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Modelling of soldier pile walls in Plaxis 2D

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ABSTRACT: Geotechnical structures are increasingly being designed using FEM. A solider pile wall can be analysed in 3D FEM software which can simulate the 3D failure mechanisms around piles. However, due to the general complexity and time consumption of 3D FEM modelling, geotechnical structures are often designed using 2D FEM. In a 2D model it becomes unclear how to account for the failure mechanisms around piles. The present research explores a new way of modelling soldier pile walls in Plaxis 2D where the piles of the wall are modelled using the embedded beam row of Plaxis 2D. The behaviour of this feature was examined by comparing results of this approach with results obtained using conventional plate elements in a 2D model, using a 3D model in Plaxis 3D, and using traditional software for retaining wall design based on the earth pressure theory of Brinch Hansen. The research has shown that the embedded beam row feature can yield results which closer resembles the results using traditional retaining wall design software. Consequently, this new approach results in a safer design avoiding overestimation of safety levels which could otherwise be present using conventional plate elements.

Keywords: Soldier pile wall; king post wall; Plaxis; embedded beam row, earth pressure theory

1 INTRODUCTION

The design of soldier pile walls in Denmark is traditionally done using classical earth pressure calculations as described by Hansen (1960) and Brinch Hansen (1953). The classical earth pressure theory is the backbone of retaining wall design and is widely used by Danish engineers. While this approach suffices for most situations, sometimes the complexity of the problem at hand becomes too high for this approach to be used efficiently and with confidence. In these situations, a 2D finite element analysis may often be used instead – e.g. in cases with a complex geometry or complex load scenarios. A 2D finite element analysis may also be used when an estimate of deformations is sought.

Applying 2D FEM software requires the designer to choose how to model the different parts of the solider pile wall. By modelling the entirety of the soldier pile wall as a plate, the wall acts a complete continuous wall similar to a sheet pile wall. The local failure which may occur around each pile are in this case not accounted for.

By defining a limit to the earth pressures along the plate element equivalent to the earth pressures which can be sustained by a row of piles, the local failure around each of the piles can be accounted for. The "embedded beam row" feature available in Plaxis 2D allows for defining such a limit. This will enable the designer to somewhat account for the 3D failures around the solider piles, while still keeping the analyses in plane strain conditions.

In the present research the approach of modelling the lower part of a soldier pile wall using the embedded beam row feature in Plaxis 2D is examined. Namely, the safety level obtained by using this approach is compared to the safety level obtained using a traditional approach based on earth pressure calculations with the software Spooks (Geo, 2003), which is implementing the classical Danish earth pressure theory for designing soldier pile walls. This approach is considered to result in lower-bound solution which will be on the safe side. In addition, the approach of using an embedded beam row elment is also compared to the safety level obtained using Plaxis 2D with a plate element representing the entire wall as well as to the safety level obtained using Plaxis 3D.

Another benefit of using a FEM model is the ability to estimate deformations. Thus, in addition, the deformations obtained through Plaxis is compared between the different modelling approaches in the present paper.

The comparisons are based on a situation with a cantilever wall placed in friction material.

2 SOLDIER PILE WALL MODEL IN PLAXIS 2D

The Plaxis 2D model considered here consists of a plate element representing the upper part of the wall, where lagging or steel plates are placed between the soldier piles. At the bottom, the plate element is connected to the embedded beam element. These two elements represent the soldier pile wall, see Figure 1.

