Kennisprogramma Natte Kunstwerken
Kennisplan 2019

Technische levensduur

De invloed van inbedding door de grond op de sterkte van een gecorrodeerd stalen damwandprofiel AZ18-800

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Dit onderzoek met ArcelorMittal is mede mogelijk gemaakt door een bijdrage vanuit TKI Deltatechnologie via het project DEL050 "Natte Kunstwerken van de Toekomst" (2016-2021)

In het **Kennisprogramma Natte Kunstwerken** (KpNK) werken Deltares, MARIN, Rijkswaterstaat en TNO samen aan de kennisontwikkeling om de vervangings- en renovatieopgave bij natte kunstwerken (stuwen, sluizen, gemalen en stormvloedkeringen) efficiënt en kostenbesparend aan te pakken.

Deltares MARIN Rijkswaterstaat *Ministerie van Infrastructuur en Waterstaat* TNO

Voor het kennisprogramma wordt er jaarlijks een inhoudelijk **Kennisplan** inclusief bijbehorend financieringsplan opgesteld. Andere partijen (zoals waterschappen en marktpartijen) worden nadrukkelijk uitgenodigd om deel te nemen.

Meer informatie over het Kennisprogramma Natte Kunstwerken kan worden gevonden op www.nattekunstwerkenvandetoekomst.nl waar ook de onderzoeksresultaten ter beschikking worden gesteld.

TOPSECTOR WATER & MARITIEM

Topsector Water en Maritiem is een van de negen topsectoren in Nederland. Hierbinnen zijn drie topconsortia voor kennis en innovatie (TKI's) opgericht om het beleid en daarmee gemoeide regelingen voor het versterken van de samenwerking tussen onderzoeksorganisaties, bedrijven en overheden in deze sectoren uit te voeren. Het voorliggende onderzoek is mede mogelijk gemaakt door de bijdrage vanuit TKI Deltatechnologie.

Meer informatie staat op www.tkideltatechnologie.nl

NKWK

De samenwerking binnen het Kennisprogramma Natte Kunstwerken vormt de uitwerking van de onderzoekslijn "Toekomstbestendige Natte Kunstwerken" binnen het **Nationaal Kennisplatform voor Water en Klimaat** (NKWK). Dit kennisplatform brengt Nederlandse overheden, kennisinstellingen en bedrijven bij elkaar om samen te werken aan pilots, actuele vraagstukken en lange termijn-ontwikkelingen op gebied van water- en klimaatvraagstukken.

Meer informatie staat op www.waterenklimaat.nl.

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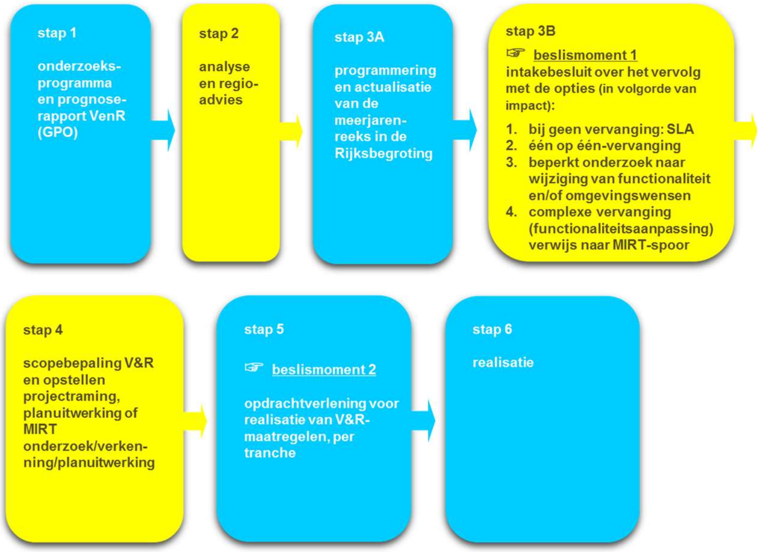
Voorwoord

Sluizen, stuwen, gemalen en stormvloedkeringen zijn belangrijke assets van beheerders zoals Rijkswaterstaat en de waterschappen. Een groot deel van deze natte kunstwerken bereikt komende decennia het einde van de (technische) levensduur waarvoor het is ontworpen. Er dient zich dan ook een aanzienlijke vervangings- en renovatieopgave van deze kunstwerken aan.

De laatste jaren wordt steeds meer gezocht naar mogelijkheden om levensduur van kunstwerken te verlengen, en om bij einde levensduur (noodzakelijke) ingrepen aan gebiedsontwikkelingen en/of functionele/netwerk ontwikkelingen te koppelen. Rijkswaterstaat heeft daartoe als asset manager een vernieuwde werkwijze voor het Vervanging en Renovatie (VenR) proces opgesteld, welke de basis vormt voor de inrichting van het Kennisprogramma Natte Kunstwerken (zie Figuur 1).



Figuur 1. Vernieuwde RWS-werkwijze Vervanging en Renovatie.

In het Kennisprogramma Natte Kunstwerken wordt kennis ontwikkeld die bijdraagt aan de verschillende stappen binnen deze vernieuwde VenR-werkwijze, met als focuspunten stap 1 (prognoserapport) en stap 2 (regio-analyse en -advies). Het prognoserapport richt zicht op de (einde) technische levensduur, het regio-advies brengt met name de relatie object-netwerk-gebied in kaart.

Het onderzoek in het Kennisprogramma Natte Kunstwerken vindt plaats langs de onderstaande 3 onderzoekssporen en heeft tot doel om een effectieve en efficiënte aanpak van de vervanging- en renovatie-opgave en nieuwbouw van natte kunstwerken mogelijk te maken:

• bestaand object	- inzicht in (einde) technische levensduur - levensduurverlenging
• object-systeem	- inzicht in (einde) functionele levensduur en object-systeemrelaties
• nieuw(e) object/objectonderdelen	- toepassen innovaties - inspelen op toekomstige ontwikkelingen.

Sinds enkele jaren is er het Nationaal Kennisplatform voor Water en Klimaat (NKWK). Hieronder lopen diverse onderzoekslijnen. Eén van de onderzoekslijnen is "Toekomstbestendige Natte Kunstwerken". Voor het praktisch laten functioneren van deze onderzoekslijn is er een Samenwerkingsovereenkomst Natte Kunstwerken en een Kennisprogramma Natte Kunstwerken opgesteld:

- Samenwerkingsovereenkomst Natte Kunstwerken. De partijen die momenteel binnen deze overeenkomst samenwerken aan onderwerpen rondom de vervangings- en renovatieopgave bij natte kunstwerken zijn Deltares, MARIN, Rijkswaterstaat en TNO.
- In het kader van de bovengenoemde Samenwerkingsovereenkomst Natte Kunstwerken en de 3 onderzoekssporen van het Kennisprogramma Natte Kunstwerken wordt er jaarlijks een inhoudelijk Kennisplan inclusief bijbehorend financieringsplan opgesteld.

Naast de genoemde partijen zijn en worden andere partijen nadrukkelijk uitgenodigd om deel te nemen aan de Samenwerkingsovereenkomst Natte Kunstwerken en/of het Kennisplan. Inzet kan zowel in kind en/of financieel zijn. In het Kennisplan 2019 is er binnen het kader van Kennisprogramma Natte Kunstwerken op verschillende onderwerpen samengewerkt met Acotec BV, Arcadis en ArcelorMittal, DIANA FEM en Boskalis.

Resultaten uit het Kennisprogramma Natte Kunstwerken worden gedeeld met de gehele sector, onder andere via de website www.nattekunstwerkenvandetoekomst.nl.

De hierop volgende samenvatting heeft betrekking op het onderliggende onderzoeksrapport "The influence of soil embedment on the strength of a corroded AZ18-800". Dit gezamenlijke onderzoek van Deltares en ArcelorMittal, dat mede door een bijdrage vanuit TKI Deltatechnologie via het project DEL050 "Natte Kunstwerken van de Toekomst" mogelijk is gemaakt, is uitgevoerd in het kader van het Kennisplan 2019. In verband met de Algemene Verordening Gegevensbescherming is het originele Deltares rapport ten behoeve van het publiceren op de website alleen qua persoonsgegevens, maar niet qua inhoud aangepast.

Samenvatting

The influence of soil embedment on strength of a corroded AZ18-800

Aanleiding

Voor een meer kosteneffectieve betrouwbare toepassing van stalen damwanden is een (fysisch) meer realistisch rekenmodel van de constructie nodig waarmee de invloed van de dominante onzekerheden op het gedrag kunnen worden beschouwd. Een van deze onzekerheden is het knikgedrag (lokale instabiliteit) van dunwandige stalen damwanden (als gevolg van corrosie) in combinatie met een inbedding van de damwand in de omringende grond. Op dit moment is er geen inzicht in hoeveel extra capaciteit inbedding door de omringende grond deze (conform de indeling in Eurocode 3) klasse 4 profielen biedt; dit aspect wordt in ontwerp en beoordelingen dan ook volledig verwaarloosd.

Onderzoeksvraag en -opzet (WAT)

Er wordt verwacht dat de inbedding van een stalen damwand door de omringende grond een positieve invloed zal hebben op de capaciteit van deze constructie, omdat deze inbedding de lokale knikeffecten onderdrukt. De grootte van de invloed zal afhangen van de grondsoort waarin de damwand is ingebed. Vooral bij dunwandige stalen damwanden kan dit aspect voor de capaciteit van belang zijn. Het voorliggende rapport presenteert de resultaten van een verdiepende onderzoeksfase met behulp van de Eindige Elementen Methode (EEM) programma's Abaqus en PLAXIS 3D met het volgende doel:

- Zijn de effecten van inbedding in de omringende grond op lokale knik van de damwand significant? Dus is het de moeite waard om de effecten van inbedding nader te onderzoeken met behulp van fysisch (model) onderzoek?

Onderzoeksaanpak en -methode (HOE)

Er is gekozen voor modellering van een gecorrodeerd AZ18-800 damwand profiel. Argumenten voor deze keuze zijn dat dit een damwand profiel is wat steeds meer wordt toegepast in de markt gezien het gunstige gewicht – sterkte verhouding. Verder zal bij het optreden van enige corrosie het profiel een klasse 4 profiel worden en daarmee gevoelig worden voor het optreden van lokale knik effecten.

Voor de EEM-modellering is gebruik gemaakt van een zogenaamde 4 punts-buigproef set-up. Een dergelijke buigproef is gangbaar in het onderzoek naar de sterkte van stalen (damwand) profielen. Bijzonder aspect in de EEM-modellering in dit geval is het gebruik van een grond omhulling met zogenaamde *stress-controlled boundaries*. Voor het damwand profiel zelf is zowel met een versimpelde geometrie gerekend als met de werkelijke geometrie.

Het EEM-programma Abaqus is gebruikt voor de modellering van, en het verkrijgen van inzicht in, het staal gedrag. Daarnaast is het EEM-programma PLAXIS 3D gebruikt voor modellering van, en het verkrijgen van inzicht in, het grondgedrag. De mogelijkheden en sterke punten van beide programma's vullen elkaar hiermee goed aan.

Onderzoeksresultaten en synthese

De resultaten uit de verschillende EEM-analyses van een 4 punts-buigproef op een gecorrodeerd AZ18-800 damwand profiel suggereren:

- '*Distorsional buckling*' is de maatgevende knik modus voor de beschouwde situatie zonder grondomhulling. Deze knikvorm geeft aanleiding tot relatief grote verplaatsing van de gedrukte flenzen van de damwand. Deze relatief grote verplaatsingen suggereren dat in het geval van grondomhulling, de grond mogelijk een significante invloed kan hebben in het onderdrukken van deze verplaatsingen en daarmee kan bijdragen aan sterkte van het profiel.
- Uit een vergelijk met PLAXIS 3D volgt dat er voor dit onderzoek geen significante verschillen lijken te zijn tussen het gebruik van het relatief eenvoudige Mohr Coulomb (MC) grond model en het meer geavanceerde Hardening Soil (HS) model. Op basis hiervan is besloten om het MC model te gebruiken in de Abaqus modellering.
- Voor de versimpelde geometrie is een toename in piek sterkte gevonden, voor de situatie met grondinbedding ten opzichte van de situatie zonder grondinbedding, van +13% voor een gemiddeld stijve grond en +20% voor een stijve grondslag. De rekenresultaten suggereren ook een kleine toename in de vervormingscapaciteit na de piek sterkte.
- Het is binnen de project randvoorwaarden niet mogelijk gebleken tot een voldoende geconvergeerd Abaqus model met de werkelijke damwand geometrie met grondinbedding te komen. Een dergelijke model is numeriek (te) uitdagend voor dit moment.

In het rapport is verder een hoofdstuk met discussie opgenomen om de juiste context te schetsen bij de gemaakte eindig elementen berekeningen. Dit hoofdstuk bespreekt aspecten welke relevant worden geacht maar niet expliciet zijn beschouwd of gevarieerd in dit onderzoek.

Gebaseerd op de resultaten van het onderzoek, met in gedachten de discussie rondom andere relevante aspecten, wordt geconcludeerd dat (nog) geen eenduidig antwoord kan worden gegeven op de onderzoeksvraag. Het is sterk afhankelijk van de situatie of de effecten van grond inbedding voldoende significant zijn en de moeite van het verder onderzoeken en kwantificeren waard zijn.

Evaluatie en vooruitblik

Het uitgevoerde onderzoek maakt aannemelijk dat, in niet-slappe grond condities, er een zekere hoeveelheid extra sterkte aanwezig is voor klasse 4, lokaal knik gevoelige, damwand profielen. Of het de moeite waard is deze extra sterkte verder te onderzoeken hangt sterk af van de situatie.

Generieke aanbeveling is dat damwand producenten (zoals ArcelorMittal) en asset managers (zoals Rijkswaterstaat) kennis nemen van dit onderzoek en voor hun situatie afwegen of verder onderzoek zinvol is voor hun situatie.

Deltares

The influence of soil embedment on the strength of a corroded AZ18-800

A finite element study

ArcelorMittal

The influence of soil embedment on the strength of a corroded AZ18-800
A finite element study

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1 Introduction

1.1 Background

Within the framework of the research programme ‘Natte Kunstwerken’ ArcelorMittal (AM) and Deltares (DLT) collaborate in a TKI- research project related to service life expectancy of steel sheet piles in Hydraulic Structures. Within this TKI-project both parties have committed to (further) developing knowledge and tools for assessment of these types of structures.

One part of the TKI-research project aims at improving the prediction of strength of thin walled (strongly corroded) steel sheet piles embedded in soil. When sheet piles become so thin walled that they experience local instability effects (“buckling”), preventing them from reaching the elastic bending moment capacity, they are referred to as Class 4 type sections in the jargon of Eurocode 3. As a result, their capacity must be reduced significantly using the Eurocode approach. In the Eurocode approach the expected positive influence of soil embedment is however not accounted for. At this moment there is no good insight in how much extra capacity (different types of) soil embedment provide and no agreed method how to quantify this effect.

This report presents the combined ArcelorMittal and Deltares effort of a systematic numerical study towards how and when soil embedment may have a positive effect on Class 4 sheet piles. This study is considered relevant as there is a tendency in the (civil engineering) market to use ever more optimized (slender) new sheet pile profiles while at the same time asset managers try to maximize the service life of their sheet pile acreage.

1.2 Dutch research programme ‘Hydraulic Structures’

Within the research programme Hydraulic Structures (Dutch: Kennisprogramma ‘Natte Kunstwerken’) the Dutch knowledge institutes Deltares, TNO and Marin develop in cooperation with the Dutch Ministry of Infrastructure and Water Management (Dutch: Rijkswaterstaat) knowledge to prepare for the vast replacement task of old Hydraulic Structures in the Netherlands. Also see the website: https://www.nattekunstwerkenvandetoekomst.nl/.

The aim of the research programme is to develop knowledge that allows for:

- An efficient use of technical and functional remaining life expectancy.
- Design of a new structure:
    - Where innovative solutions can be used.
    - That is adaptable to future needs.

In relation to an efficient use (maximum residual life) of existing hydraulic structures it is essential that the structure can be realistically modelled and as such the dominant uncertainties can be reduced. One of these aspects is the behaviour of thin walled steel sheet piles in combination with a soil embedment.

1.3 Previous work done

Within the context of the research programme Hydraulic Structures some first exploratory calculations were performed by Deltares with PLAXIS into the beneficial effects of soil embedment on the strength of slender sheet piles. Furthermore, at the start of this TKI project

ArcelorMittal and Deltares performed some additional (validation) tests with Abaqus and PLAXIS. Also see appendix A.

The results of these first calculations suggested there may be a significant effect and that it may be worthwhile to perform a further numerical study. Since these first calculations also indicated the limitations of PLAXIS of modelling structural behaviour it was clear that a further numerical study should also make use of a more structural FE package like Abaqus.

1.4 Research goals

The main goals related to the research into the behaviour of thin walled steel sheet piles embedded in soil are:

- *How much extra capacity do, local buckling sensitive, Class 4 sections have when embedded in soil?*
- *How can this extra capacity be quantified in a reliable manner?*

To achieve this goal a mixed approach is expected to be needed, i.e. a combination of numerical and experimental work.

The sub goal set for this TKI research project is:

To investigate by means of a finite element (FE) study if the effects of soil embedment on the capacity of thin walled sheet piles are significant, i.e. is it worthwhile to further investigate the effects of soil embedment with physical scale testing?

Special attention points:

- How realistically should the soil be modelled, i.e. which type of constitutive soil material model should be used in the FE model?
- Are the beneficial effects of the soil embedment related to both a possible increase in (peak) strength and/or an increase in rotation capacity?

1.5 Approach and outline of report

Local buckling is a complex structural mechanism. This mechanism is in general studied with structural finite element (FE) programs such as DIANA or Abaqus, which have specific tools to deal with buckling (e.g. efficient methods of applying initial eccentricities and dealing with post-buckling behaviour). The options for modelling soil and soil-structure interaction however are in general more limited in these structural finite element (FE) programs.

When dealing with soil and soil-structure interaction in general use is made of different FE programs that have more focus on the modelling of soil behaviour. Such a program is PLAXIS which enables the use of a range of constitutive soil models. These constitutive soil models allow for modelling effects such as stress and stress path dependent stiffness and strength and soil arching. The options for modelling structures and complex mechanisms such as local buckling are in general however more limited.

To reach the formulated sub goal of this TKI research project it is anticipated to use a mix of PLAXIS and Abaqus analyses. The results of the Abaqus models are first used to verify the structural results of the PLAXIS models for the situation without soil. Then the PLAXIS models are used to investigate the effects of the used constitutive soil model. With the latter results and insights, a choice is made for the soil model to be used in Abaqus for the final calculations.

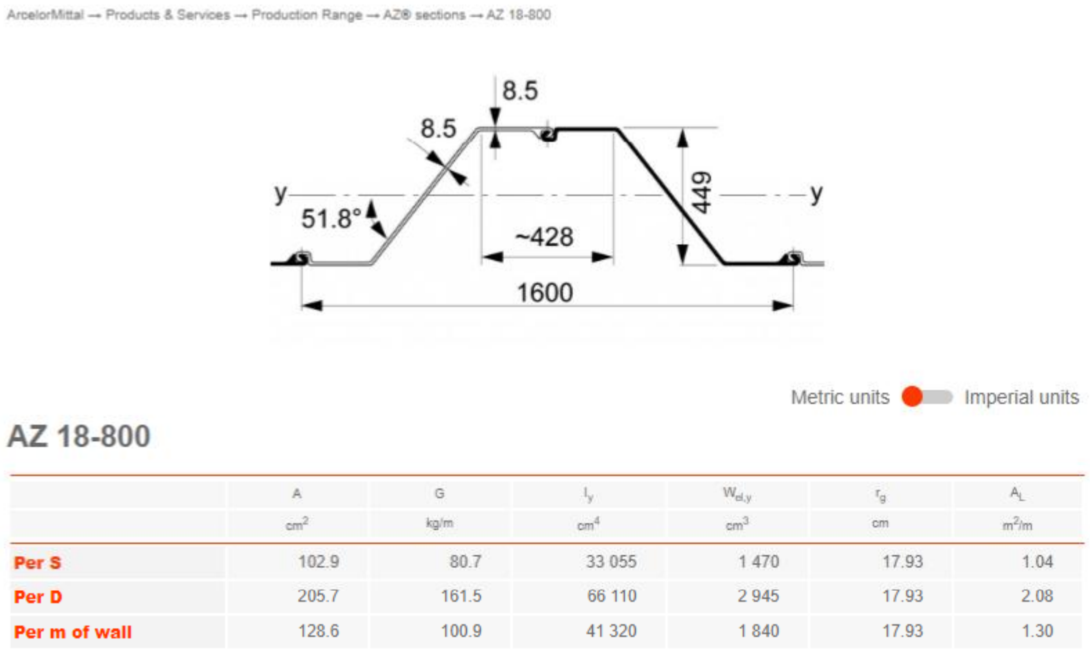
The outline of the report is chosen in the following manner: in Chapter 2 the starting points for the Case Study are elaborated. In Chapter 3 first the response of the sheet pile without soil embedment is analysed. In Chapter 4 the soil effect is studied in PLAXIS using different constitutive soil models. With the results and insights found here the analysis is made in Abaqus with soil and reported in Chapter 5. Chapter 6 discusses in a more qualitative manner other relevant variables and issues. Finally, in Chapter 7 the main findings are presented as well as a conclusion based on these findings.

2 Starting points for Case Study

2.1 Introduction

In the search for a good Case Study the following arguments played a role:

- A slender profile, that with some corrosion should become a Class 4, such that local buckling becomes decisive for the strength over the elastic capacity.
- Ideally a Z profile is used as these types of profiles are in general preferred by the market due to their economic weight to strength ratio.



AZ 18-800

	A	G	I_y	$W_{el,y}$	r_g	A_L
	cm^2	kg/m	cm^4	cm^3	cm	m^2/m
Per S	102.9	80.7	33 055	1 470	17.93	1.04
Per D	205.7	161.5	66 110	2 945	17.93	2.08
Per m of wall	128.6	100.9	41 320	1 840	17.93	1.30

Figure 2.1 Properties of the AZ18-800 sheet pile

2.2 FE model set-up

When the interaction of the sheet pile with the soil becomes relevant then ideally the full 3D situation, i.e. full sheet pile length + soil, is modelled. This would include amongst others the full length of the wall, a large part of the soil including relevant boundary conditions at a sufficiently far distance, the relevant phases and a sufficient fine mesh to make sure the detail level where the local buckling in the sheet pile happens is included. See Figure 2.2 for an illustration of such a situation. Such a model is however expected to become too large and complex for this TKI project. It was therefore decided upfront to choose a different approach with a smaller and simpler model.

How such a smaller and simpler model should look like is debatable. There is no evident choice. Here it was decided to start from the four-point bending test which is commonly used for investigating the strength of sheet piles sections.

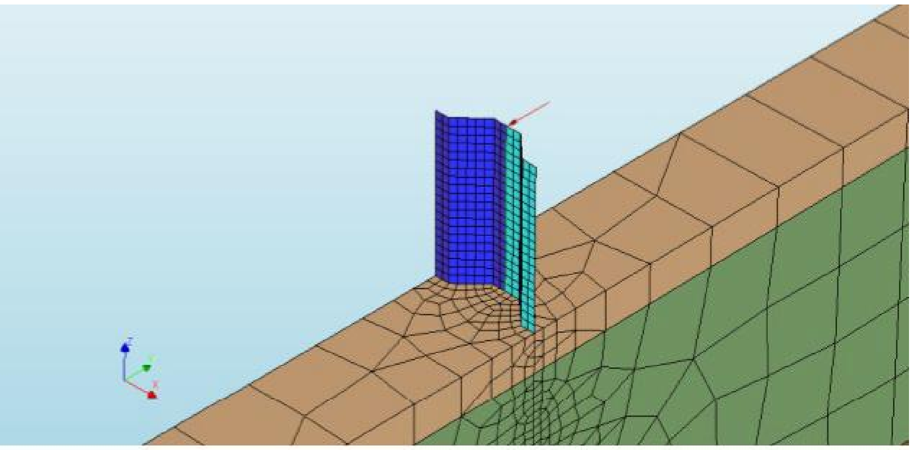


Figure 2.2 Illustration of full 3D sheet pile model including wall and soil

Four-point bending

Common approach when investigating the (bending) strength of steel sheet pile sections is performing a four-point bending test. Advantages of this test is that it is relatively easy and straight forward to perform and a pure bending moment (no shear forces) in the middle part of the “beam” is obtained which makes interpretation of results easier. See Figure 2.3 for an example of such a test.

