Validation and Application of the Embedded Pile Row-Feature in PLAXIS 2D

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The modelling of piles in a 2D finite element model brings limitations because pile-soil interaction is a strongly 3D phenomenon. Pile-soil interaction is difficult to model and traditional methods in which pile rows are modelled either as plates or as node-to-node anchors have clear drawbacks. The embedded pile row has been developed to model a row of piles in the out-of-plane direction, which is available in PLAXIS 2D 2012. It is supposed to result in a more realistic pile-soil interaction behaviour compared to other methods. This article discusses the principle and validation of the feature, which has been performed in a MSc thesis study (TU Delft). Recently, the embedded pile row feature has been applied by Witteveen+Bos in the design of a quay wall for the General Cargo terminal of the New Baku International Sea Trade Port.

In the past, plates and node-to-node anchors have been used to model piles in PLAXIS 2D. Both methods have some advantages compared to each other, but both also have clear drawbacks:

- Plate elements have pile properties, converted to properties per unit width in out-of-plane direction. Interface elements are used to manipulate the pile-soil interaction. However, the use of interface elements separates the soil mesh, which results in a minor interaction between both sides of the pile. Using a plate element is therefore limited to low out-of-plane spacing $L_{spacing}$ compared to the pile diameter D_{eq} (e.g. $L_{spacing}$ / D_{eq} < 2 to 3).
- Using a node-to-node anchor, the soil mesh is continuous and there is no interaction with the soil. Soil can 'flow' independent from the pile, however, in reality there is always some sort of interaction. Moreover, a node-to-node anchor has no properties in lateral direction, which limits the use of this method to fully axial loaded piles only. Some sort of pile foot modelling is needed in order to sustain axial forces in the pile, since a single node at the foot is generally insufficient and leads to mesh dependent results.

The embedded pile row combines the advantages of the plate and node-to-node anchor. It has pile properties similar to the plate element and a continuous mesh similar to a node-to-node anchor. This is done by separating the pile and the soil. The pile, represented by a Mindlin beam element, is not 'in' the 2D mesh, but superimposed 'on' the mesh. A special out-of-plane interface is developed to connect the beam with the soil nodes and represents the pile-soil interaction.

Principle

When drawing an embedded pile row in PLAXIS 2D, two lines are created: a geometry line and the embedded pile. If a mesh is generated, the elements are generated around the geometry line. The element edges and nodes along the geometry line are duplicated. The original and duplicate nodes are connected with interface elements.

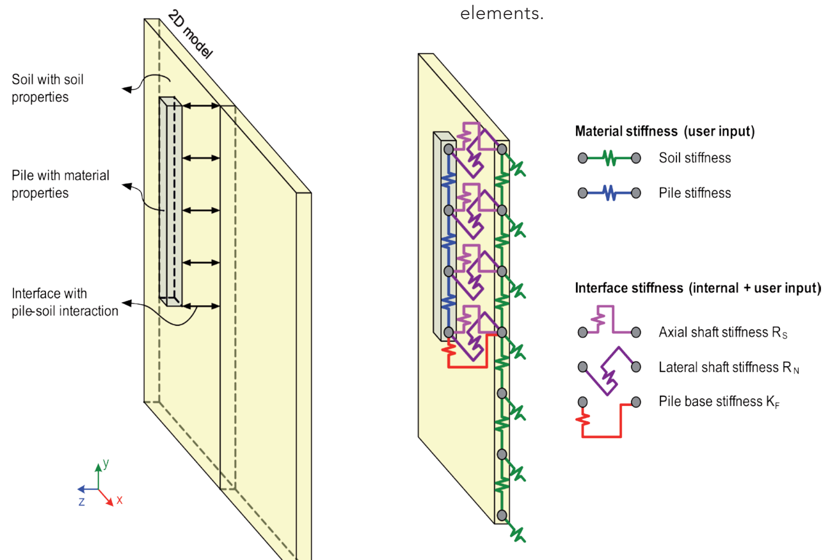
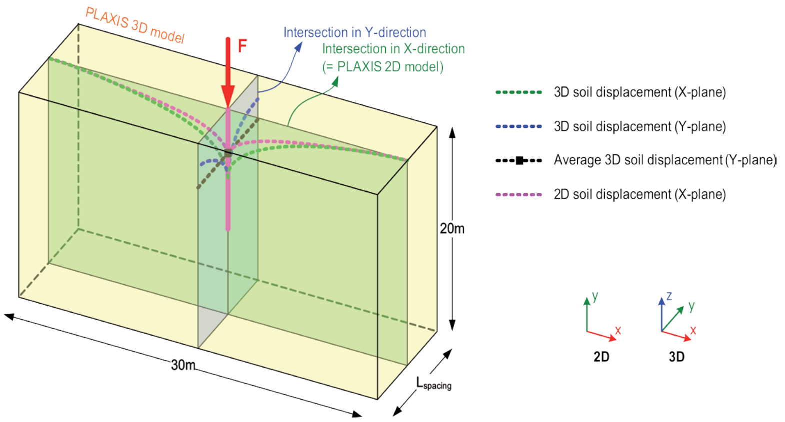


