Validation of numerical model components of LTP by means of experimental data
Validation des composants d'un modèle numérique d'une PTC par des résultats expérimentaux

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ABSTRACT
At Delft University, research was conducted on the validation of the numerical model components of a model to determine the bending moments in slender piles of a Load Transfer Platform (LTP) using the 2D and 3D FEM software PLAXIS. A reliability analysis of PLAXIS was applied on the following five aspects: soil arching, pull-out behaviour of a geogrid, direct shear behaviour of a geogrid, laterally loaded piles by a horizontal force on the pile cap and laterally loaded piles by an embankment. The reliability analysis of PLAXIS for all different aspects is based on an executed laboratory test. The information about the test is obtained from literature.

RÉSUMÉ
A l'université de Delft, Pays-Bas, une recherche a été réalisée sur la validation des composants d'un modèle numérique pour la détermination des moments fléchissants dans les pieux d'une PTC (Plateforme de Transfert des Charges). Ceci a été fait en utilisant les versions 2D et 3D du logiciel PLAXIS. Dans l'analyse paramétrique ont été étudiés les aspects suivants: les effets de voûte dans le sol, le comportement à l'arrachement du géotextile, le comportement au cisaillement localisé du géotextile et celui de pieux sollicités horizontalement par une force appliquée en tête et par un remblai. L'analyse paramétrique de ces différents aspects a été basée sur des essais réalisés au laboratoire tirés de la littérature.

Keywords : LTP, PLAXIS 2D, PLAXIS 3D Foundation, Load Transfer Platform, Soil arching, Pull-out resistance, Direct shear test, Laterally loaded piles.

1 INTRODUCTION

Load Transfer Platforms (LTPs) or piled embankments generally consist of a large number of piles, installed at a small spacing, overlain by geogrids in a platform of material with a high friction, the so-called load transfer platform. The location of the geogrids and the number of geogrids vary per design method. Because of an emphasis on reducing construction time, lateral movements near buildings and reducing the disturbance to the surrounding area during the construction of embankments, several LTP/piled embankments have been constructed in the Netherlands in the past 5 years (Van der Stoel et al. 2006a, 2006b, 2007a, 2007b). As a result of this development in the market, several (Dutch national) committees studying design and execution of piled embankments were initiated.

One of the recommendations for further study was to investigate the possibility of using the Finite Element code PLAXIS for determination of the bending moments in the piles. However, care should be taken when using PLAXIS, because experience with modelling 3D reality in a 2D plane strain model is essential to obtain reliable results. Also, since the calculation models and the soil behaviour are quite complex, it is important to verify the validity of PLAXIS calculation results.

2 VERTICAL FORCE ON PILE CAP WITH THE USE OF GEOGRIDS

To examine the reliability of PLAXIS calculating soil arching, the test of (Zaeske, 2001) was used (see Figure 2). This test simulates soil arching of an infinite pile field with a square pile pattern with and without a reinforcement layer of geogrid. In the test program, the influence of the embankment height, surcharge load and reinforcement were investigated.

The soil arching test was simulated in PLAXIS 2D and 3D. The geometry of the test set-up using PLAXIS 2D is shown in Figure 3. Since PLAXIS 2D is two-dimensional design software and the LTP is a three-dimensional construction, the three-dimensional geometry had to be converted into a two-dimensional geometry, taking into account that the calculation results of PLAXIS 2D are given per meter width.

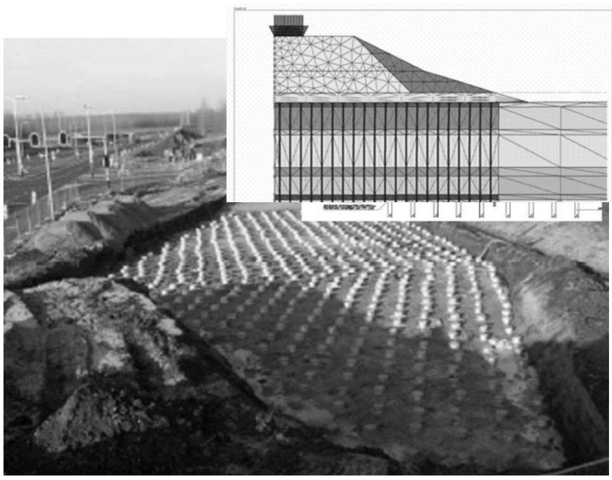

Figure 1. Example, LTP at Almere, Netherlands, Van der Stoel (2007b).

