POVM Eemdijkproef

Numerieke DIANA analyses POT Product I5

POV MACRO STABILITEIT

Auteur: T. Naves

Datum: november 2018

Definitief

POV MACRO STABILITEIT

Project
11200956-008-GEO-0011

Pagina's
1

Samenvatting

Om het werkelijke gedrag van een met damwandconstructie versterkte waterkering (de 'blauwe dijk') onder extreme condities tot na bezwijken betrouwbaar in kaart te brengen is binnen de POV|Macrostabiliteit voor deze principetechniek een full-scale bezwijkproef (FSP) voorzien.

Om de doelstellingen rondom deze hoofdproef te kunnen behalen is geconcludeerd dat een aantal "kleinschalige" fysieke proeven noodzakelijk is waarin verschillende configuraties van damwandprofiel omver worden getrokken. In het vervolg worden deze bezwijkproeven aangeduid als de Pull-Over Tests (afgekort tot POTs).

In dit rapport wordt een samenvatting gegeven van de uitgevoerde numerieke DIANA-analyses (deelproduct I5). Doordat deze analyses mede ten grondslag liggen aan het definitieve ontwerp van de POT, is deze memo al gerapporteerd als Bijlage F van het DO (deelproduct I6/I7). In het voorliggende rapport wordt deze memo nogmaals apart (en meteen definitief) opgeleverd.

Versie	Datum	Auteur	Paraaf	Review	Paraaf	Goedkeuring	Paraaf
01	juli 2018	T. Naves		H.J. Lengkeek		L. Voogt	
		A. Bougioukos					

Status
Definitief

Inhoud

0 Productoverzicht

Als verantwoording voor de invulling van het proefprogramma rondom de POV|M Eemdijkproef zijn de volgende hoofdproducten[1] in Tabel 0.1 voorzien:

Code	Hoofdproducten
A	Algemene werkzaamheden
B	Externe stuurinformatie
C	Interne stuurinformatie
D	Inkoop installatie monitoring, veld- en laboratoriumonderzoek
E	Vergunningen
F	Geotechnisch basisrapport proeflocatie
G	Voorlopig ontwerp aanleg/opbouw FSP
H	Voorlopig ontwerp proef POT
I	**Definitief ontwerp proef/herstel FSP/POT**
J	Monitoringsplannen FSP en POT (aanleg, opbouw en proef)
K	Inkoop grondwerk t.b.v. aanleg en opbouw FSP
L	Inkoop grondwerk t.b.v. (tussentijds) herstel proef FSP/POT
M	Inkoop en installatie damwanden en hulpconstructies FSP/POT
N	Inkoop overig materieel t.b.v. uitvoering proef FSP/POT
O	Draaiboeken voor aanleg, opbouw, proef en herstel FSP/POT
P	Factual report en analyse reststerkte & restprofiel proef FSP
Q	Factual report en analyse opbouw en proef POT
R	Factual report aanleg FSP (groene en blauwe dijk)
S	Analyse aanleg FSP (groene en blauwe dijk)
T	Factual report opbouw FSP (groene en blauwe dijk)
U	Factual report proef FSP (groene en blauwe dijk)
V	Analyse proef FSP/POT (groen en blauwe dijk, push-over)
W	Dataverwerking en dataopslag

Tabel 0.1 Overzicht van producten bij proefprogramma POV|M Eemdijkproef

Het voorliggende deelproduct betreft de numerieke DIANA-analyses die ten grondslag liggen aan het definitieve ontwerp van de pull-over test (**deelproduct I5**). Dientengevolge maakt het ook onderdeel uit van **deelproduct I6/I7** (DO van POT) en **hoofdproduct I**.

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[1] *zie aanbieding met Deltares kenmerk 11200956-001-GEO-0003-ydh van 10 mei 2017*

1 Inleiding

1.1 Inleiding

Als onderdeel van de POV Macrostabiliteit (POV|M) is er een full-scale damwandproef voorzien. Deze proef heeft als doel om sterkte en vervormingsgedrag van een combinatie van constructieve elementen en (on)gedraineerde grond onder extreme (hoogwater)condities betrouwbaarder te kunnen voorspellen. In deze proef zal een stabiliteits-verhogende langs-constructie in een gronddijk tot bezwijken worden gebracht. Op basis hiervan kan uiteindelijk antwoord worden gegeven op relevante kennisvragen zoals benoemd in Bijlage A.

In de definitiefase[1] is geconcludeerd dat voor het bepalen van de bovenstaande doelstelling een optimale mix van numeriek en fysiek (groot- en kleinschalig) onderzoek noodzakelijk is. Hierbij is als “kleinschalige” fysieke proef een proef voorzien waarin een damwandprofiel omver wordt getrokken, in het vervolg aangeduid als Pull-Over Test (POT).

Om de predicties uit het VO[2] te updaten is een aantal geavanceerde 3D berekeningen met het pakket DIANA uitgevoerd, waarbij is uitgegaan van grondparameters conform de interpretatie[3]. Deze rapportage behandelt deze analyseresultaten.

1.2 Doelstelling Pull-Over Test

De POT heeft als doelstelling de invloed van de ondersteuning door grond op het gedrag van een (dis)continue damwand te valideren. Hierin wordt met name gekeken naar de plasticiteit van de damwand en de resulterende grond-constructie interactie. De POT zal antwoord geven op de volgende specifieke kennisvragen in Bijlage A:

1. Hoe goed kunnen de beschikbare rekenmodellen het werkelijk optredend gedrag in de proeven (in dit geval de POT) voorspellen.
2. Welke invloed hebben het (dis)continue karakter van de damwand én mate van inbedding in grond op doorsnedeklasse volgens Eurocode 3 - deel 5?
3. Hoe gedraagt zich een in grond ingebedde plank na het ontstaan van een plastisch scharnier. Is er met volledig ingebedde damwand een hoger moment toelaatbaar dan zonder inbedding?

In aanvulling op het beantwoorden van bovenstaande kennisvragen zal de POT ook dienen om ervaring op te doen voor de Full-Scale damwandproef (FSP). Kennis die wordt opgedaan met het (gedrag van de profielen tijdens het) inbrengen van de damwanden, met de proef en de mate waarin het functioneren van de hierop aangebrachte monitoringsinstrumenten hierdoor wordt beïnvloed zal gebruikt worden bij de opbouw en analyses van de FSP.

1.3 Numerieke analyses

In de uitgevoerde analyses met het Eindige Elementen Methode-pakket DIANA is het niet-lineaire gedrag van een (dis)continue wand opgebouwd uit AZ13-profielen in de grond-opbouw van de POT proef beschouwd.

De beschrijving van de uitgangspunten is in de memo in Bijlage B opgenomen.

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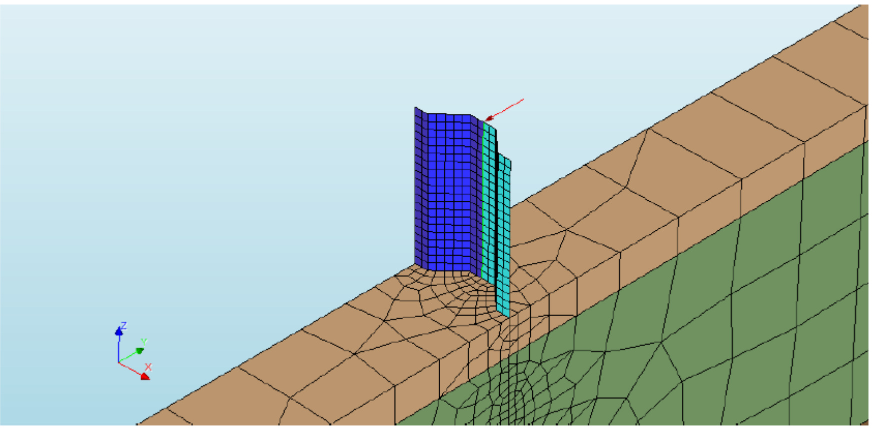
[1] *POV|M full-scale test, Activiteit 2 - Definitiefase, v1,0 definitief, februari 2017;*

[2] *POV|M Full-scale damwand proef, VO Pull-Over Test (POT), v2.0 definitief, juli 2017;*

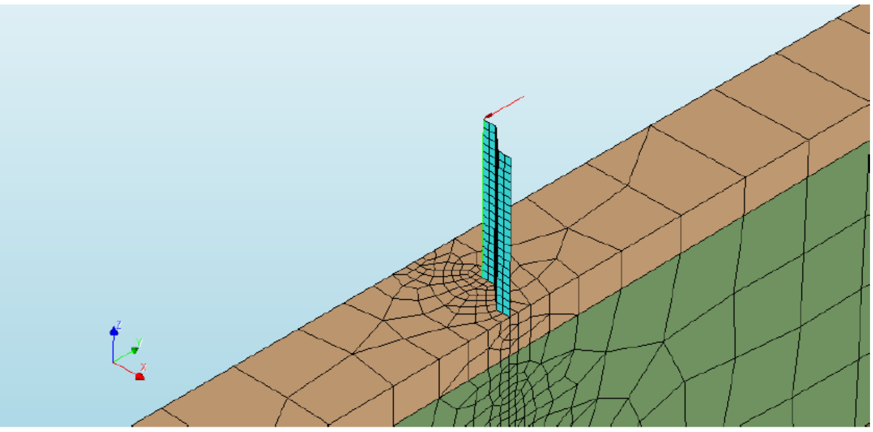
[3] *POV|M full-scale test, Grondinterpretatie rapport, 2017;*