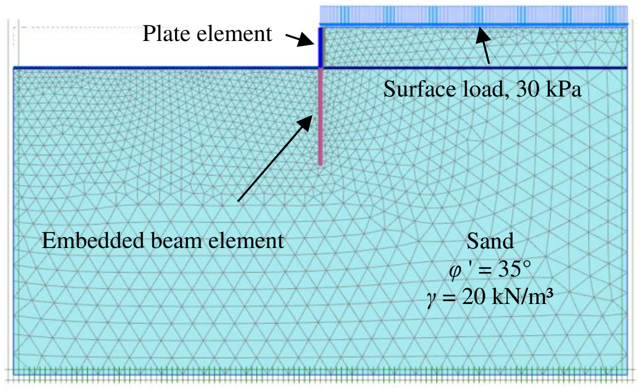

Figure 1. Model of a soldier pile wall in Plaxis 2D using the embedded beam row element

For both the plate element and the embedded beam row element a bending and axial stiffness needs to be defined. In the present paper the plate element and embedded beam row element is given the same stiffness based solely on the soldier piles, disregarding any stiffness contribution from the lagging.

The embedded beam row element works as a plate element superimposed onto the mesh via a special interface, in contrast to the ordinary plate element which is directly connected to the mesh (Plaxis, 2019). The interface between the embedded beam row element and the mesh allows the deformations of the element to exceed those of the underlying mesh, mimicking failure around the piles. The relation between the deformations of the embedded beam row element and the soil are governed by the interface stiffness. A limit can be given to the lateral resistance i.e. the net pressure along the element, allowing the element to deform plastically.

For the purpose of modelling a soldier pile wall the maximum lateral resistance and interface stiffness along the pile needs to be defined according to that of the soldier piles. Specifically, the maximum lateral resistance must reflect that only part of the passive earth pressure will develop during failure as compared to the passive earth pressure developed for a wall in plain strain.

2.1 *Lateral resistance*

Brinch Hansen (1961) presented the following expression for calculation earth pressure on a laterally loaded pile:

$$e^D = \bar{q}K_q^D + cK_c^D \qquad (1)$$

Here K_q^D and K_c^D represent the earth pressure coefficients of the net pressure of the active and passive earth pressure along a pile. Eq. (1) is based on a pile placed in a level terrain. The soldier piles in a soldier pile wall will, however, be affected by a larger active earth pressure due to the higher ground level behind the wall. To take this into account, an additional term is introduced to Eq. (2).

$$e^D = \left(D\gamma' + p_f\right)K_q^D + cK_c^D - (h\gamma' + p_b)K_q^A \qquad (2)$$

Here p_f and p_b denotes the load in front and behind the wall respectively. h denotes the height of the soldier pile wall while K_q^A denotes the active earth pressure coefficient at shallow depth as used by Brinch Hansen (1961) presented in Eq. (3).

$$K_q^A = \exp\left(-\left(\frac{1}{2}\pi - \varphi\right)\tan\varphi\right) \cdot \cos\varphi \tan\left(45° - \frac{1}{2}\varphi\right) \qquad (3)$$

The active earth pressure contribution from cohesion is disregarded here. The lateral resistance to be used for the embedded beam row element is obtained by Eq. (4)

$$T_{lat} = e_D B \qquad (4)$$

where B is the width of the soldier pile.

2.2 *Lateral stiffness*

The lateral stiffness of the interface between the embedded beam row element and the mesh is by default predefined from the pile width and pile spacing entered in Plaxis 2D. The stiffness may be adjusted manually, however, in the present paper, the default stiffness has been considered. The default interface stiffness is described in detail by Plaxis (2019).

3 APPROACH FOR COMPARISON

When designing a soldier pile wall, the main parameter to determine is the pile depth required to satisfy the required safety level. Hence, a comparison of the safety level associated with a given pile depth is presented, comparing the described modelling approach in Plaxis 2D (using plate and embedded beam row elements) and the following alternative approaches:

- Using the software Spooks which determines pile length based on equilibrium of earth pressure based on Brinch Hansen (1953) and Hansen (1978).
- Using Plaxis 2D with plate elements representing the entire wall.
- Using Plaxis 3D where each pile is modelled individually as discrete elements.

The safety level associated with a given pile depth is compared between these approaches for varying centre-to-centre distance, d, between the piles.

For the comparison, a scenario with a 2.5 m high wall made with 0.3 m wide soldier piles with a stiffness equal to that of an HE400B steel profile is considered. The wall is considered placed in friction material with a friction angle of φ = 35° and a specific weight of γ = 20 kN/m³. Behind the wall a load of 30 kN/m² is considered. The layout is indicated in Figure 1.