It is also feasible to model such tests in an FE model, see Figure 2.4. It is known that these FE models can come to realistic results, i.e. results that are comparable to the results of a real test.

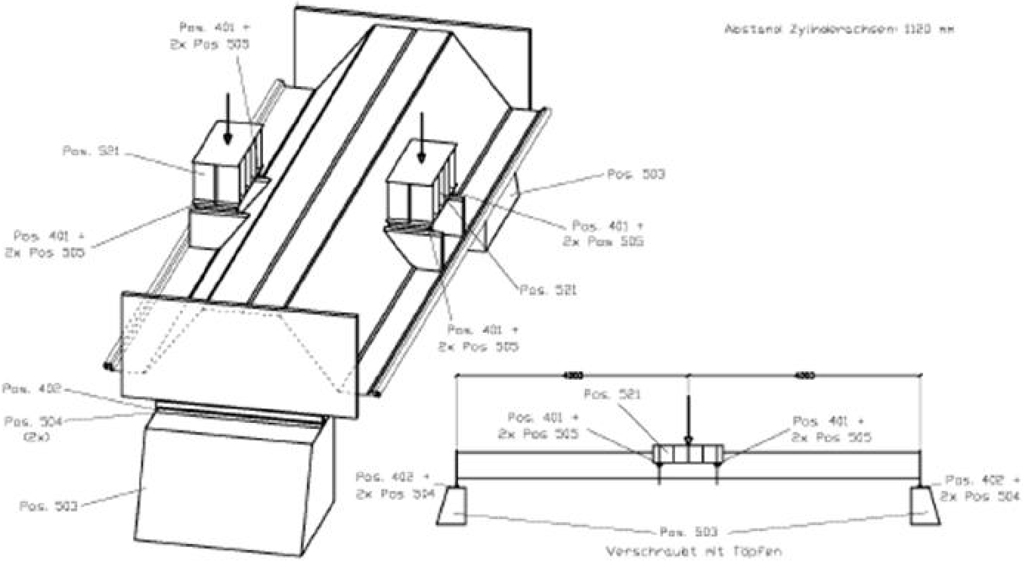


Figure 2.3 Principle of a four-point bending test on a sheet pile section

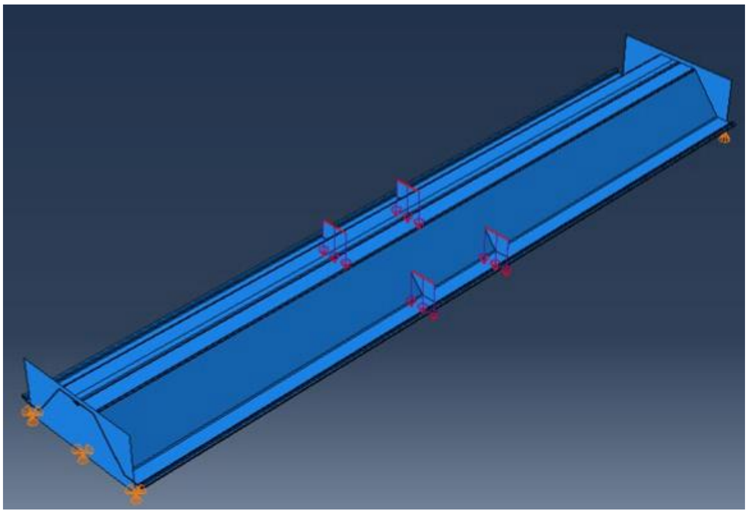


Figure 2.4 Abaqus FE model of a four-point bending test on sheet pile wall. Using a stiffener plate at the support point. Load introduction by means of prescribed displacements at the lower (tensile) flanges

Four-point bending with soil

The approach chosen in this TKI project is to add soil to the four-point bending test in the FE model. An example of how this looks like is shown in Figure 2.5. Note that in this figure use is made of symmetry, only half of the span of the four-point bending test is modelled.

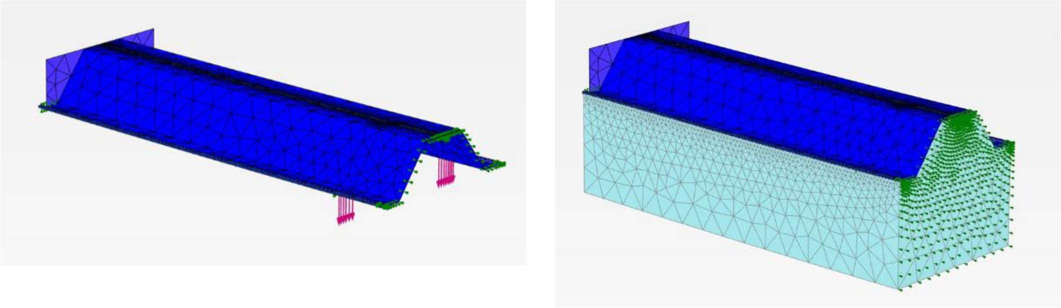


Figure 2.5 PLAXIS FE model of a four-point bending test without soil (left) and with soil (right). Note that here use is made of symmetry, only half of the span of the four-point bending test is modelled. The small green arrows in the figure indicate boundary conditions used to impose the symmetry conditions

Four-point bending with soil versus a cantilevered sheet pile wall

A logical question that can be asked is: how does such a four-point bending test with soil compare to a real-life situation? It may be argued that the four-point bending test with soil has similarities to a cantilevered sheet pile. See Figure 2.6.

There are of course obvious differences between the two situations, but the curvature imposed on the sheet pile is similar.

Furthermore, it may seem that in the four-point bending test the sheet pile wall is ‘pushed into’ the soil, whereas in the cantilevered situation the soil pushes on the wall. But by applying stress-controlled boundaries (instead of deformation-controlled boundaries) on the soil in the four-point bending test similar behaviour is obtained.

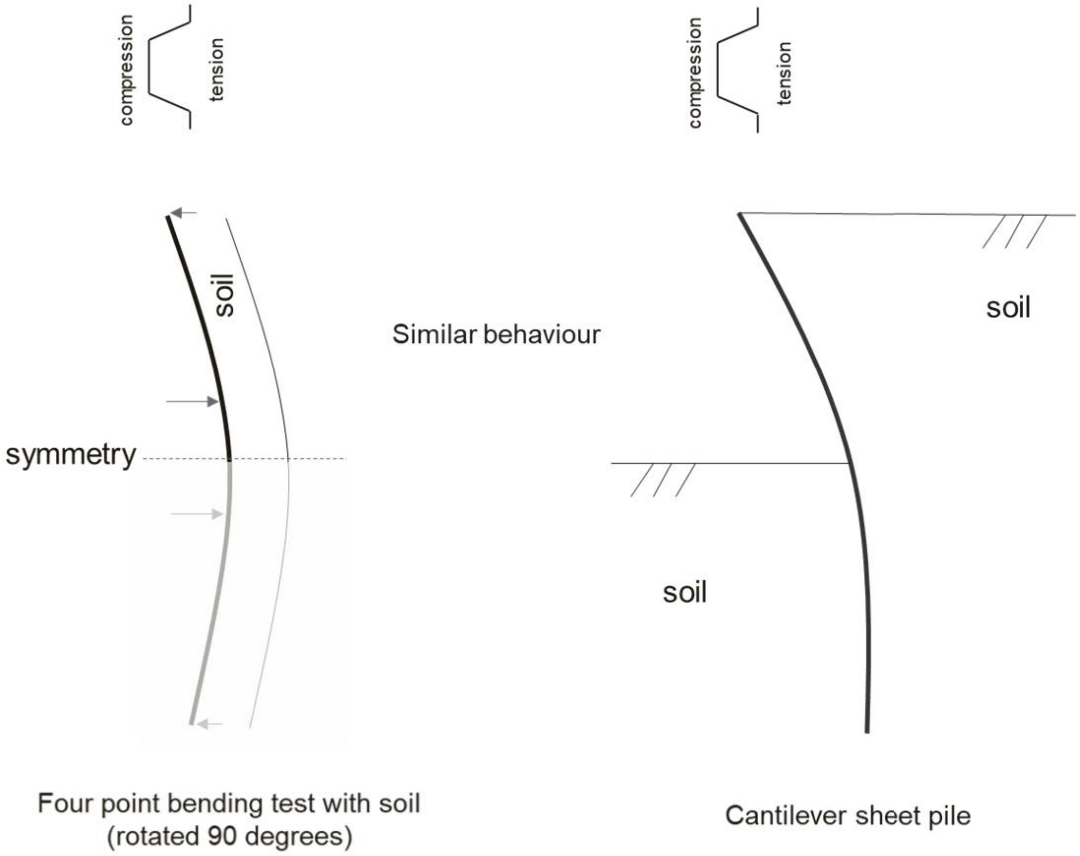
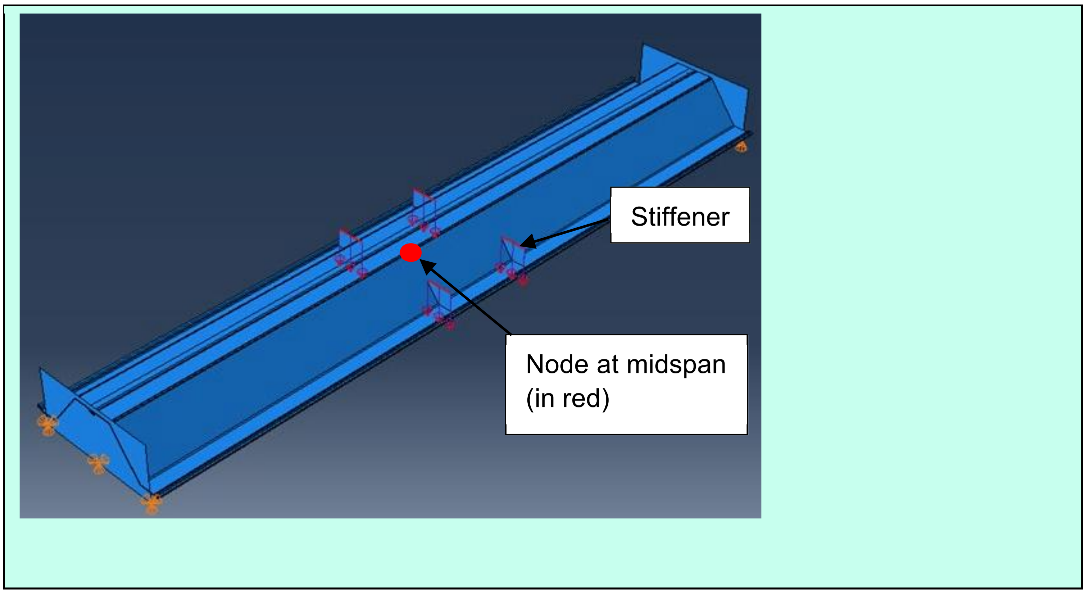


Figure 2.6 Comparing the four-point bending test with a cantilevered sheet pile wall. The bending behaviour / curvature is similar

Further details about the modelling of the sheet pile and the soil are presented in the following paragraphs.

Load-displacement curve

To gain insight into the strength of the sheet pile and the effects of soil support use is made of so-called load-displacement curves in this report. In a graph the total applied load on the structure is plotted against the vertical deformation of a reference point. The total applied load is the total applied load at the four stiffeners and is equal to the sum of the reaction forces in the two supports. Two different locations have been used in this study for the reference point: the (average) vertical deformation of the stiffeners and a point selected at midspan at the corner between compressed flange and web. Also see the graph below. It was noted the vertical deformation at midspan is somewhat larger than at the location of the stiffeners, however differences are relatively small. In the graphs presented in this report the reference point at midspan is used.

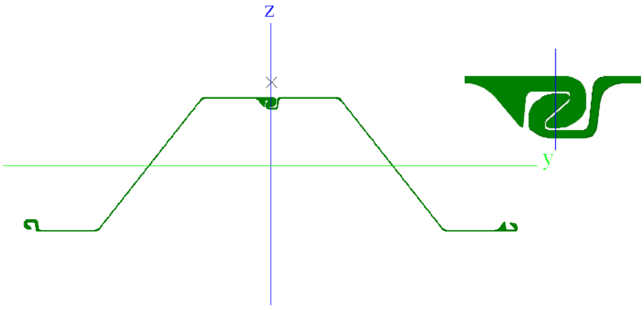


2.3 Modelling the sheet pile geometry

For the modelling of the sheet pile geometry it was decided to use both the exact geometry as well as a simplified version of the geometry. See Figure 2.7. The reasons for including a simplified version of the sheet pile section are:

- It is not feasible to include the exact geometry in PLAXIS, for this a simplified model is needed.
- Running an exact model with detailed interlock modelling with contact elements is complicated and may result in numerical issues and long calculation times even in Abaqus. A simplified model may allow for quicker analysis in this stage of the research.

To come about the simplified geometry for AZ18-800, a simple trace was done on of the exact geometry and considering the limitations of PLAXIS, all the curvatures were converted to straight lines with uniform thicknesses in flanges and webs except in interlocks. The two single sheet piles are connected through a thin element to behave as one for numerical reasons, although still allowing for some flexibility.
Several trials were made on the shape of the interlock always checking for the following main geometrical properties: Area, Inertia and Modulus. The difference between the exact and simplified geometries in terms of properties always remained lower than 2%, which was assumed to be reasonable to continue further analysis. The characteristic cross-section properties were sought using structural analysis program SCIA and the final simplified interlock shape can be seen in Figure 2.7.



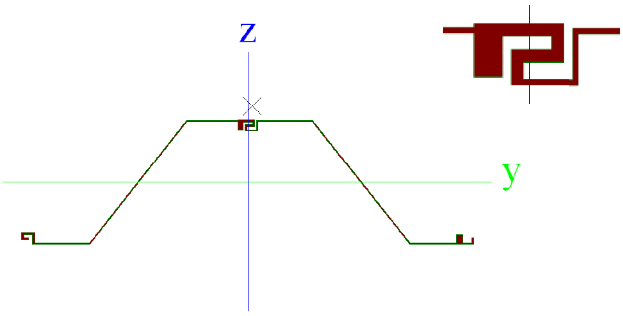


Figure 2.7 *Exact sheet pile geometry (top) vs. simplified geometry (bottom). The simplifications are introduced by using straight sections to simulate the interlocks and corners. Note that these are both the corroded sections, i.e. from one side (back) up to 4mm*

Corrosion

A following choice is related to the amount of corrosion that is included in the sheet pile geometry. Corrosion may be expected to occur during the life span of a steel pile structure. As an effect the pile will become slenderer and hence more prone to local buckling effects.

In this study multiple corrosion rates were considered but finally the following choices were made:

- A uniform amount of corrosion on all parts of the sheet pile.
- An amount of corrosion was chosen such that the flanges are reduced in thickness from 8.5 mm to 4 mm. This is effectively a corrosion value of 4.5 mm. These kind of corrosion values are considered realistically for (unprotected) structures fully embedded in the soil with an expected lifespan of 100 years or (unprotected) partially embedded waterfront structures with a lifespan of 50 to 100 years.
- Cross-section is reduced from one side only (back).

2.4 Modelling the soil

Modelling soil is complex. Different types of soil occur, i.e. clay or sand. The density of the soil may vary, i.e. loose to dense. Furthermore, it is known that the behaviour of soil is dependent on many things, amongst others one can distinguish stress and stress path dependency. Stress dependency means that when soil is subjected to higher (mean) stresses it will behave stiffer and stronger. Stress path dependency means that soil will behave different when loaded in shear, volumetric compression or unloading/reloading. In the different area's around a sheet pile one can distinguish all these different stress levels and different stress-paths. Around a sheet pile one may furthermore distinguish more active states (i.e. the soil pushes on the sheet pile) or more passive states (i.e. the sheet pile pushes on the soil).

It will also make a difference whether the soil is present on only one side of the sheet pile or on both sides of the sheet pile. Within this TKI study it is not possible to analyse all possible soils and conditions. As such some choices are made for the situations analysed. Arguments used here:

- Conditions chosen are relatively simple for this study.
- The situation chosen is not too pessimistic as to be able to show the potential, but neither too optimistic to prevent over-estimating potential.

From a list of possible options given in Table 2.1, options 3 and 5 are selected for this study.

#	Soil one sided	Soil two sided	Soft soil	Medium stiff soil	Stiff soil	Comment
1	X		X			Not analysed
2		X	X			Not analysed
3	X			X		Analysed
4		X		X		Not analysed
5	X				X	Analysed
6		X			X	Not analysed

Table 2.1 Possible options for modelling the soil around the sheet pile

Applying the soil in the FE model
The soil is applied to the sheet pile and stress-controlled boundaries are applied to the soil. The purpose of these stress-controlled boundaries is:

- To generate 'internal' stresses in the soil such that a strength and stiffness is generated. Note that without the stress boundaries the soil (modelled with MC or HS) would have no strength (or stiffness in case of HS model).
- To be able for the soil to move along with sheet pile when it is displacement controlled loaded by the four-point bending.
- By varying the ratio between the stresses on the boundaries one can simulate a more active, neutral or passive stress state in the soil. The principle of this approach is shown in Figure 2.8.

Note that in the calculation first the stress-controlled boundaries need to be applied to the soil before activating the displacement-controlled loading of the sheet pile.

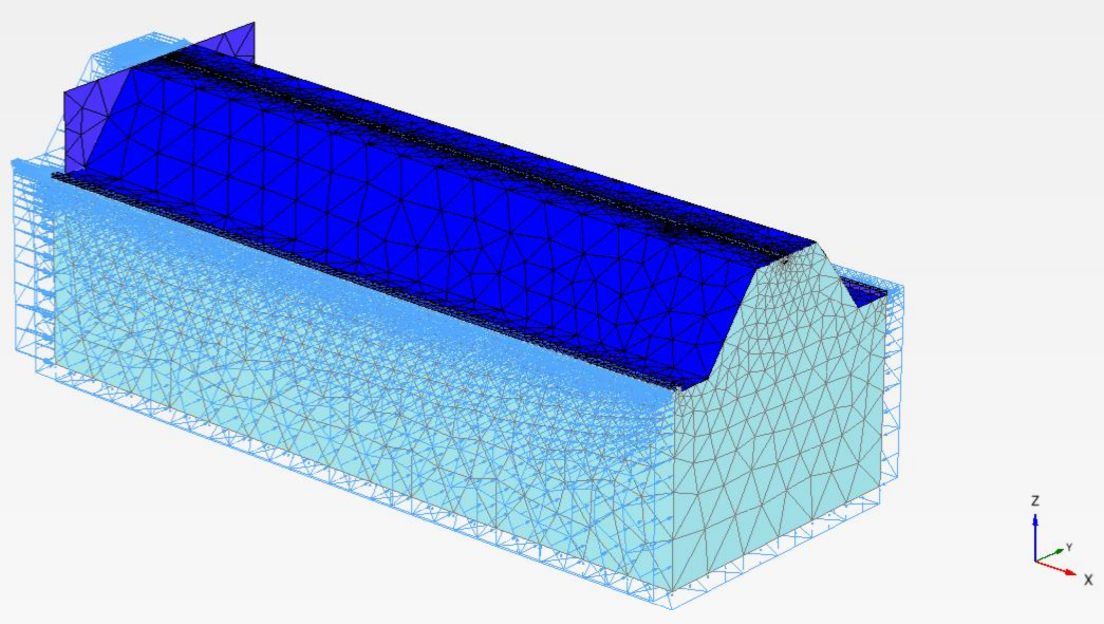


Figure 2.8 PLAXIS FE model of a four-point bending test with soil. Note that here use is made of symmetry, only half of the span of the four-point bending test is modelled. By means of surface stresses a stress-controlled boundary condition is applied to the soil. Note: the boundaries in y-direction may perhaps also be taken as fixities to account for plane strain behaviour. For now, it is chosen to use stress-controlled boundaries as this would seem the more conservative approach (related to judging the effect of the soil embedment)

Half symmetric model in PLAXIS
As explained before it is not desired feasible for this project to use a large FE model which includes the full sheet pile wall and surrounding soil. Especially for modelling in PLAXIS this was expected to be relevant. It was therefore chosen to make use of half a four-point bending test in PLAXIS. The principle of this approach is shown in Figure 2.8.

Constitutive soil model and model parameters
The material models considered in PLAXIS are the relative simple Mohr Coulomb (MC) model and the more advanced Hardening Soil (HS) is considered. For more background information on these constitutive soil models reference is made to [Plaxis manuals]. An active soil state is considered.

Soil type	Friction angle	Secant stiffness (HS)	Youngs modulus (MC)	Cohesion	Dilatancy angle	Stresses Vertical / K_0 / K_a	Friction angle soil-sheet pile interface
	ϕ[deg]	$E_{50;ref}$ [kPa]	E' [kPa]	c [kPa]	ψ [deg]	$\sigma'_{1/2/3}$ [kPa]	δ [deg]
Medium stiff	30	1.00E+04	3162	1	0	30 / 15 / 10	21
Stiff	35	4.50E+04	12831	1	0	30 / 13 / 8	25

Table 2.2 Soil parameters used for the two different types of soil analysed and the two different constitutive material models (HS) and (MC)

Furthermore, following assumptions and starting points used:

- For the vertical stress a value of 30 kPa is assumed, which corresponds roughly to a depth of 2 to 3 m below soil surface in Dutch soil conditions.
- $K_0 = 1 - \sin(\phi)$.
- $K_a = (1 - \sin(\phi)) / (1 + \sin(\varphi))$.
- $E' = E_{50;ref} * (\sigma'_3/p_{ref})^m$ (assume m = 0.5 and p_{ref} = 100 kPa).
- $\delta = \mathrm{atan}(2/3 * \tan(\phi))$.
- Soil behaves in a drained manner.
- Tension cut off = 0 in soil.

In Abaqus the relative simple MC model will be used. By means of the sensitivity analysis in PLAXIS it can be judged to what extend the soil constitutive model will influence results.

2.5 Other relevant model aspects

Since PLAXIS and Abaqus are different programs it may be required to use a different model set up. In Table 2.3 the most relevant model aspects and settings are shown for both the PLAXIS and Abaqus models.

Variable	PLAXIS 3D	Abaqus
How to model structure	Shell elements	Shell elements for simplified geometry. Volume elements for the exact geometry
Sheet pile shape	Simplified: • Interlock simplified • Straight corners	First simplified (ala PLAXIS 3D) then as realistically as possible.
Steel stress-strain curve	Elasto-perfect plastic with a yield stress of 430 N/mm^2	See Figure 2.9.
Soil-structure interaction	Yes, using default interface. Delta = atan(2/3 * tan(φ))	Surface to surface (standard). Alternatively, surface to node.