Er zijn drie situaties voor het opleggen van de kopverplaatsing beschouwd:

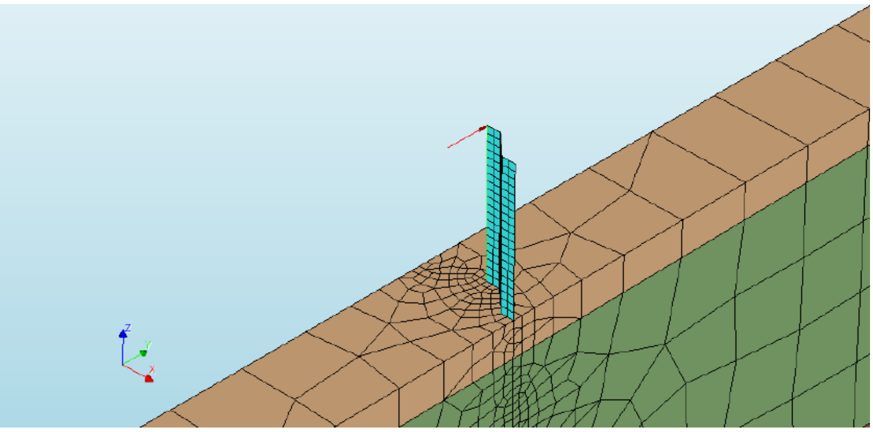
- een continue (doorlopende) wand (zie Figuur 1.1)
- een discontinue wand belast in de normale richting (zie Figuur 1.2)
- een discontinue wand belast in de tegengestelde richting (zie Figuur 1.3)



Figuur 1.1 Schematisering continue (doorlopende) wand in DIANA



Figuur 1.2 Schematisering discontinue wand belast in normale richting in DIANA



Figuur 1.3 Schematisering discontinue wand belast in tegengestelde richting in DIANA

2 Conclusies

Op basis van de uitgevoerde analyse naar het elasto-plastische gedrag van drie verschillende AZ13-damwandconfiguraties in de POT met EEM-software DIANA worden in de memo opgenomen als Bijlage B de volgende conclusies getrokken:

- het DIANA-model is gevalideerd op basis van analytische resultaten[4] en een PLAXIS-model[5] (vervorming alleen lineair gedrag van de damwand) en de vergelijking geeft een goede overeenkomst over de resultaten;
- in de huidige DIANA-versie is het onmogelijk om een geometrisch niet-lineaire analyse uit te voeren wanneer er grond (met volume elementen) wordt meegenomen;
- over het algemeen geldt dat er bij de drie beschouwde configuraties geen significante verschillen qua horizontale vervorming en interne krachtswerking optreden;
- bij alle beschouwde configuraties wordt de theoretische plastische capaciteit (M_{pl}) bij een verplaatsing van $u_y = 0{,}6$m bereikt;
- de kracht die bij de discontinue wand nodig is om plasticiteit te krijgen is vergelijkbaar met de kracht die daarvoor in de doorlopende wand nodig is;
- bij de discontinue wand treedt tussen de planken boogwerking op, in combinatie met het feit dat meer verplaatsing is vereist (en dus meer grond moet worden gemobiliseerd) en er een grotere kracht nodig om plasticiteit in de discontinue wand te laten plaatsvinden;
- er wordt geen verschil waargenomen in het vervormingspatroon van en verloop van de buigende momenten in de discontinue wand wanneer deze wordt belast in de normale en dan wel de tegengestelde richting;
- de reden, dat er naar verwachting slechts marginale verschillen tussen de configuraties optreden, is het feit dat een geometrische lineaire analyse is toegepast.

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[4] *qua initiële verticale en horizontale grondspanningen;*

[5] *qua horizontale vervorming en krachtswerking continue en discontinue wand;*

A Kennisvragen proevenprogramma

De push-over tests en full-scale proeven op een groene en blauwe dijk moeten uiteindelijk leiden tot een complete en betrouwbare dataset, op basis waarvan in de analysefase antwoord kan worden gegeven op de volgende kennisvragen[6]:

	4PBP simulaties zónder grond	**4PBP simulaties mét grond**	**POT (dis)continue wand**	**FSP restprofiel en –sterkte binnentalud**	**FSP groene dijk**	**FSP blauwe dijk**
Hoe goed kunnen de beschikbare rekenmodellen het werkelijk optredende gedrag in de proeven voorspellen?	X	X	X	X	X	X
Welke invloed hebben het (dis)continue karakter van de damwand én mate van inbedding in grond op doorsnede-klasse volgens Eurocode 3 - deel 5?	X	X	X			
Hoe gedraagt zich een in grond ingebedde plank na het ontstaan van een plastisch scharnier. Is er met inbedding een hoger moment toelaatbaar dan zonder inbedding?	X	X	X			
Wat is de meest werkelijkheidsgetrouwe benaderingsmethode voor het restprofiel en de reststerkte?				X		
Wat is het waterkerende vermogen van de blauwe dijk uitgaande van de elastische capaciteit van de damwand? En wat is deze na bereiken van een plastisch scharnier?					X	X
Hoe werkt de krachtsverdeling in de onverankerde damwand onder extreme condities?						X
In welke verhouding worden de sterkte van grond en damwand gemobiliseerd, gaande van nul belasting naar doorgaand bezwijken?						X
Hoeveel vervorming van het systeem is nodig in het traject van elastisch naar plastisch gedrag van de damwand (voor het ontstaan van een plastisch scharnier)?						X
Hoe ziet het vervormingsproces tot na bezwijken eruit, inclusief het ontstaan van restprofiel? Welke volgorde van deelmechanismen treedt er daarbij op?						X
Wat zijn de vervormingen tot aan bezwijken: • …bij een waterkering zonder SVLC (groene dijk)? • …bij een waterkering met SVLC (blauwe dijk)? • …ter plaatse van 'aansluiting' (oftewel de verschil-vervorming tussen de groene en blauwe dijk, beredeneerd op basis van de resultaten van de groene en blauwe dijk)?					 X X	 X X
Tot welke (relatieve) vervormingen in de omgeving leidt het vervormingsproces van de waterkering met SVLC?					X	X

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[6] *ontleend aan Deltares aanbieding met kenmerk 11200956-0001-GEO-0001-jvm van 6 april 2017;*

B Memo DIANA-analyses

MEMORANDUM

Subject -Modelling of push over sheet pilling test in Diana
Project -Pushover sheet pilling test
Date 26 June 2017
Author(s) ir. Apostolos Bougioukos

Checked by ir. T. Naves
Approved by ir. H.J. Lengkeek
Initials

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1 INTRODUCTION

This memorandum describes the modelling of the pushover test of sheet pilling in the FEM software DIANA. This analysis was contacted in order to examine the nonlinear behaviour of the sheet pilling subjected to prescribed displacement, when it is surrounded by soil.
Three models will be examined:

- Continuous wall under prescribed displacement (Figure 1.1).
- Discontinuous wall, under prescribed displacement in the normal direction (Figure 1.2).
- Discontinuous wall, under prescribed displacement in the reversed direction (Figure 1.3).

Figure 1.1 Continuous wall.

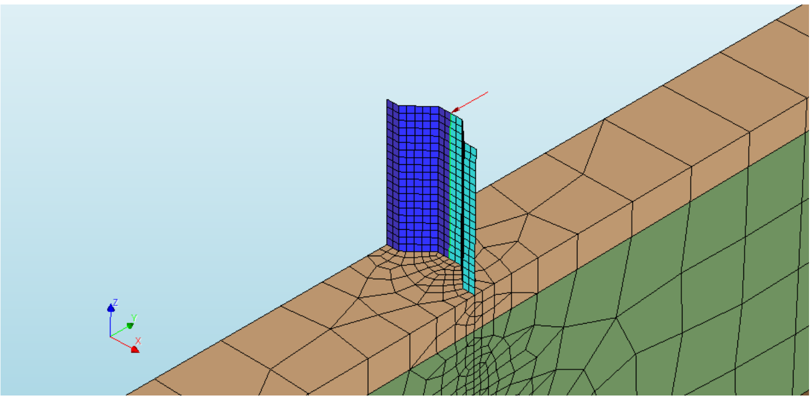


Figure 1.2 Discontinuous wall, normal loading.

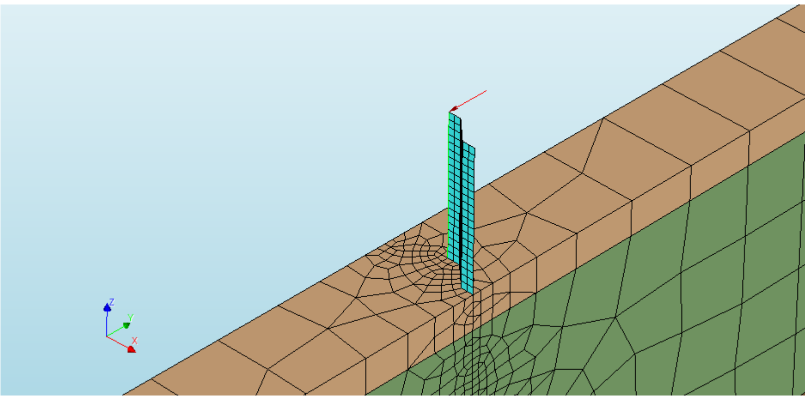
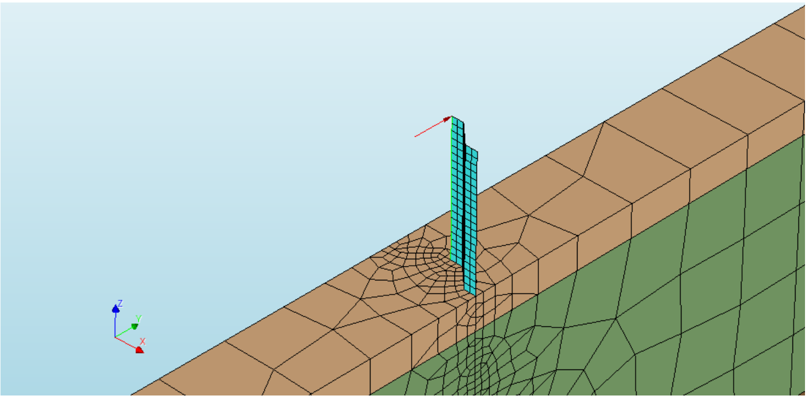


Figure 1.3 Discontinuous wall, reversed loading.