Fig. 1: Principle of the embedded pile row (Sluis, 2012)



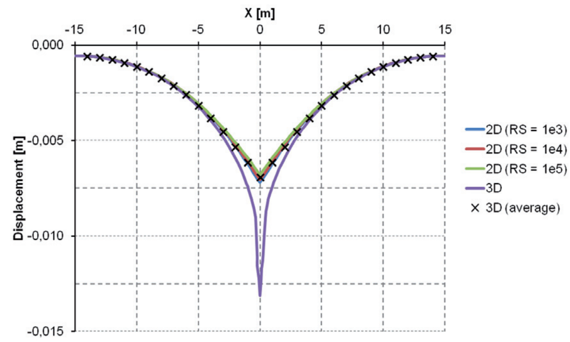


Fig. 3: 2D soil displacement at surface level for varying interface stiffness, compared to (average) 3D soil displacement (Sluis, 2012)

Fig. 2: Modelling of a pile row with a single embedded pile in PLAXIS with various pile spacing (Sluis, 2012)

Along the pile there is a line-to-line interface represented by springs with numerical stiffnesses in axial and lateral direction (R_S and R_N). The springs in axial direction are limited by a plastic slider, representing the shaft capacity of the pile. There is no limitation of the spring forces in lateral direction. At the base there is a point-to-point interface, represented by a spring and plastic slider, which take care of the end bearing of the pile. The interface is visualised in Figure 1 (sliders are not shown in this figure).

The pile capacity is an input parameter, similar to the embedded pile in PLAXIS 3D, for which a shaft capacity $T_{S;max}$ and base capacity $F_{bot;max}$ should be defined. The pile capacity is defined in the material set, together with the stiffness, weight and dimensions of the pile. These pile properties are entered per pile, which are converted to properties per unit width in out-of-plane direction during the calculation. This is done by using the out-of-plane centre-to-centre distance of the pile row $L_{spacing}$, which is also an input parameter.

The deformation behaviour between the pile and the soil is an interaction between pile stiffness, soil stiffness and interface stiffness, as shown in Figure 1. The interface stiffnesses R_S, R_N and K_F are related to the shear modulus of the soil G_{soil} and the out-of-plane centre-to-centre distance $L_{spacing}$ and radius of the pile r:

$$R_s = ISF_{RS} = \frac{G_{soil}}{L_{spacing}} = [-] \bullet \frac{\left[kN/m^2 \right]}{[m]} = \left[\frac{kN/m^2}{m} \right]$$

$$R_N = ISF_{RN} \bullet \frac{G_{soil}}{L_{spacing}} = [-] \bullet \frac{\left[kN/m^2 \right]}{[m]} = \left[\frac{kN/m^2}{m} \right]$$

$$K_F = ISF_{KF} \bullet \frac{G_{soil} \bullet r}{L_{spacing}} = [-] \bullet \frac{\left[kN/m^2 \right] \bullet [m]}{[m]} = \left[\frac{kN/m}{m} \right]$$