3.1 Approach of setting up models

The benchmark models in Spooks are created by defining the considered scenario and using the "king post wall" feature. In Spooks the safety level is given as an input and the pile depth is given as an output. The outset in the Spooks calculations is a factor of safety on $\tan(\varphi')$ of 1.32. The pile depth associated with a factor of safety of 1.32 is then determined for varying centre-to-centre distance, d.

The models in Plaxis 2D and 3D can subsequently be created using the pile depth determined in Spooks. This way the geometry for a given d is the same between the different approaches. In Plaxis 2D and 3D the safety level associated with that pile depth can thus be compared to the safety level originally specified in Spooks. In Plaxis 2D and 3D the safety level is determined through a safety calculation, where the strength parameters of the soil are gradually reduced until failure.

The benchmark model in Plaxis 2D with plate elements is created just like the model with the embedded beam row element but with a plate element representing the lower part of the wall instead.

The benchmark model in Plaxis 3D is created by defining the piles as plates of 0.3 m width. Between the piles representing the solider piles, secondary plates are defined representing the lagging or steel plates. To optimize the performance of the model, advantage is taken of the symmetry planes in the wall geometry reducing the geometry to a section with a width equal to half the centre-to-centre distance between the piles as shown in the example in Figure 2.

The series of calculations in Plaxis 2D and 3D with varying pile spacing have been set up using a python script with the remote scripting server functionality of Plaxis. Using this script, the results from Spooks are easily converted into needed Plaxis models.

It should be noted that the point of failure has proven difficult to define rigorously for the Plaxis 3D calculations as the safety level can be increased continuously without a distinct maximum value. Hence for practicality the safety calculations in Plaxis 3D are set to carry out 300 calculation steps. After these steps the deformations are generally seen to be large and increasing more rapidly with increased safety level. At this point the wall is assessed to have failed albeit without being in a situation with fully developed plastic deformations. An ambiguous point of failure was also observed from the lateral load testing of piles presented by Christensen (1961).

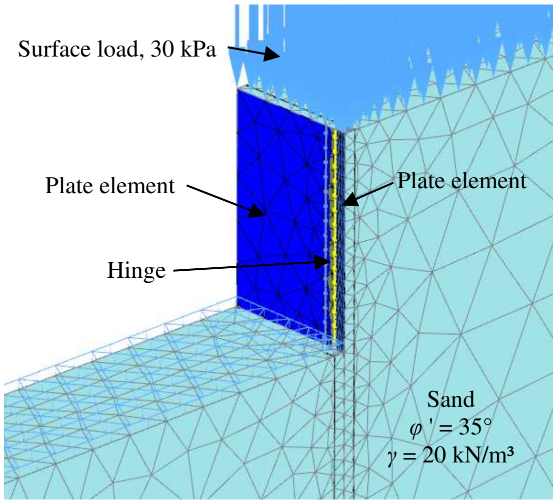

Figure 2. Example of Plaxis 3D model of a soldier pile wall.

4 RESULTS

In Figure 3 the safety factor achieved using the modelling approach with the embedded beam row element for varying pile spacing is compared to that determined using the considered alternative approaches. As mentioned, a fixed value 1.32 is used as an input for the calculations in Spooks. Consequently, the pile depth considered increases as the pile spacing increases. It should be noted that the same pile depth is considered between each approach for a given pile spacing.

From the comparison, it is evident that the approach of using embedded beam row elements to model soldier pile walls generally yields a factor of safety below what is determined using a Plaxis 3D model or a Plaxis 2D plate model. When compared to the results from Spooks, the factor of safety is generally found to be a bit higher. However, for a d/B ratio up to around 3 all approaches arrive at around the same factor of safety. The difference between the considered approaches then increases as the pile spacing increases.