2 MODELLING

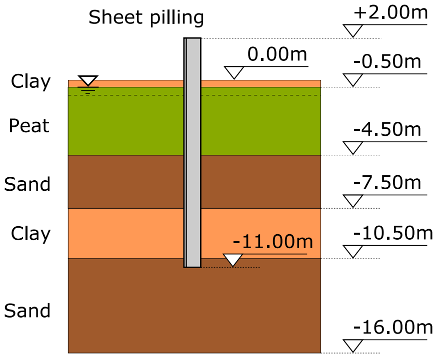
The modelling of the pushover test of the sheet pilling is consisted of three types of material and three types of elements. Solid elements have been used for the modelling of the soil. Shell elements with 3 Gaussian points have been used for the sheet pilling and nonlinear interface elements have been used for the interface between the soil and the wall.

2.1 Soil

The soil is consisted of five layers (

Figure 2.1). The soil layers are modelled based on the Mohr-Coulomb model. The properties that have been assigned to each soil layer can be seen in Table 2.1. These properties have been chosen in such a way that they correspond to the ones used for the modelling of the same problem in PLAXIS.

Figure 2.1 Layers of soil



However, it is worth mentioning that in PLAXIS the wet density of the soil is used, while in DIANA the dry density of the soil is used. For that reason appropriate values of the dry density and the porosity of each soil layer have been specified in DIANA, in order to correspond to the ones of PLAXIS. Additionally, it should be noted that drained behaviour is assumed for every soil layer for consistency reasons.

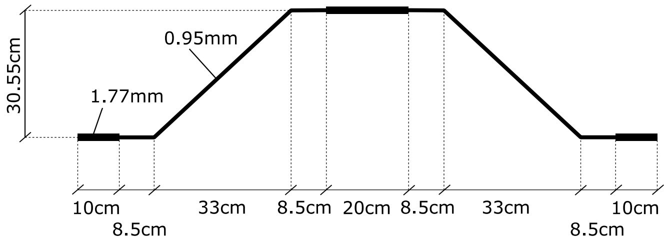
Table 2.1 Soil properties of each layer.

Property	Clay (top)	Peat	Sand (top)	Clay (bottom)	Sand (bottom)
Young's modulus (kN/m^2)	2000	1000	25000	5000	30000
Cohesion (kN/m^2)	10	10	1	10	1
Friction angle (degrees)	30	30	35	30	35
Dilatancy angle (degrees)	0	0	5	0	5
Poisson's ratio	0.33	0.33	0.2987	0.33	0.2987
Density (dry) (kg/m^3)	1229	770	1637	1229	1637
Porosity	0.3	0.3	0.3	0.3	0.3
K0, for initial stresses	0.5	0.5	0.426	0.5	0.426

2.2 Sheet pilling

For this project sheet pilling AZ 13-700 has been chosen. In order to simplify the 3D modelling of this cross-section, an equivalent cross-section with similar properties has been calculated (Figure 2.2).

Figure 2.2 Equivalent cross-section of the sheet pilling.



The material properties of the sheet pilling can be seen bellow:

- Young's modulus: 210 GPa
- Poisson's ratio: 0.3
- Mass density: 7850 kg/m^3
- Yield stress: 300 MPa
- Theoretical elastic bending moment (M_{el}): 391,5 kNm/m × 1.4m (x 0.7m) = 548 kNm (274 kNm)

2.3 Interface

In both sides of the wall interfaces have been applied between the wall and the soil. Coulomb friction interface elements have been used for the modelling of the interfaces in DIANA, with properties calculated based in the following formulas:

- Shear stiffness of interface: $D_{tt} = D_{ss} = \frac{E_{soil}}{2(1+v_{soil})} \frac{A^2}{0.01}$
- Normal stiffness of interface: $D_{nn} = f \cdot D_{ss}$
- Cohesion: $c = A \cdot c_{soil}$
- Friction angle: $tan\varphi = A \cdot tan\varphi_{soil}$

where A is a reduction factor (0.5÷1.0) and f is a multiplication factor (10÷100). Here it has been chosen A=0.6 and f=50.

3 ANALYSIS (PHASED ANALYSIS)

For problems where it is important to calculate the initial stresses of the soil a phased analysis is required.

For this particular project, three phases have been created.

- Phase 1: Initialization of stresses of the soil.
- Phase 2: Installation of the sheet pilling.
- Phase 3: Application of the prescribed displacement.

In the first phase the initial stresses of the soil are calculated. For that reason the structural elements should be deactivated. After the completion of this phase the displacements are suppressed. Following this, the second phase begins taking into account the soil stresses of the previous phase. The sheet pilling is installed in the soil and subsequently the prescribed displacement is applied in five steps of 20cm each.

4 VALIDATION OF THE MODEL

The model is validate in two ways. Firstly, the initial stresses of the soil are compared to the initial stresses calculated analytically with the K0 procedure. Secondly, the stresses and deformations of an equivalent sheet-pile with linear elastic behaviour are calculated with DIANA and compared to the ones calculated with PLAXIS.

4.1 Check of initial soil stresses

Observing the Figure 4.1 and Figure 4.2 it can be concluded that there is a very good agreement between the initial stresses calculated with DIANA and the initial stresses calculated analytically. This agreement applies for vertical and horizontal, total and effective initial stresses.

Figure 4.1 Initial stresses of the soil in the vertical direction: total (left), effective (right).

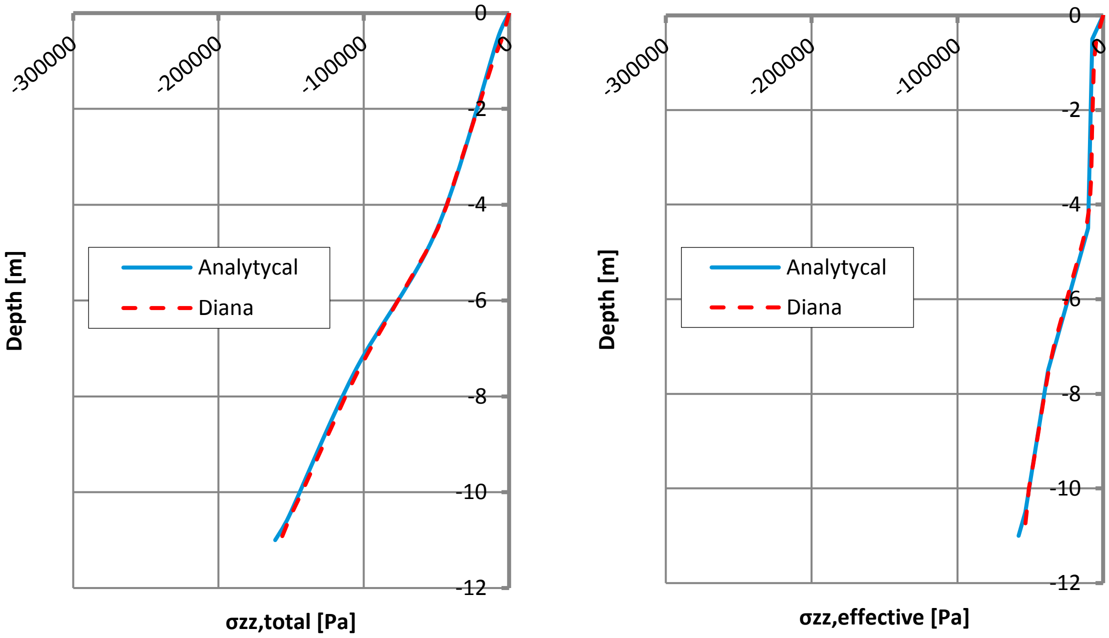
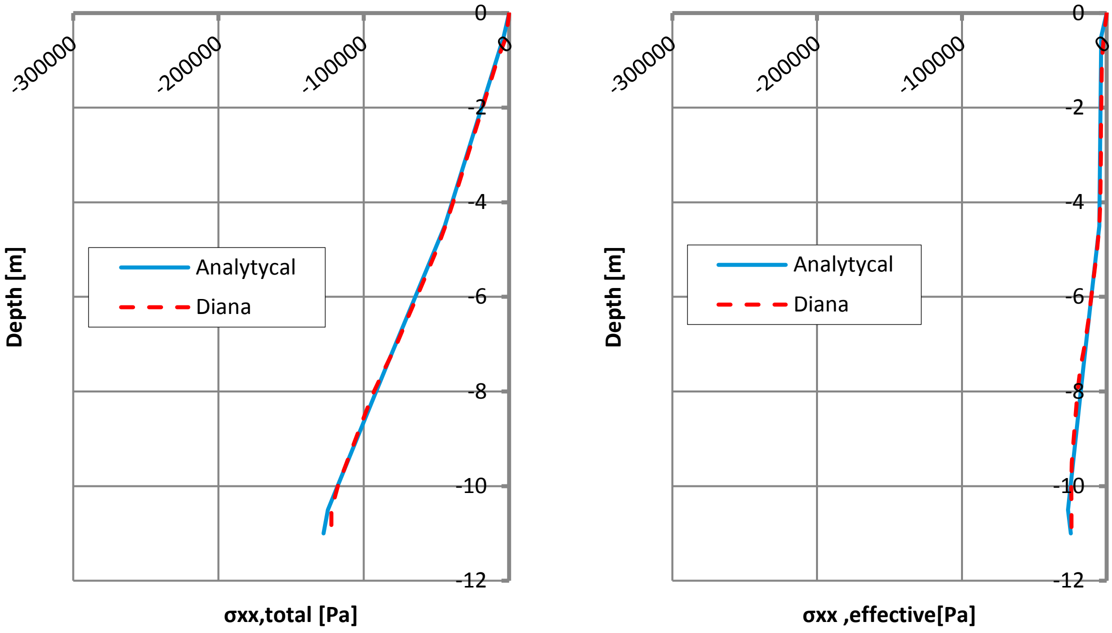


Figure 4.2 Initial stresses of the soil in the horizontal direction: total (left), effective (right).