Variable	PLAXIS 3D	Abaqus
Interlock Friction	N/a	Friction coefficient of 0.19
Soil approach and material model	As continuum using default material models: MC and HS	As continuum using default material model MC. Possibly start even with Linear Elastic.
Soil stiffness and strength	Use of two different material sets. See Table 2.2	Material set for MC
Boundary conditions	Such that (part of) a four-point bending test is modelled	Such that (part of) a four-point bending test is modelled
How to model initial eccentricities	By using small loads	Superposition of weighted mode shapes. Alternatively, manually add small geometric imperfection(s).
Geometrical non-linear	Yes by using UM functionality	Yes
Load or displacement controlled	Displacement controlled	Displacement controlled or Riks

Table 2.3 Model set up in PLAXIS vs Abaqus

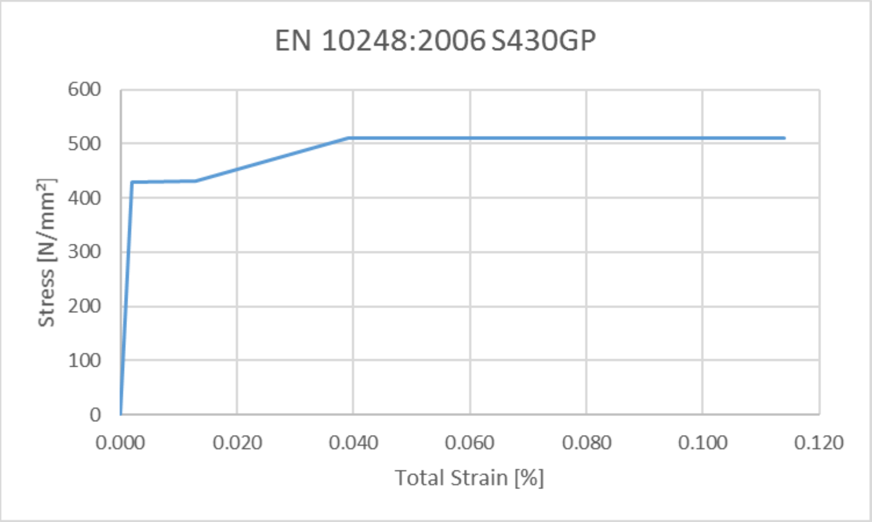


Figure 2.9 The used material curve in Abaqus

2.6 Model runs to be made

The calculations to be made are listed below in the table. The runs are indicated with the numbers (1) to (6).

AZ18-800 (*)	PLAXIS	Abaqus
Exact – corroded 4 mm – no soil	-	1
Simplified – corroded 4 mm – no soil	3	2
Simplified – corroded 4 mm – with soil	4 (**)	5 (***)
Exact – corroded 4 mm– with soil	-	6 (***)

Table 2.4. FE models to be run

Notes:
(*) The coding of the different calculations is:
AZ18-800_[ABQ/PLX]_[Exact/Simp]_[Corr/Nocorr]_ [Nosoil/MC/HS]”

(**) Calculation (4) consists of a series of calculations using different soils and different constitutive models. Main question to be answered: is there a, for buckling, relevant fundamental difference in behaviour between MC and HS for this situation?
(***) calculation 5 and 6 consist of a series of calculations, for both medium stiff and stiff soils

Based on this sequence of calculations the following questions are to be answered:

- (1) -> (2) -> (3) series:
  - What is the effect of simplifying the sheet pile geometry?
  - Do PLAXIS and Abaqus generate similar results for the simplified geometry?
- (3) -> (4) series.
  - First insight into effect of adding soil to the sheet pile?
  - What are the effects of using different constitutive soil models?
  - How large is the error if MC is used in Abaqus?
- (4) -> (5) series:
  - Insight into differences between PLAXIS and Abaqus.
  - Are the effects in Abaqus similar to Plaxis, why or why not?
- (5) -> (6) series:
  - What are the differences between exact and simplified model?
  - What are the expected effects of adding soil?

2.7 Verification and validation of FE models

Relevant questions that come to mind when using an FE model:

- Is the model able to ‘predict’ the relevant effects?
  - Is PLAXIS able to model local buckling in a sufficient manner?
  - Is Abaqus able to model soil behaviour in a sufficient manner?
- Are the model results realistic?

Here by ‘verification’ it is meant the process of checking that the FE model is working as it is anticipated, i.e. the output is logical. Verification of the models has been done in this project by running models both in PLAXIS and Abaqus and comparing results.

Here by ‘validation’ it is meant the process of checking that the FE model is able to represent reality in a sufficient manner. Validation of model results has been done by comparing FE results with results of physical scale testing. Also see appendix A

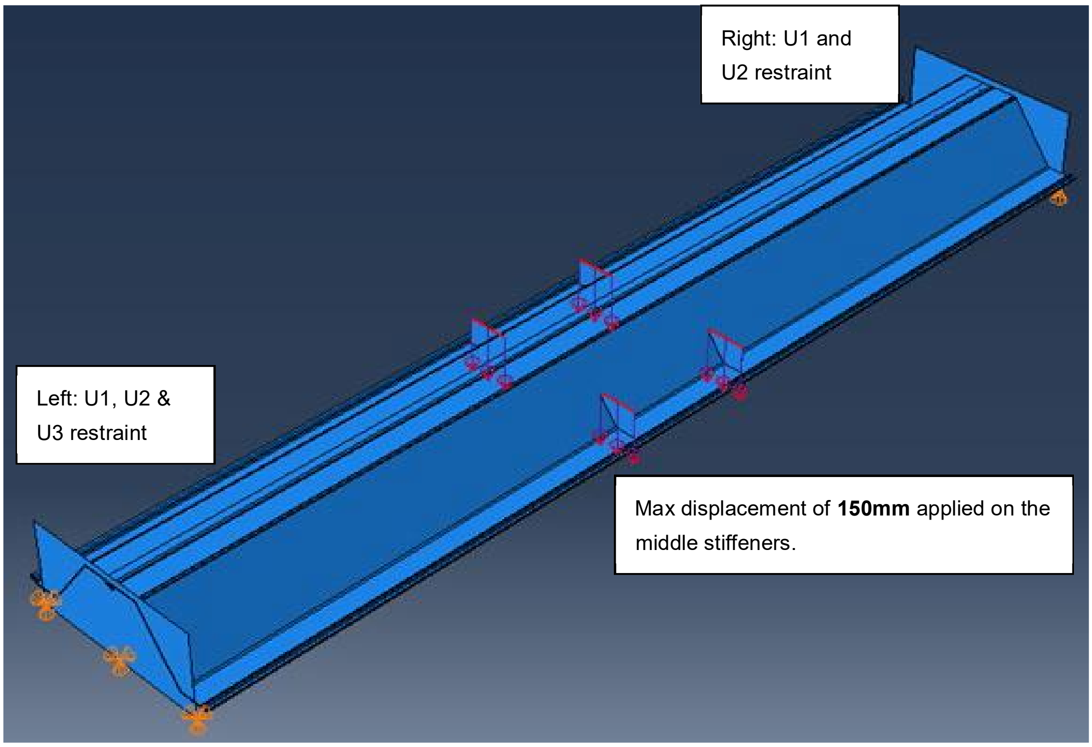
3 Case Study without soil

This chapter discusses the finite element (FE) models in Abaqus and PLAXIS without soil. At first, the FE model expected to approach reality in the best possible way is run, i.e. the Abaqus model with the exact geometry using contact elements to simulate the interlock. Next, the geometry in the Abaqus model is simplified, to be able to implement the geometry in a PLAXIS analysis, and it is investigated how much this approach differs from the exact geometry. Finally, the simplified geometry is implemented in a PLAXIS model and it is investigated how much this approach differs from the Abaqus approach. This PLAXIS model is the starting point for the analyses in the following Chapter with soil (Chapter 4). The Abaqus model with simplified interlock geometry as presented in this chapter also is the starting point for the Abaqus analyses with soil (Chapter 5).

3.1 ABQ, exact geometry (1)

The general dimensions and starting points are explained in the previous chapter. The FE model is shown in Figure 3.1. The interlock is modelled using contact elements with a friction penalty/coefficient of 0.19. An elastic material is used for the stiffeners and end plates. A S430GP steel quality is used for modelling the steel sheet pile section.

The numerical analysis model (Figure 3.1) created in Abaqus tries to mimic the experimental setup shown in Figure 2.3.



*Note
Where U1,U2 and U3 are local x, y and z direction as shown in Figure 3.3.

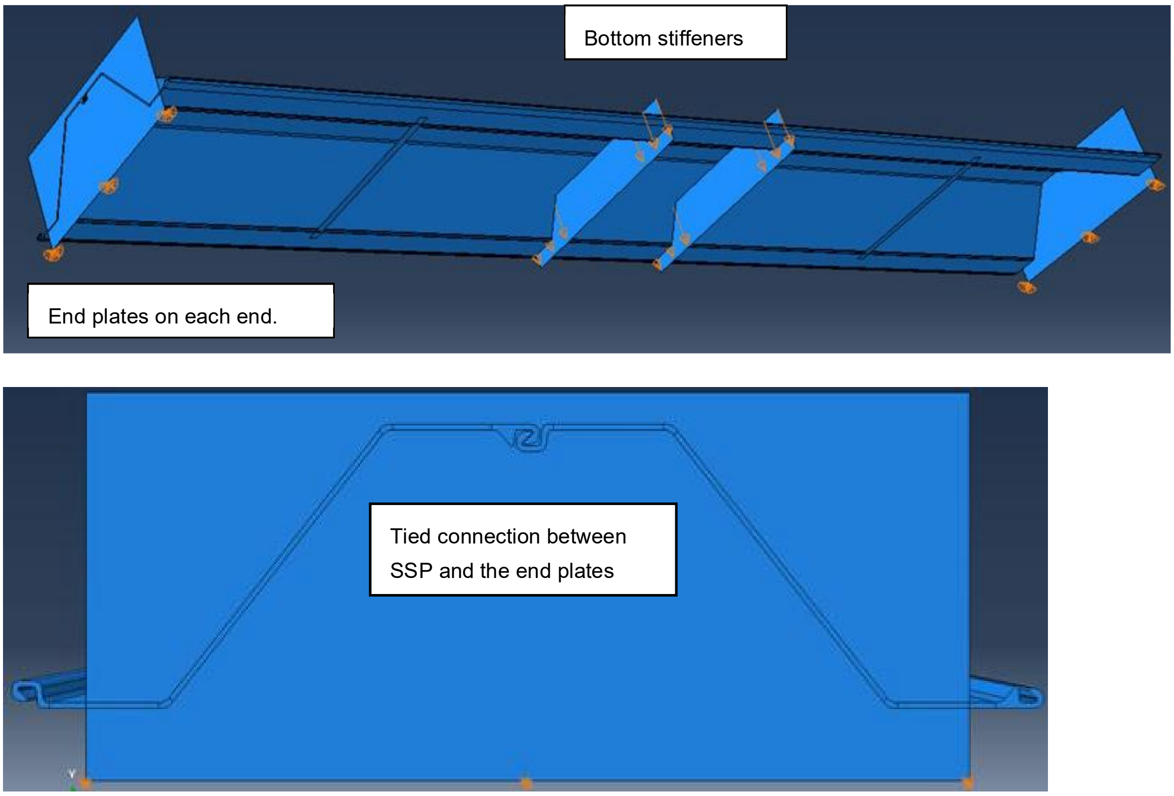


Figure 3.1 A top view of the Abaqus FE model of the four-point bending test is shown in the top figure. The middle figure shows a bottom view of the FE model. The bottom figure shows a side view of the end plate

Numerical model assumptions:

Meshing and Element types:

Flanges and webs of the SSP (except curvatures) are modelled as continuum shells using SC8R element type with at least 4 elements per thickness. The interlock and the corners are modelled using solid elements of type C3D8R as shown below.

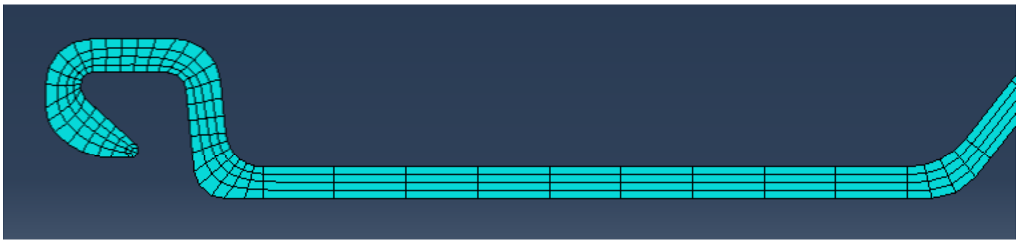


Figure 3.2 Meshing of elements

Constraints and Contact

The stiffener plates at the ends and in the middle are tied to the SSP, replicating welded connection, where as in interlock a contact with tangential behaviour is assumed with a friction value of 0.19.

Analysis Type

Convergence was reached using standard static general analysis.

Numerical Analysis Outputs

Output of the analysis for the exact corroded geometry is shown in Figure 3.3 and Figure 3.4. Respectively deformed mesh at the peak load was shown and load deformation curves were plotted. Note that in appendix B as a reference the output for the exact uncorroded geometry is presented.

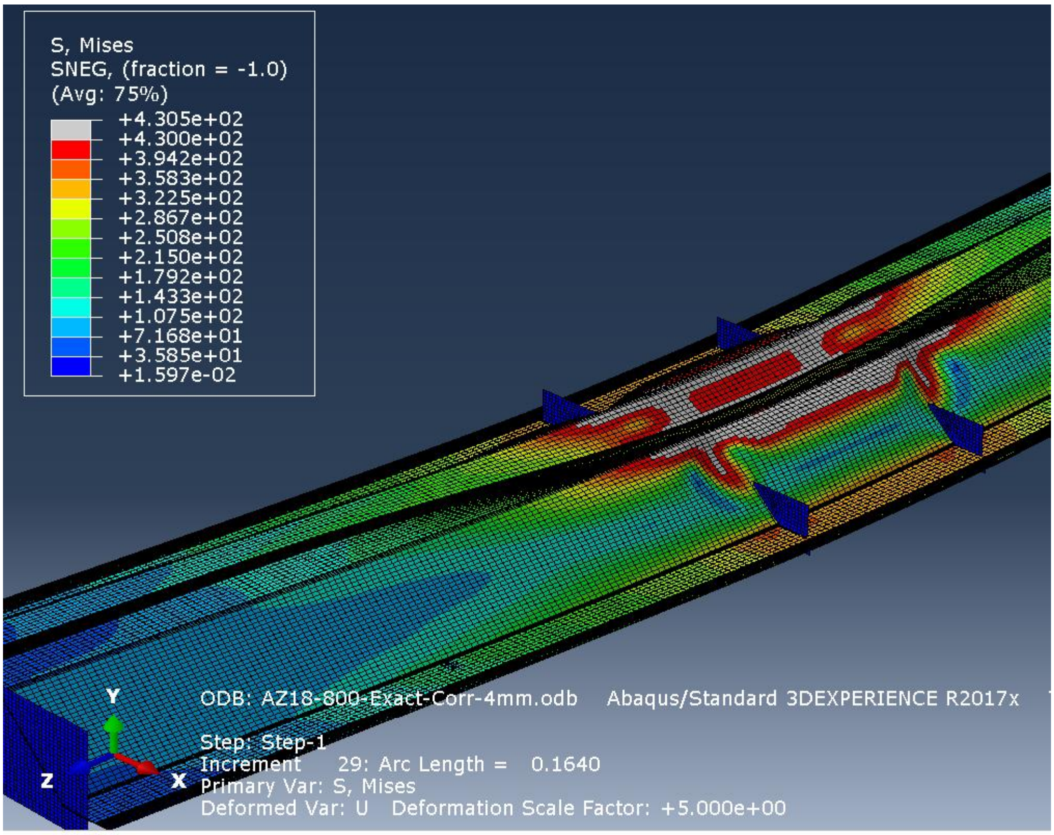


Figure 3.3 Deformed shape (V,Mises stress) , just before buckling load for AZ18-800 (Exact, corroded geo)

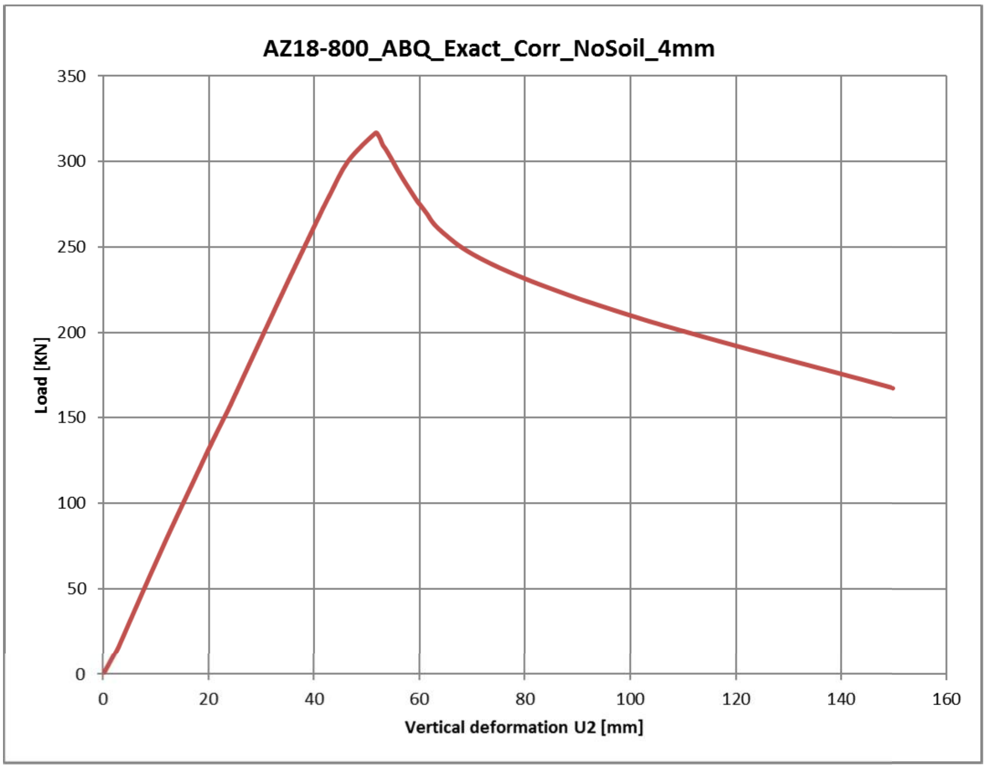


Figure 3.4 Load-deformation curve for AZ18-800 (Exact, corroded geometry). The load on the vertical axis is the total load applied in the four-point bending test. The value shown on the horizontal axis is the vertical deflection at midspan

3.2 ABQ, simplified geometry (2)

The general dimensions and starting points are explained in the previous chapter. The FE model as shown in Figure 3.1. is adjusted such that the exact geometry of the sheet pile section is replaced with the simplified geometry as shown in Figure 2.7.

For the simplified geometry similar assumptions for the FE model setup are used as previously done with exact geometry, except for contacts in the interlock, which are no longer required in simplified geometry. As mentioned in section 2.3 the sheet pile is corroded up to a thickness of 4 mm (flanges and web). Analysis on this very slender cross-section results in different buckling shape at failure as shown below compared to the simplified uncorroded geometry as shown in appendix B.1.

To overcome the convergence issues of the models, static general method was replaced by RIKS analysis to get the post buckling behaviour. The deformed shape and load-displacement curves are shown in the figures below.

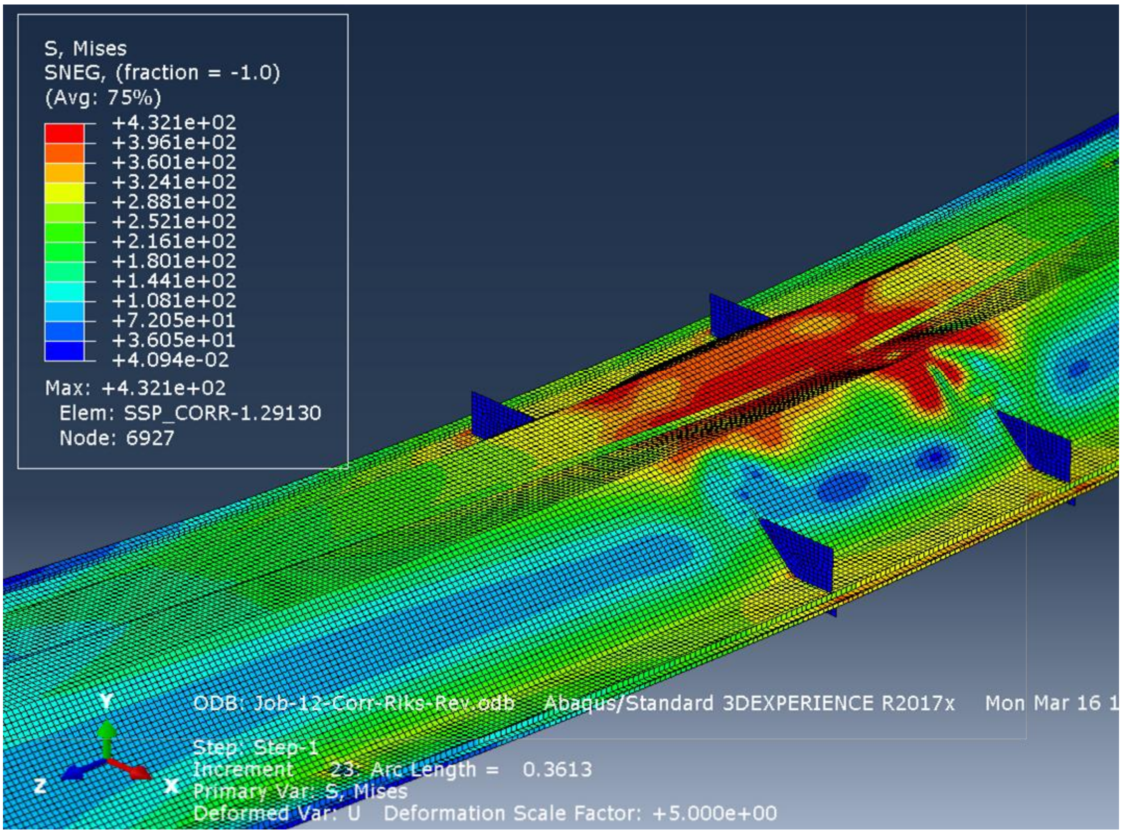


Figure 3.5 Deformed shape at peak load (simplified, corroded geometry)

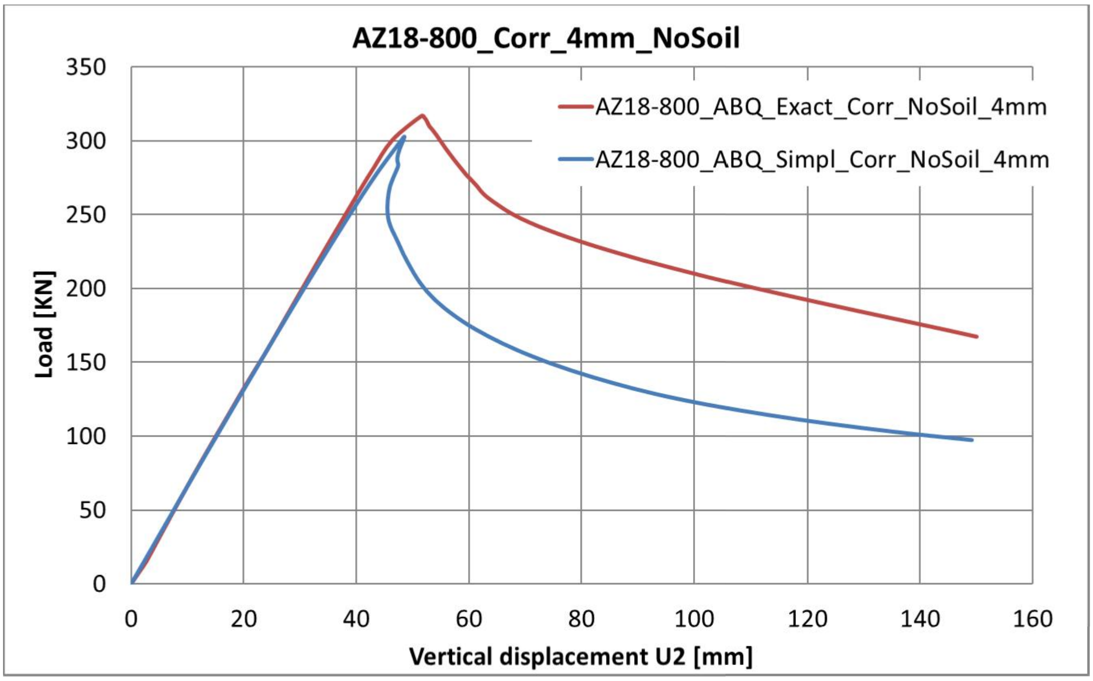


Figure 3.6 Load-deformation curve for corroded simplified and exact cross-section

Comparison of the simplified and exact corroded geometries shows good concurrence of the peak loads. Whereas the buckled shape of the corroded cross-section shows more distortional behaviour compared to more localised failure in uncorroded cross-section (see appendix B.1).