ISF_{xx} is the interface stiffness factor, a dimensionless factor to manipulate the deformation behaviour. Default values have been derived by Plaxis as part of the validation (Sluis, 2012) and are related to the out-of-plane spacing and pile diameter:

$$ISF_{RS} = 2.5 \bullet \left(\frac{L_{spacing}}{D_{eq}} \right)^{-0.75}$$

$$ISF_{RN} = ISF_{RS} = 2.5 \bullet \left(\frac{L_{spacing}}{D_{eq}} \right)^{-0.75}$$

$$ISF_{KF} = 25 \bullet \left(\frac{L_{spacing}}{D_{eq}} \right)^{-0.75}$$

The interface stiffness factors can be overruled by the user, because the formulas are derived for only a limited number of cases. Moreover, by overruling the default values the user is able to fit the load-displacement curve of the embedded pile row with for example measurement data from a pile load test.

Validation

The embedded pile row has been tested and validated as part of a MSc thesis study (TU Delft). The behaviour of the embedded pile row, soil displacement and pile displacement, was evaluated for four loading directions:

- Axial compression loading
- Axial tension loading
- Lateral loading by external force

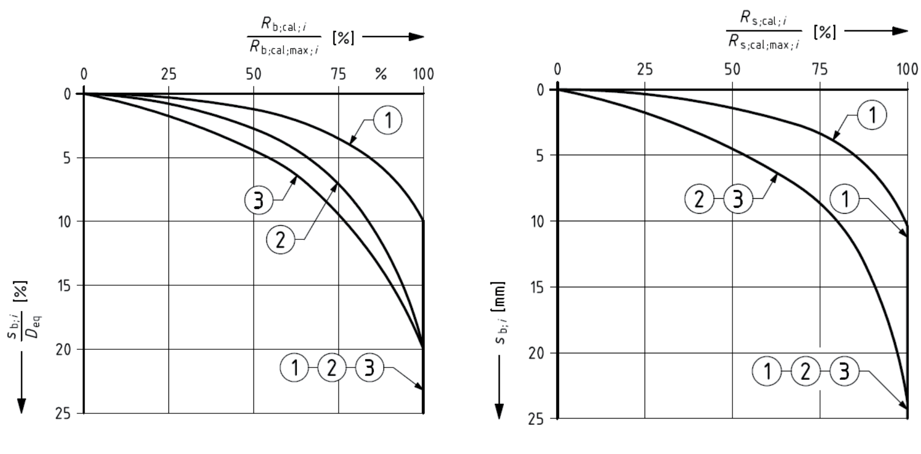


Fig. 4: Subsidence of the pile head due to force on pile base (left) and shear force on pile shaft (right) in % of maximum force for ground displacement piles (1), auger piles and piles with little soil disturbance (2) and bored piles (3) (NEN 9997-1, 2012)

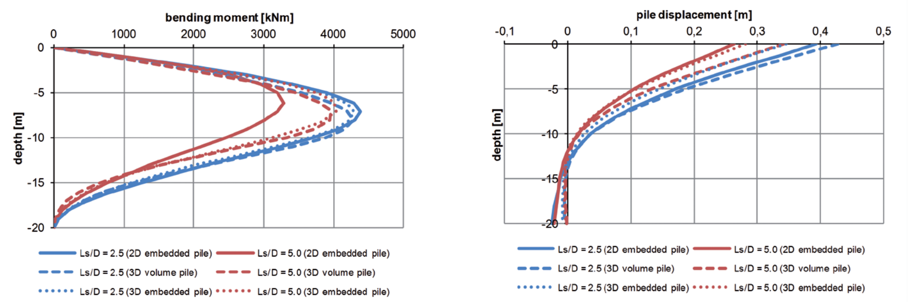


Fig. 5: Bending moment and pile displacement for a lateral loaded pile in soft clay, comparing 2D embedded pile row with 3D volume pile and 3D embedded pile.

- Lateral loading by soil movement.

For soil displacement the PLAXIS 2D embedded pile row was compared with that of PLAXIS 3D for various pile spacings. A sketch of the 3D model is given in Figure 2 (for axial compression loading). The intersection in X-direction represents the 2D model, the parameter $L_{spacing}$ of the 2D embedded pile row is modelled in 3D as the length of the model in Y-direction.