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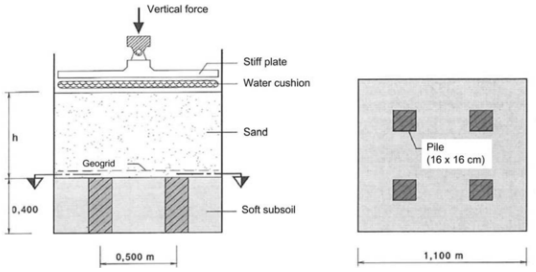

Figure 2. Test set-up (Zaeske D., 2001)

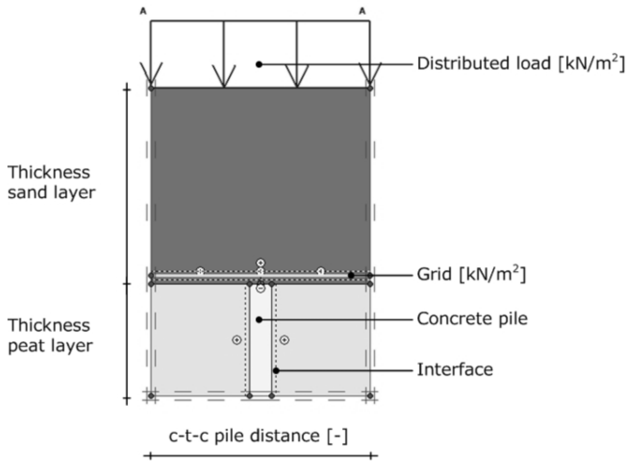

Figure 3. Geometry soil arching PLAXIS 2D

Table 1. Soil Properties soil Arching

Soil properties	Sand	Peat
Unsaturated volumetric weight, γ_{dry} (kN/m^3)	18.1	8.0
Saturated volumetric weight, γ_{sat} (kN/m^3)	18.1	8.0
Horizontal permeability, k_x/k_y (m/day)	10.5	$8 \cdot 10^{-5}$
Cohesion, c (kN/m^2)	0	8.5
Angle of internal friction, φ (°)	38	24
Tangent stiffness for primary oedometer loading, E_{oed}^{ref} (kN/m^2)	28.000	-
Parameter for one dimensional compression, C_c (-)	-	2.48
Parameter for one dimensional recompression, C_s(-)	-	0.5
Initial void ratio, e_{init} (-)	-	8.162

From the simulation of the soil arching was concluded that the stiffness of the geogrid does not influence the vertical force on the pile cap. This behaviour is expressed by the test results and the calculation results of both PLAXIS 2D and 3D.

Compared to the test results, PLAXIS 3D and PLAXIS 2D seriously overestimate the vertical force on top of the pile cap in case the embankment height is less than the distance between the piles (diagonal centre to centre). PLAXIS 3D and PLAXIS 2D slightly overestimate the vertical force on top of the pile cap if the embankment height is more than the diagonal centre to centre pile distance.

3 PULL OUT BEHAVIOUR

To examine the reliability of PLAXIS for calculation of the pull out behaviour, the test of (Alfaro et al., 1995) was used (see Figure 4). For the pull-out tests six-ribbed lengths geogrid specimen were tested, having a total length of 94cm and a width of 44cm. A surcharge load was applied on top of the soil-geogrid system. The effects of the surcharge load on the pull-out force and the distribution of the displacements along the geogrid were measured in the test program.

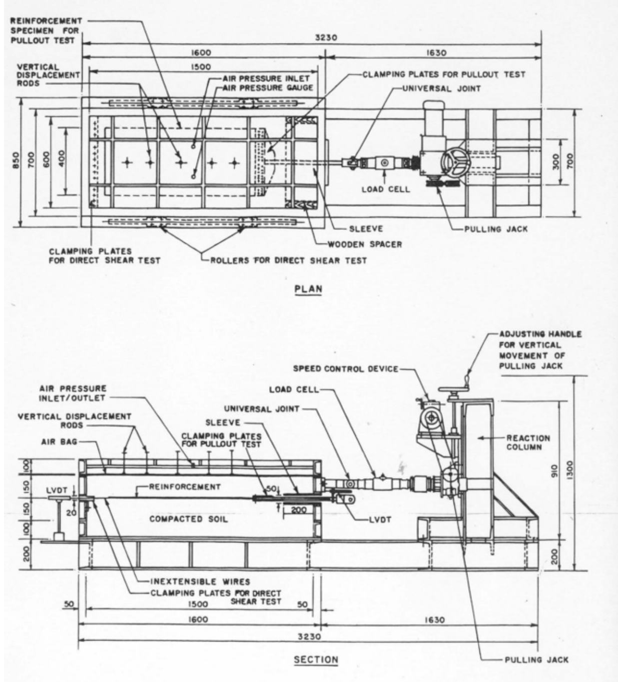

Figure 4. Pull-out/direct shear test apparatus by (Alfaro M.C. et al, 1995)

The pull-out test was only simulated in PLAXIS 2D. A pull-out test (if performed correctly) is a two-dimensional test. The geometry of the model is shown in Figure 5.