The main findings from the Abaqus analysis were verified using the finite strip method, CUFSM. The results from the CUFSM analyses are reported in appendix B.2 and confirm the main findings from the Abaqus analyses:

- Distortional buckling is the dominant buckling mode for the corroded section.
- The critical bending moment for the corroded simplified section is 462 kNm (CUFSM) vs. 300/2 * 3.5 m = 525 kNm in ABQ (difference is 14%).

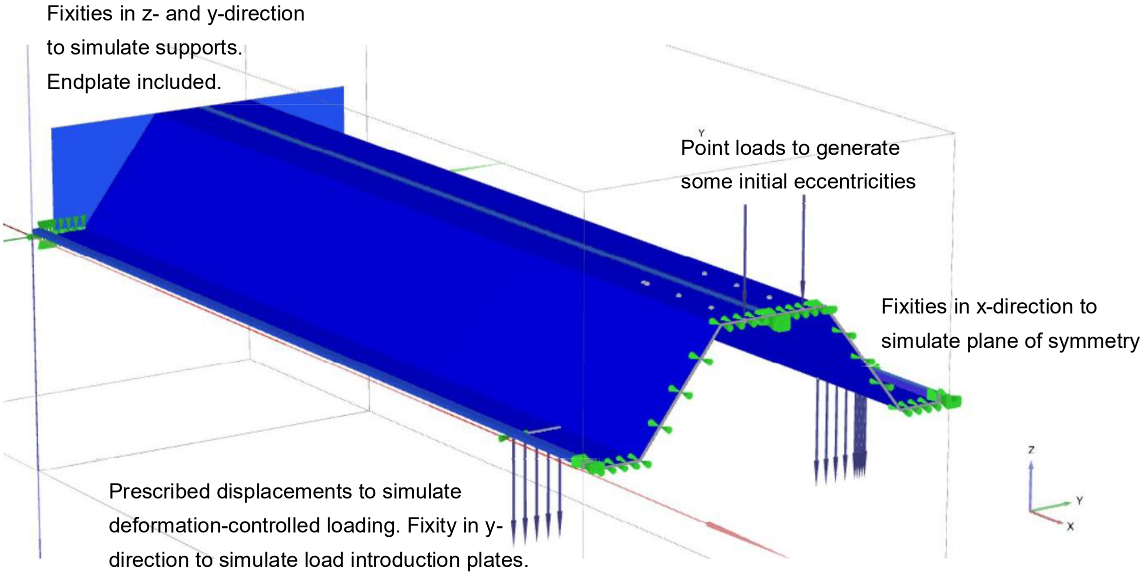
3.3 PLX, simplified geometry (3)

A FE Model is also made of the four-point bending test in PLAXIS. General dimensions are similar as explained in the previous paragraphs. For the sheet pile section, the simplified geometry is used.

Other differences between the Abaqus and PLAXIS model:

- See differences in Table 2.3.
- In PLX use is made of symmetry, only half of the four-point bending test is modelled.
- Stiffeners at load introduction are not explicitly modelled, use is made of constraints.
- Use of local point loads to introduce small eccentricities to stimulate local buckling.

In Figure 3.7 a screenshot is shown of the (half-symmetric) PLAXIS model.


Fixities in z- and y-direction to simulate supports. Endplate included.

Point loads to generate some initial eccentricities

Fixities in x-direction to simulate plane of symmetry

Prescribed displacements to simulate deformation-controlled loading. Fixity in y-direction to simulate load introduction plates.

Figure 3.7 3D view of the model set-up in PLAXIS. Shown is a half-symmetric model

In Figure 3.8 a screenshot is shown of the deformed mesh near peak strength. Note that the deformations are scaled up by a factor 10.

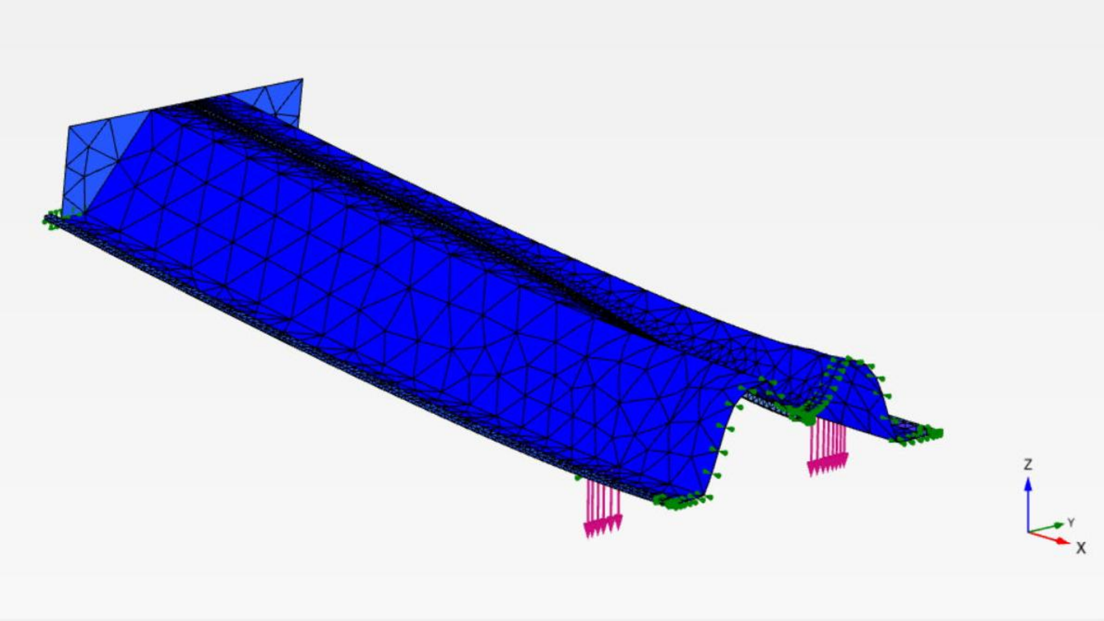


Figure 3.8 3D view of deformed mesh at peak load. Scale factor x10

For the load-deformation curve a node is selected on the plane of symmetry, on the transition of upper (compressed) flange to web. The load-displacement curve is plotted in Figure 3.9.

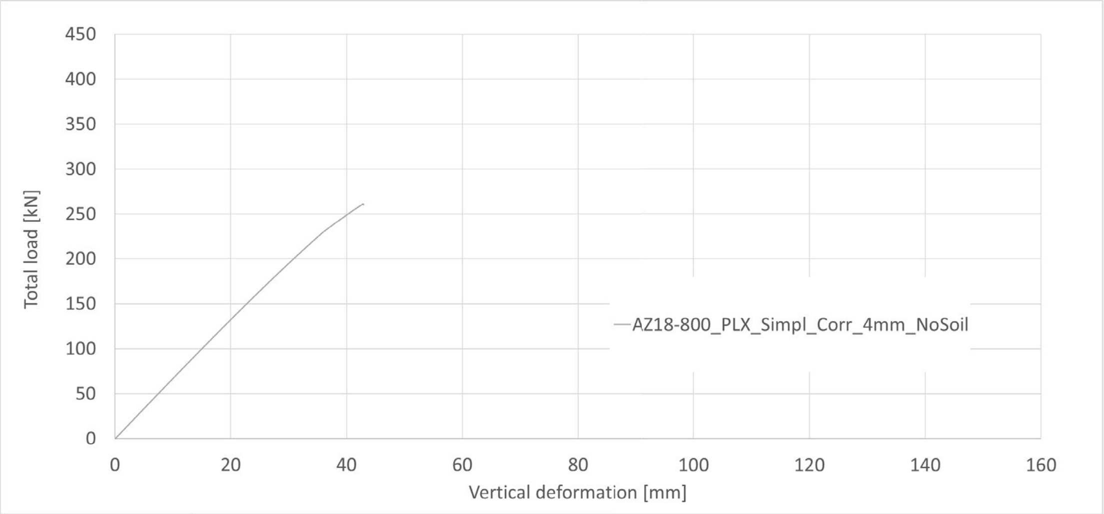


Figure 3.9 Load-displacement curve of corroded simplified geometry in PLX

Observations based on output of the PLAXIS calculation:

- The relatively large downward dipping of the interlock due to distorsional buckling behaviour.
- The start of local buckling in flanges and web.
- The stiffness of the model is less than the theoretical stiffness (as expected).
- Although not very well visible in the load-displacement curve some softening can be observed before the calculation stops due to numerical issues, suggesting that the peak strength is reached in this model.

3.4 Resume and conclusions

In this chapter the following main findings are derived:

- A simplified geometry of an AZ18-800 was generated such that the peak load of this profile matches the peak load of an exact AZ18-800 reasonably well. The post-peak behaviour of the simplified geometry shows more brittle behaviour compared to the exact geometry.
- It is possible to run the simplified geometry in PLAXIS. The observed overall behaviour, i.e. deformed shape and peak load is comparable to Abaqus with simplified geometry and considered sufficient for further analysis of the impact of the constitutive soil model in PLAXIS in the next chapter. No conclusions can be drawn from the PLAXIS runs on post-peak (softening) behaviour.
- Interesting to note is the dominant effect of the distortional buckling for the corroded AZ18-800. This is interesting to note since it indicates that there may be significant potential for the soil embedment to suppress the corresponding relatively large deformations of the compressed flange and interlock.

In Figure 3.10 the relevant load-displacement curves from the Abaqus and PLAXIS runs without soil are shown together in one figure. As a reference two additional lines have been added for the theoretical stiffness and strength. Also see the explanation given in the green frame below.

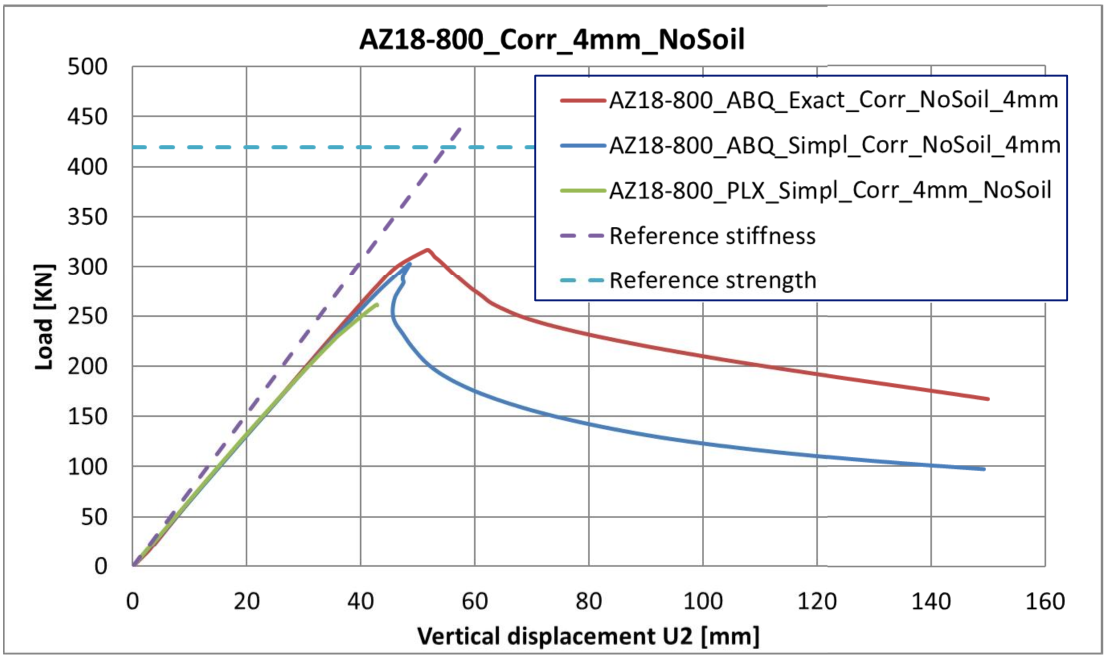
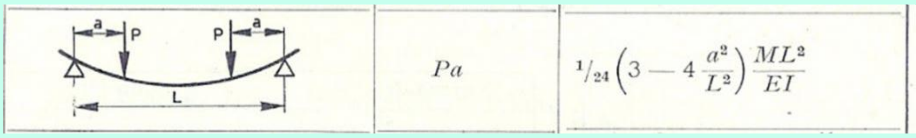


Figure 3.10 Combined plot of load-displacement curves for corroded exact and simplified geometry without soil. As a reference two lines have been added to indicate the theoretical stiffness and theoretical elastic strength, see green frame below

Reference stiffness and strength

Figure 3.10 contains a line that serves as a reference for the stiffness. This line is determined based on the analytical solution for the vertical deformation of the four-point bending test, also see the used formula below. The first column shows the mechanical scheme, the second column gives the formula for max bending moment (M) and the third column gives the formula for the maximum vertical displacement at midspan.



	Pa	$\frac{1}{24}\left(3-4\frac{a^2}{L^2}\right)\frac{ML^2}{EI}$

Furthermore Figure 3.10 contains a line that serves as a reference for the strength. This line is determined based on the theoretical elastic strength for this corroded profile. The corroded section modulus W_{el} is determined using CUFSM, see Error! Reference source not found.: 1707300 mm^3. Together with the yield stress of 430 N/mm^2 this gives a theoretical bending capacity of 734 kNm. The corresponding peak load in a four-point bending test can be calculated as (734 kNm / 3.5 m) * 2 = 420 kN.

4 Case Study with soil, PLAXIS

This chapter discusses the finite element (FE) models with soil in PLAXIS. The analyses made in this chapter are used to gain insight in the effect of the type of constitutive model used for simulating the soil. The analysis made are based on using a simplified geometry for the sheet pile. In the previous chapter it was shown that although the simplified model of the sheet pile is not able to generate exactly the same behaviour, the most important elements of the behaviour are there and as such it is believed that this simplified model can be used to gain insight in the effect of the soil and the different possible constitutive models that can be used.

The chapter discusses two different soil types modelled (i.e. a medium stiff and stiff soil) and two different constitutive models i.e. Mohr Coulomb (MC) and Hardening Soil (HS). In the analyses first the stress-controlled boundaries are applied to the soil before activating the displacement-controlled loading of the sheet pile. Conclusions are drawn on the applicability of the MC model in the Abaqus runs in the next chapter. Also, a first insight is obtained in the effect of the soil support.

4.1 Simplified geometry, medium stiff soil (4a)

The model described in paragraph 3.3 is built by adding soil, see Figure 4.1. The soil is added at the ‘bottom’ of the sheet pile in line with the approach elaborated and shown in Figure 2.6.

The properties taken for the soil are for a medium stiff soil. Use is made of the MC and in a separate model the HS constitutive soil model to simulate the soil. The used parameters are presented in Table 2.2.

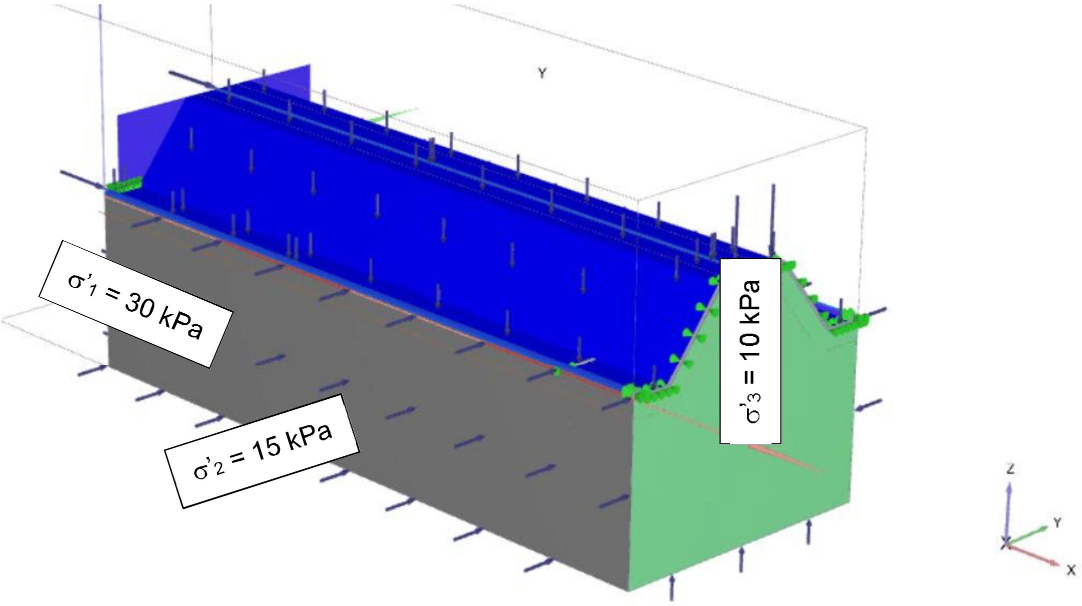


Figure 4.1 3D view of the model set-up in PLAXIS. Shown is the half-symmetric model. Soil is added at the ‘bottom’ of the sheet pile. Stress controlled boundaries are applied to the soil to generate initial stresses in the soil and hence stiffness and strength. σ'_1 works in global x direction. σ'_2 works in global y direction and σ'_3 works in global z-direction

In Figure 4.2 a screenshot is shown of the deformed mesh near peak strength. Note that the deformations are scaled up by a factor 10.

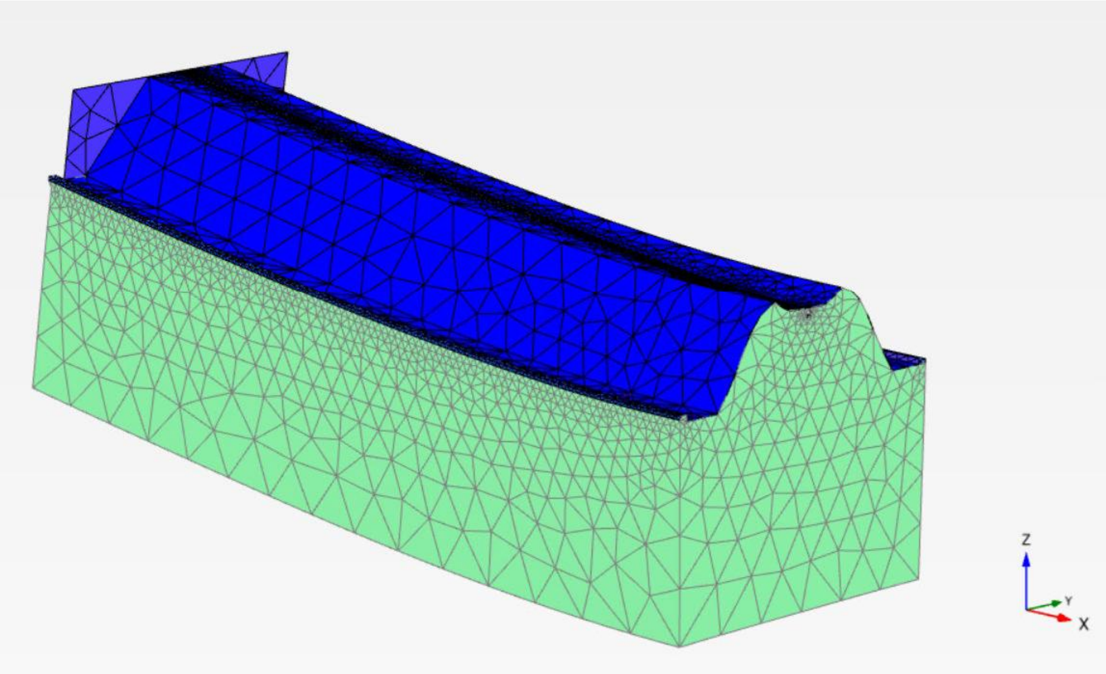


Figure 4.2 3D view of deformed mesh for the model with medium stiff MC soil. Deformation scale factor x10. The stress-controlled boundaries are not shown in this figure

For the load-deformation curve a node is selected on the plane of symmetry, on the transition of upper (compressed) flange to web. The load-displacement curve is plotted in Figure 3.9.

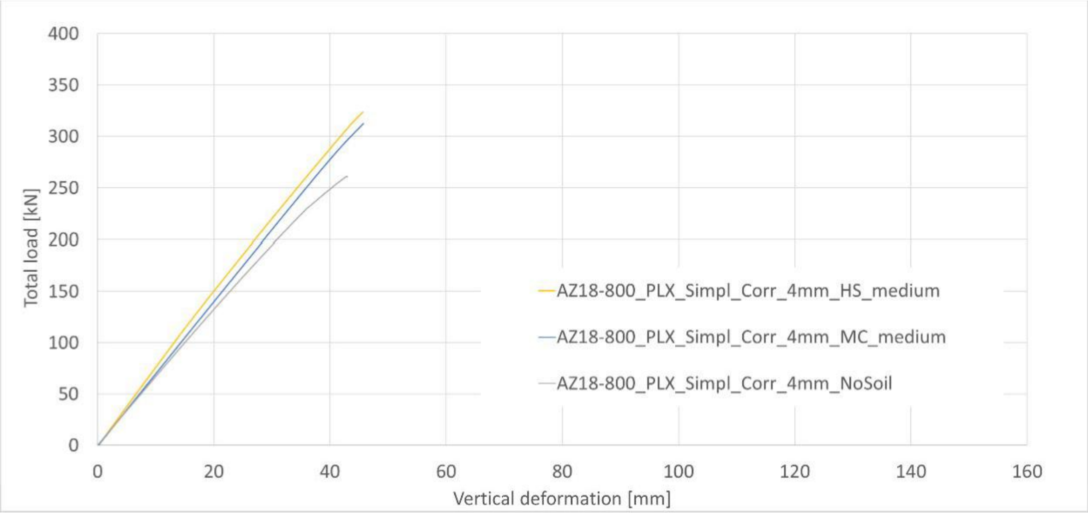


Figure 4.3 Load-displacement curves for the model with medium stiff soil modelled with MC and HS. As a reference the load-displacement curve for the model without soil is included

Observations:

- The dipping of the interlock is reduced compared to the situation without soil.
- The lines for MC and HS are more or less similar and indicate a stiffer behaviour and a higher peak strength compared to the situation without soil. The stiffness is more in line with the theoretical stiffness.

- No clear softening was observed in the models with soil, so it is not clear whether peak strength has been reached.

4.2 Simplified geometry, stiff soil (4b)

The set-up for the model with stiff soil is the same as for the model with medium stiff soil, see Figure 4.1. The soil properties are however adjusted to match the stiff soil. Again use is made of the MC and the HS constitutive soil model to simulate the soil. The used parameters are presented in Table 2.2.

The deformed mesh with stiff soil is for both constitutive models similar to the deformed mesh of the situation with medium stiff soil with the main difference that the deformations of especially the interlock are suppressed more.

For the load-deformation curve a node is selected on the plane of symmetry, on the corner of upper (compressed) flange to web. The load-displacement curves are plotted in Figure 4.4.