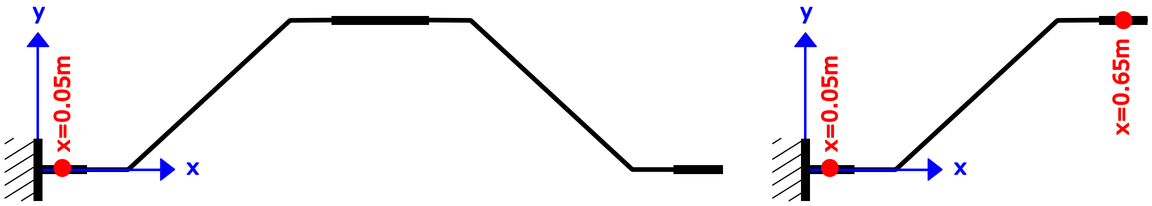
4.2 Check of the sheet-pile with elastic behaviour

Before we examine the elastoplastic behaviour of the sheet pile, the behaviour of an equivalent sheet pile with linear elastic behaviour will be calculated in the FEM software DIANA. The results will be validated with respect to the results calculated with the FEM software PLAXIS for the same models.

For this purpose two identical models of a continuous wall and a discontinuous wall are built in DIANA and PLAXIS. Exactly the same soil layers with the properties given in Table 2.1 based on the Mohr-Coulomb model have been used in both cases. Great care has been taken in order to make sure that similar soil-structure interface properties apply in DIANA model and in PLAXIS model.

For the continuous wall the results of the nodes located in a distance of x=0.05m from the edge of the cross-section of the sheet pile are examined (Figure 4.3 (left)). For the discontinuous wall the results of the nodes located at two positions of the cross-section of the sheet pile are examined; in a distance of x=0.05m and in a distance x=0.65m from the edge (Figure 4.3 (right)). This is because in the later case the sheet pile is free to move at the one edge, so differences are expected on the deflections and the stresses of the sheet pile at positions x=0.05m and x=0.65m.

Figure 4.3 Position at the cross-section of the sheet pile where the results are measured for: (left) continuous wall and (right) discontinuous wall.



In the Figure 4.4 - Figure 4.6 the results calculated for the continuous and discontinuous wall which behave linear elastic, subjected to lateral displacement of u_y=0.6m, calculated with DIANA and PLAXIS are presented. Given the fact that these two softwares are using different solvers, different iterative procedures and different tolerances, the small differences that appear are acceptable.

Figure 4.4 Deflection in the lateral direction (left) and distributed force per meter of cross-section of the sheet-pile (right), for the continuous wall subjected to prescribed displacement, calculated with DIANA and PLAXIS at the position x=0.05m of the cross-section.

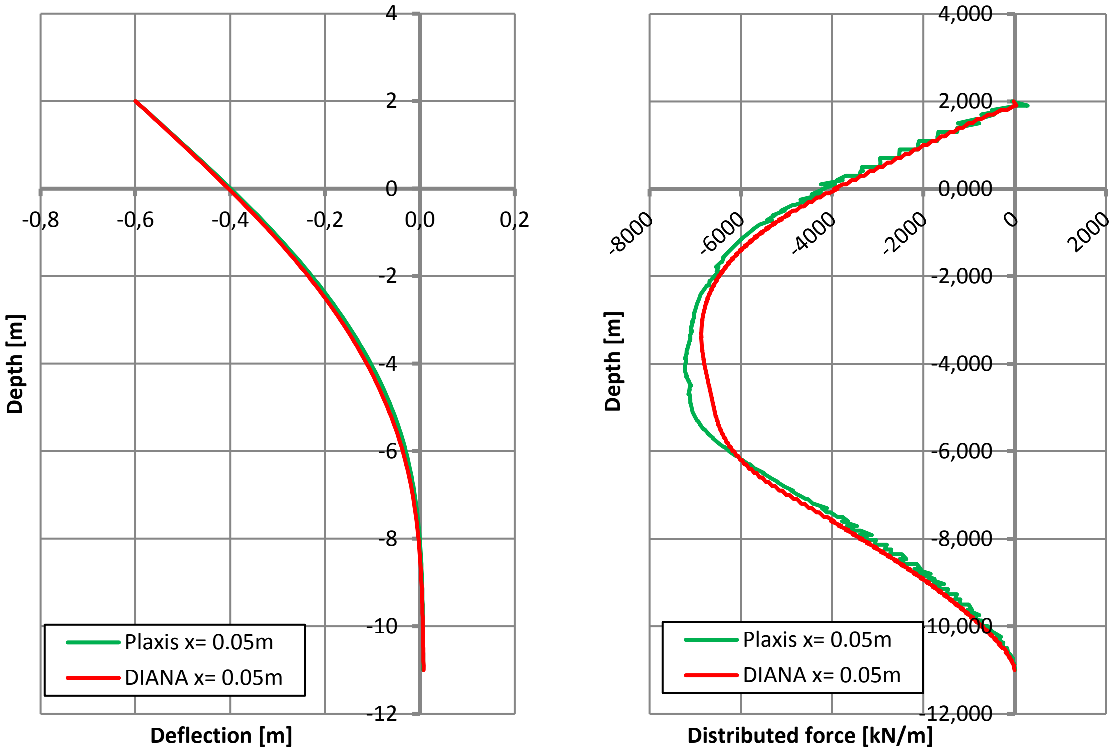


Figure 4.5 Deflection in the lateral direction for the discontinuous wall subjected to prescribed displacement in the normal direction calculated with DIANA and PLAXIS at the positions x=0.05m and x=0.65m of the cross-section.

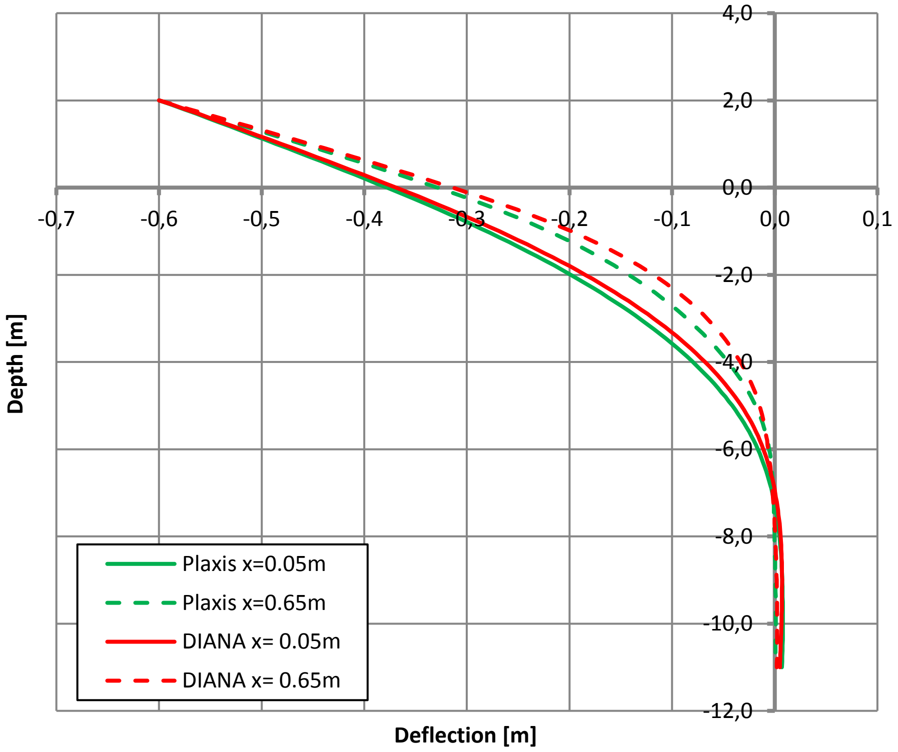
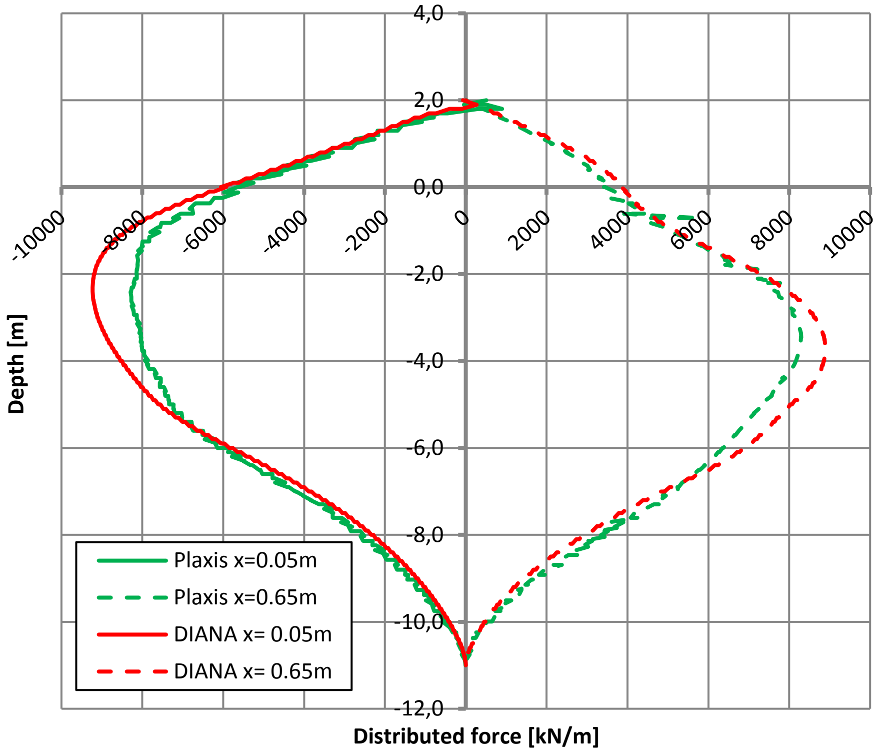