The 2D soil displacement is an average of the out of plane soil displacement, which is visualised in Figure 2. The 3D soil displacement in the Y-plane (blue dashed line) is averaged (black dashed line), which is equal to the 2D soil displacement (pink dashed line). This can be explained by realising that in the 2D model and an equivalent 3D model the same amount of force per unit meter is transmitted to the soil, giving the same (average) deformations. Calculations by Sluis (2012) support this, also for other loading directions, and also shows that this is independent of the interface stiffness (Figure 3).

Because the soil deformation is independent of the interface stiffness (factor), the ISF can be used to manipulate the pile displacement (relative to the soil displacement).

For axial loading, the interface stiffness factors ISF_{RS} and ISF_{KF} were derived by fitting the load displacement curves with the deformation curves of NEN 9997-1 (2012). These curves, shown in Figure 4, are from the Dutch national annex of Eurocode 7 and are based on pile load tests.

Because installation effects are not taken into account in PLAXIS, the embedded pile row is most suitable for bored piles. Curve 3 of Figure 4 was used for fitting.

For lateral loading, interface stiffness factor ISF_{RN} was derived by comparing the 2D embedded pile row with the 3D embedded pile, using a similar model as shown in Figure 2. When using $ISF_{RN} = ISF_{RS}$, a satisfying fit is obtained for relatively small pile spacing ($L_{spacing}/D_{eq} < 4$). For larger pile spacing, the results deviate from 3D calculations, which is probably caused by the absence of a plastic slider in lateral direction.

For example, in 3D a large horizontal force on top of the pile results in soil failure near the pile top, which results in the pile being pulled through the soil, giving large deformations. In 2D, the force should be divided by the pile spacing. For large pile spacing this results in a relatively low line load and no soil failure. To fit the displacement at the pile head, a relatively low ISF should be applied. However, this also results in larger displacements at the pile base. This is illustrated in Figure 5.

In this figure, the 2D embedded pile is also compared with a 3D volume pile, part of a recent study by Witteveen+Bos for the design of a quay wall, to better understand the behaviour of the embedded pile row in lateral loading conditions. In this study the embedded pile row was validated by applying the project-specific pile properties and soil types. A better fit of the pile displacement and bending moment as shown in figure 5 was not possible by varying the interface stiffness. For the design of the quay wall, the default values were applied and a workaround has been found and applied to overcome the current limitation of lateral loading for relatively large pile spacing ($L_{spacing}/D_{eq} > 4$).

Application

The ministry of Transport of Azerbaijan intends to make a new port 65 km outside of Baku. A map of the area including the location of the new port are presented in figure 6.

Witteveen+Bos is assisting a local contractor Evrascon to make an alternative design for the quay walls. At the moment a basic design is made for the general cargo quay wall. The construction consists of an anchored diaphragm wall connected to a deck on bored concrete piles. The anchor structure consists of a bored pile wall.

A schematic cross section is presented in figure 7. The subsoil consists of 2.5m general fill, 2m earth fill, 4-8m very silty sand layer, 40m stiff to hard clay. The first three row of piles are Ø1.5m bored piles with a spacing of 6m and the last row Ø1.2m bored piles with a spacing of 3m.

In PLAXIS 2D it is difficult to calculate accurate forces in the piles, without using the embedded pile feature. This is related to the pile spacing of 4D which exceeds the range where modelling the pile row as a plate is realistic. On the other hand modelling of the piles as node-to-node anchors will also give unrealistic interaction behaviour and result in too high forces in the frontwall. The importance of soil-structure interaction and the effect of interaction stiffness on the distribution of structural forces has been the reason why it was decided to use the embedded pile row feature.

The bored piles below the deck are modelled with the embedded pile feature of PLAXIS 2D. The properties for ultimate shaft friction are determined based on 'floating' pile calculation according to Poulos (Poulos, 2007). Base resistance of the piles is calculated according to the API/ISO (ISO 19902). The bored pile anchor wall is modelled in PLAXIS 2D as a plate because the pile spacing is approximately equal to the pile diameter.