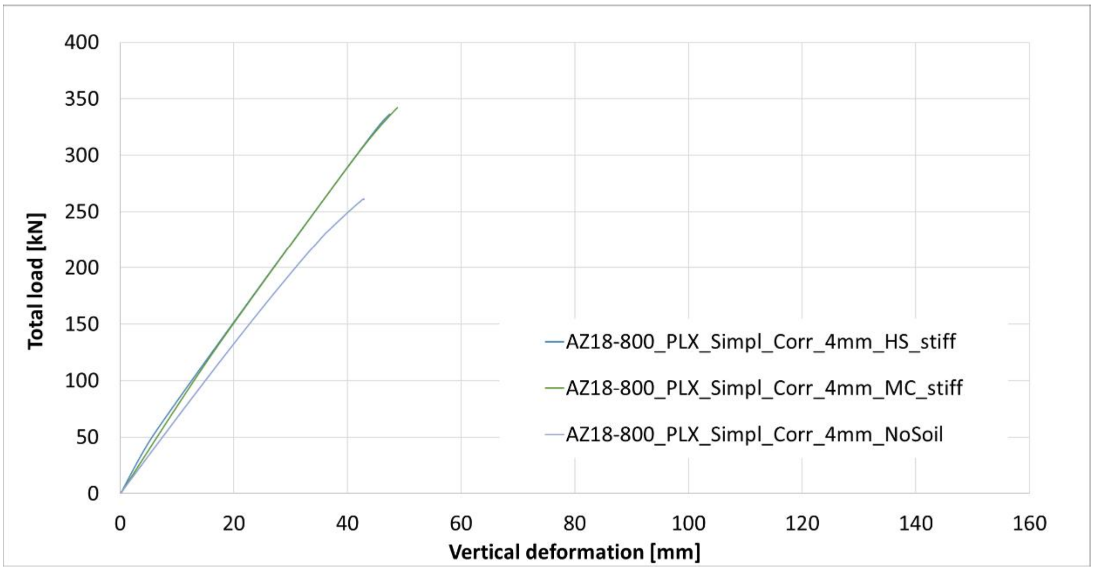


Figure 4.4 Load-displacement curves for the model with stiff soil modelled with MC and with HS. As comparison the results for the situation without soil are included

For the stiff soil similar observations are made as for the case with medium stiff soil. In addition, it is observed:

- While inspecting output in more detail no significant differences are observed between the MC and HS model relevant for this stage of the research. Also see appendix C for some more detailed model output.

4.3 Resume and conclusions

The following conclusions are made:

- Post peak behaviour cannot be captured with PLAXIS and as such no conclusions can be drawn regarding the effect of the constitutive soil model on post-peak behaviour;
- Results when running PLAXIS with MC and HS soil did not show significant differences in stiffness behaviour and/or peak load and lead to believe that working with the MC constitutive soil model in Abaqus is acceptable for this stage of the research.
- PLAXIS results suggest there may be a significant positive effect of the soil embedment on peak strength of the sheet pile.

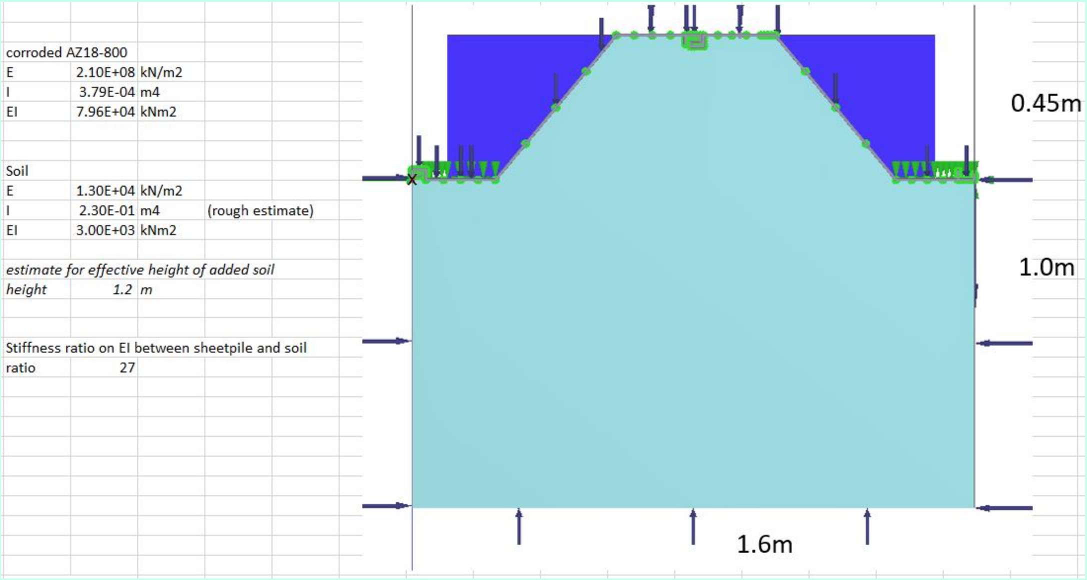
Cause for observed difference in stiffness between model without soil and model with soil

Interesting to note is the difference in (initial) stiffness observed in the load-displacement curves of the model without soil and with soil. The differences can be assigned to two issues:

- The dipping of the interlock, in the model without soil, causing an effective lower height of the sheet pile profile and hence a lower bending stiffness.
- The added (bending) stiffness of the soil volume in the model with soil.

For the second issue a rough estimate can be made what the bending stiffness is of the soil volume compared to the bending stiffness of the sheet pile profile. See the figure below. It is concluded that there is a stiffness ratio between sheet pile profile and the soil volume of (roughly) 27. This suggests that the bending stiffness of the soil volume has a very small influence on the overall bending stiffness of the model.

Another indication that the soil does not add too much bending stiffness is the comparison with the theoretical stiffness. The model with soil has a good match with this theoretical (expected) stiffness.



corroded AZ18-800			
E	2.10E+08	kN/m2	
I	3.79E-04	m4	
EI	7.96E+04	kNm2	
Soil			
E	1.30E+04	kN/m2	
I	2.30E-01	m4	(rough estimate)
EI	3.00E+03	kNm2	
estimate for effective height of added soil			
height	*1.2*	*m*	
Stiffness ratio on EI between sheetpile and soil			
ratio	27		

5 Case Study with soil, Abaqus

This chapter discusses the finite element (FE) models with soil in Abaqus. The analyses made in this chapter are used to gain insight in the supporting effect of the soil on the strength of the thin sheet pile. The analysis is based on using a soil modelled with either purely elastic soil or with elastoplastic Mohr Coulomb (MC) model. The starting point of the analyses is the Abaqus FE model without soil and with simplified interlock geometry as presented in Chapter 3. The results of the Abaqus analyses with soil are compared with the Abaqus analyses without soil and with the PLAXIS analyses.

5.1 Numerical model assumptions

Meshing and Element types

The starting point of the models with soil is the Abaqus model without soil and with simplified interlock geometry, see Chapter 3. In line with the PLAXIS models, a soil body is added to the ‘bottom’ of the sheet pile in this model. The mesh and element types of the sheet pile are as explained in Chapter 3. The soil is a solid with element type C3D8R (An 8-node linear brick, reduced integration, hourglass control). At the cross-sectional interface of the soil with the sheet pile, the mesh size of the soil is set equal to the mesh size of the sheet pile. In longitudinal direction the mesh size of the soil is at maximum 10 times larger than the smallest element. See Figure 5.1.

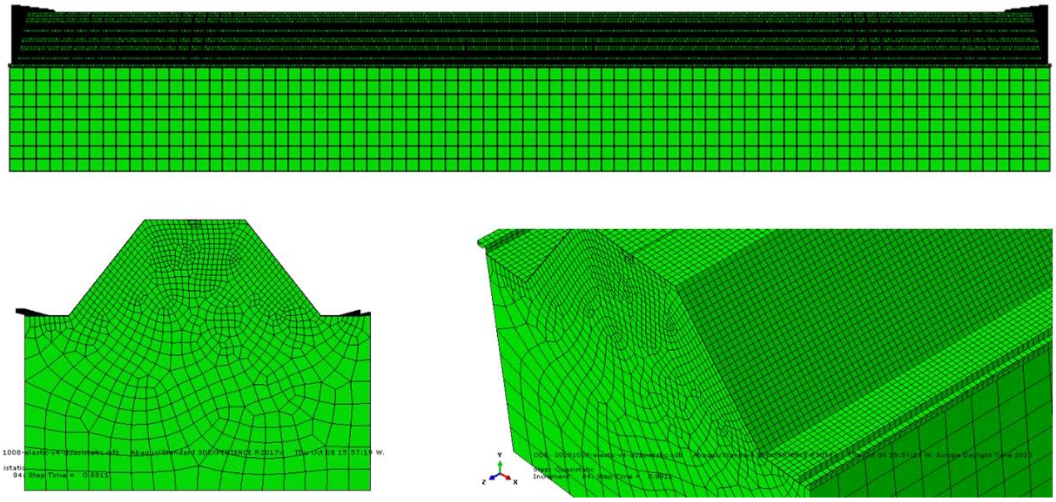


Figure 5.1 Geometry and mesh of the Abaqus model with soil

Constraints and Contact

The constraints of the sheet pile and stiffeners are as explained in Chapter 3. In the models with soil, an additional interface is defined between the ‘bottom’ of the sheet pile and the ‘top’ of the soil. It must be noted that there is no interaction defined between any stiffeners of the sheet pile and the soil. This means the soil can deform and move as if there were no stiffeners present.

Furthermore, because the simplified interlock geometry is intended to represent the stiffness of the exact interlock rather than to represent its geometry, only interaction with the ‘top’ of the simplified interlock was defined. This prevents artificial interactions due to the shape of the interlock. See Figure 5.2.

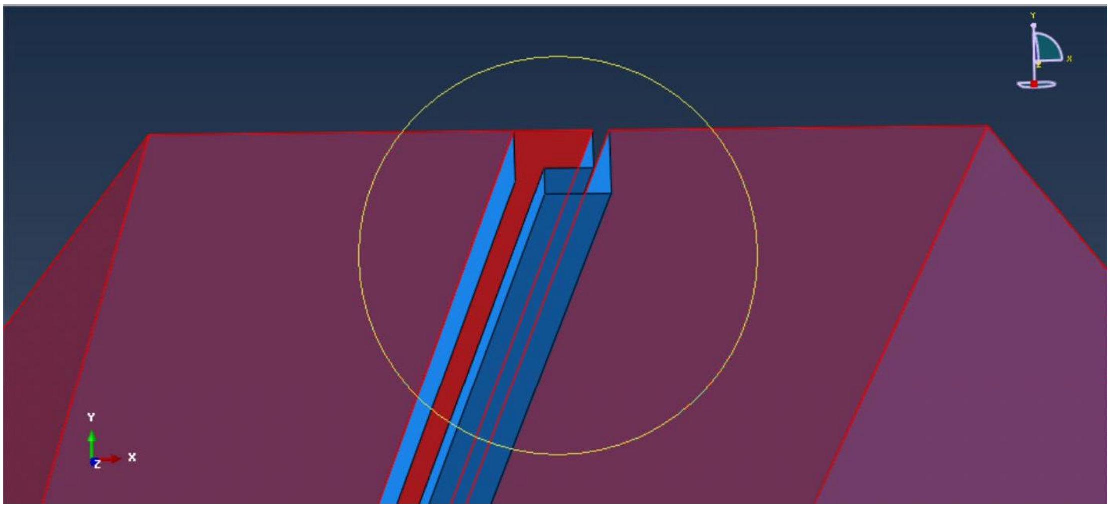


Figure 5.2 Interface between sheet pile and soil, indicated with red. The blue part of the interlock does not interact with the soil

The interface between the soil and the sheet pile has tangential behaviour with a defined isotropic friction coefficient and penalty friction formulation. The friction coefficient μ depends on the friction angle of the soil material ($\mu = \frac{2}{3}\tan(\phi) = \tan(\delta)$).

Loading steps
The loading steps are equal to PLAXIS, where first the prestress in the soil is applied before the displacement is applied to the loading points. The applied pre-stress depends on the soil stiffness.

Analysis Type
The first step, where the prestress was applied to the soil, is calculated using the static general analysis.
However, standard static general analysis and RIKS analysis both fail to calculate the post-buckling behaviour for the sheet pile with soil. Separation of the interface sheet pile with soil due to buckling causes the convergence issues in the RIKS analysis (contact is overall challenging with RIKS).
Therefore, dynamic implicit analyses with quasi-static setting were performed to calculate the buckling and post-buckling (following recommendation from Abaqus support).

5.2 Simplified geometry, medium stiff soil (5a)

Due to numerical issues a number of different settings and approaches were tried to come to good results. The following runs were made:

- Standard static general and RIKS analysis using elastic soil and Mohr Coulomb soil. These approaches failed to calculate the post-buckling behaviour. These results are not further included here in the report.
- Dynamic implicit analyses with quasi-static setting using elastic soil and Mohr-Coulomb. These runs were successful, and results are included in this paragraph.

The properties of the soil are for a medium stiff soil. The used parameters are presented in Table 2.2, whereas for the elastic soil the Mohr-Coulomb plasticity is not included.

In Figure 5.3 and Figure 5.4 screenshots are shown of the deformed mesh near peak strength for the sheet pile supported by elastic soil and MC soil. Note that the deformations are scaled up by a factor 10.

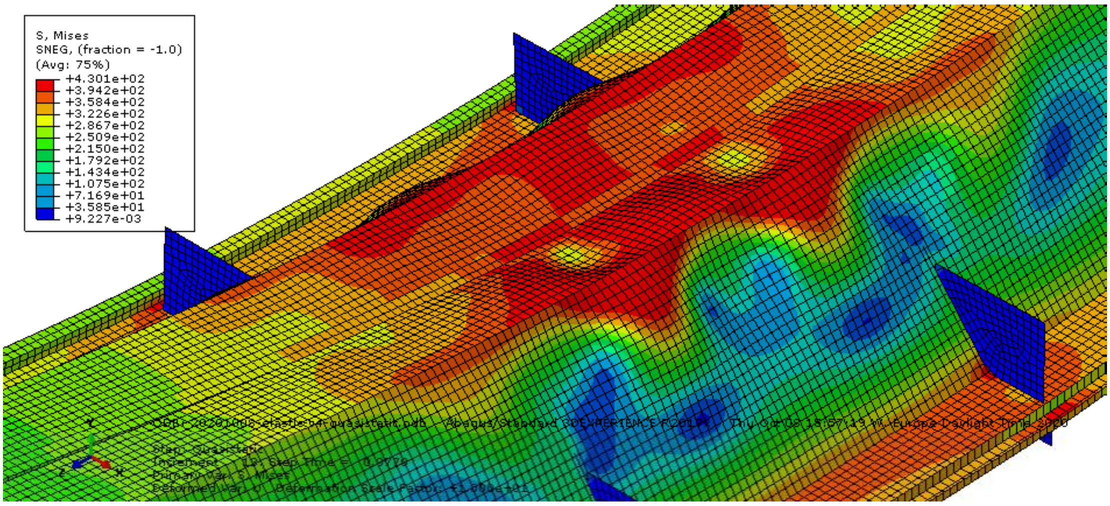


Figure 5.3 Shape of the sheet pile at peak force supported by elastic soil (soil not shown)

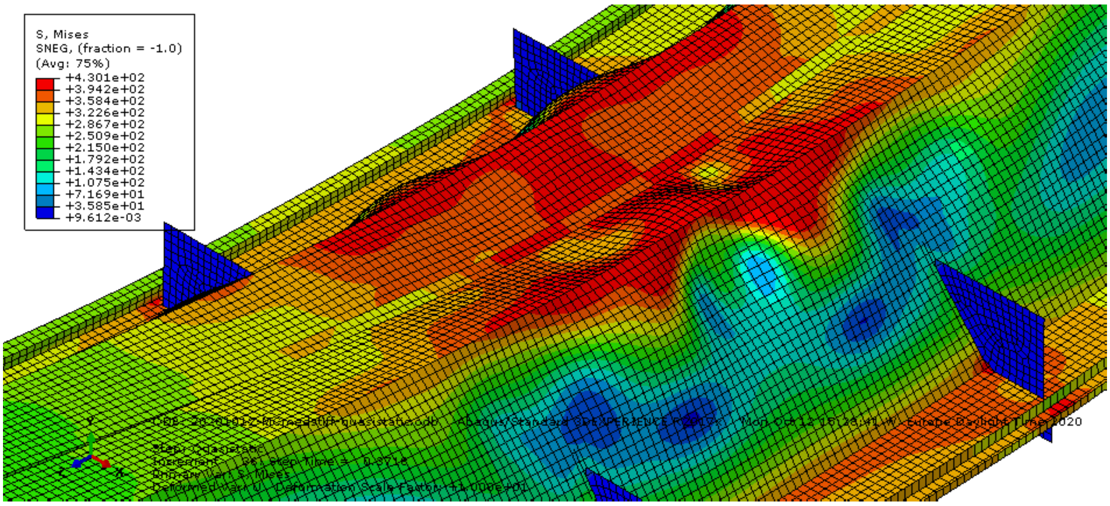


Figure 5.4 Shape of the sheet pile at peak force supported by medium stiff Mohr-Coulomb soil (soil not shown)

The vertical reaction force of the load introduction points is extracted from the model, together with the vertical displacement of the midpoint (same node as in PLAXIS models). This results in the force-deflection curve presented in Figure 5.5.

The shape of the sheet pile at the peak strength looks similar for medium stiff Mohr-Coulomb soil and medium stiff elastic soil. However, small differences are observed such as lower Von Mises stress near the centre, which is likely due to plasticity of the soil, reducing the reaction force in the soil and hence in the sheet pile. The plasticity of the soil results in a slightly lower peak strength compared to the elastic soil (+13% instead of +15% compared to the model without soil), see Figure 5.5.

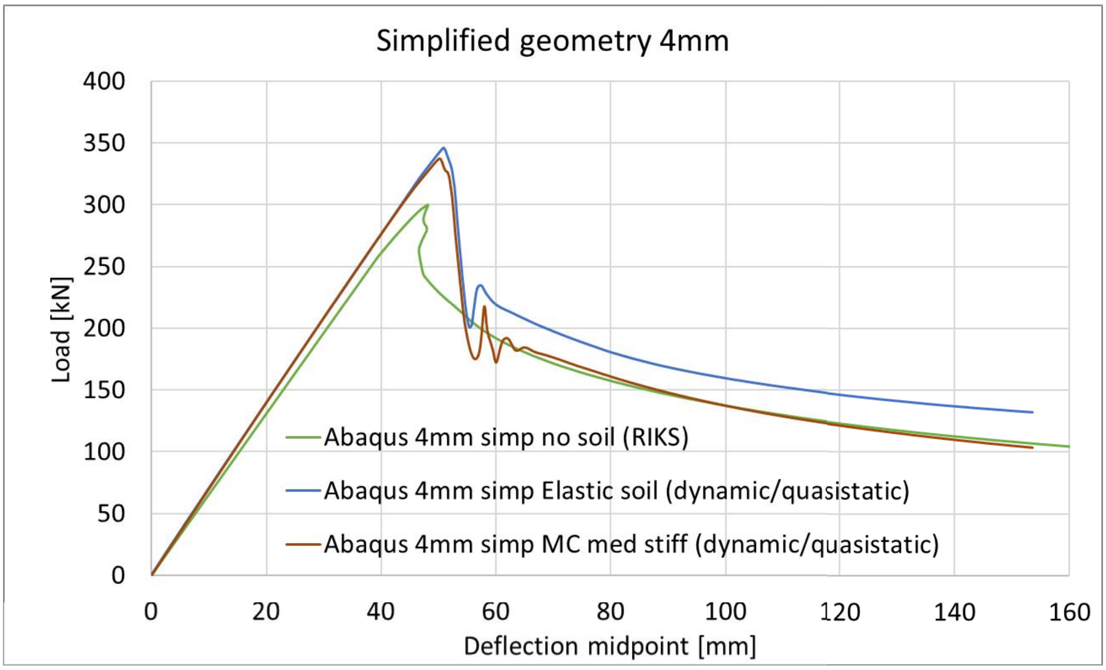


Figure 5.5 Force deflection curves for Abaqus model without soil (green), Abaqus model with medium stiff elastic soil (blue) and Abaqus model with medium stiff Mohr-Coulomb soil (red)

Observations:

- The load-displacement curve of the Abaqus model with medium stiff Mohr Coulomb soil matches the load-displacement curve of the PLAXIS model with medium stiff Mohr Coulomb soil (shown in Figure 4.3), but the peak force and corresponding deflection at midpoint found in the Abaqus analysis are higher compared to the PLAXIS model.
- The load-displacement curve of the Abaqus model with medium stiff Mohr-Coulomb soil shows a significantly higher peak strength (+13%) and corresponding deflection at the midpoint (+4%) compared to the Abaqus model without soil. The post buckling behaviour of the soil supported model seems (slightly) improved compared to the model without soil, also see appendix E. The post-buckling behaviour furthermore appears to converge to the same curve for the model with medium stiff Mohr-Coulomb and the model without soil.
- The elastic model gives a bit higher peak strength and corresponding deflection compared to the MC model. The post-buckling shows somewhat higher force for the Abaqus model with medium stiff elastic soil compared to the Abaqus model without soil.

5.3 Simplified geometry, stiff soil (5b)

The model with stiff Mohr-Coulomb soil uses the material properties from Table 2.2. The friction coefficient of the interface between the sheet pile and the soil is changed (since the friction coefficient depends on the friction angle of the soil material), and the pre-stresses in the soil are changed as well.

The shape of the sheet pile at the peak force is shown in Figure 5.6.Note that the deformations are scaled up by a factor 10.

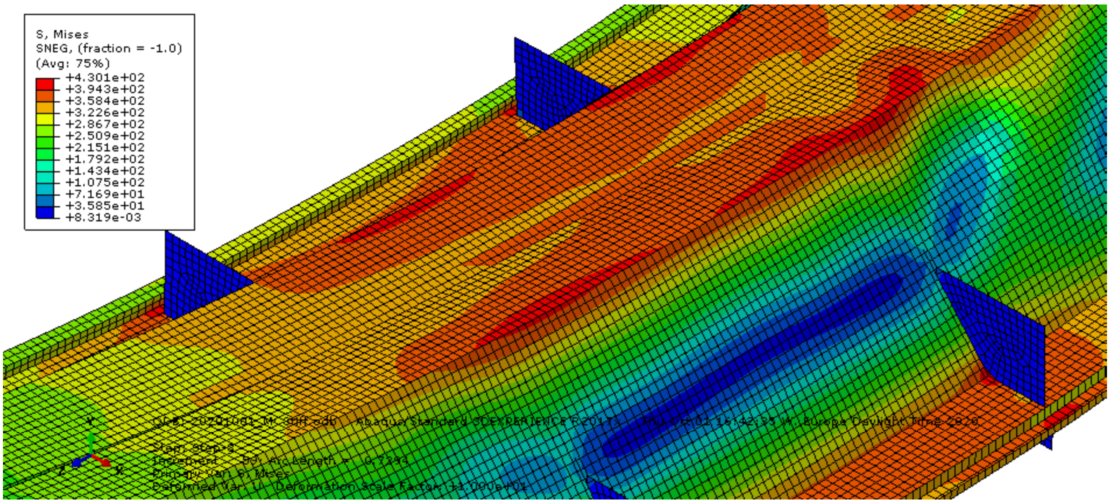


Figure 5.6 Shape of the sheet pile at peak force supported by stiff Mohr-Coulomb soil (soil not shown)

Unlike the models with medium stiff elastic and Mohr-Coulomb soil, the dynamic implicit analysis with quasi-static option failed to calculate the post-buckling behaviour. For the models with medium stiff soil, the peak force found in the RIKS analysis and general static analysis were the same as the peak force found in the dynamic implicit analysis with quasi-static option. After the peak, the stiffness (derivative of the force-deflection curve) becomes negative, indicating buckling. The stiffness versus deflection at midspan is plotted in Figure 5.7.