Figure 4.6 Distributed force per meter cross-section of the sheet-pile for the discontinuous wall subjected to displacement in normal direction calculated with DIANA and PLAXIS at x=0.05m and x=0.65m of cross-section.



5 RESULTS

In this section the results of the sheet pile with elastoplastic behaviour are presented for the cases of the continuous wall subjected to lateral displacement and the discontinuous wall subjected to lateral displacement in the normal and in the reversed direction. It should be noted that only physical nonlinearity is applied, while geometrical nonlinearity is not considered.

The fact that geometrical nonlinearity is not taken into account means that the equilibrium equations are based on the unreformed shape of our model. In this sense, the increase/decrease of the stiffness of the sheet pile when its cross-section is deformed, due to large prescribed displacement, will not be captured. Therefore, it is expected that the differences of the developed internal forces between the discontinuous wall loaded in the normal direction and the discontinuous wall loaded in the reversed direction will not be apparent. The reason that we do not apply geometric nonlinear analysis here is that in the current version of DIANA the application of geometric nonlinear analysis when soil elements are present in the model causes convergence issues.

5.1 Continuous wall

In the Figure 5.2 one can see the evolution of the bending moments of the continuous wall, when the lateral displacement at the top is increasing. It is clear that the sheet pile fails when lateral displacement between 0.6m and 0.8m is applied at the top of the sheet pile. The developed bending moments for lateral displacement 0.2m are bellow the theoretical maximum elastic bending moment (548kNm), which is in line with the stresses of the sheet pile which do not exceed the yield stress (f_y =300MPa) (Figure 5.1 (left)). In contrast for lateral displacement larger than 0.4m the developed bending moments exceed the theoretical maximum elastic bending moment of the sheet pile, which is in line with the stresses of the sheet pile which exceed the yield stress in the flanges of the sheet pile (Figure 5.1 (right)).
The maximum bending moments (between 660kNm and 672kNm) carried by the sheet pile appear in depth between 1.2m and 3.9m, when lateral displacement of 0.6 is applied at the top of the sheet pile. For larger

prescribed displacement we see only a slight increase in the developed bending moments of the sheet pile. This means that for larger lateral displacements the sheet pile mainly deforms without carrying additional load. This can be seen in the Figure 5.4, which gives the force-displacement diagram at the top of the sheet pile. It can be seen that the maximum lateral load that can be applied at the top of the sheet pile is 236kN.

In addition, in the Figure 5.3 one can see the deflection of the sheet pile with respect to the depth at the position x=0.05m of the cross-section when the lateral displacement at the top of the sheet pile is increasing. The deflections of the sheet pile are the same at the position x=0.05 and x=0.65m of the cross-section; therefore only the deflections at the position x=0.05m are presented here.

Figure 5.1 Developed stresses in the continuous sheet pile under prescribed displacement at the top of 0.2m (left) and 0.4m (right).

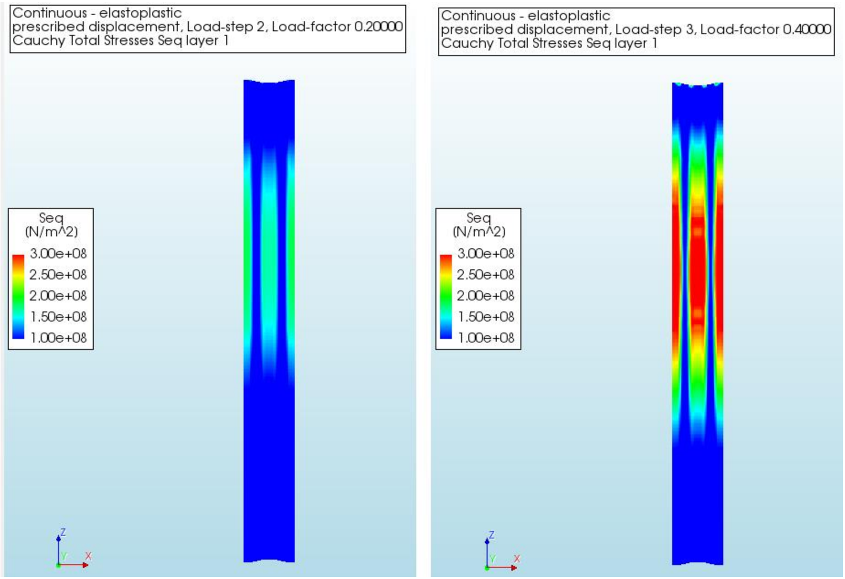


Figure 5.2 Bending moments of the elastoplastic continuous wall subjected to lateral displacement at the top of the sheet pile equal to u_y=0.2... 1.0m

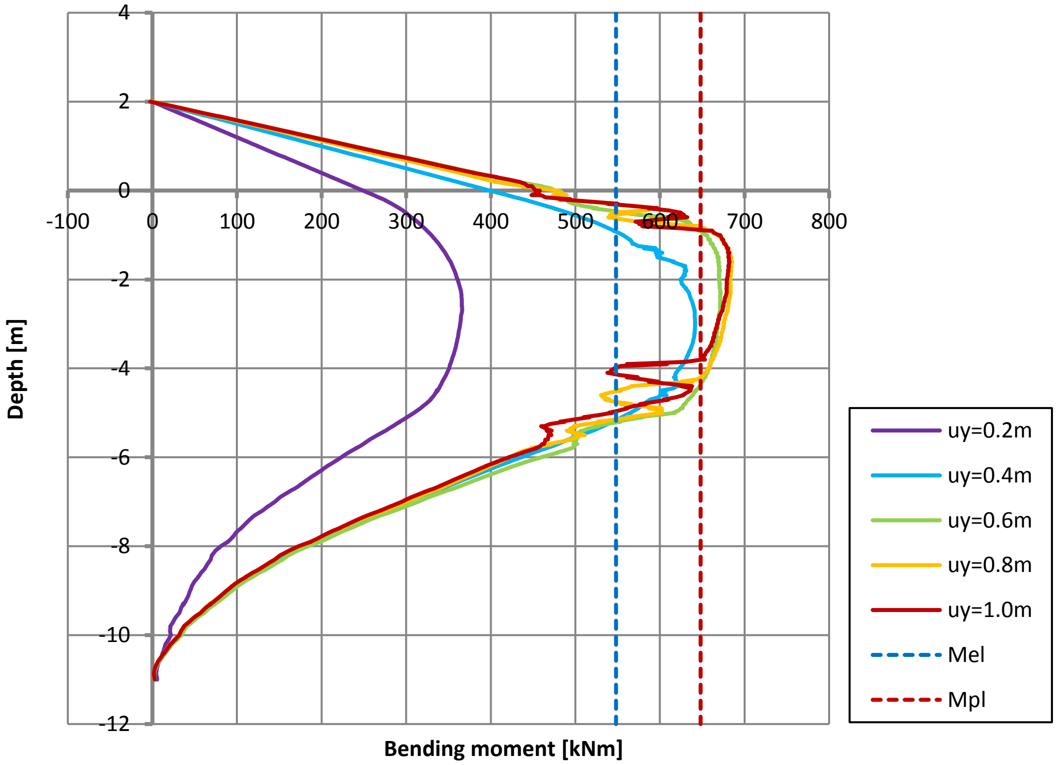


Figure 5.3 Deflections of the elastoplastic continuous wall subjected to lateral displacement at the top of the sheet pile equal to u_y=0.2... 1.0m

