B Annex) – Set 2	bm5-1m	2.03	2.03	0.00

Use D-SHEET PILING input files bm5-1a.shi to bm5-1m.shi to run this benchmark.

5.2 Additional horizontal pressure due to a surcharge load

5.2.1 Description

This benchmark is the same as benchmark 3-10 (section 3.7). The additional horizontal stress distribution due to the triangular surcharge is compared to the additional vertical distribution calculated with the Deltares Systems program D-SETTLEMENT (formerly known as MSettle) using the Boussinesq theory.

5.2.2 D-SETTLEMENT results

The soil weight γ can't be set to zero, therefore the final and initial effective tresses must be subtracted to get the additional vertical effective stress due to the triangular surcharge. The surcharge load is divided into elements of 0.1 m width and the Boussinesq theory is chosen. D-SETTLEMENT results at different depths are presented in the table below.

5.2.3 D-SHEET PILING results

To compare vertical and horizontal stresses, the earth pressure coefficients must be set to 1 using the *Manual* option in the *Start Calculation* window.

Table 5.5: *Results of benchmark 5-2 – Effective stress distribution acc. to Boussinesq*

Depth [m NAP]	**D-SETTLEMENT [kN/m^2]**	**D-SHEET PILING [kN/m^2]**	**Relative error [%]**
–2 m	15.15	15.15	0.00
–4 m	11.41	11.41	0.00
–6 m	8.85	8.85	0.00
–8 m	7.11	7.11	0.00
–10 m	5.90	5.92	0.34

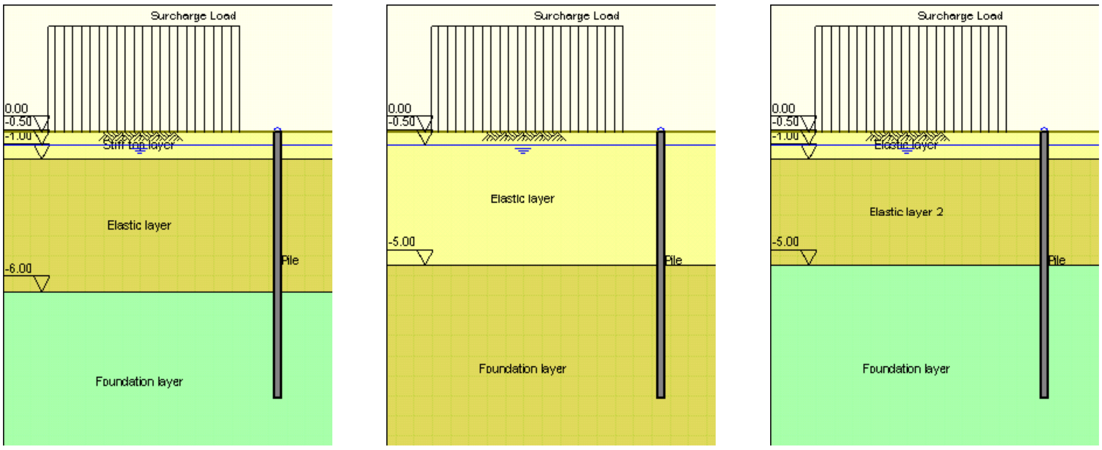
Use D-SHEET PILING input file bm5-2.shi to run this benchmark.

5.3 Horizontal displacements and stresses acc. to De Leeuw tables

5.3.1 Description

The calculated horizontal displacements and stresses are compared to the results of the program LEEUWIN.EXE based on the tables of De Leeuw. A surcharge load (magnitude: 10 kN/m^2, width: 10 m, distance to sheet piling: 2 m) is applied. Three cases are considered (Figure 5.3):

- ◇ Case A (bm5-3a): stiff top layer of 1 m thick and elastic layer of 5 m thick (E = 1500 kN/m^2 i.e. γ_{unsat} = 18 kN/m^3);
- ◇ Case B (bm5-3b): same as case A without the stiff top layer;
- ◇ Case C (bm5-3c): without stiff top layer and with a layered elastic cluster: top layer of 1 m thick (E = 1500 kN/m^2 i.e. γ_{unsat} = 18 kN/m^3) and a bottom layer of 4 m thick (E = 575 kN/m^2 i.e. γ_{unsat} = 10 kN/m^3). The average modulus is E_{avg} = (1 × 1500 + 4 × 575) / 5 = 760 kN/m^2.



***(a)** Case A* ***(b)** Case B* ***(c)** Case C*

***Figure 5.3:** Geometry overview (bm5-3)*

5.3.2 LEEUWIN results

The three situations described above are modeled with the program LEEUWIN.EXE and results are shown in Figure 5.4.

Case A)

```
TABELLEN VAN DE LEEUW  (C) Grondmechanica Delft
==============================================

Geval 2A   :  Rekstijve bovenlaag, strookbelasting
Laagdikte                  (m)   =     5.000
Strookbreedte              (m)   =    10.000
Afstand tot de rand        (m)   =     2.000
Belasting q            (kN/m²)   =    10.000
E - modulus            (kN/m²)   =  1500.000

Diepte          U(tab)           U(m)       Sigma(tab)    Sigma(kN/m²)

  0.00         0.00000        0.00000        0.00000         0.00000
  1.00         0.11416        0.00381        0.25183         2.51832
  2.00         0.17711        0.00590        0.35775         3.57750
  3.00         0.17916        0.00597        0.36625         3.66247
  4.00         0.12164        0.00405        0.31345         3.13452
  5.00        -0.00004       -0.00000        0.18257         1.82570
```

Case B)

```
TABELLEN VAN DE LEEUW  (C) Grondmechanica Delft
===============================================

Geval 1A  :  Niet rekstijve bovenlaag, strookbelasting
Laagdikte            (m)   =    5.000
Strookbreedte        (m)   =   10.000
Afstand tot de rand  (m)   =    2.000
Belasting q        (kN/m²) =   10.000
E - modulus        (kN/m²) = 1500.000

Diepte         U(tab)            U(m)     Sigma(tab)   Sigma(kN/m²)

  0.00        0.27308         0.00910        0.04384        0.43838
  1.00        0.29252         0.00975        0.25170        2.51697
  2.00        0.28592         0.00953        0.33941        3.39412
  3.00        0.23742         0.00791        0.34551        3.45509
  4.00        0.14436         0.00481        0.30167        3.01675
  5.00       -0.00008        -0.00000        0.19046        1.90462
```

Case C)

```
TABELLEN VAN DE LEEUW  (C) Grondmechanica Delft
===============================================

Geval 1A  :  Niet rekstijve bovenlaag, strookbelasting
Laagdikte            (m)   =    5.000
Strookbreedte        (m)   =   10.000
Afstand tot de rand  (m)   =    2.000
Belasting q        (kN/m²) =   10.000
E - modulus        (kN/m²) =  760.000

Diepte         U(tab)            U(m)     Sigma(tab)   Sigma(kN/m²)

  0.00        0.27308         0.01797        0.04384        0.43838
  1.00        0.29252         0.01924        0.25170        2.51697
  2.00        0.28592         0.01881        0.33941        3.39412
  3.00        0.23742         0.01562        0.34551        3.45509
  4.00        0.14436         0.00950        0.30167        3.01675
  5.00       -0.00008        -0.00001        0.19046        1.90462
```

Figure 5.4: *Horizontal displacements and stresses acc. to LEEUWIN program*

5.3.3 D-SHEET PILING results

the D-SHEET PILING and LEEUWIN results are compared in the tables below.