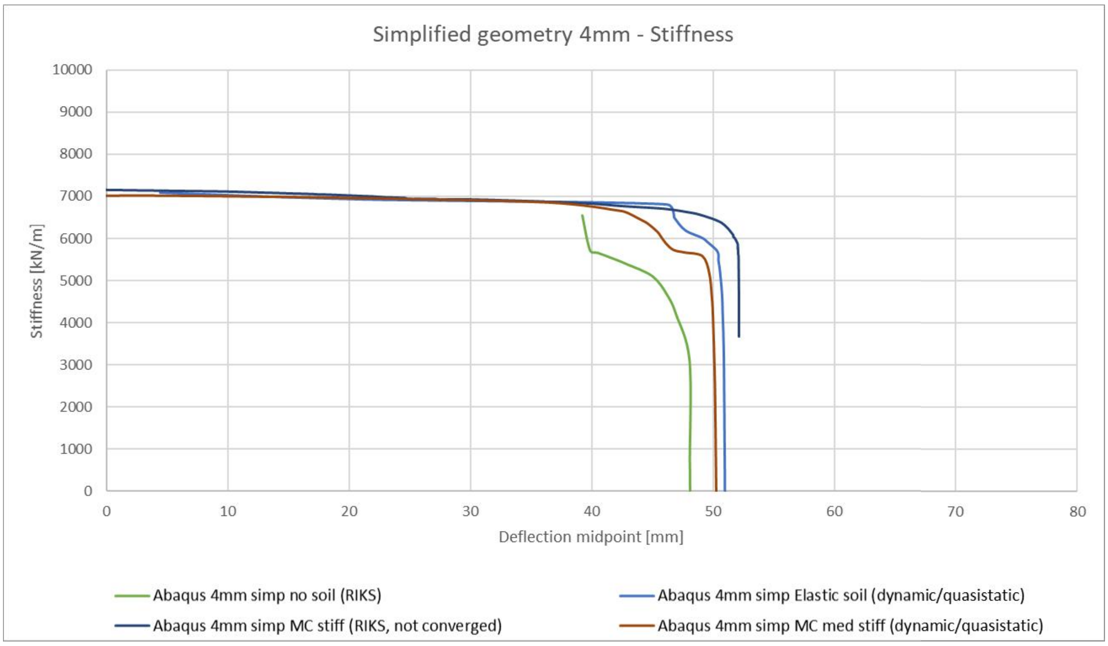


Figure 5.7 Stiffness versus deflection at midspan

The stiffness for the stiff Mohr-Coulomb soil did not become negative in the analysis. However, the clear downward trend indicates initiation of the buckling. Therefore, the peak value found in the analysis is believed to be very close to the actual peak value.

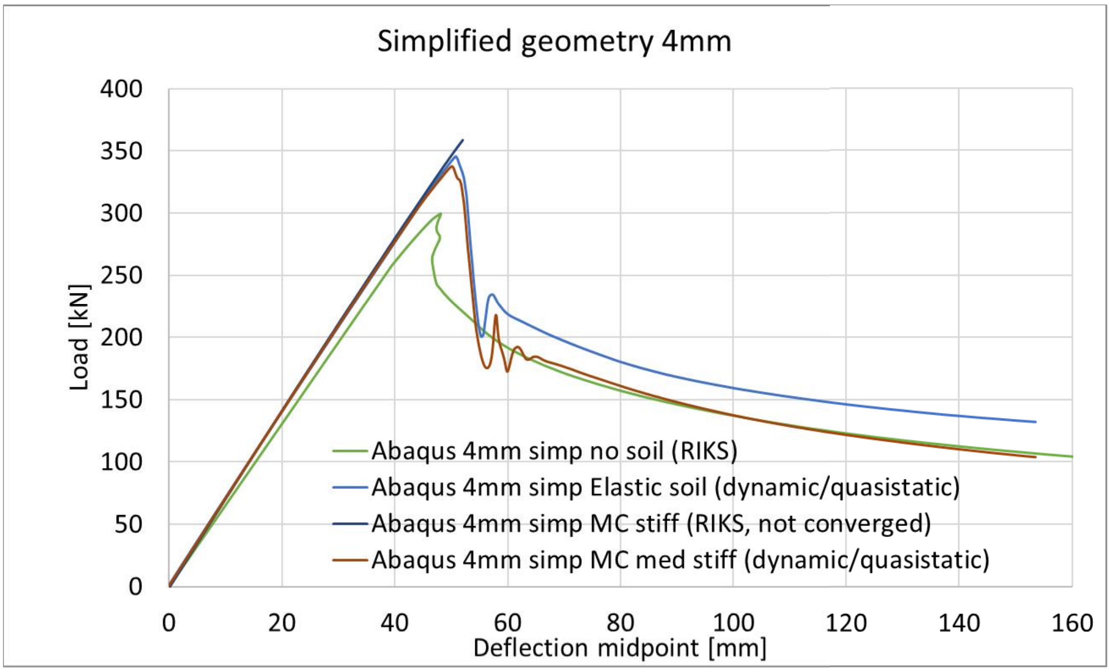


Figure 5.8 Force-deflection curves for the analyses with simplified geometry with medium stiff and stiff soil combined

<u>Observations:</u>

- The load-displacement curve of the stiff soil with Mohr-Coulomb plasticity gives a higher peak value compared to the medium stiff elastic soil and medium stiff soil with Mohr-Coulomb plasticity.
- The force-displacement curve of the Abaqus model with stiff Mohr-Coulomb soil shows a significantly higher peak strength (+20%) and corresponding deflection at the midpoint (+8%) compared to the Abaqus model without soil.

5.4 Exact geometry (6)

In analogy with the calculations made with the simplified geometry a model was set up with the exact sheet pile geometry with soil. In this exact sheet pile geometry use is made of contact elements for the interlock modelling. Upfront it was already expected that this calculation would be numerical challenging. This expectation proved to be correct during the project. Several attempts were made but it was not possible, within the project boundaries, to come to a sufficiently converged model. It was therefore decided to finish this report without the quantitative results of the model with exact geometry and soil.

In the next chapter ‘Outlook and discussion’ some discussion is added on the expected differences between the simplified and exact sheet pile model.

5.5 Resume and conclusions

It is found that running the Abaqus model with soil is numerically challenging. So far it has been possible to run the simplified geometry with soil for the medium stiff soil and find peak strength and post-peak behaviour. For the stiff soil it is believed that the peak strength is found, but post-peak behaviour is not captured. At this moment no results have been found for the exact geometry with soil.

In Figure 5.9 the load-displacement curves from the Abaqus runs with soil are summarised and shown together in one figure. As a reference two additional lines have been added for the theoretical stiffness and strength. Also see the explanation given in the green frame in paragraph 3.4.

The analyses made suggest that the presence of the soil results in higher peak strength. The increase in peak strength found in the analyses for simplified geometry is:

- +13% for medium stiff soil with Mohr-Coulomb plasticity.
- +20% for stiff soil with Mohr-Coulomb plasticity.

The deflection at midspan corresponding to the peak strength increases due to the presence of the soil, according to the analyses for simplified geometry:

- +4% for medium stiff soil with Mohr-Coulomb plasticity.
- +8% for stiff soil with Mohr-Coulomb plasticity.

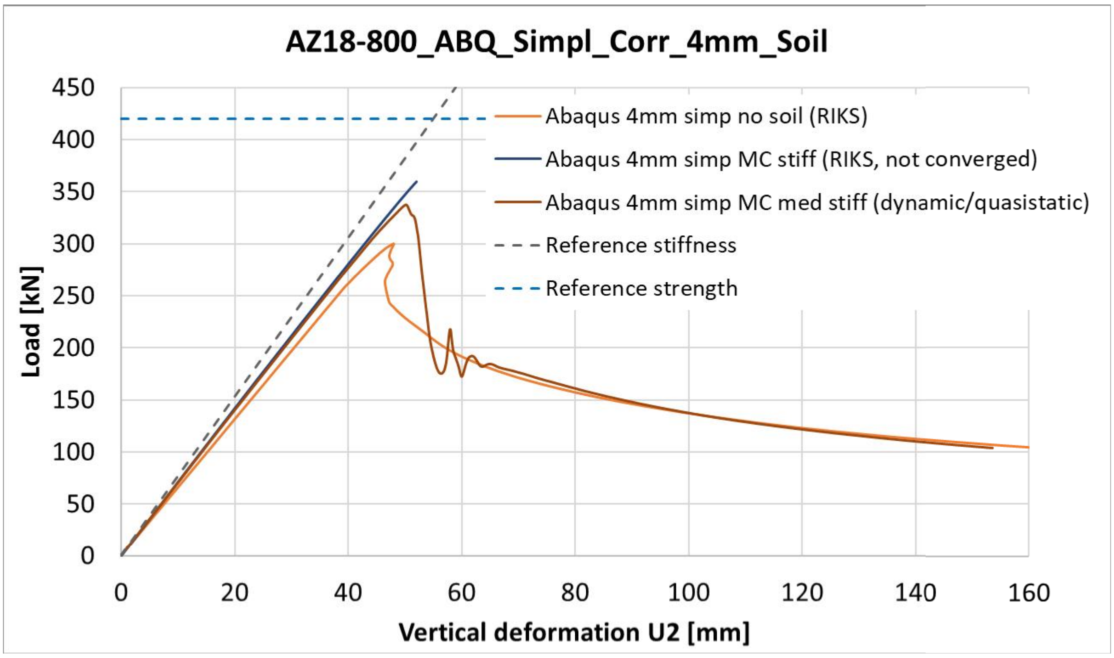


Figure 5.9 Summary of load-displacement curves for the Abaqus runs with simplified sheet pile geometry and soil. A reference stiffness and reference strength line have been added, see the explanation of these reference lines in paragraph 3.4

6 Outlook and discussion

In this chapter the results of the FE calculations are put into perspective. The outlook and discussion are used to gain some more insight in other relevant aspects and situations. This chapter does not pretend to be exhaustive.

6.1 Outlook

For the applicability of the results of this study two trends seem relevant:

1. The tendency to construct new structures with ever more optimized (but ever more slender) sheet pile profiles. An example of such an optimized sheet pile profile is the AZ18-800 profile used in this study.
2. The tendency for asset managers to maximize the service life span of their sheet piles acreage (and thus resulting in even more slender sheet piles due to the increasing amount of corrosion).

Both aspects are good arguments for investigating the ‘real’ strength of sheet pile profiles embedded in soil.

6.2 Cantilever vs anchored walls

As explained in paragraph 2.2 the FE model set-up used here (i.e. four-point bending with soil) resembles a cantilever sheet pile wall. Logical question is then how the results found here relate to the situation for an anchored wall? In Figure 6.1. the situation belonging to an anchored wall situation is shown, also compare this figure to Figure 2.6 for the cantilevered situation.

To get more insight in the situation for an anchored wall situation an additional model run is made. In this model the medium stiff soil is transferred to the other side of the sheet pile. All other settings are like the runs made and explained in this report. The results of this additional run are shown in Appendix D. It is concluded from this run that the influence of the soil becomes somewhat less compared to the model with soil on the other side but still the effect appears significant. The increase in peak strength is +9% relative to the situation with no soil, compared to +13% relative to the situation with no soil for the Case Study described in the main text of this report.

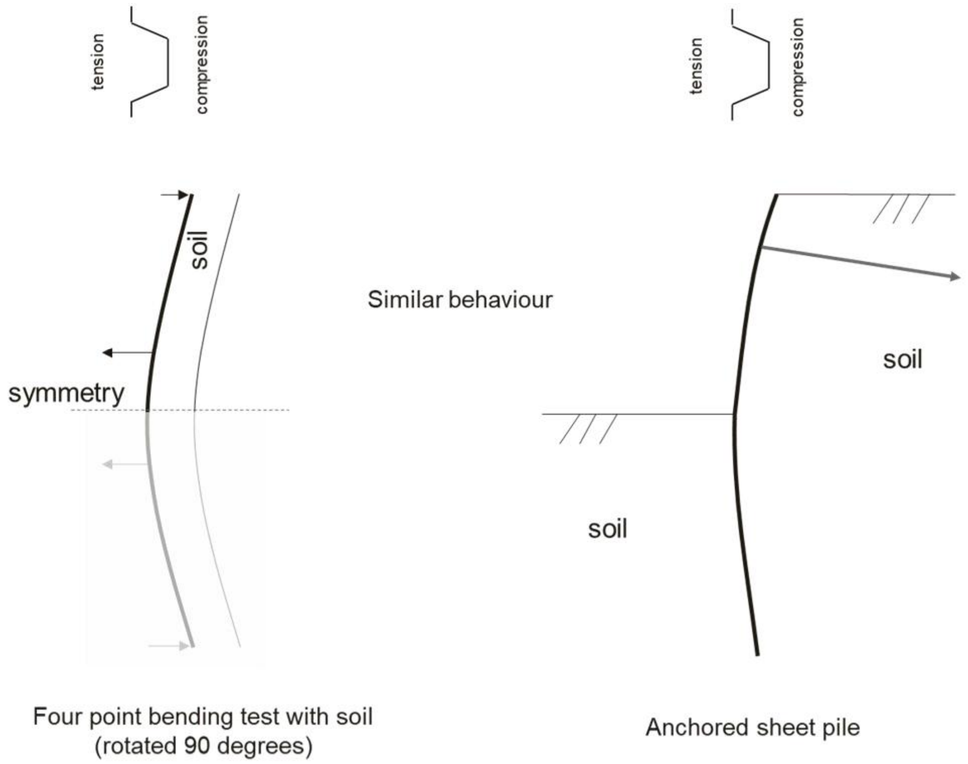


Figure 6.1 Comparing the four-point bending test with an anchored sheet pile wall. The bending behaviour / curvature is similar

6.3 Z-piles vs U-piles

In this report it was chosen to investigate a corroded AZ18-800 profile as this is a commercially available profile used in practice. Also, in practice more Z-piles are used as their strength properties are in general favourable compared to U-piles.

It was found in this study that for slender (highly corroded) Z-profiles distortional buckling becomes the dominant mechanism. Here the degree of freedom allowed by the interlock plays an important role. This distortional behaviour, and the resulting relatively large (sideways) deformations of flange and interlock, allow the soil to have a relatively large (positive) influence on the behaviour of the sheet pile.

For a U-pile it is however expected that distortional buckling is less dominant (local buckling becomes more relevant) resulting in less positive influence of the soil compared to a Z-pile with a comparable slenderness. Also see appendix A where results are presented of previous research on Ω-piles. Ω-piles with continuous flange under compression can be compared to U-piles.

6.4 Buckling inward or outward

Important assumption made in the models run here is that the compressed flange has the tendency to move in such a way that the ‘height’ of the sheet pile profile becomes less. This in general may be expected to be the direction in which the compressed flange wants to move. However, there is a dependency on initial eccentricities. It may happen that the compressed flange has an initial eccentricity which is so large that the flange has the tendency to move in such a way the ‘height’ of the profile increases. This situation has not been investigated in this report, but it may be expected that the strength and stiffness behaviour of the profile will not be less. This is a logical result of the fact that the ‘height’ (the internal arm) of the profile increases.

6.5 Soil one sided, two sided, active or passive, higher stress level

In this study a one-sided soil in an active state at a relatively low stress level is used. This can be considered a careful approach since it may be expected that situations with two-sided soil, with passive soil pressures and or higher stress levels will generate more soil support and thus higher strengths of the sheet pile. On the other side it was chosen to use medium stiff and stiff soils which may be expected to generate more soil support compared to soft soils.

It is believed that the approach chosen in this report is not an extremely negative or positive approach but is a realistic approach in trying to gain insight in the potential of soil support on the strength of thin walled sheet piles.

6.6 Water pressures

In the Case Study used in this report no influence of water pressures was considered. It may be expected that water pressures will reduce the positive effects of the soil embedment since the water cannot sustain shear stresses (leading to arching effects).

6.7 Simplified vs exact sheet pile geometry

As mentioned in chapter 5 it has been possible to generate results for the simplified sheet pile geometry with soil. Unfortunately, this has not been possible, within the project boundaries, for the exact sheet pile geometry with soil. Relevant question is if the exact sheet pile geometry with soil may have resulted in significant different results.

At this moment it is believed that the model with exact sheet pile geometry would not yield significantly different conclusions as those based on the model with simplified sheet pile geometry. This believe comes from the comparable shape and size of the deformation pattern of both models without soil, as shown in Figure 6.2. The shape and size of the deformation pattern in the situation without soil is a good measure for the expected influence of the soil.

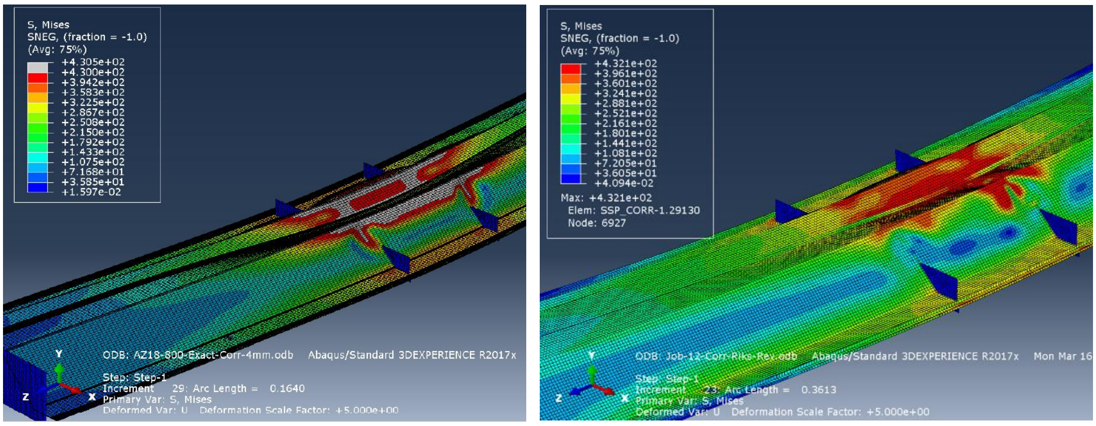


Figure 6.2 Comparing the deformation behaviour of the model with exact sheet pile geometry without soil (left) and the model with simplified sheet pile geometry without soil (right). Note that both models have the same scale factor of 5

6.8 Other relevant aspects not considered yet

Many other aspects can be thought of that may be relevant and which are not considered in this report. To name a few:

- Overconsolidation of soils.
- Multi-layered soils.
- Initial stresses of soil.
- Loading history of the soil and sheet pile.
- Influence of shear and normal forces in the sheet pile.
- Possibility of cavities in the soil due to sheet pile installation and/or the filling process behind the wall.
- Undrained behaviour of soils.

These effects may have a positive or negative effect on the strength of the sheet pile. In this stage of the research these effects are not further investigated. Most likely these effects can also not be investigated fully with just an FE study, a combination with physical scale testing is needed. However as described in the research goal of this report the approach chosen here is just a first step in investigating the potential.

7 General conclusions and recommendations

To be able to draw conclusions first the research goal is repeated:

> *To investigate by means of a finite element (FE) study if the effects of soil embedment on the capacity of thin walled sheet piles are significant, i.e. is it worthwhile to further investigate the effects of soil embedment with physical scale testing?*

7.1 Conclusions

From the Case Study considered in this report, simulating a cantilevered sheet pile structure, it is concluded that:

- Distortional buckling is the dominant buckling mode for the corroded AZ18-800 profile resulting in relatively large (side-ways) deformations of the compressed flanges and interlock for the situation without soil. These relatively large deformations suggest, in a qualitative sense, that soil can have a significant influence on suppressing these deformations and hence on increasing (peak) strength and post-peak deformation capacity.
- From a comparison in PLAXIS it is concluded that for this moment it seems there are no significant differences in using the relatively simple Mohr Coulomb (MC) constitutive soil model or the more advanced Hardening Soil model. As such the MC model is used for modelling soil in Abaqus.
- The quantitative increase in peak strength found in Abaqus for the simplified sheet pile geometry between the model without soil and with soil is in the order of +13% for a medium stiff soil and in the order of +20% for a stiff soil. The quantitative results of the Abaqus model with simplified geometry also suggest an (slight) increase in post-peak deformation capacity.
- Unfortunately, no results have been derived yet for the exact sheet pile geometry with soil in Abaqus as this calculation appears to be (too) numerical challenging for now. Nevertheless, it is not expected that the results of this model would lead to significantly different conclusions as currently made based upon the simplified sheet pile geometry with soil.

An additional Abaqus calculation with a model set-up more representative of an anchored wall situation, using a simplified sheet pile geometry, is also made. The quantitative results of this model suggest less favourable effects of the soil embedment but still significant, i.e. +9% for a medium stiff soil relative to the situation with no soil (instead of +13%).

Based on the results, while keeping in mind the outlook and discussion from chapter 6 in this report, it is concluded that not one final answer can be given to the research question. It is highly dependent on the situation if the effects of the soil embedment are significant and worthwhile quantifying.

7.2 Recommendations

It is recommended that sheet pile manufacturers (such as ArcelorMittal) and asset managers (such as the Dutch Rijkswaterstaat) take notice of the results of this study and consider for themselves whether it is worthwhile to further perform research on this subject.

This research furthermore illustrates that it is likely that in non-soft soil conditions class 4 sheet piles are more robust as they have (some) more strength/rotation as accounted for in design. This effect might be of direct use in risk assessments.

8 References

[PLAXIS manual]
Reference manual and Materials model manual
https://www.bentley.com/en/products/brands/plaxis

[Deltares, 2019a]
Kennisprogramma Natte Kunstwerken – The influence of soil embedment on local instability of a Class 4 profile, April 2019
Included at https://www.nattekunstwerkenvandetoekomst.nl/

[Deltares, 2019b]
PLAXIS validation (confidential memo to ArcelorMittal), July 24th 2019

[Deltares, 2019c]
Kennisprogramma Natte Kunstwerken – Effect of soil embedment on thin walled (corroded) sheet piles, November 15th 2019

[TU Darmstadt, 2010]
Test report No. 10-31p (confidential), Tests to determine the bending resistance of ArcelorMittal Cold formed sheet piles, 22 november 2010 (english version 10 march 2011)

A Summary of previous work on the subject

This appendix elaborates on previous work done on the subject [Deltares, 2019a and c]. More specifically the following models are described:

- Plate model.
- PAU2440.
- PAZ4350.

Included in this appendix is a description of the verification and validation done of the FE models at the start of the TKI project with ArcelorMittal. Verification is done between PLAXIS and Abaqus. Validation is done based upon available test results [TU Darmstadt, 2010] [Deltares, 2019b] for the PAU2440 and PAZ4350 cold formed sheet pile profiles.

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B Uncorroded AZ18-800 and CUFSM verification

In this appendix the results of the Abaqus calculation for the uncorroded AZ18-800 are shown for information. Furthermore the results of a verification calculation using the finite strip method are shown.