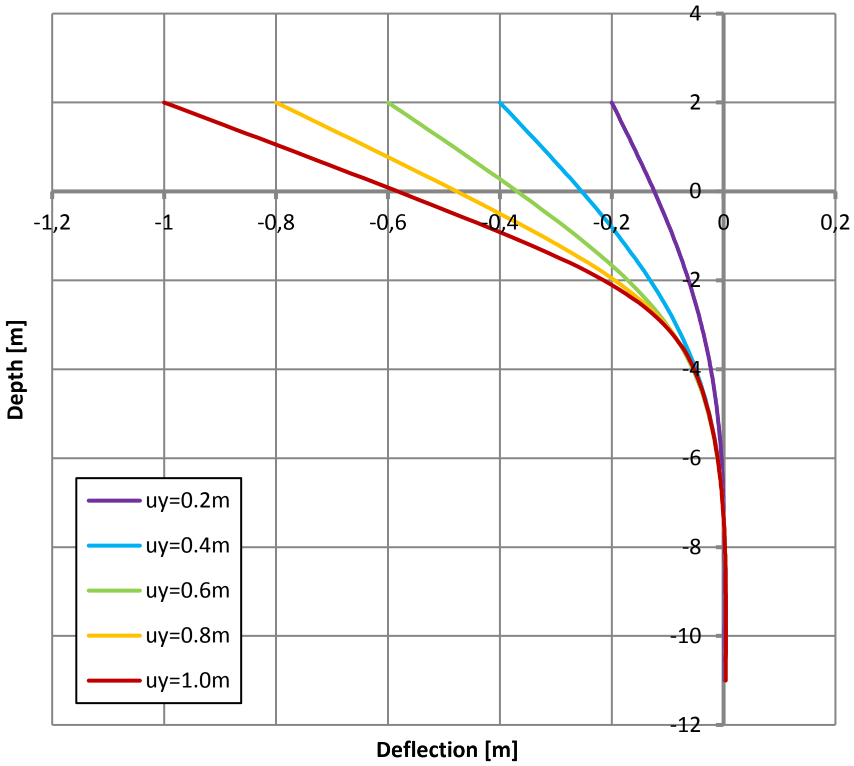
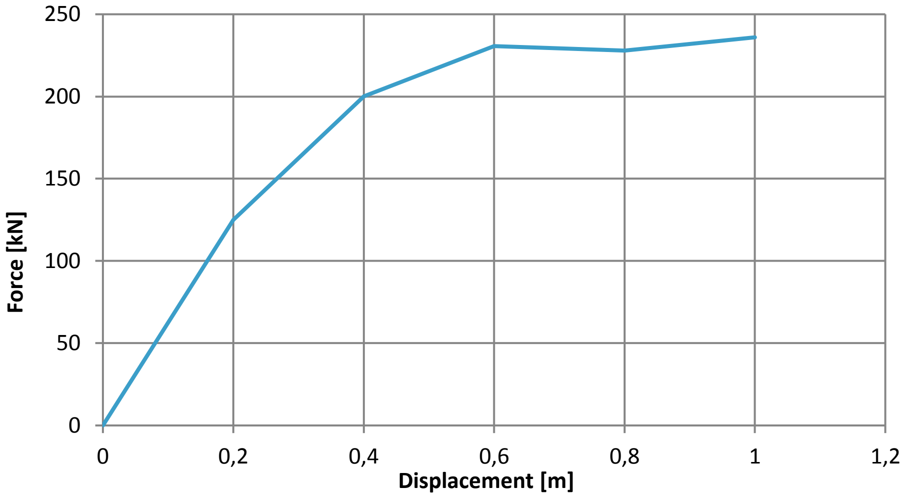


Figure 5.4 Force - displacement diagram (measured at the top of the sheet pile) of the elastoplastic continuous wall.



5.2 Discontinuous wall, loaded in normal direction

In order to compare the bending moments that are developed in the continuous wall with those developed in the discontinuous wall, we will divide the bending moments of the continuous wall by a factor of 2, due to the fact that the model has double cross-section and we are allowed to do that because there is symmetry in the out-of-plane direction. In By comparing the maximum developed bending moments it can be seen that it is larger in the continuous wall (Figure 5.2) compared to the ones of the discontinuous wall loaded in the normal direction wall (Figure 5.5) (e.g. for prescribed displacement u_y=0.6m, $M_{max,cont}/2$ =336kNm against $M_{max,disc}$=333kNm). Similarly, the force needed to deform the top of the discontinuous pile 1.0m is slightly smaller than the load needed to deform the top of the continuous wall 1.0 m (113kN against 236/2=118kN).

Figure 5.5 Bending moments of the elastoplastic discontinuous wall subjected to lateral displacement in the normal direction at the top of the sheet pile equal to u_y=0.2... 1.0m

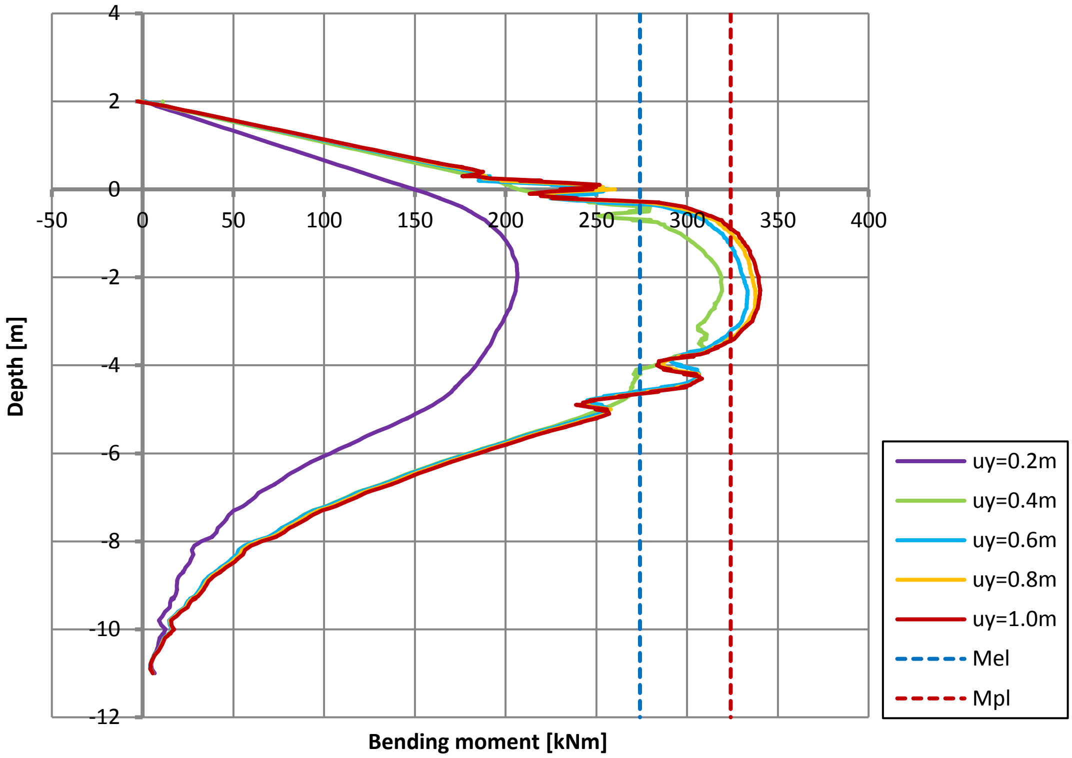
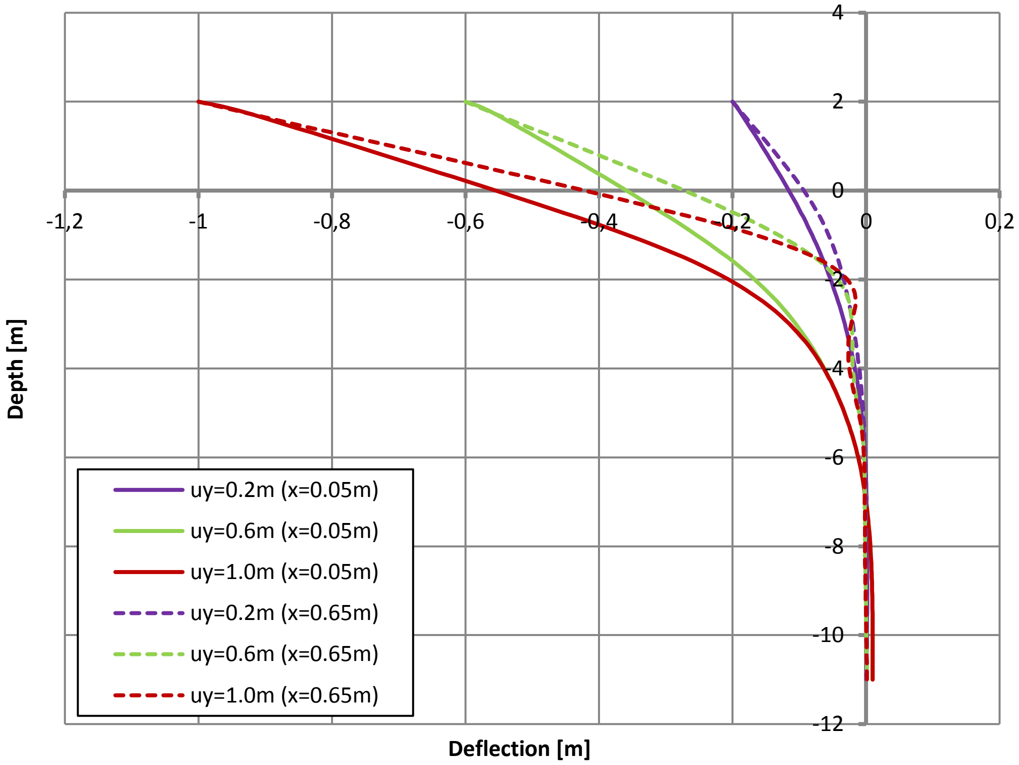
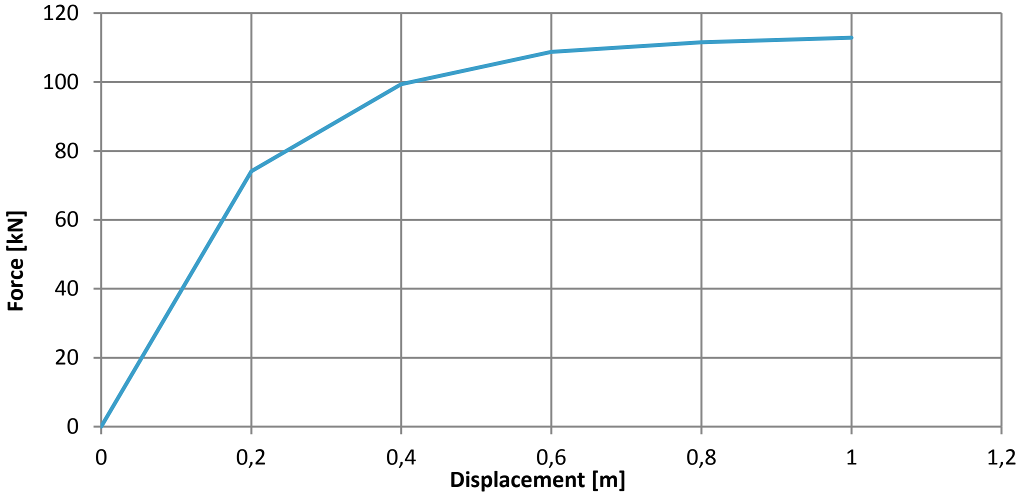