Table 5.6: *Results of benchmark 5-3a – Horizontal modulus of subgrade reaction for case A*

Depth [m NAP]	Layer	LEEUWIN [kN/m^3]	D-SHEET PILING [kN/m^3]	Relative error [%]
0	Stiff	100000.00	100000.00	0.00
-1	Elastic	100000.00	100000.00	0.00
-2	Elastic	1982.93	1985.40	0.12
-3	Elastic	1819.07	1817.97	0.06
-4	Elastic	1840.44	1839.87	0.03

Table 5.6: Results of benchmark 5-3a – Horizontal modulus of subgrade reaction for case A

Depth [m NAP]	Layer	LEEUWIN [kN/m^3]	D-SHEET PILING [kN/m^3]	Relative error [%]
-5	Elastic	2321.87	2319.19	0.12
-6	Foundation	100000.00	100000.00	0.00
-10	Foundation	100000.00	100000.00	0.00

Table 5.7: Results of benchmark 5-3b – Horizontal modulus of subgrade reaction for case B

Depth [m NAP]	Layer	LEEUWIN [kN/m^3]	D-SHEET PILING [kN/m^3]	Relative error [%]
0	Elastic	144.52	179.97	19.70
-1	Elastic	774.45	774.41	0.01
-2	Elastic	1068.45	1068.37	0.01
-3	Elastic	1310.40	1309.73	0.05
-4	Elastic	1881.55	1880.72	0.04
-5	Elastic	100000.00	100000.00	0.00
-10	Foundation	100000.00	100000.00	0.00

Table 5.8: Results of benchmark 5-3c – Horizontal modulus of subgrade reaction for case C

Depth [m NAP]	Layer	LEEUWIN [kN/m^3]	D-SHEET PILING [kN/m^3]	Relative error [%]
0	Elastic	73.19	91.18	19.73
-1	Elastic	392.46	392.37	0.02
-2	Elastic	541.33	541.31	0.00
-3	Elastic	663.59	663.60	0.00
-4	Elastic	952.66	952.90	0.03
-5	Elastic	100000.00	100000.00	0.00
-10	Foundation	100000.00	100000.00	0.00

Use D-SHEET PILING input files bm5-3a.shi to bm5-3c.shi to run this benchmark.

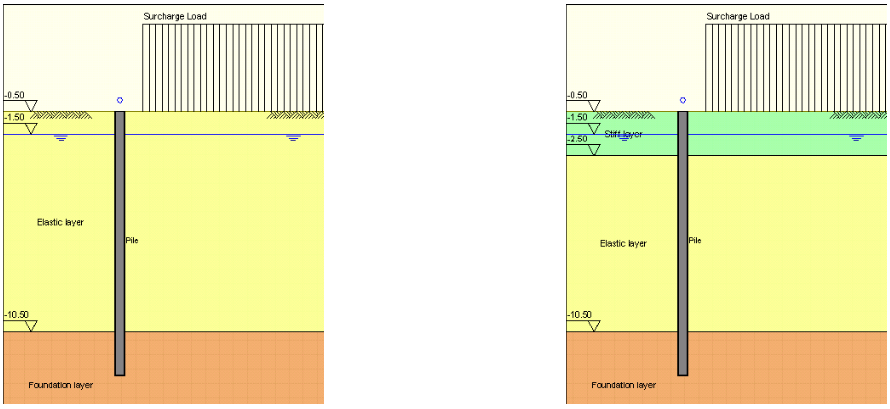
5.4 Single pile loaded by calculated soil displacements

5.4.1 Description

The results of a pile loaded with calculated soil displacements are compared to the results of the program MHORPILE, dedicated to horizontal laterally loaded piles. In appendix 2 of Geo (June 1999), the inputs and outputs of two demo files are completely described. A concrete square pile (length 12 m, stiffness EI = 63900 kNm^2) is loaded with a surcharge (height 4 m, unit weight 15 kN/m^3) starting 3.25 m to the right side of the pile until 60 m. The soil profile is different for both demos:

◇ Demo-1b (bm5-4a): elastic layer with a thickness of 10 m (E = 1500 kN/m^2);

◇ Demo-2b (bm5-4b): stiff top layer with a thickness of 2 m and elastic layer with a thickness of 8 m (E = 1500 kN/m^2).



(a) *Case 1 (bm5-4a)* ***(b)*** *Case 2 (bm5-4b)*

Figure 5.5: *Geometry overview (bm5-4)*

5.4.2 MHORPILE results

The two situations described above are modeled with the program MHORPILE and results are shown in Figure 5.6.

5.4.3 D-Sheet Piling results

In D-Sheet Piling, the layers are divided into sub-layers of 1 m with an adapted friction angle φ in order to get a passive earth pressure coefficient K_p (acc. to Brinch-Hansen) equal to 2.5 in the elastic layer and 5 in the stiff layers, to be in accordance with MHORPILE.

the D-Sheet Piling and MHORPILE results are compared in the tables below.