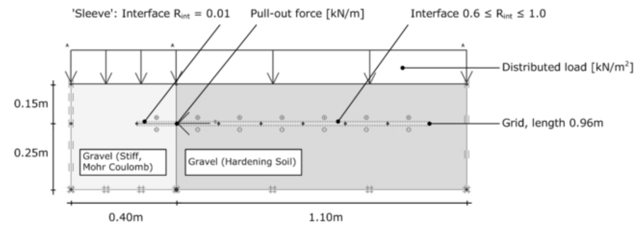

Figure 5. Geometry pull-out test PLAXIS 2D

Table 2. Soil Properties pull out test and direct shear test

Soil properties	Gravel
Unsaturated volumetric weight, γ_{dry} (kN/m^3)	19.0
Saturated volumetric weight, γ_{sat} (kN/m^3)	19.0
Cohesion, c (kN/m^2)	0
Angle of internal friction, φ (°)	45
Secant stiffness in standard drained triaxial test, E_{50}^{ref} (kN/m^2)	75.000

The conclusions that can be drawn from the simulation of the pull out behaviour, are that extensible reinforcements develop a non-uniform shear stress displacement distribution along the length of the grid in a pull-out test. A large portion of the shear stress is mobilized at the place of ‘pulling’. Compared to the test results, the stress redistribution for ribs located further from the ‘pulling location’ is calculated less accurately by PLAXIS.

PLAXIS 2D gives reliable results until 75% of the maximum pull-out resistance. This also complies for the calculation results in which the procedure of the *Updated Mesh* has not been used. However, in this case PLAXIS does not calculate failure at 75%, but at about 90% of the pull-out load. The calculation- and test results differ between 75% to 90% of the maximum pull-out force.

4 DIRECT SHEAR BEHAVIOUR

To examine the reliability of PLAXIS for direct shear behavior again the test of (Alfaro et al., 1995) was used, see Figure 4. The test simulated a soil over soil and a soil over geogrid direct shear test. In the test program, the shear stress over the geogrid versus the shear displacement of the upper box of the test was tested. The direct shear test was only simulated in PLAXIS 2D. A direct shear test (if performed correctly) is a two-dimensional test. The geometry of the model is shown in Figure 6.

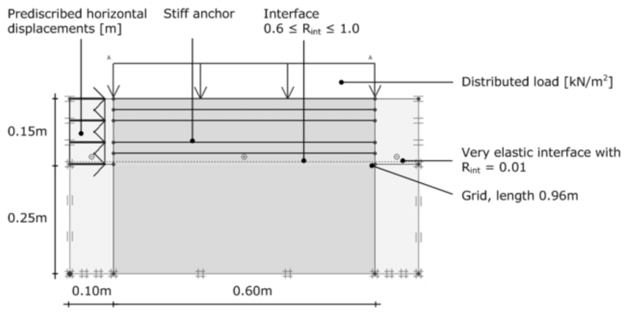

Figure 6. Geometry direct shear test PLAXIS 2D

The conclusions that can be drawn from the simulation of direct shear behaviour are that, in contradiction to the test results, a large part of the maximum direct shear resistance in PLAXIS is mobilized with small differencial displacements of the soil particles in the upper and lower shear box.

PLAXIS calculated large boundary effects at the edge of the shear box, due to high calculated strains of the geogrid near the edges. However, the calculated shear stresses in the middle of the test are quite constant and seem to be reliable up to an enforced horizontal displacement to 20mm.

5 LATERALLY LOADED PILES BY LATERAL FORCE ON PILE HEAD

To examine the reliability of PLAXIS for examination of laterally loaded piles by a lateral force on the pile head, the test results of (Ilyas et al.., 2004) were used, see Figure 7. To examine the effect of laterally loaded piles a series of centrifuge tests were performed. The aim of the experiments was to analyze the pile deflection and the bending moment in the piles for end-bearing piles, loaded by horizontal displacement of the pile cap. Also, the *shadowing effect* phenomenon of laterally loaded piles was studied.