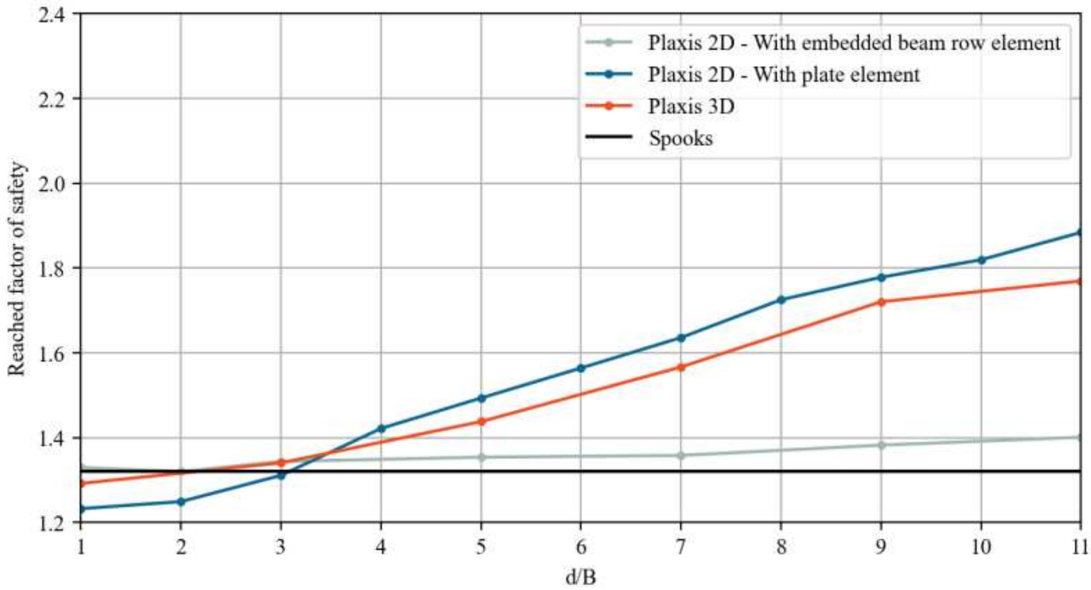

Figure 3. Comparison of safety factor for varying pile spacing using the considered modelling approaches.

In Figure 4 and Figure 5 the failure mechanism obtained in Plaxis 2D using the embedded beam row element is shown for a d/B ratio of 2 and 3 respectively. In both cases failure occurs in the soil volume behind the upper part of the wall, yet the depth of the failure mechanism differs between the two ratios. For a d/B ratio of 3, the maximum lateral resistance is reached along the embedded beam row element, thus creating a failure in the interface rather than in the soil volume, allowing the soil to move between the solider piles (Figure 5). For a d/B ratio of 2 the close centre-to-centre distance does not allow for this mechanism as the soldier piles behave as a full wall (Figure 4).

From Figure 3 the results from Plaxis 3D are seen to closely follow the results from Plaxis 2D using only plate elements. Looking at the failure mechanisms from Plaxis 3D as shown in Figure *6* and Figure 7 for a d/B ratio of 3 and 11 respectively it is evident that the observed failure mechanisms resemble more that of a full wall even for larger d/B ratios.

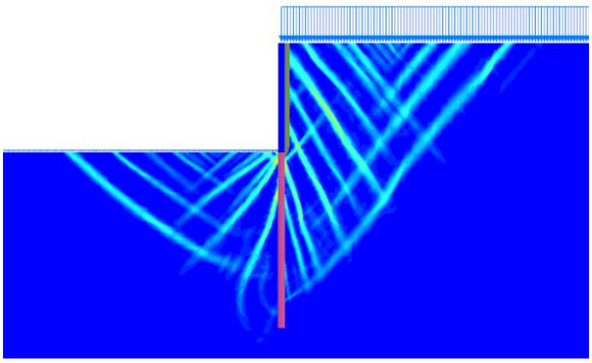

Figure 4. Incremental deviatoric strain in logarithmic scale visualising the failure mechanism for a d/B ratio of 2.