Table 5.9: *Results of benchmark 5-4a – Case 1*

		MHORPILE (Demo-1b)	**D-Sheet Piling (bm5-4a)**	**Rel. error [%]**
Maximum moment	[kNm]	104.7	124.5	15.93
Minimum moment	[kNm]	-7.8	-11.3	31.16
Maximum shear force	[kN]	30.9	45.5	32.04
Minimum shear force	[kN]	-100.3	-115.8	13.42
Max. displacement	[mm]	199.5	198.2	0.64
Max. soil displacement	[mm]	159	159	0.00

Table 5.10: *Results of benchmark 5-4b – Case 2*

		MHORPILE (Demo-2b)	**D-Sheet Piling (bm5-4b)**	**Rel. error [%]**
Maximum moment	[kNm]	49.6	46.8	6.03
Minimum moment	[kNm]	-127.1	-128.8	1.34
Maximum shear force	[kN]	56.8	89.1	36.27
Minimum shear force	[kN]	-53.9	-55.1	2.11
Max. displacement	[mm]	19.2	19.9	3.52
Max. soil displacement	[mm]	59	59	0.00

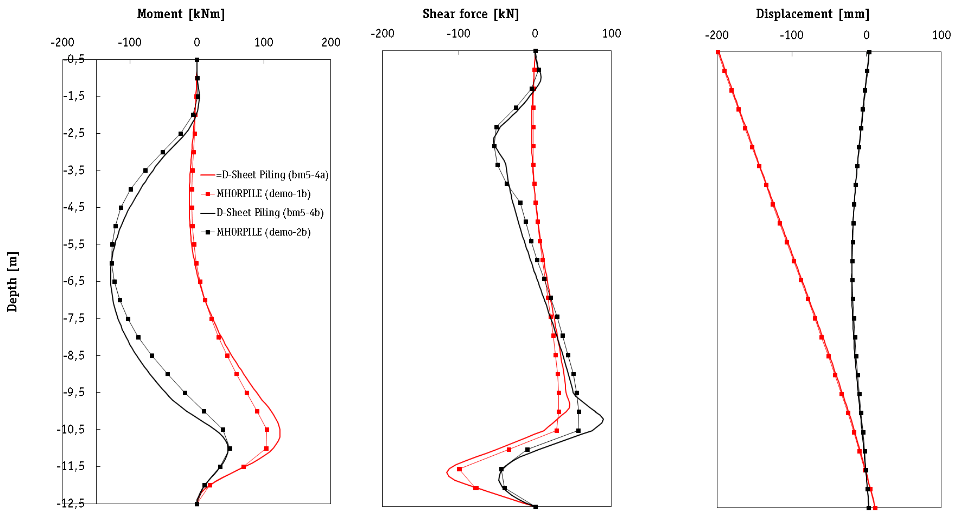


Figure 5.6: Comparison between D-SHEET PILING and MHORPILE results for both cases

Use D-SHEET PILING input files bm5-4a.shi and bm5-4b.shi to run this benchmark.

5.5 Single pile loaded by horizontal load

5.5.1 Description

The results of a pile loaded with calculated soil displacements are compared to the results of the program MHORPILEMHORPILE, dedicated to horizontal laterally loaded piles. In appendix 2 of Geo (June 1999), the inputs and outputs of two demo files are completely described. A concrete pile (length 18.39 m, stiffness EI = 2750 kNm^2) is loaded with a horizontal force of 78.4 kN on the top. At the pile top level -4.59 m NAP, a fixed support prevents rotation. The soil consists of 6 layers. The soil properties are given in Table 5.11. The earth pressure coefficients are calculated according to Brinch-Hansen formulas. The moduli of subgrade reaction are calculated acc. to Ménard theory.

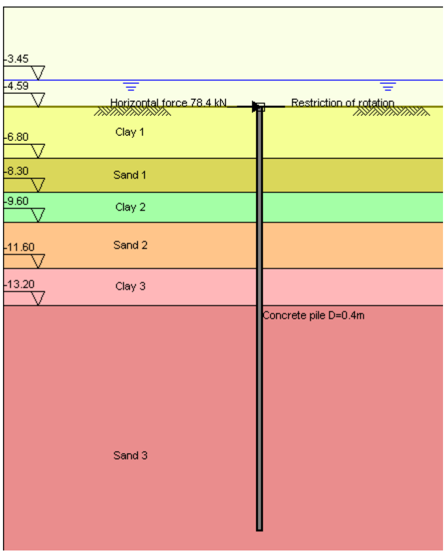


Figure 5.7: Horizontal load on pile (bm5-5)

Table 5.11: Soil properties for bm5-5

Material	Top level	γ_{unsat}	γ_{sat}	c	φ	E_m
	[m NAP]	[kN/m^3]	[kN/m^3]	[kN/m^2]	[°]	[kN/m^2]
Clay 1	-4.59	15	15	0	22.5	2000
Sand 1	-6.8	18	20	0	32.5	2000
Clay 2	-8.3	15	15	10	22.5	4000
Sand 2	-9.6	18	20	0	32.5	4000
Clay 3	-11.6	17	17	10	17.5	4000
Sand 3	-13.2	18	20	0	32.5	9000

5.5.2 MHORPILE results

The MHORPILE results are given in the tables below.

5.5.3 D-SHEET PILING results

the D-SHEET PILING and MHORPILE results are compared in Table 5.12 and Table 5.13.

Table 5.12: Results of benchmark 5-5 – Passive earth pressure coefficients and fictive cohesion acc. to Brinch-Hansen and modulus of subgrade reaction acc. to Ménard

	MHORPILE (Demo-4)			D-SHEET PILING (bm5-5)			Relative error [%]		
	c*	K_p	k	c*	K_p	k	c*	K_p	k
Clay 1	0.00	4.23	9317	0.00	4.23	9317	0.00	0.00	0.00
Sand 1	0.00	13.12	13770	0.00	13.12	13771	0.00	0.00	0.01
Clay 2	50.82	5.82	18630	50.82	5.83	18634	0.00	0.17	0.02
Sand 2	0.00	16.41	27540	0.00	16.41	27543	0.00	0.00	0.01
Clay 3	47.31	3.96	18630	47.32	3.96	18634	0.02	0.00	0.02
Sand 3	0.00	19.80	61970	0.00	19.80	61971	0.00	0.00	0.00

Table 5.13: Results of benchmark 5-5 – Moments/Shear forces/Displacements

		MHORPILE (Demo-4)	D-SHEET PILING (bm5-5)	Relative error [%]
Maximum moment	[kNm]	127.2	127.2	0.00
Minimum moment	[kNm]	-54.3	-54.3	0.00
Maximum shear force	[kN]	28.9	30.4	4.93
Minimum shear force	[kN]	-78.4	-78.4	0.00
Max. displacement	[mm]	99.3	99.4	0.10

Use D-SHEET PILING input file bm5-5.shi to run this benchmark.

5.6 Settlement by vibration in homogeneous and saturated subsoil

5.6.1 Description

For the verification of the option *Settlement by vibration*, a comparison is made between the results by the original program TRILDENS3 and the results by the implementation In D-SHEET PILING. This benchmark concerns a simple situation with a homogeneous subsoil (Sand) with relative density of I_D = 50%. Groundwater level is at ground surface.