Figure 5.6 Deflections (measured at x=0.05m and x=0.65m) of the elastoplastic discontinuous wall subjected to lateral displacement in the normal direction at the top of the sheet pile equal to u_y=0.2m, 0.6m, 1.0m



By comparing the deflections developed at the clamped edge and the free edge (Figure 5.6) of the discontinuous wall, significant differences appear due to the fact that the latter is free to rotate .

Figure 5.7 Force - displacement diagram (measured at the top of the sheet pile) of the elastoplastic discontinuous wall subjected lateral displacement in normal direction.



5.3 Discontinuous wall, loaded in reversed direction

The results of the discontinuous wall loaded in the reversed direction (Figure 5.9 - Figure 5.10) appear insignificant differences compared to the results of the discontinuous wall loaded in the normal direction; therefore the same remarks apply also in this case. However, this behaviour does not align with what we were expecting. In other words different behaviour for reversed and normal load because the cross section of the discontinuous wall is rotating, thus the stiffness of the sheet pile is changing (increase for reversed loading and decrease for normal loading) when the load is increasing. The reason that this differences are not apparent here is due to the fact that the models do not account for the geometrical nonlinearity, for the reason that is explained at the beginning of this chapter.

Figure 5.8 Bending moments of the elastoplastic discontinuous wall subjected to lateral displacement in the reversed direction at the top of the sheet pile equal to u_y=0.2... 1.0m

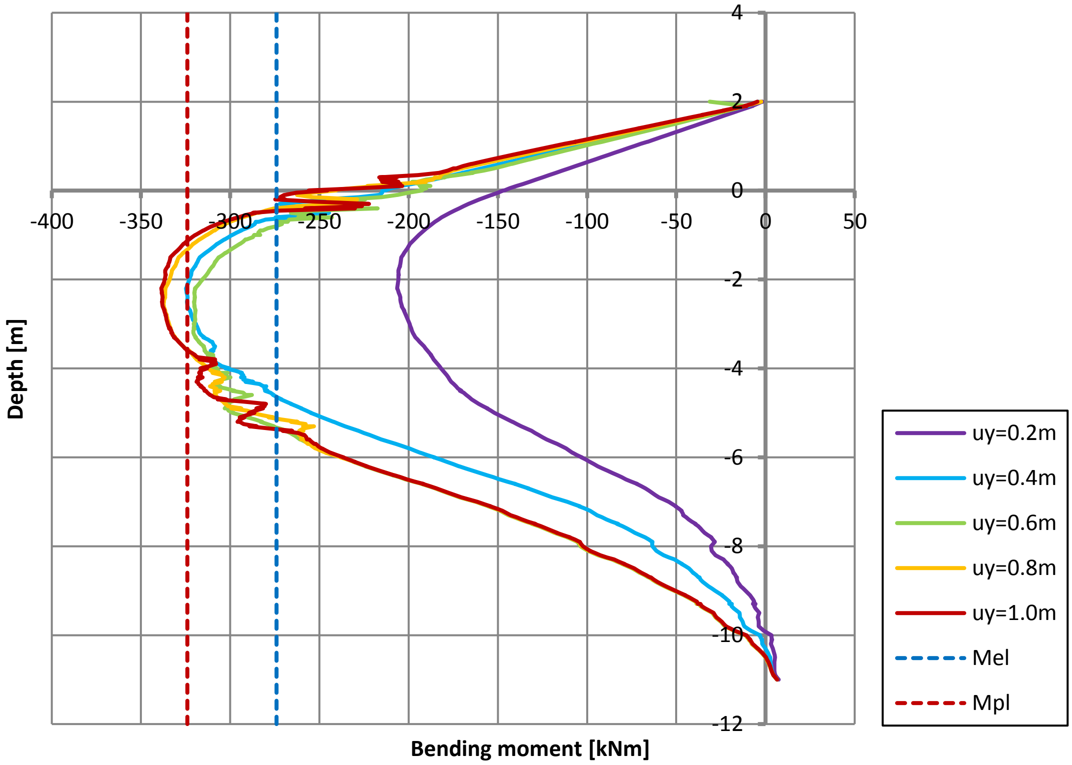


Figure 5.9 Deflections (measured at x=0.05m and at x=0.65m) of the elastoplastic discontinuous wall subjected to lateral displacement in the reversed direction at the top of the sheet pile equal to u_y=0.2m, 0.6m, 1.0m.

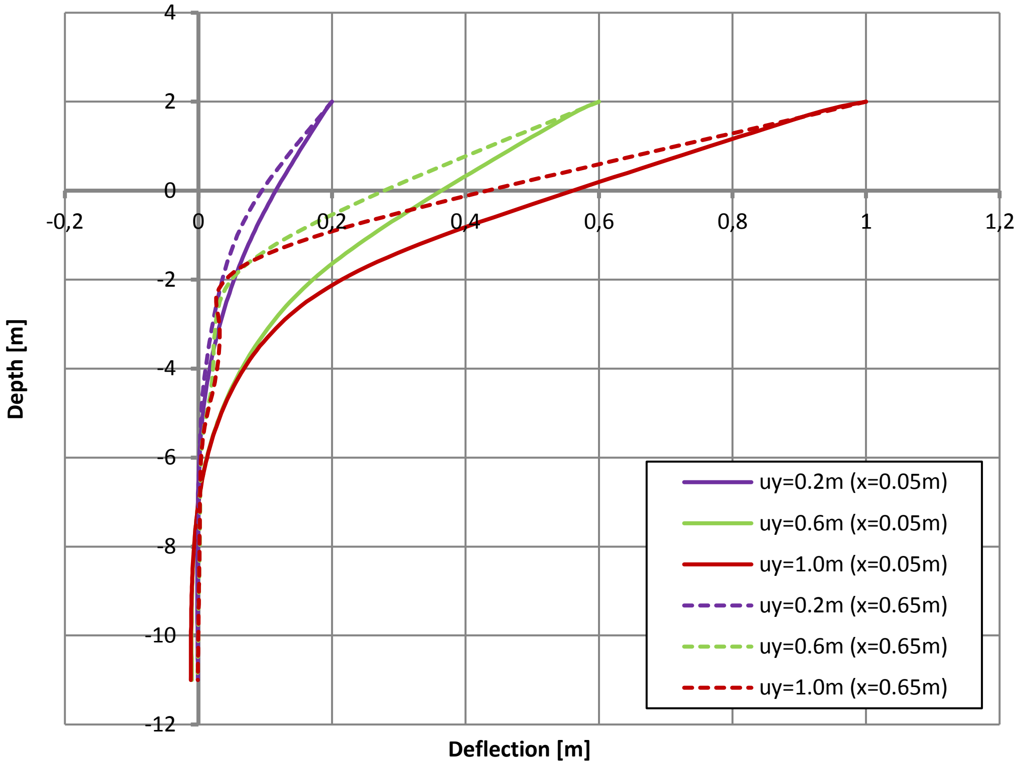
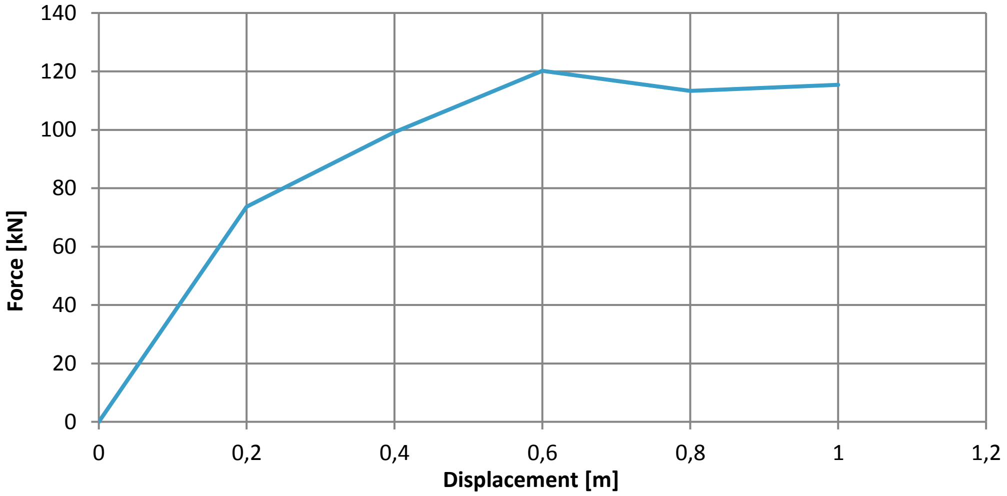


Figure 5.10 Force - displacement diagram (measured at the top of the sheet pile) of the elastoplastic discontinuous wall subjected lateral displacement in reversed direction.