Outputs of the model are the distribution of bending moments, axial forces, shear forces and displacements along the pile. In figure 8, an overview of the model is presented. In figure 9, output figures are given for bending moments and axial forces.

In the embedded pile feature, a lateral slider is currently not included. Therefore, the PLAXIS 2D embedded pile row cannot be used as a tool for lateral capacity design of the piles. Within this project the capacity of the soil in lateral direction is checked separately. Ultimate lateral capacities are calculated based on p-y expressions provided by API / ISO 19902 standards. In this calculation soil layering and pile group effects are included as well. First the lateral mobilisation of the soil by the piles is calculated from the embedded pile row shear force distribution, thereafter it is assessed whether the lateral capacity of the soil is exceeded. This assessment is done over the total length of the pile.

The poorest interaction performance of the embedded pile row is observed in case of a soil profile with relatively stiff shallow soil layers. In PLAXIS, these layers result in a large mobilisation of lateral soil pressure which exceeds the ultimate lateral soil capacity, as shown in figure 10. In this case in reality redistribution of soil-structure interaction takes place, which is not included in PLAXIS. Hence, at high lateral pile loads in just described soil conditions one should be aware of unrealistic interaction behaviour.

For this project a workaround was found by iteratively adjusting locally the stiffness of soil clusters around the piles in the model. Although this procedure is not ideal in terms of time, it is effective and allowed the designers to use the embedded pile rows feature as a valuable new feature of PLAXIS 2D. The implementation of a lateral slider in the embedded pile row feature is however strongly recommended for future updates of PLAXIS 2D, as it will significantly extend the range of practical applications of the embedded pile row feature in PLAXIS 2D.

Conclusions and Recommendations

The embedded pile row feature in PLAXIS 2D 2012 brings new possibilities for the modelling of line elements with soil-structure interaction, compared to 'old' methods with plates and node-to-node anchors. It combines the advantages of these methods, having pile properties and a continuous mesh. The special developed interface between the pile and the soil represents the soil-structure interaction.

As part of a MSc thesis study the embedded pile row has been tested and validation in various situations and loading conditions. The soil displacement is found to be independent of the interface stiffness and is an average of the out-of-plane soil displacement. Formulas have been derived for the interface stiffness to fit the pile displacement. For axial loading the pile displacement was fit with the load-displacement curves from the Dutch annex of Eurocode 7. For lateral loading a comparison was made with PLAXIS 3D embedded pile. The formulas provide default values for the interface stiffness factor (ISF) as a function of the out-of-plane pile spacing. The values can be overruled by PLAXIS users to match the pile displacement for their specific case.

Recently, the embedded pile row feature has been applied by Witteveen+Bos in the design of a quay wall for the General Cargo terminal of the New Baku International Sea Trade Port. Limitations were found with respect to lateral loading of the pile, due to the absence of a plastic slider in lateral direction, which limits the soil mobilisation. A workaround was found and successfully applied to overcome this limitation. The implementation of a plastic slider in lateral direction is however strongly recommended for future updates of PLAXIS 2D, as it will significantly extend the range of practical applications of the embedded pile row feature in PLAXIS 2D.

References

- NEN 9997-1 (2012). Eurocode 7: Geotechnical Design, Part 1: General rules', including Dutch national annex and NCCI.
- Sluis, J.J.M. (2012). Validation of Embedded Pile Row in PLAXIS 2D, Master of Science thesis, Delft University of Technology.
- Poulos, H.G., A practical design approach for piles with negative skin friction, 2007
- API Recommended Practice for Planning, Designing and Constructing Fixed offshore platforms - Working Stress Design, December 2002
- ISO 19902:2006 Petroleum and Natural Gas Industries - Fixed Steel Offshore Structures