The characteristics of the sheet pile are:

- ◇ Length: 15 m
- ◇ Cross section: 200 cm^2/m
- ◇ Acting width: 1.2 m (double sheet pile)

The reference case (case A) considers a single stage where the ground surface coincides with the top of the sheet pile, at both sides of the sheet piling (see Figure 5.8).

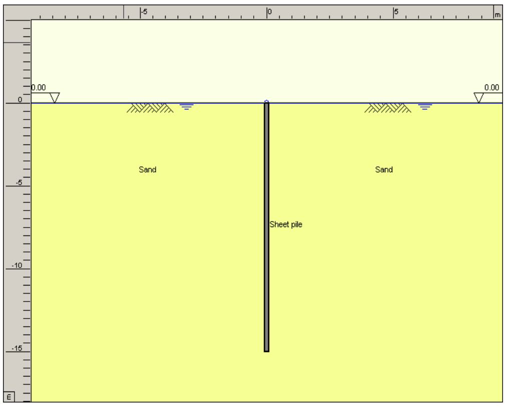


Figure 5.8: *Geometry of the reference case (case A)*

In order to check that the settlements are calculated for the active side of the sheet pile, two other cases are considered (cases B and C) where an excavation of 5 m is modeled at the left side for case B and at the right side for case C.

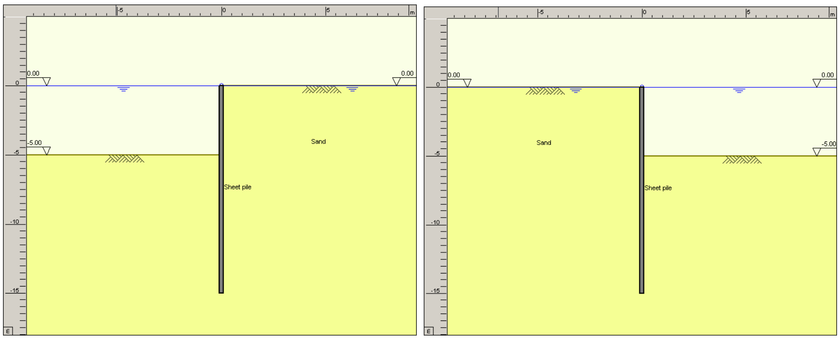


Figure 5.9: *Geometry of cases B and C*

In order to check that the settlements are calculated for a ground level corresponding to the level next to the sheet pile wall, a fifth case is considered (case D) where the ground level is not horizontal.

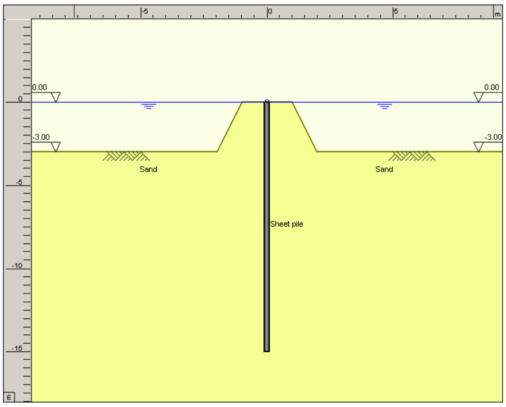


Figure 5.10: *Geometry of case D*

In order to check that the settlements are calculated for the first (initial) stage, a fourth case is considered (case E) where an excavation of 5 m is modeled at the left side during the first stage and an excavation of 10 m is modeled at the right side during the second stage.

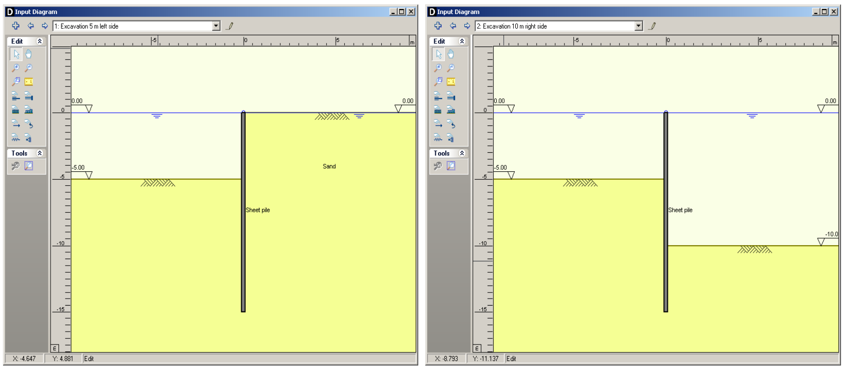


Figure 5.11: *Geometry of case E for both stages*

Four those five cases, it is expected that results will be the same.

5.6.2 TRILDENS3 results

The input data used by TRILDENS3 is given in Figure 5.12.

```
subsoil parameters
- - - - - - - - - - - - - - - - - - -
number of soil layers:              1
power in attenuation relation: -1.0000
reference stress is:         100.0000
unit weight water is:         10.0000

layer   number  top    I_D  g_dry g_wet  nmin  nmax   Gref      mv0      phi   k
     layer   1   0.00   0.50  16.00  20.00 0.32  0.45   68743  3.637E-0005 34.00  1.000E-0004

layer adamp  aBarkan history  amcycle bmcycle THETA       C1      C2      PEC
 1    0.010  4.000     333.00  0.480   0.200   0.700    9.6000  0.1300  0.022

properties sheetpile
- - - - - - - - - - - - - - - - - - -
embedment sheetpile, start:       0.00
embedment sheetpile, end:       -15.00
width of sheetpile:               1.20
cross section of sheetpile:      0.024
time of vibrating:            450.0000
frequency of vibrator:         38.0000
reference velocity at r0=5m:    0.0020
force of vibrator:              533.96
vibration velocity at r0=5m:    0.0024
ratio delta/phi:                1.0000

properties geometry
- - - - - - - - - - - - - - - - - - -
inner and outer radius:         0.3820  20.0000
depth of mesh:                -20.0000
groundwaterlevel is:            0.0000
no.of elements radial:        40
no.of elements depth:         40
minimum number of steps       9500
width of element:               0.4905

calculation options
- - - - - - - - - - - - - - - - - - -
source model:                      1  standard model
propagation model:                 2  stress attenuation
densification model:               5  C/L method (Sawicki)
summation model:                   2  vertical with spreading

angle volume spreading:  30.00
```