B.1 Results of the uncorroded AZ18-800

Exact uncorroded geometry

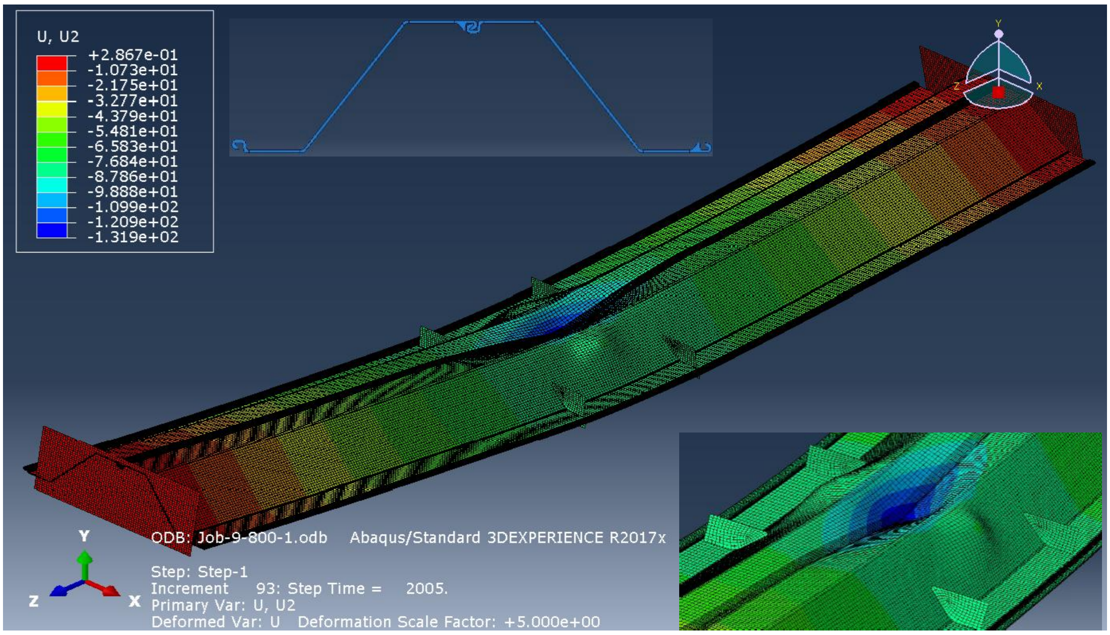


Figure B.1 Deformed shape with U2 at peak load for AZ18-800(Exact, uncorroded, no soil)

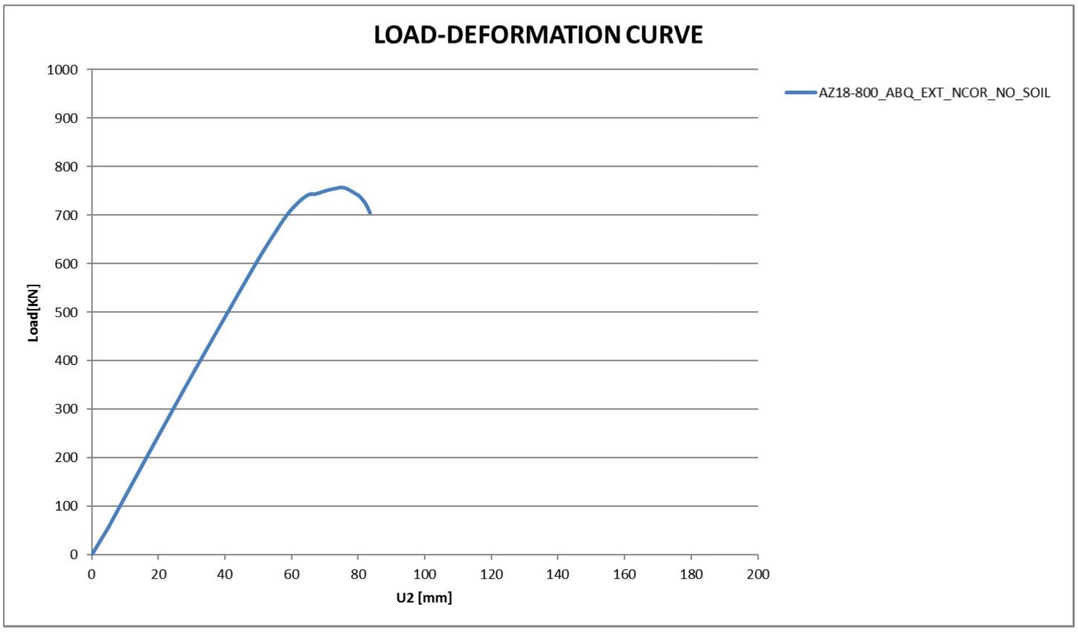


Figure B.2 Load-deformation curve for AZ18-800(Exact, uncorroded, no soil)

Simplified uncorroded geometry

With the simplified geometry of the interlock a similar buckling shape and mode(local) is observed as for exact uncorroded geometry

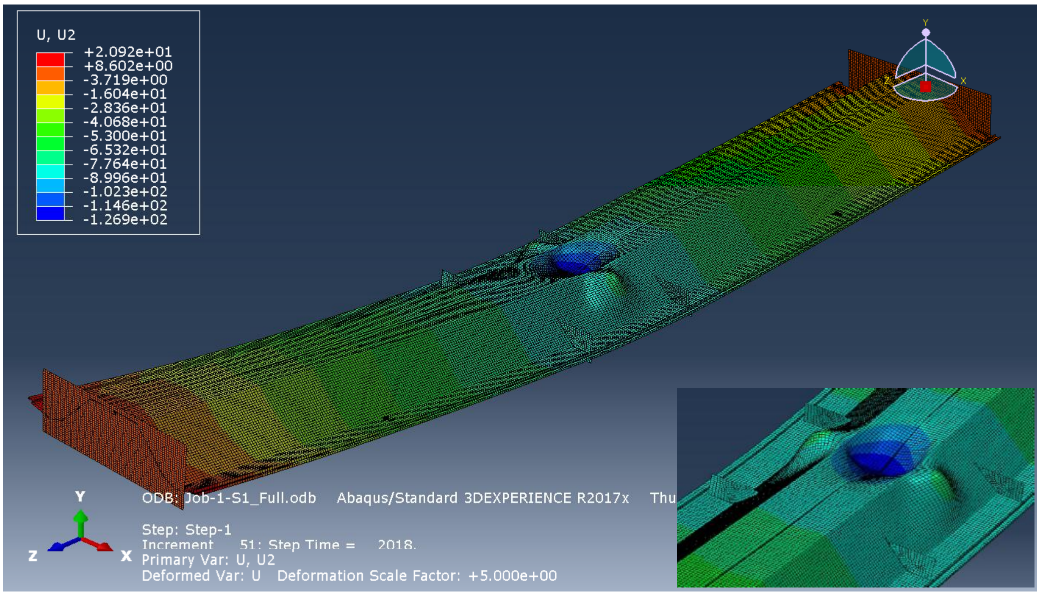


Figure B.3 Deformed shape just before buckling load for AZ18-800 (Simplified, uncorroded geo)

While comparing the load deformation behaviour of the simplified geometry with exact, the peak loads were found to be reasonably close.

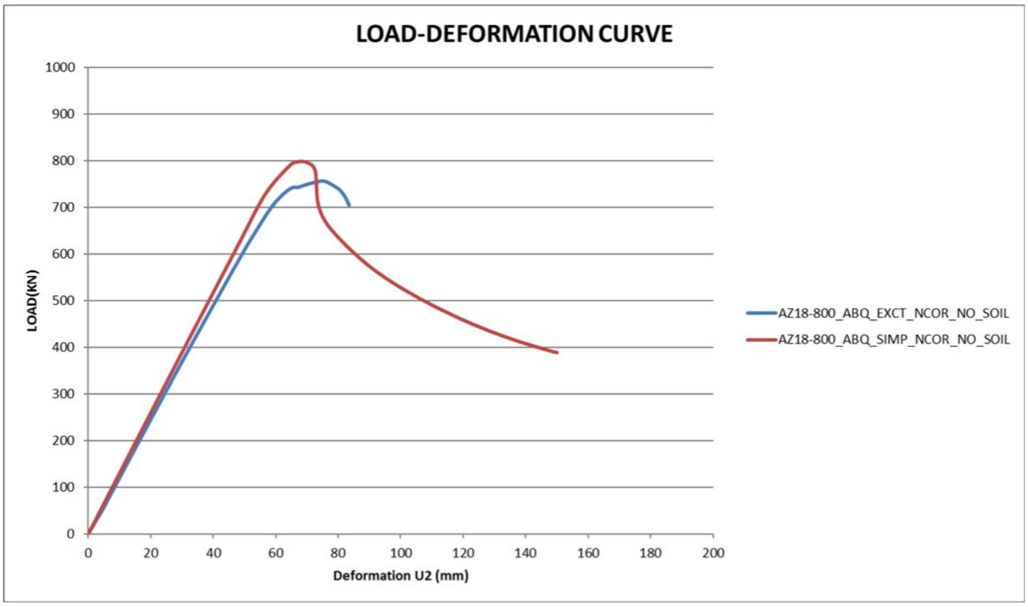


Figure B.4 Load-deformation curves for AZ18-800 (Exact vs Simplified uncorroded geometry)

B.2 Verification with the CUFSM finite strip method

To verify the observed behaviour of the corroded sheet pile in the FE analysis an analysis was made with CUFSM - finite strip method. Graphical results of the analysis are shown in Figure B.5. whereas numerical results are shown in Table B.1.

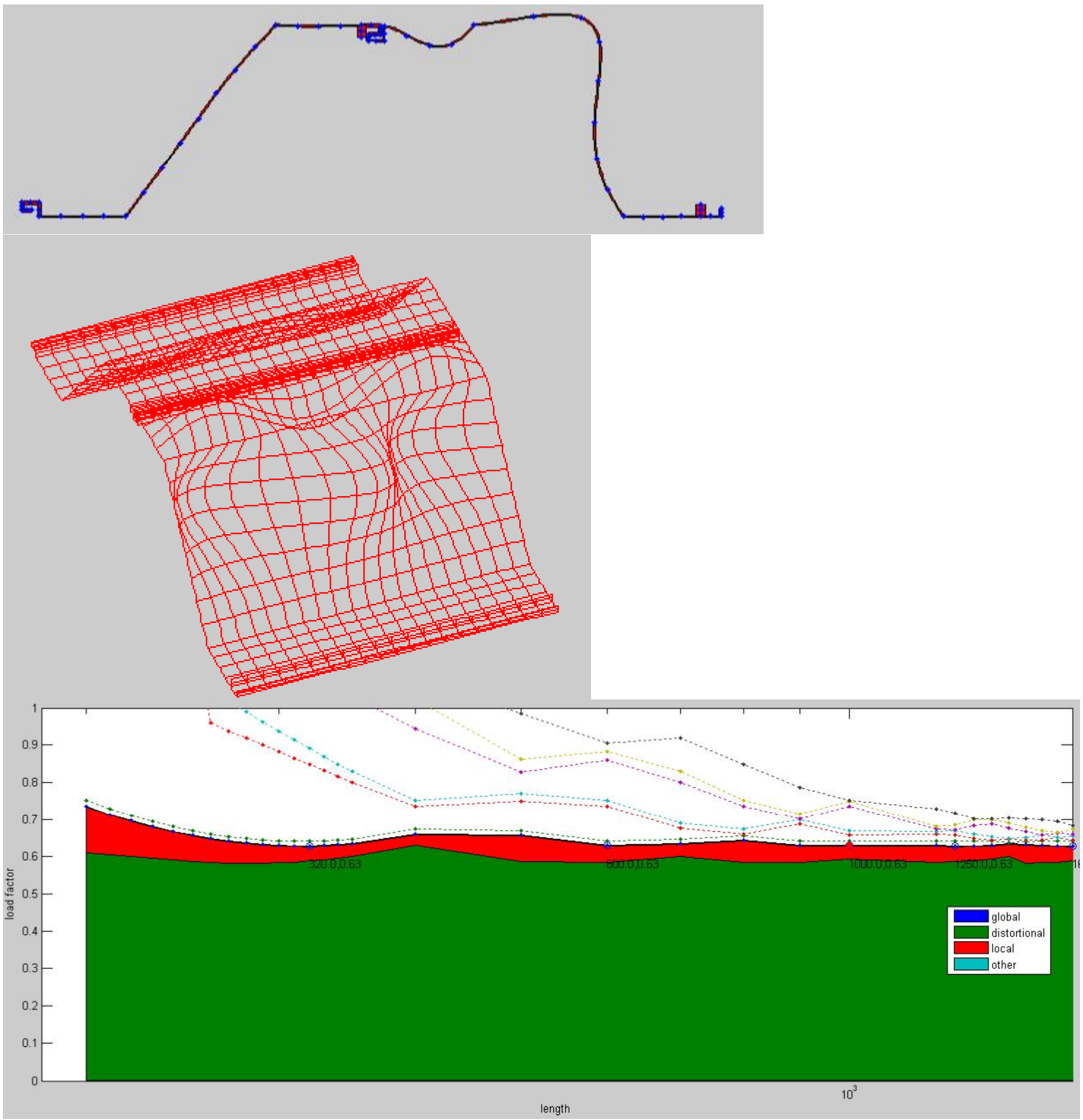
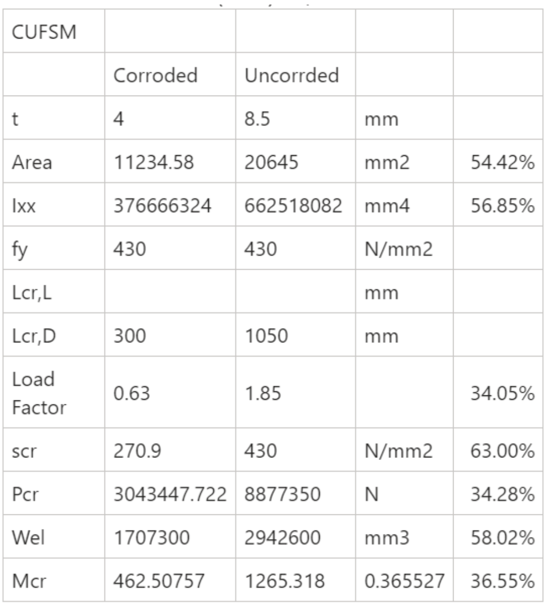


Figure B.5 (a) Buckled shape of corroded cross-section, (b) Buckled shape for half wavelengths, (c) Contribution of different buckling modes (dominant mode is distortional)



CUFSM				
	Corroded	Uncorrded		
t	4	8.5	mm	
Area	11234.58	20645	mm2	54.42%
Ixx	376666324	662518082	mm4	56.85%
fy	430	430	N/mm2	
Lcr,L			mm	
Lcr,D	300	1050	mm	
Load Factor	0.63	1.85		34.05%
scr	270.9	430	N/mm2	63.00%
Pcr	3043447.722	8877350	N	34.28%
Wel	1707300	2942600	mm3	58.02%
Mcr	462.50757	1265.318	0.365527	36.55%

Table B.1 Numerical results from the CUFSM analysis for the simplified corroded and uncorroded section

The main findings from the CUFSM confirm the main findings from the Abaqus analysis:

- Distortional buckling is the dominant buckling mode for the corroded section.
- The critical bending moment for the corroded simplified section is 462 kNm (CUFSM) vs 300/2 * 3.5 m = 525 kNm in ABQ (difference is 14%).
- The critical bending moment for the uncorroded Simplified section is 1265 kNm (CUFSM) vs 800/2 * 3.5 m = 1400 kNm in ABQ (difference is 11%).

C Detailed model output

In this appendix more detailed model output for several calculations are shown.

C.1 PLX, Simplified geometry, stiff soil (4b)

The figures in this paragraph give insight into the arching effects that occur into the soil and that are the reason why the soil has a positive effect on the strength of thin walled sheet piles. It shows that when parts of the sheet pile ‘move at a different speed compared to the soil’ the soil then wants to suppress these effects. By means of arching the stress is ‘focussing’ on these parts.

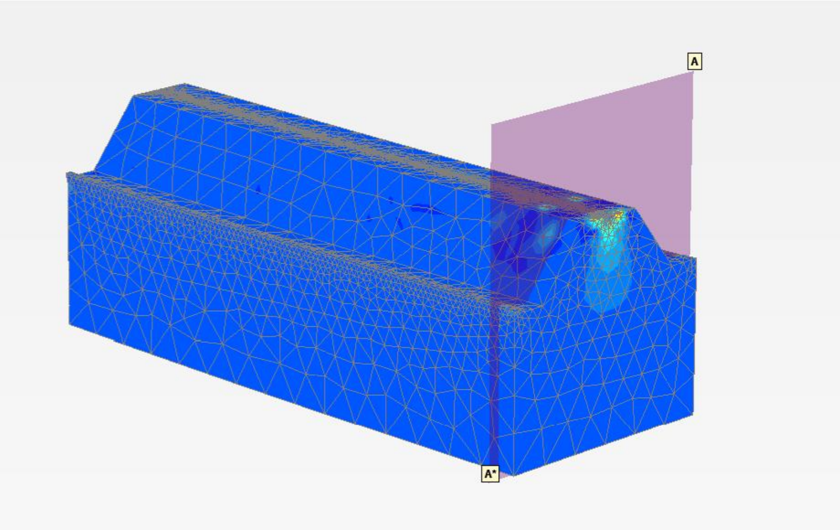
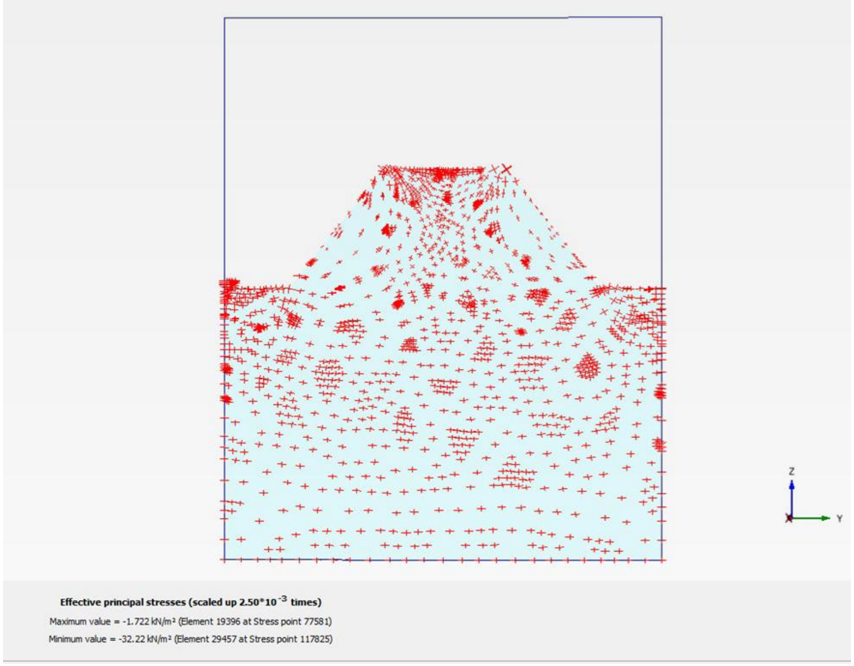


Figure C.1 Slice through the model, plate elements not shown

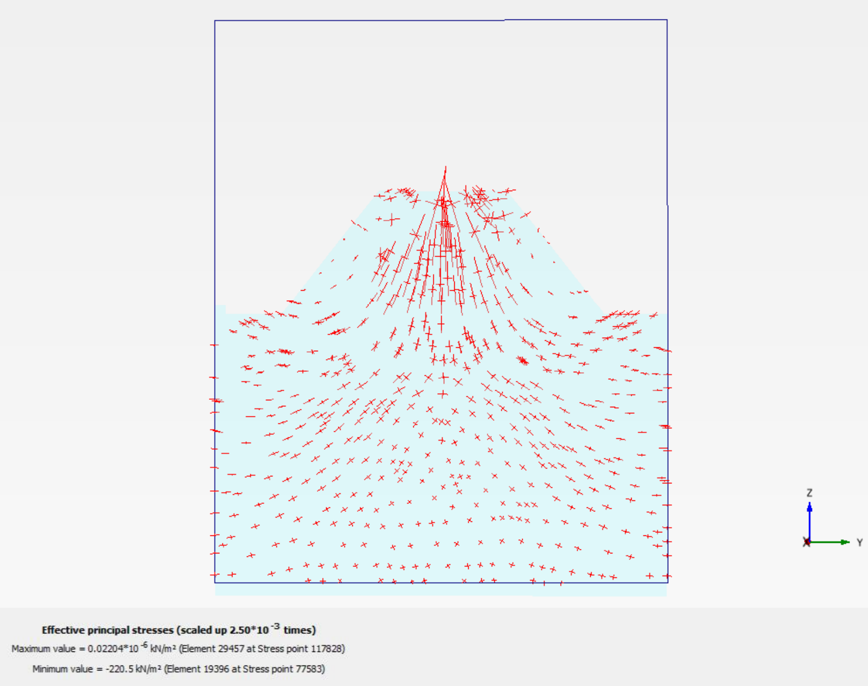


Effective principal stresses (scaled up $2.50*10^{-3}$ times)

Maximum value = -1.722 kN/m² (Element 19396 at Stress point 77581)

Minimum value = -32.22 kN/m² (Element 29457 at Stress point 117825)

Figure C.2 Principal stress just prior to loading



Effective principal stresses (scaled up 2.50*10^{-3} times)

Maximum value = 0.02204*10^{-6} kN/m² (Element 29457 at Stress point 117828)

Minimum value = -220.5 kN/m² (Element 19396 at Stress point 77583)

Figure C.3 Principal stress just after loading

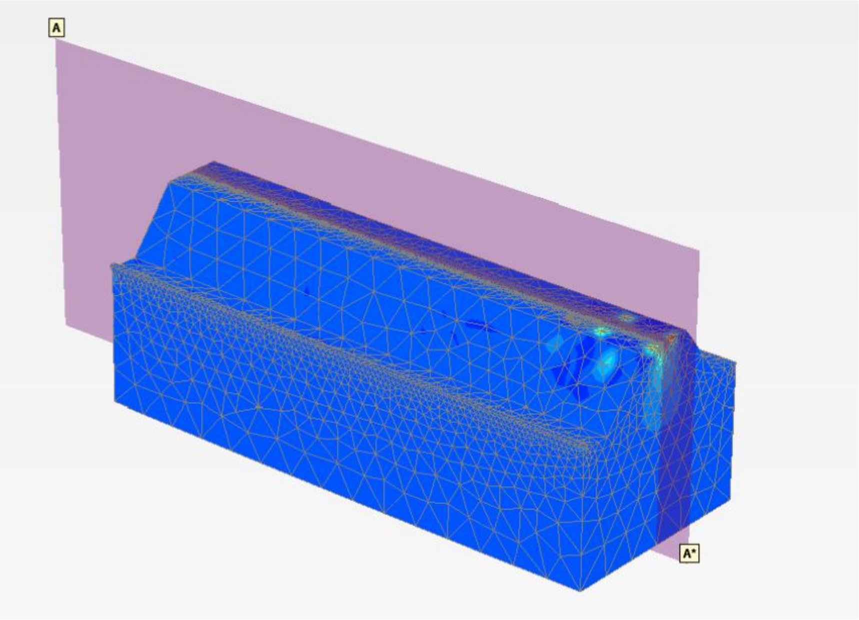
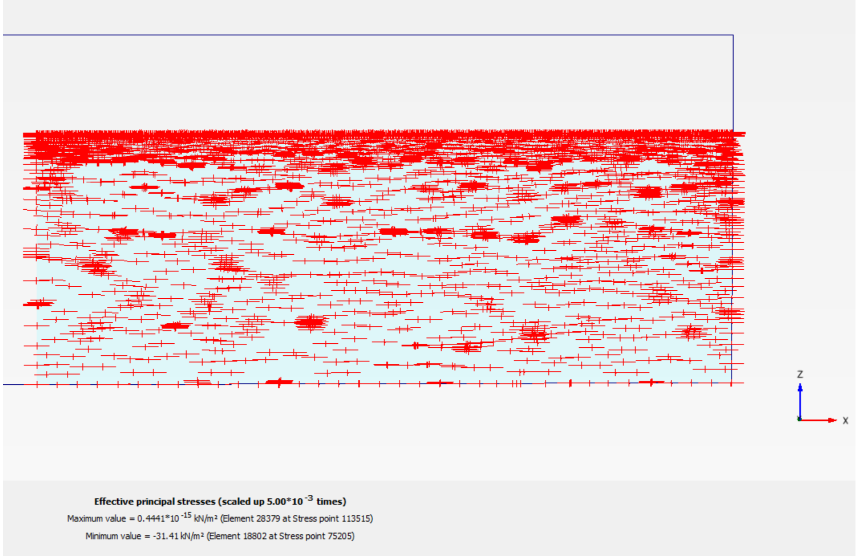
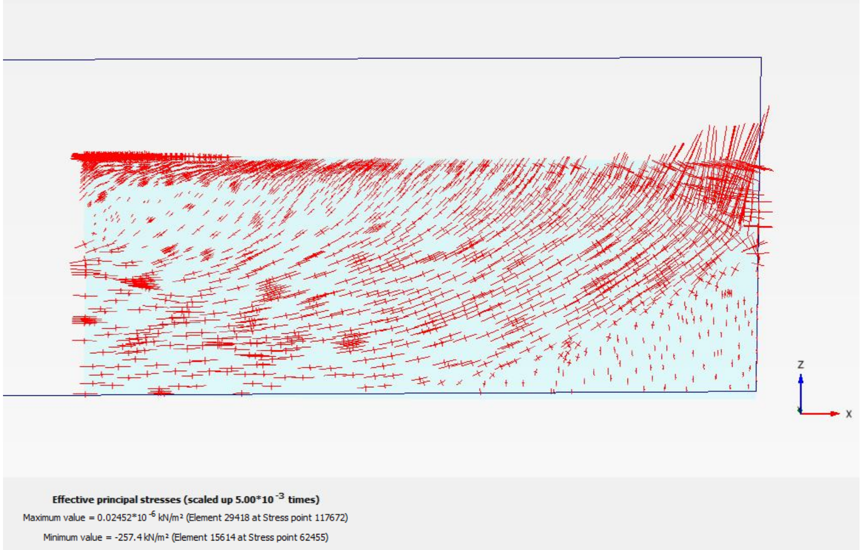


Figure C.4 Slice through model, plate elements not shown



Effective principal stresses (scaled up $5.00*10^{-3}$ times)
Maximum value = $0.4441*10^{-15}$ kN/m² (Element 28379 at Stress point 113515)
Minimum value = -31.41 kN/m² (Element 18802 at Stress point 75205)

Figure C.5 Principal stress just prior to loading



Effective principal stresses (scaled up $5.00*10^{-3}$ times)
Maximum value = $0.02452*10^{-6}$ kN/m² (Element 29418 at Stress point 117672)
Minimum value = -257.4 kN/m² (Element 15614 at Stress point 62455)

Figure C.6 Principal stress just after loading

C.2 Abaqus, simplified geometry, medium stiff soil

This section presents the same figures as the previous section, but for the Abaqus model. The figures were generated for the simplified 4mm sheet pile with MC medium stiff soil model and quasi-static analysis. Peak = frame 57.