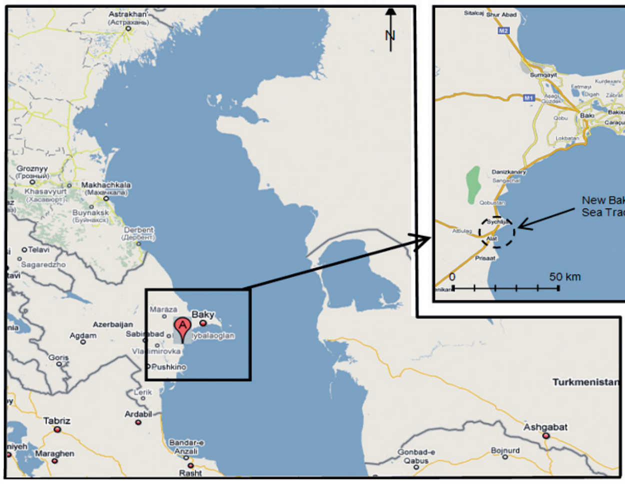


Fig. 6: Location of the new Baku port development

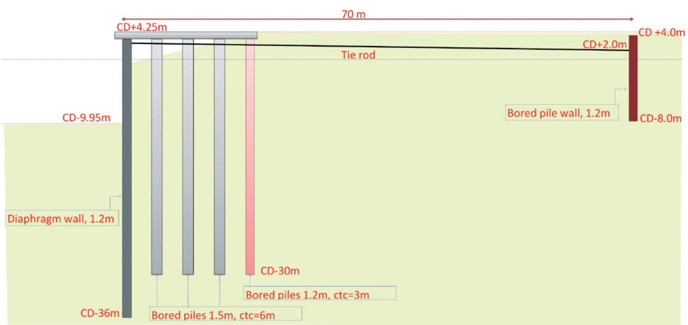


Fig. 7: Sketch cross section quay wall structure

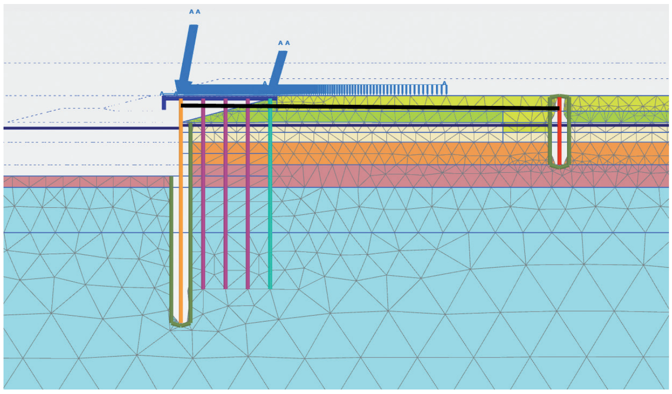


Fig. 8: Overview model

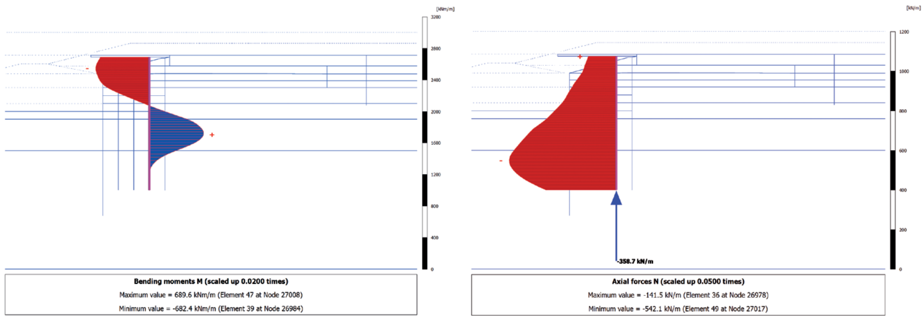


Fig. 9: Output pile bending moments and axial forces

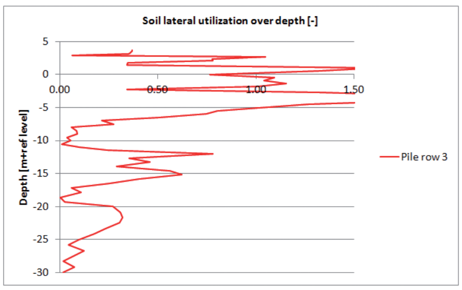


Fig. 10: Soil mobilisation (note the too high mobilisation of shallow layers