Figure 5.12: *Input data's in TRILDENS for benchmark 5-6*

The longtable results are given in Figure 5.13.

```
calculated settlement at level:   0.000
used summation model:      2  vertical with spreading
volumeloss due to densification, one side, m3/m:    -0.5204
- - - - - - - - - - - - - - - - - - - - - - - - - -
              radius  densification   sheetpile-volume   total
 location:     0.191    -0.198597        0.058279      -0.140318
 location:     0.191    -0.198597        0.058279      -0.140318
 location:     0.627    -0.150211        0.046732      -0.103479
 location:     1.118    -0.127617        0.034855      -0.092761
 location:     1.608    -0.109920        0.027857      -0.082063
 location:     2.099    -0.092615        0.025192      -0.067423
 location:     2.589    -0.079972        0.020845      -0.059127
 location:     3.079    -0.069589        0.017373      -0.052216
 location:     3.570    -0.058337        0.015866      -0.042471
 location:     4.060    -0.049769        0.013198      -0.036572
 location:     4.551    -0.041448        0.010886      -0.030562
 location:     5.041    -0.033922        0.009836      -0.024086
 location:     5.532    -0.027214        0.007910      -0.019303
 location:     6.022    -0.021350        0.006177      -0.015173
 location:     6.513    -0.016544        0.004602      -0.011943
 location:     7.003    -0.011594        0.003865      -0.007730
 location:     7.494    -0.007587        0.002478      -0.005108
 location:     7.984    -0.004532        0.001195      -0.003337
 location:     8.474    -0.001641        0.000587      -0.001053
 location:     8.965    -0.000444        0.000000      -0.000444
 location:     9.455    -0.000081        0.000000      -0.000081
 location:     9.946    -0.000003        0.000000      -0.000003
 location:    10.436     0.000000        0.000000       0.000000
 location:    10.927     0.000000        0.000000       0.000000
 location:    11.417     0.000000        0.000000       0.000000
 location:    11.908     0.000000        0.000000       0.000000
 location:    12.398     0.000000        0.000000       0.000000
 location:    12.888     0.000000        0.000000       0.000000
 location:    13.379     0.000000        0.000000       0.000000
 location:    13.869     0.000000        0.000000       0.000000
 location:    14.360     0.000000        0.000000       0.000000
 location:    14.850     0.000000        0.000000       0.000000
 location:    15.341     0.000000        0.000000       0.000000
 location:    15.831     0.000000        0.000000       0.000000
 location:    16.322     0.000000        0.000000       0.000000
 location:    16.812     0.000000        0.000000       0.000000
 location:    17.303     0.000000        0.000000       0.000000
 location:    17.793     0.000000        0.000000       0.000000
 location:    18.283     0.000000        0.000000       0.000000
 location:    18.774     0.000000        0.000000       0.000000
 location:    19.264     0.000000        0.000000       0.000000
 location:    19.755     0.000000        0.000000       0.000000
```

Figure 5.13: *longtable results of TRILDENS3 for benchmark 5-6*

5.6.3 D-SHEET PILING results

The D-SHEET PILING results are given in the tables below and compared to TRILDENS3 results. Correlation is very good. The five D-SHEET PILING cases (A, B, C, D and E) give the same results.

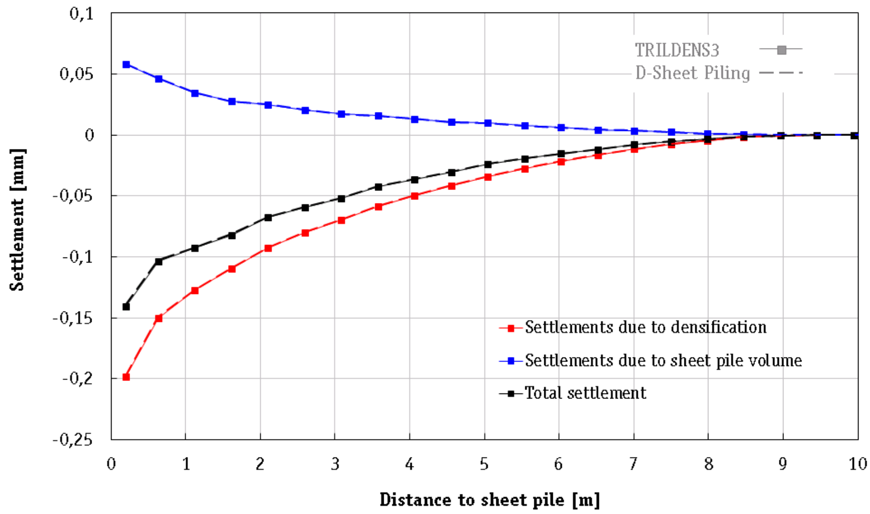


Figure 5.14: *Comparison of TRILDENS3 and* D-SHEET PILING *for benchmark 5-6, Settlements during installation of the sheet piling*

Table 5.14: *Results of benchmark 5-6 – Settlements due to densification (during installation)*

Distance to sheet pile [m]	**TRILDENS3** [mm]	**D-SHEET PILING** [mm]	**Relative error** [%]
0.191	-198.60	-197.67	0.47
0.627	-150.21	-149.16	0.70
1.118	-127.62	-126.77	0.67
1.608	-109.92	-109.19	0.67
2.099	-92.62	-91.99	0.68
2.589	-79.97	-79.44	0.67
3.079	-69.59	-69.12	0.68
3.57	-58.34	-57.91	0.74
4.06	-49.77	-49.41	0.73
4.551	-41.45	-41.15	0.73
5.041	-33.92	-33.66	0.77
5.532	-27.21	-26.98	0.85
6.022	-21.35	-21.17	0.85
6.513	-16.54	-16.39	0.92
7.003	-11.59	-11.46	1.13
7.494	-7.59	-7.49	1.34
7.984	-4.53	-4.46	1.57
8.474	-1.64	-1.58	3.80
8.965	-0.44	-0.42	4.76
9.455	-0.08	-0.08	0.00
9.946	0.00	0.00	0.00
10.436	0.00	0.00	0.00

Table 5.15: Results of benchmark – Settlements due to sheet pile volume (during installation)

Distance to sheet pile [m]	**TRILDENS3** [mm]	**D-SHEET PILING** [mm]	**Relative error** [%]
0.191	58.28	58.28	0.00
0.627	46.73	46.73	0.00
1.118	34.86	34.86	0.00
1.608	27.86	27.86	0.00
2.099	25.19	25.19	0.00
2.589	20.85	20.85	0.00
3.079	17.37	17.37	0.00
3.57	15.87	15.87	0.00
4.06	13.20	13.20	0.00
4.551	10.89	10.89	0.00
5.041	9.84	9.84	0.00
5.532	7.91	7.91	0.00
6.022	6.18	6.18	0.00
6.513	4.60	4.60	0.00
7.003	3.87	3.86	0.26
7.494	2.48	2.48	0.00
7.984	1.20	1.19	0.84
8.474	0.59	0.59	0.00
8.965	0.00	0.00	0.00
9.455	0.00	0.00	0.00
9.946	0.00	0.00	0.00
10.436	0.00	0.00	0.00