5.4 Comparison results

In this chapter we examined the results of the analysis of a continues wall, a discontinuous wall subjected to normal load and a discontinuous wall subjected to reversed load. It is found out that all the models start to yield for lateral displacement between u_y=0.2 and u_y=0.4m .For all the models, full yielding of the cross-section (development of plastic moment) appears for lateral displacement of u_y=0.6m (Figure 5.12).

Every double-Z sheet pile is able to carry horizontal load up to 236kN, applied at the top of the sheet-pile (+2.0m above the soil surface). The discontinuous wall loaded in the normal direction is able to carry horizontal load at the top of the sheet pile up to 226kN (2×113kN), whereas the discontinuous wall loaded in the reversed direction is able to carry horizontal load at the top of the sheet pile up to 230kN (2×115kN) (Figure 5.11). Regarding the deformed shape, insignificant differences appear between the continuous and the discontinuous wall (Figure 5.13).

Figure 5.11 Force displacement diagram of the elastoplastic continuous and discontinuous wall.

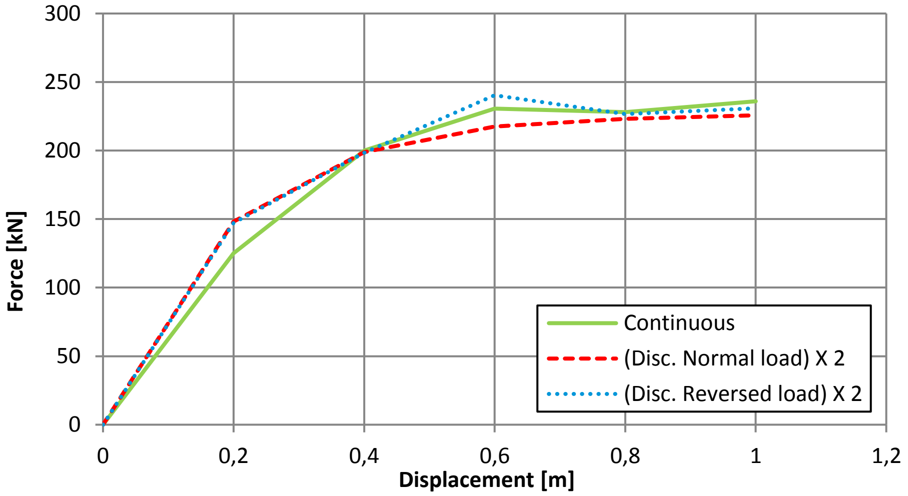


Figure 5.12 Bending moments of the elastoplastic continuous and discontinuous wall, subjected to lateral displacement at the top of the sheet pile equal to u_y=0.6m.

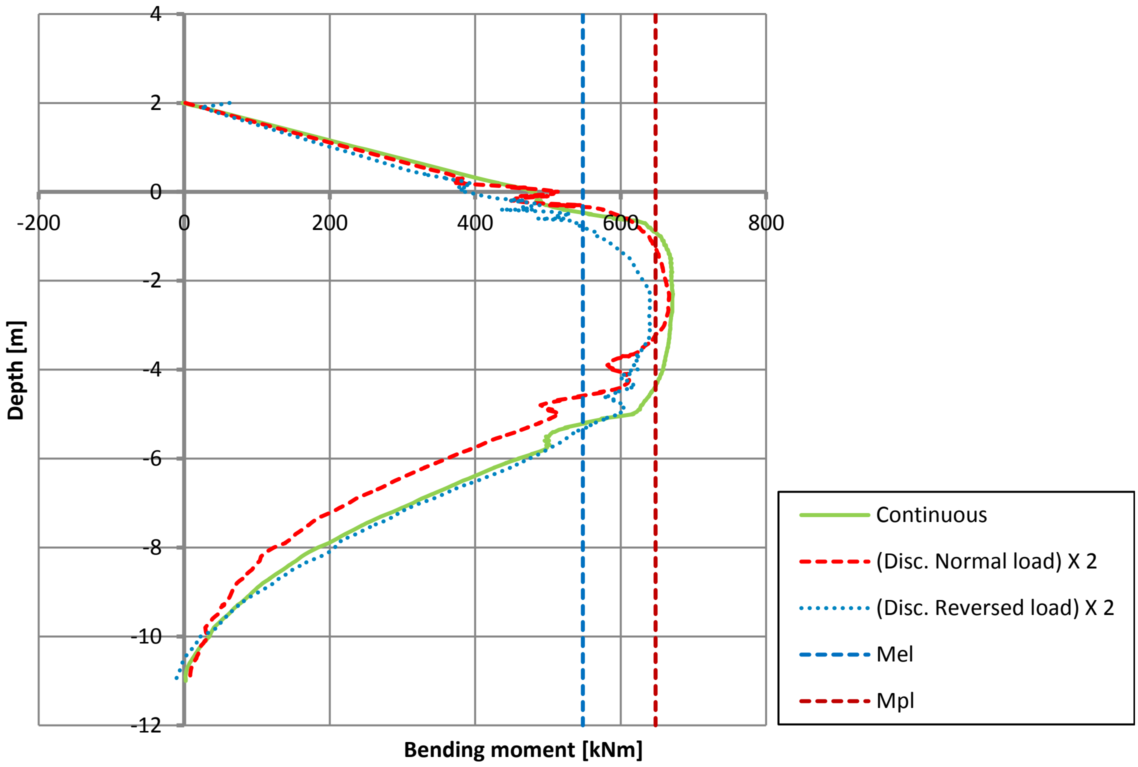
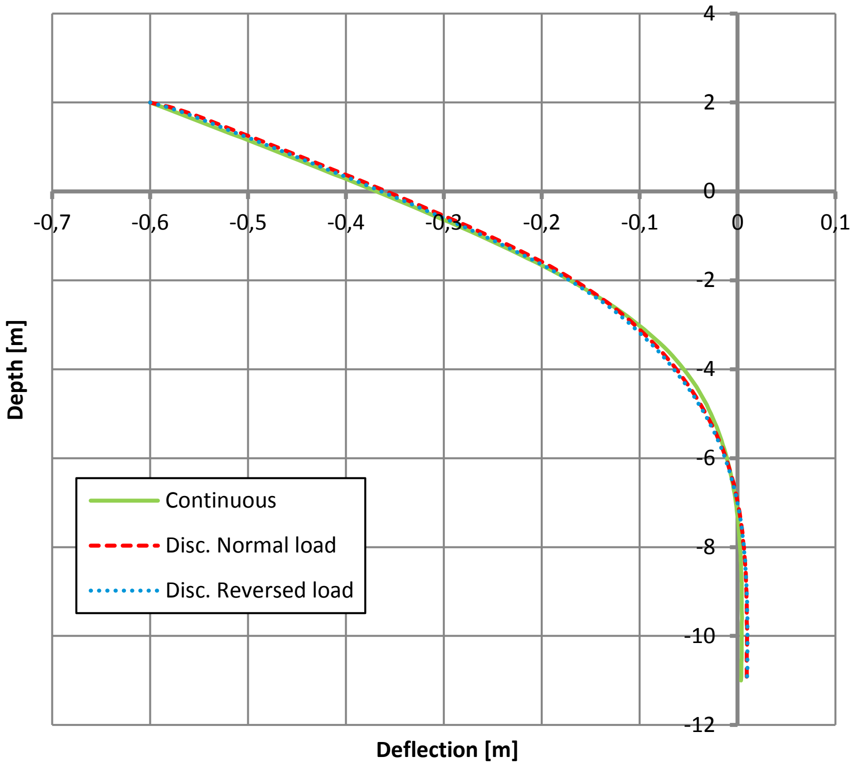


Figure 5.13 Deflections of the elastoplastic continuous and discontinuous wall, subjected to lateral displacement at the top of the sheet pile equal to u_y=0.6m.



6 CONCLUSIONS

From the analysis of the push-over test of the elastoplastic sheet pilling in FEM software DIANA the following conclusions can be drawn:

- The DIANA model is validated based on analytical results and a PLAXIS model (linear behaviour of the sheet pile only) and the comparison gives a good agreement on the results.
- In the current version of DIANA it is not possible to apply geometrically nonlinear analysis when soil elements are present.
- Overall, it can be said that no significant differences appear on the internal forces and displacement of the three different models of the sheet/pile.
- All the models reach the theoretical full bending capacity, for a displacement of u_y=0.6m.
- The force required for plasticity in the discontinuous wall is comparable to the one in the continuous wall. In case of the discontinuous wall, arching between the sheet piles occurs, in combination with the fact that there is more displacement required (and therefore more soil has to be mobilized) a larger force is required for plasticity to occur in the discontinuous wall.
- No difference observed in the deformed shape and the bending moments of the discontinuous wall when it is loaded in the normal and when it is loaded in the reversed direction.
- The reason that only insignificant differences appear between the three models is expected to be the fact that geometric linear analysis is applied.