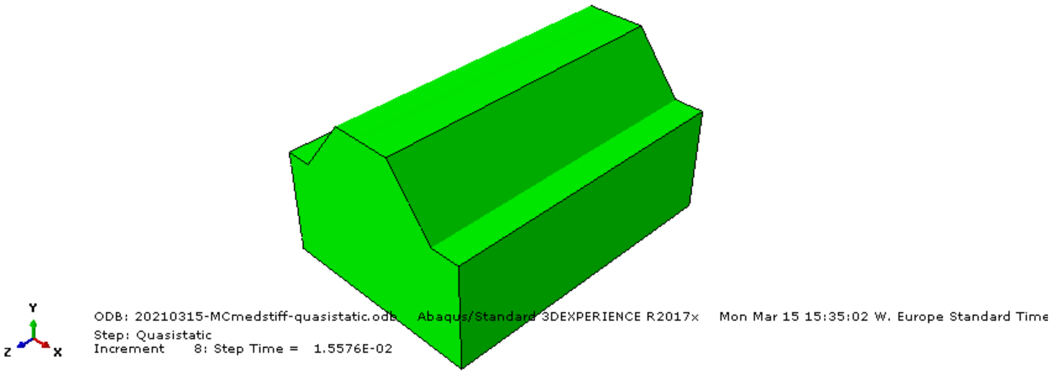


Figure C.7 Slice through the model

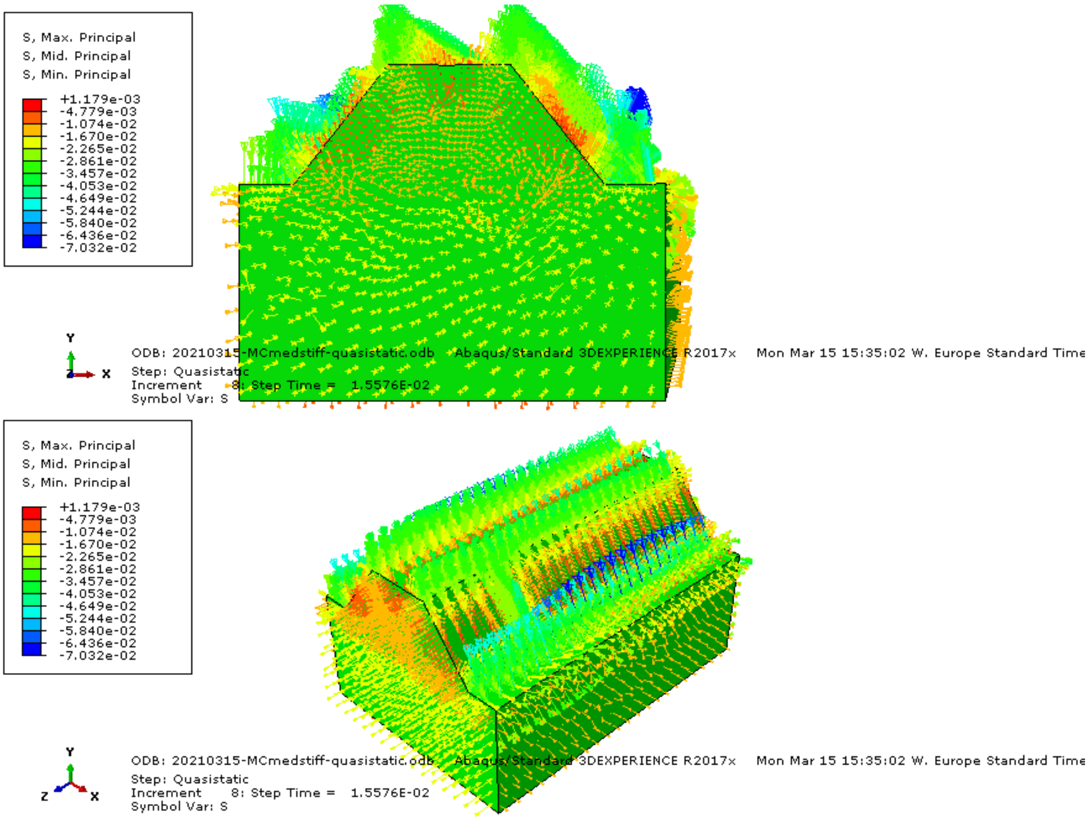


Figure C.8 Principal stress, after prestressing the soil, prior to loading

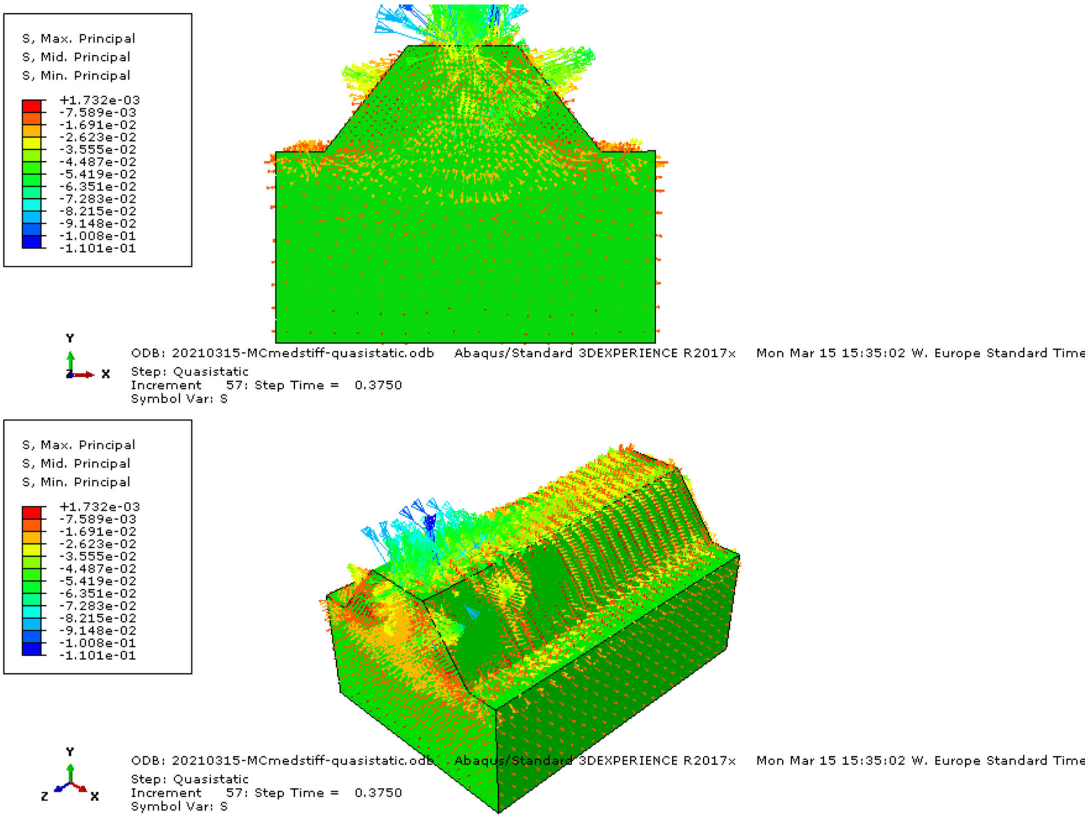


Figure C.9 Principal stress near the peak load

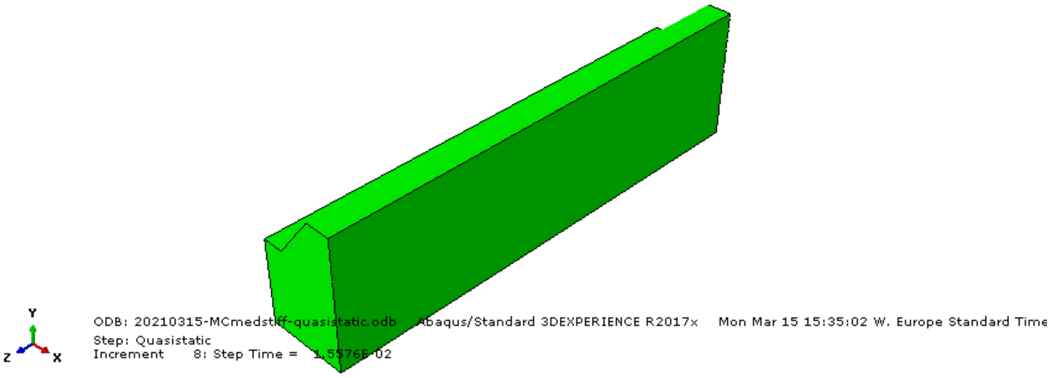


Figure C.10 Slice through model

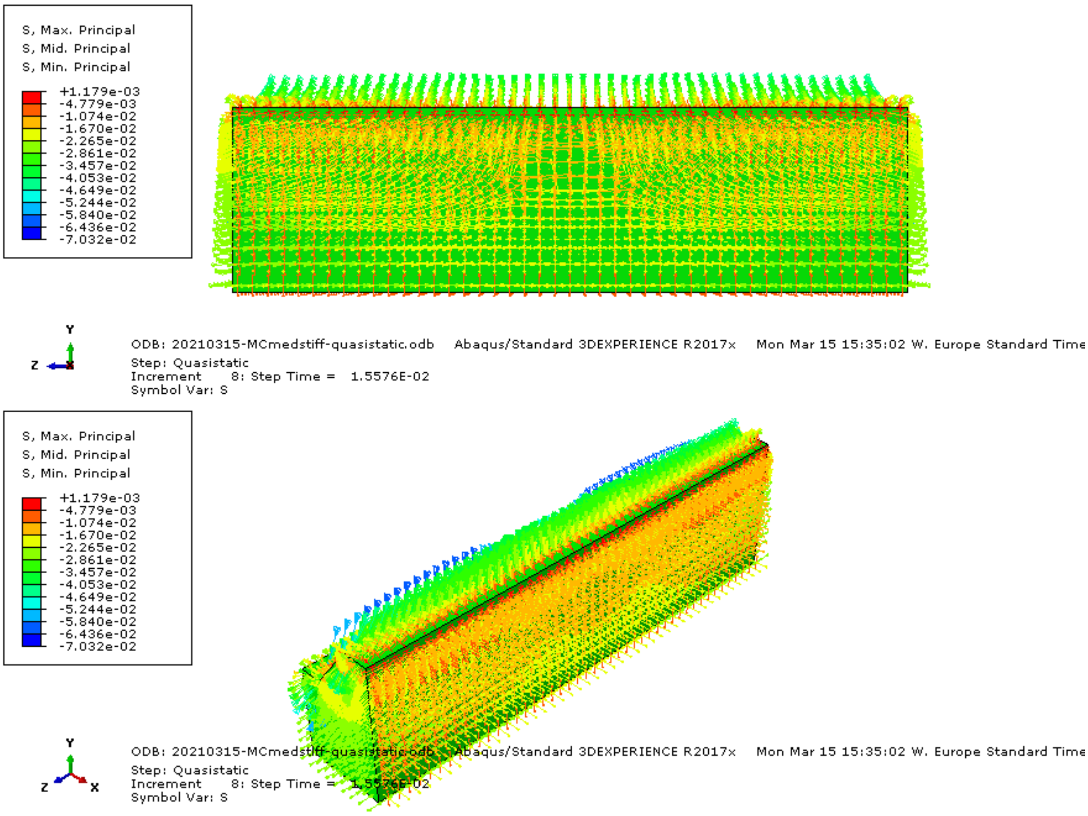


Figure C.11 Principal stress, after prestressing the soil, prior to loading

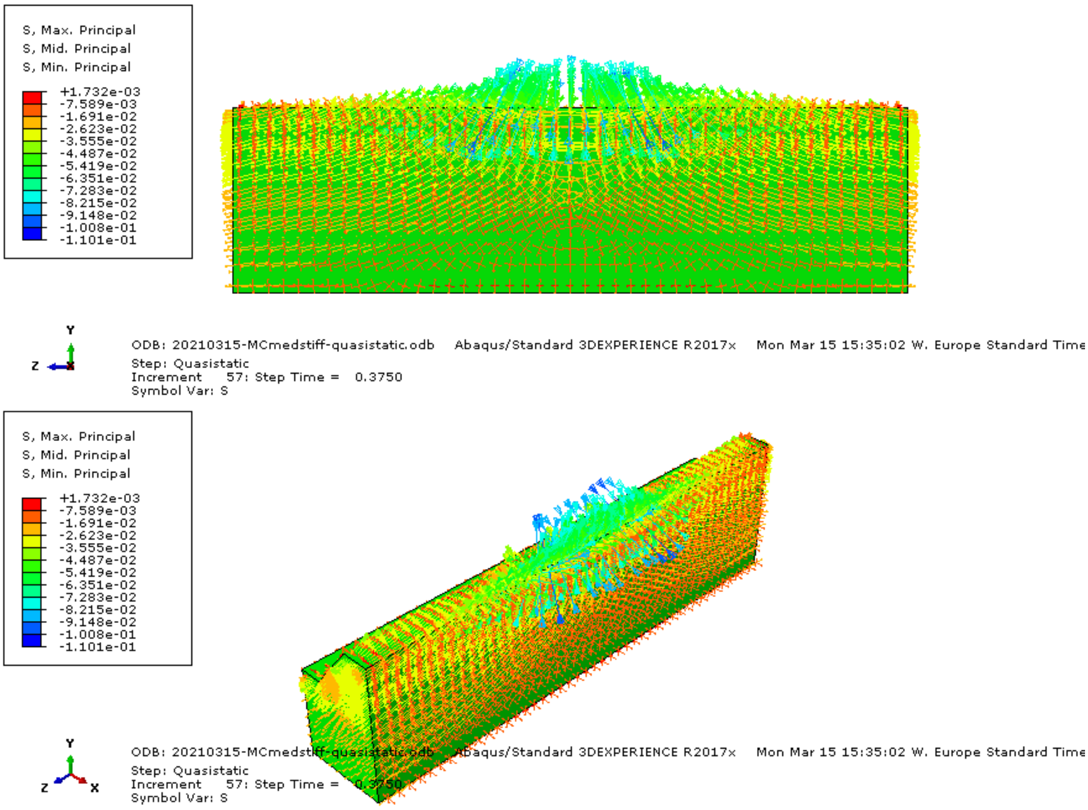


Figure C.12 Principal stress near the peak load

D FE model results for anchored wall situation

An Abaqus run was made where the soil is transferred to the other side of the sheet pile compared to the runs shown in the main text. The situation with the soil on ‘the other side’ represents the anchored wall situation. All other starting points are kept the same.

The analysis type for the anchored wall situation was a RIKS analysis. The analysis was performed for MC medium stiff soil.

The RIKS analysis was not able to find a solution beyond the peak. The shape of the sheet pile for the last step of the RIKS analysis is shown in Figure D.1.

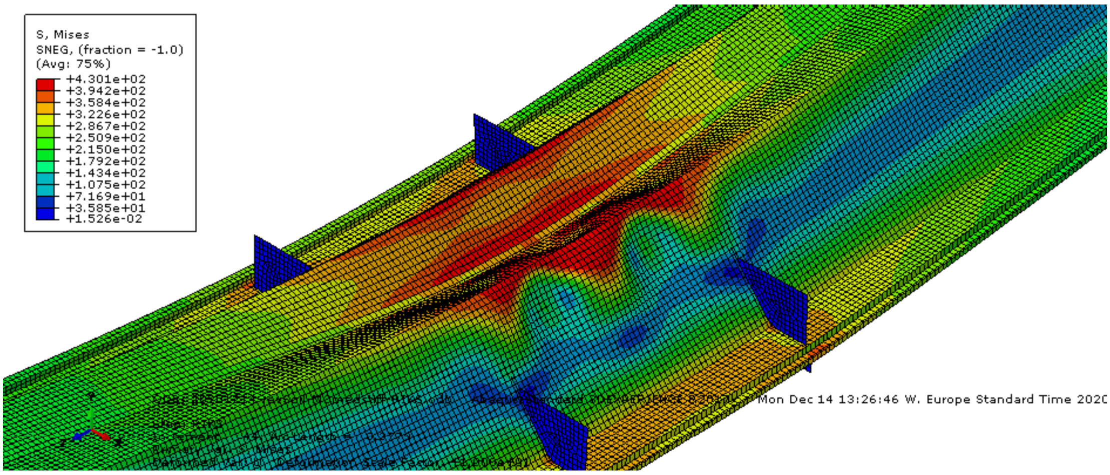


Figure D.1 Shape of the sheet pile for the anchored wall situation (soil not shown) at the peak. Deformations are magnified with a factor 10

The load-displacement curve for the anchored wall situation is plotted in Figure D.2. below. Although the RIKS analysis did not converge, the following conclusions can be drawn:

- Peak force +8% relative to no soil (+13% for soil on initial side).
- Max displacement +3% relative to no soil (+4% for soil on initial side).

The results of the Abaqus calculation are in line with a shadow calculation made with PLAXIS, i.e. the peak force becomes somewhat less compared with the original model but still significant.

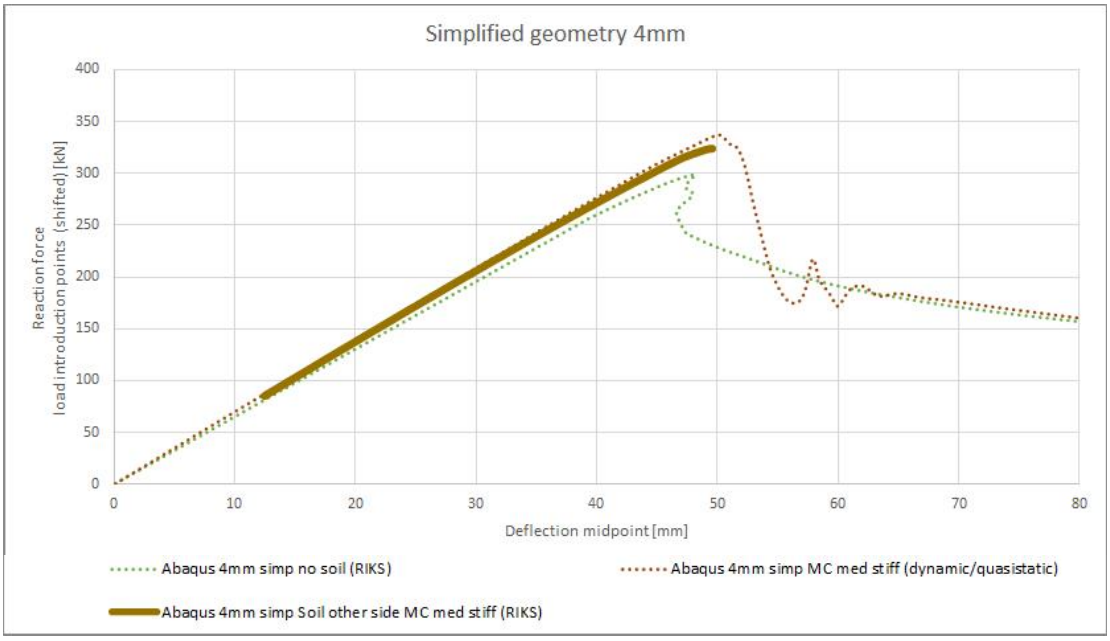


Figure D.2 Abaqus results with and without soil. The brown solid line shows results of RIKS analysis with medium stiff soil 'on the other side' of the sheet pile, representing the anchored wall situation

To check the results in the RIKS analysis, the quasi-static approach was tried next. The results of the quasi-static analysis show significant dynamic effects already in the loading step, see figure D.3. However, near the peak the RIKS analysis and the quasi-static analysis show similar behaviour, where the peak force of the quasi-static is slightly higher (+9%) and so is the maximum displacement (+4%).

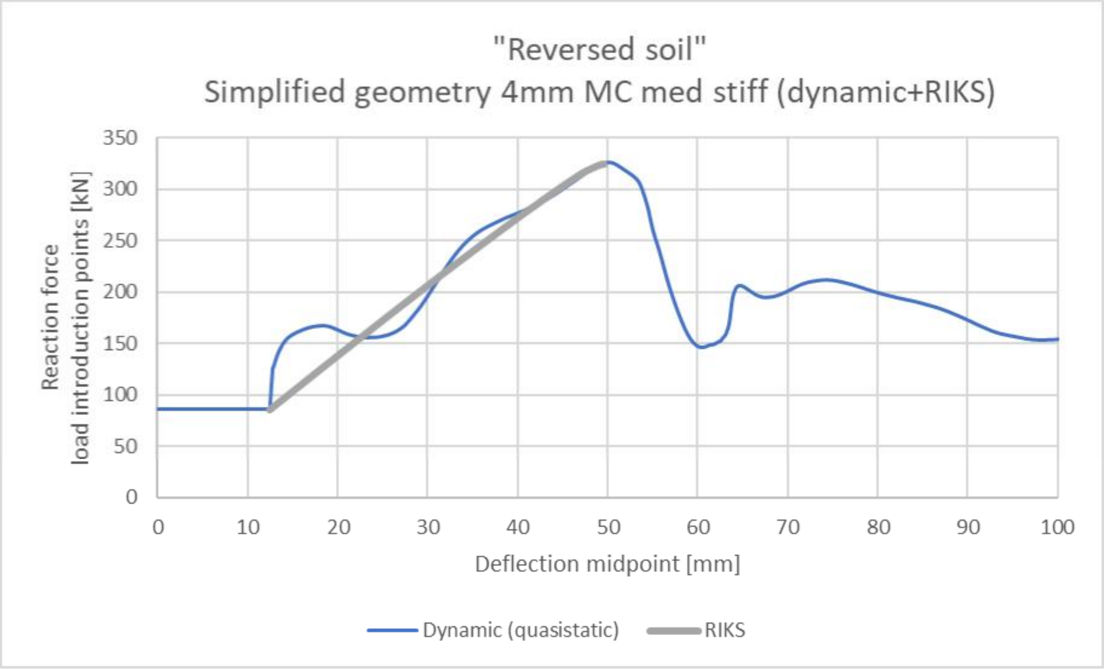


Figure D.3 Results of Abaqus run with soil 'on the other side'. Comparing results of quasi-static/dynamic and RIKS analysis. The peak force is similar

E Moment – rotation graph

To be able to analyse the post-buckling behaviour of the soil supported AZ18-800 in more detail it was decided in the final stage of the project to plot, besides the load – displacement graphs, the moment – rotation diagram for the AZ18-800 simplified geometry without and with MC medium stiff soil.

From the model with and without soil the moment – rotation curve is extracted. The moment is calculated as the support reaction force times the length of the support to the closest load introduction point (= 3.5 m). The rotation is calculated as the rotation of the end plate at the supports (arc tangent of the “horizontal deformation of the top of the end plate minus the horizontal deformation of the bottom of the end plate divided by the height of the end plate of 615 mm”). The results are presented in the graph below.

Figure E.1. Comparison of the moment - rotation curves of the AZ18-800 simplified without soil and with medium stiff MC soil. Note that the results are only presented for a bending moment of 300 kNm and higher, disregarding numerical dynamic effects taking place below the bending moment of 300kNm.

From the moment – rotation curves the same conclusion is drawn as from the load – displacement curves: the results suggest an (slightly) improved post peak behaviour (less brittle behaviour) of the sheet pile supported by soil compared to the sheet pile without soil support.

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