Table 5.16: *Results of benchmark 5-6 – Total settlements (during installation)*

Distance to sheet pile [m]	**TRILDENS3** [mm]	**D-SHEET PILING** [mm]	**Relative error** [%]
0.191	-140.32	-139.39	0.67
0.627	-103.48	-102.43	1.03
1.118	-92.76	-91.91	0.92
1.608	-82.06	-81.33	0.90
2.099	-67.42	-66.80	0.93
2.589	-59.13	-58.59	0.92
3.079	-52.22	-51.75	0.91
3.57	-42.47	-42.04	1.02
4.06	-36.57	-36.21	0.99
4.551	-30.56	-30.26	0.99
5.041	-24.09	-23.82	1.13
5.532	-19.30	-19.07	1.21
6.022	-15.17	-14.99	1.20
6.513	-11.94	-11.79	1.27
7.003	-7.73	-7.60	1.71
7.494	-5.11	-5.01	2.00
7.984	-3.34	-3.27	2.14
8.474	-1.05	-0.99	6.06
8.965	-0.44	-0.42	4.76
9.455	-0.08	-0.08	0.00
9.946	0.00	0.00	0.00
10.436	0.00	0.00	0.00

Use D-SHEET PILING input files bm5-6a.shi until bm5-6e.shi to run this benchmark.

5.7 Settlement by vibration in homogeneous and unsaturated subsoil

5.7.1 Description

For the verification of the option *Settlement by vibration*, a comparison is made between the results by the original program TRILDENS3 and the results by the implementation In D-SHEET PILING. The same situation as in the previous benchmark (section 5.6) is considered, the difference is that the ground water table is well below the tip of the sheet pile. In this example the situation of dry soil is thus considered.

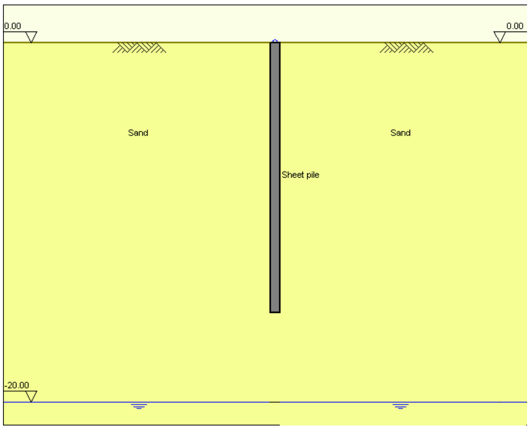


Figure 5.15: *Geometry of benchmark 5-7 (homogeneous unsaturated subsoil)*

5.7.2 TRILDENS3 results

The input data used by TRILDENS3 is given in Figure 5.16.

```
subsoil parameters
- - - - - - - - - - - - - - - - - -
number of soil layers:              1
power in attenuation relation: -1.0000
reference stress is:          100.0000
unit weight water is:          10.0000

layer   number  top    I_D  g_dry g_wet  nmin  nmax   Gref      mv0       phi   k
     layer   1   0.00   0.50  16.00  20.00 0.32  0.45   68743  3.637E-0005 34.00  1.000E-0004

layer adamp  aBarkan history  amcycle bmcycle THETA       C1      C2      PEC
 1    0.010  4.000     333.00  0.480   0.200   0.700    9.6000  0.1300   0.022

properties sheetpile
- - - - - - - - - - - - - - - - - -
embedment sheetpile, start:       0.00
embedment sheetpile, end:       -15.00
width of sheetpile:               1.20
cross section of sheetpile:      0.024
time of vibrating:            450.0000
frequency of vibrator:         38.0000
reference velocity at r0=5m:    0.0020
force of vibrator:              533.96
vibration velocity at r0=5m:    0.0024
ratio delta/phi:                1.0000

properties geometry
- - - - - - - - - - - - - - - - - -
inner and outer radius:         0.3820  20.0000
depth of mesh:                -20.0000
groundwaterlevel is:          -20.0000
no.of elements radial:        40
no.of elements depth:         40
minimum number of steps       9500
width of element:               0.4905

calculation options
- - - - - - - - - - - - - - - - - -
source model:                    1  standard model
propagation model:               2  stress attenuation
densification model:             5  C/L method (Sawicki)
summation model:                 2  vertical with spreading

angle volume spreading:  30.00
```

Figure 5.16: *Input data's in TRILDENS for benchmark 5-7*

The longtable results are given in Figure 5.17.

```
calculated settlement at level:   0.000
used summation model:      2  vertical with spreading
volumeloss due to densification, one side, m3/m:    -0.6995
- - - - - - - - - - - - - - - - - - - - - - - - - -
              radius  densification   sheetpile-volume   total
 location:    0.191    -0.254109        0.058279      -0.195830
 location:    0.191    -0.254109        0.058279      -0.195830
 location:    0.627    -0.211483        0.046732      -0.164750
 location:    1.118    -0.169590        0.034855      -0.134735
 location:    1.608    -0.147739        0.027857      -0.119882
 location:    2.099    -0.124366        0.025192      -0.099174
 location:    2.589    -0.106029        0.020845      -0.085184
 location:    3.079    -0.092222        0.017373      -0.074849
 location:    3.570    -0.078532        0.015866      -0.062665
 location:    4.060    -0.067276        0.013198      -0.054078
 location:    4.551    -0.055974        0.010886      -0.045088
 location:    5.041    -0.046033        0.009836      -0.036197
 location:    5.532    -0.037281        0.007910      -0.029371
 location:    6.022    -0.029622        0.006177      -0.023445
 location:    6.513    -0.023233        0.004602      -0.018632
 location:    7.003    -0.016722        0.003865      -0.012858
 location:    7.494    -0.011409        0.002478      -0.008931
 location:    7.984    -0.007406        0.001195      -0.006211
 location:    8.474    -0.003566        0.000587      -0.002979
 location:    8.965    -0.001672        0.000000      -0.001672
 location:    9.455    -0.000712        0.000000      -0.000712
 location:    9.946    -0.000282        0.000000      -0.000282
 location:   10.436    -0.000065        0.000000      -0.000065
 location:   10.927    -0.000002        0.000000      -0.000002
 location:   11.417     0.000000        0.000000       0.000000
 location:   11.908     0.000000        0.000000       0.000000
 location:   12.398     0.000000        0.000000       0.000000
 location:   12.888     0.000000        0.000000       0.000000
 location:   13.379     0.000000        0.000000       0.000000
 location:   13.869     0.000000        0.000000       0.000000
 location:   14.360     0.000000        0.000000       0.000000
 location:   14.850     0.000000        0.000000       0.000000
 location:   15.341     0.000000        0.000000       0.000000
 location:   15.831     0.000000        0.000000       0.000000
 location:   16.322     0.000000        0.000000       0.000000
 location:   16.812     0.000000        0.000000       0.000000
 location:   17.303     0.000000        0.000000       0.000000
 location:   17.793     0.000000        0.000000       0.000000
 location:   18.283     0.000000        0.000000       0.000000
 location:   18.774     0.000000        0.000000       0.000000
 location:   19.264     0.000000        0.000000       0.000000
 location:   19.755     0.000000        0.000000       0.000000
```

Figure 5.17: *longtable results of TRILDENS3 for benchmark 5-7*

5.7.3 D-SHEET PILING results

the D-SHEET PILING results are given in Figure 5.18 and compared to TRILDENS3 results. Correlation is very good.