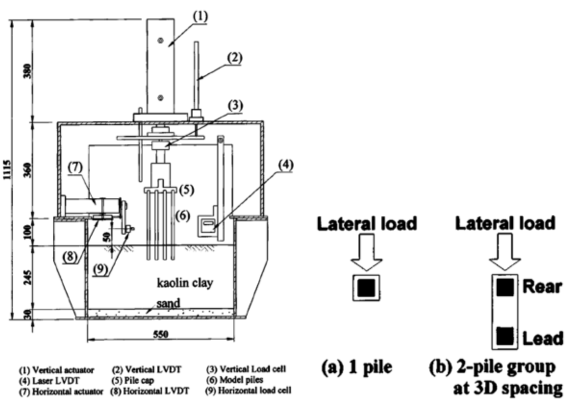

Figure 7. Centrifuge model setup (Ilyas et al.., 2004)

The geometry of the PLAXIS 3D model is shown in Figure 8.

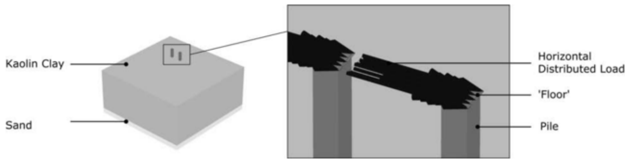

Figure 8. Geometry 'lateral load on head of pile' experiment PLAXIS 3D

Table 3. Soil properties experiment 'lateral load on pile head'

Soil properties	Kaolin clay	Sand
Unsaturated volumetric weight, γ_{dry} (kN/m^3)	16.0	17.0
Saturated volumetric weight, γ_{sat} (kN/m^3)	16.0	20.0
Horizontal permeability, k_x/k_y (m/day)	$2{\cdot}10^{-8}$	10
Cohesion, c (kN/m^2)	0	0.1
Angle of internal friction, φ (°)	16.6	32
Tangent stiffness for primary oedometer loading, E_{oed}^{ref} (kN/m^2)	-	15.00 0
Parameter for one dimensional compression, C_c (-)	1.872	-
Parameter for one dimensional recompression, C_s(-)	1.053	-
Initial void ratio, e_{init} (-)	0.64	-

The conclusion that can be drawn on laterally load piles is that the lateral displacements calculated by PLAXIS 2D exceed the lateral displacements of the test results by far. The calculation results of PLAXIS 3D show less lateral displacement of the pile cap at the same horizontal applied load on the pile cap as the test results. Due to the absence of the Updated Mesh procedure in PLAXIS 3D the second order effects are not taken into account, which causes too small lateral displacements of the pile. A three dimensional FEM model using 15 node wedge elements may show a more stiff behaviour due to interlocking effects. The simulated pile shows a similar deflection curve as the pile in the test results. The calculated bending moments using PLAXIS 3D are nearly the same as the test results for the same horizontal displacement of the pile cap.

6 LATERALLY LOADED PILES BY EMBANKMENT

To examine the reliability of PLAXIS for examination of piles that are loaded laterally by an embankment, the test results of a centrifuge test (Feddema et al, 2008) were used (see Figure 9).

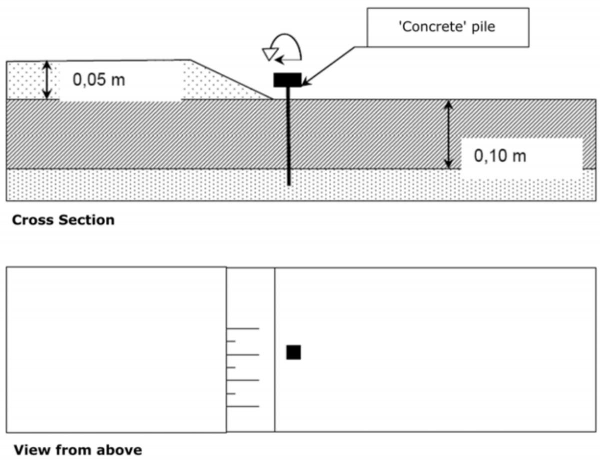

Figure 9. Test set-up by soil laterally loaded piles; model scale (Feddema et al, 2008)

In the test, two piles have been installed at two different moments in time: before the embankment was constructed and after. Only the pile that was installed before construction of the embankment was simulated in PLAXIS 2D and 3D.

The geometry of the PLAXIS 2D model is shown in Figure 20.

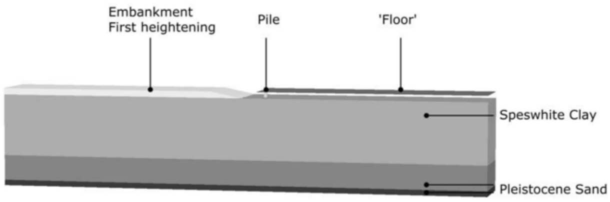

Figure 10. PLAXIS 3D geometry of piles loaded laterally by an embankment

The geometry of the PLAXIS 3D model is shown in Figure 21.