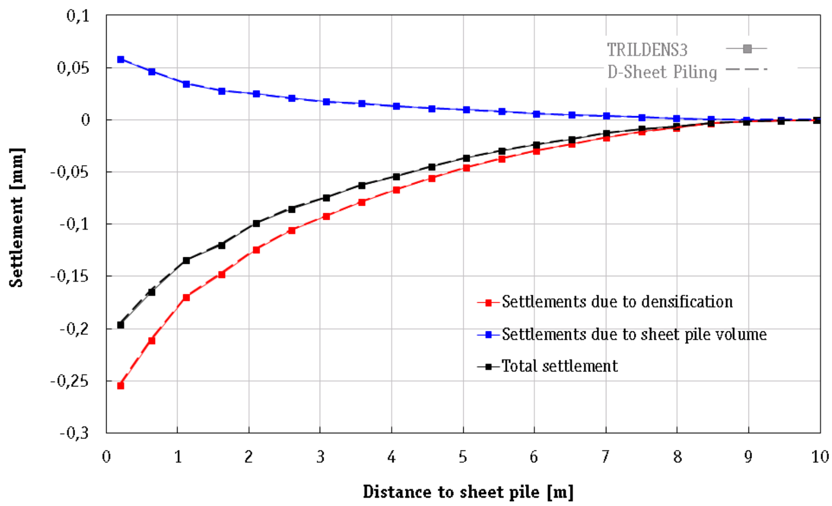


Figure 5.18: *Comparison of TRILDENS3 and DSheet Piling for benchmark 5-7, Settlements during installation of the sheet piling*

Table 5.17: Results of benchmark 5-7 – Settlements due to densification (during installation)

Distance to sheet pile [m]	TRILDENS3 [mm]	D-SHEET PILING [mm]	Relative error [%]
0.191	-254.11	-253.16	0.38
0.627	-211.48	-209.73	0.83
1.118	-169.59	-168.49	0.65
1.608	-147.74	-146.70	0.71
2.099	-124.37	-123.47	0.73
2.589	-106.03	-105.29	0.70
3.079	-92.22	-91.56	0.72
3.57	-78.53	-77.91	0.80
4.06	-67.28	-66.73	0.82
4.551	-55.97	-55.53	0.79
5.041	-46.03	-45.63	0.88
5.532	-37.28	-36.92	0.98
6.022	-29.62	-29.32	1.02
6.513	-23.23	-22.98	1.09
7.003	-16.72	-16.51	1.27
7.494	-11.41	-11.24	1.51
7.984	-7.41	-7.27	1.93
8.474	-3.57	-3.45	3.48
8.965	-1.67	-1.59	5.03
9.455	-0.71	-0.67	5.97
9.946	-0.28	-0.27	3.70
10.436	-0.07	-0.06	16.67

Use D-SHEET PILING input file bm5-7.shi to run this benchmark.

5.8 Settlement by vibration in layered subsoil

5.8.1 Description

For the verification of the option *Settlement by vibration*, a comparison is made between the results by the original program TRILDENS3 and the results by the implementation In D-SHEET PILING. For this benchmark, a situation with a layered subsoil is considered. The subsoil consists of 5 m Clay on top and Sand below with a relative density of 50%. Groundwater level is at ground surface. The dimensions of the sheet pile are equal to the dimensions used for benchmark 5-6 (section 5.6). Compared to benchmark 5-6 the volume of soil that will densify is less, which will result is less settlement near the sheet pile wall.

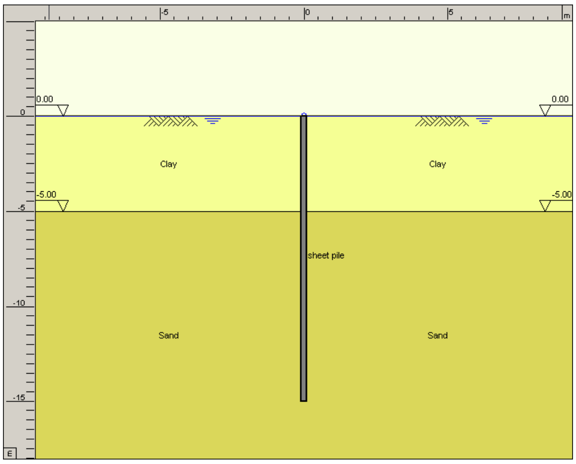


Figure 5.19: *Geometry of benchmark 5-8 (layered sub soil)*

5.8.2 TRILDENS3 results

The input data used by TRILDENS3 is given in Figure 5.20.

```
subsoil parameters
- - - - - - - - - - - - - - - - - -
number of soil layers:              2
power in attenuation relation: -1.0000
reference stress is:          100.0000
unit weight water is:          10.0000

layer   number  top    I_D  g_dry g_wet  nmin  nmax   Gref      mv0       phi   k
      clay   1   0.00   0.50  16.00  20.00 0.32  0.45   68743  3.637E-0005 34.00  1.000E-0004
      sand   2  -5.00   0.50  16.00  20.00 0.31  0.45   68743  3.637E-0005 34.00  1.000E-0004

layer adamp  aBarkan history  amcycle bmcycle THETA       C1      C2      PEC
 1     0.010  4.000     333.00  0.480   0.200   0.700   0.0000  0.1300   0.022
 2     0.010  4.000     333.00  0.480   0.200   0.700   9.6000  0.1300   0.022

properties sheetpile
- - - - - - - - - - - - - - - - - -
embedment sheetpile, start:       0.00
embedment sheetpile, end:       -15.00
width of sheetpile:               1.20
cross section of sheetpile:      0.024
time of vibrating:            450.0000
frequency of vibrator:         38.0000
reference velocity at r0=5m:    0.0020
force of vibrator:              533.96
vibration velocity at r0=5m:    0.0024
ratio delta/phi:                1.0000

properties geometry
- - - - - - - - - - - - - - - - - -
inner and outer radius:         0.3820  20.0000
depth of mesh:                -20.0000
groundwaterlevel is:            0.0000
no.of elements radial:        40
no.of elements depth:         40
minimum number of steps       9500
width of element:               0.4905

calculation options
- - - - - - - - - - - - - - - - - -
source model:                    1  standard model
propagation model:               2  stress attenuation
densification model:             5  C/L method (Sawicki)
summation model:                 2  vertical with spreading

angle volume spreading:  30.00
```

Figure 5.20: *Input data's in TRILDENS for benchmark 5-8*

The longtable results are given in Figure 5.21.

```
calculated settlement at level:   0.000
used summation model:      2  vertical with spreading
volumeloss due to densification, one side, m3/m:    -0.3670
- - - - - - - - - - - - - - - - - - - - - - - - - -
```

	radius	densification	sheetpile-volume	total
location:	0.191	-0.071965	0.058279	-0.013686
location:	0.191	-0.071965	0.058279	-0.013686
location:	0.627	-0.071965	0.046732	-0.025233
location:	1.118	-0.071965	0.034855	-0.037110
location:	1.608	-0.071965	0.027857	-0.044108
location:	2.099	-0.071454	0.025192	-0.046262
location:	2.589	-0.069417	0.020845	-0.048572
location:	3.079	-0.065029	0.017373	-0.047657
location:	3.570	-0.056707	0.015866	-0.040841
location:	4.060	-0.049196	0.013198	-0.035999
location:	4.551	-0.040929	0.010886	-0.030043
location:	5.041	-0.033500	0.009836	-0.023663
location:	5.532	-0.026867	0.007910	-0.018957
location:	6.022	-0.021073	0.006177	-0.014896
location:	6.513	-0.016319	0.004602	-0.011717
location:	7.003	-0.011433	0.003865	-0.007568
location:	7.494	-0.007482	0.002478	-0.005004
location:	7.984	-0.004470	0.001195	-0.003275
location:	8.474	-0.001621	0.000587	-0.001034
location:	8.965	-0.000441	0.000000	-0.000441
location:	9.455	-0.000081	0.000000	-0.000081
location:	9.946	-0.000003	0.000000	-0.000003
location:	10.436	0.000000	0.000000	0.000000
location:	10.927	0.000000	0.000000	0.000000
location:	11.417	0.000000	0.000000	0.000000
location:	11.908	0.000000	0.000000	0.000000
location:	12.398	0.000000	0.000000	0.000000
location:	12.888	0.000000	0.000000	0.000000
location:	13.379	0.000000	0.000000	0.000000
location:	13.869	0.000000	0.000000	0.000000
location:	14.360	0.000000	0.000000	0.000000
location:	14.850	0.000000	0.000000	0.000000
location:	15.341	0.000000	0.000000	0.000000
location:	15.831	0.000000	0.000000	0.000000
location:	16.322	0.000000	0.000000	0.000000
location:	16.812	0.000000	0.000000	0.000000
location:	17.303	0.000000	0.000000	0.000000
location:	17.793	0.000000	0.000000	0.000000
location:	18.283	0.000000	0.000000	0.000000
location:	18.774	0.000000	0.000000	0.000000
location:	19.264	0.000000	0.000000	0.000000
location:	19.755	0.000000	0.000000	0.000000

Figure 5.21: *longtable results of TRILDENS3 for benchmark 5-8*

5.8.3 D-SHEET PILING results

the D-SHEET PILING results are given in Figure 5.22 and compared to TRILDENS3 results. Correlation is very good.

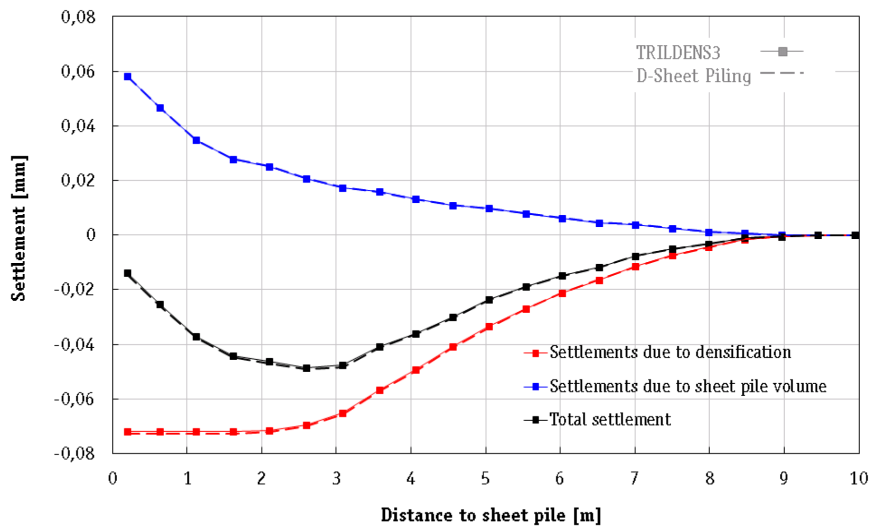


Figure 5.22: *Comparison of TRILDENS3 and DSheet Piling for benchmark 5-8, Settlements during installation of the sheet piling*

Table 5.18: *Results of benchmark 5-8 – Settlements due to densification (during installation)*

Distance to sheet pile	**TRILDENS3**	**D-SHEET PILING**	**Relative error**
[m]	[mm]	[mm]	[%]
0.191	-71.97	-72.61	0.88
0.627	-71.97	-72.61	0.88
1.118	-71.97	-72.61	0.88
1.608	-71.97	-72.61	0.88
2.099	-71.45	-72.11	0.92
2.589	-69.42	-70.09	0.96
3.079	-65.03	-65.67	0.97
3.57	-56.71	-57.20	0.86
4.06	-49.20	-49.61	0.83
4.551	-40.93	-41.27	0.82
5.041	-33.50	-33.75	0.74
5.532	-26.87	-27.04	0.63
6.022	-21.07	-21.20	0.61
6.513	-16.32	-16.41	0.55
7.003	-11.43	-11.47	0.35
7.494	-7.48	-7.49	0.13
7.984	-4.47	-4.46	0.22
8.474	-1.62	-1.59	1.89
8.965	-0.44	-0.42	4.76
9.455	-0.08	-0.08	0.00
9.946	0.00	0.00	0.00
10.436	0.00	0.00	0.00

Use D-SHEET PILING input file bm5-8.shi to run this benchmark.

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