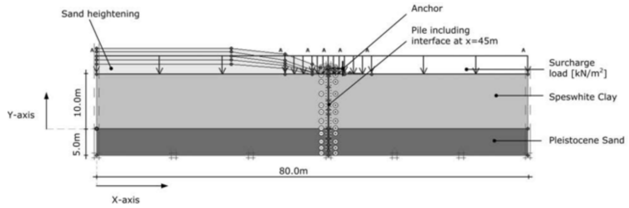

Figure 11. PLAXIS 2D geometry of piles loaded laterally by an embankment

Table 4. Soil properties piles loaded laterally by an embankment

Soil properties	Speswhite clay	Pleistocene	Baskarp
Unsaturated volumetric weight, γ_{dry} (kN/m^3)	16.2	18.0	18.0
Saturated volumetric weight, γ_{sat} (kN/m^3)	16.2	20.0	20.0
Horizontal permeability, k_x/k_y (m/day)	$4{\cdot}10^{-4}/2{\cdot}10^{-4}$	1.0	1.0
Cohesion, c (kN/m^2)	0.5	0.1	1.0
Angle of internal friction, φ (°)	22	35	42
*Youngs modulus, E_{ref} (kN/m^2)	1.872**	75.000*	10.000*
**Secant stiffness in standard drained triaxial test, E_{50}^{ref} (kN/m^2)			
Tangent stiffness for primary oedometer loading, E_{oed}^{ref} (kN/m^2)	1.053	-	-
Modified swelling index, κ* (-)	0.09	-	-
Modified compression index, λ* (-)	0.024	-	-

The conclusions that can be drawn on piles that are laterally loaded by an embankment are that the calculated lateral soil displacements are larger than the occurring displacements. A first reason for the lateral soil displacement being calculated too large by PLAXIS, might be the anisotropic behaviour of clay. Unfortunately PLAXIS does not contain anisotropic behaviour, and therefore horizontal strains of the soil will be calculated too large for a parallel embankment load situation. Secondly, the horizontal displacements were measured using cameras, which is not a very accurate method for measuring small displacements. Finally, the absence of the Updated Mesh procedure in PLAXIS 3D effects the calculated stability off the embankment, which in term influences the lateral displacements of the soil and the pile.

The calculated bending moments in the pile are larger than the occurring bending moments of the pile in the test for all simulations. The bending moment in the pile is related to the horizontal displacement of the soil. If the lateral displacement of the soil is calculated too large, the bending moment of the pile will also be computed too large. PLAXIS 3D gives slightly better results than PLAXIS 2D for the calculated bending moments compared to the observed bending moments in the pile of the test for all heightening steps. However, a three-dimensional FEM model using 15 node wedge elements may result in stiffer calculated behaviour than the output of a two dimensional FEM model using 15 node triangular elements due to interlocking effects.

The calculated level of the absolute maximum and minimum bending moments is equal to the maximum and minimum bending of the test results.

7 CONCLUSIONS & RECOMMENDATIONS

Calculation results of PLAXIS 2D and 3D overestimate the vertical force on the pile caps for an embankment height less than the diagonal pile spacing. PLAXIS also underestimates the vertical soil settlements compared to the test results, while the calculated vertical force on the pile cap seems reliable.
For the pull-out test, reliable results are calculated until 75% of the maximum pull-out resistance.

For the direct shear test, PLAXIS calculates the direct shear resistance too high at small displacements. Large boundary effects were calculated at the edge of the shear box, due to high calculated strains of the geogrid near the edges.

The behaviour of piles loaded laterally by a horizontal force on a pile cap, is well simulated for small lateral displacements using PLAXIS 3D. The calculated bending moments using PLAXIS 3D are nearly the same as the test results at a given horizontal displacement of the pile cap. If the *Updated Mesh* procedure would be available in PLAXIS 3D improved calculation results may be expected. Because of model limitations, the simulation using PLAXIS 2D gives very poor results.

The calculated lateral soil displacements resulting from a parallel embankment are larger than the actual occurring displacements, although the absolute differences are small. This could be caused by the determination of the soil parameters, the software or the measurements. The calculated lateral displacements using PLAXIS 2D and 3D seem reliable for slightly laterally loaded piles as found in LTP systems. Almost all calculated bending moments in the pile were overestimated compared to the occurring bending moments. However, as the bending moment in the pile are direct related to the horizontal soil displacements, this can be expected if the lateral soil displacement are computed too large. The calculated depths of the absolute maximum and minimum moments are equal to the test results.

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