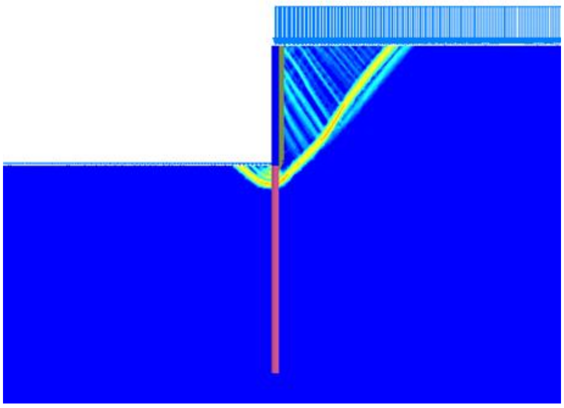

Figure 5. Incremental deviatoric strain in logarithmic scale visualising the failure mechanism for a d/B ratio of 3.

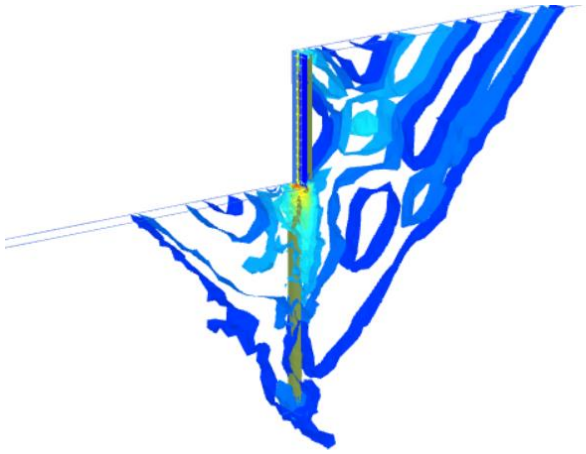

Figure 6. Iso surfaces of incremental deviatoric strain in logarithmic scale visualising the failure mechanism for a d/B ratio of 3.

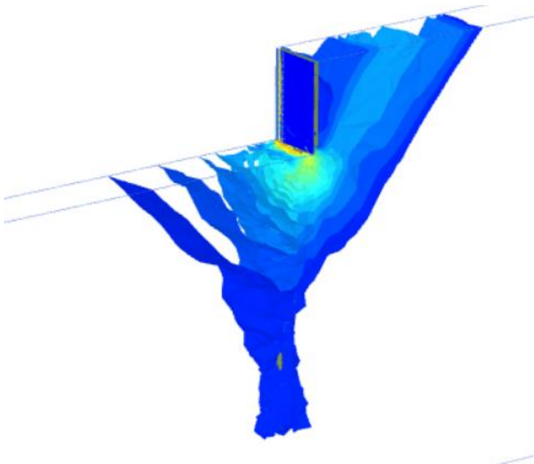

Figure 7. Iso surfaces of incremental deviatoric strain in logarithmic scale visualising the failure mechanism for a d/B ratio of 11.

4.1 Displacements

An important benefit of the FEM-approach is the opportunity to perform displacement analyses of the retaining system and the soil body behind it. In Figure 8 the calculated displacement in the top of the wall is presented. As evident from the figure, the use of a simple plate to model a soldier wall yields significantly smaller displacements compared to using discrete plate elements in Plaxis 3D or embedded beam rows – especially for larger *d/B*-ratios. This is in line with the expectations due to the very different size of the activated soil body comparing a continuous plate with discrete piles.

From Figure 8 it is clear that applying a Plaxis 2D analysis using plate elements to model a soldier pile wall is quite on the unsafe side, whereas the displacement determined from 2D models using the embedded beam row element displays a larger deformation compared to the 3D analyses. It is possible that the difference here can be minimized by adjusting the interface stiffness for the embedded beam row elements in Plaxis 2D. Yet the applied approach shows that embedded beam rows are on the conservative side using the standard configuration in this case.

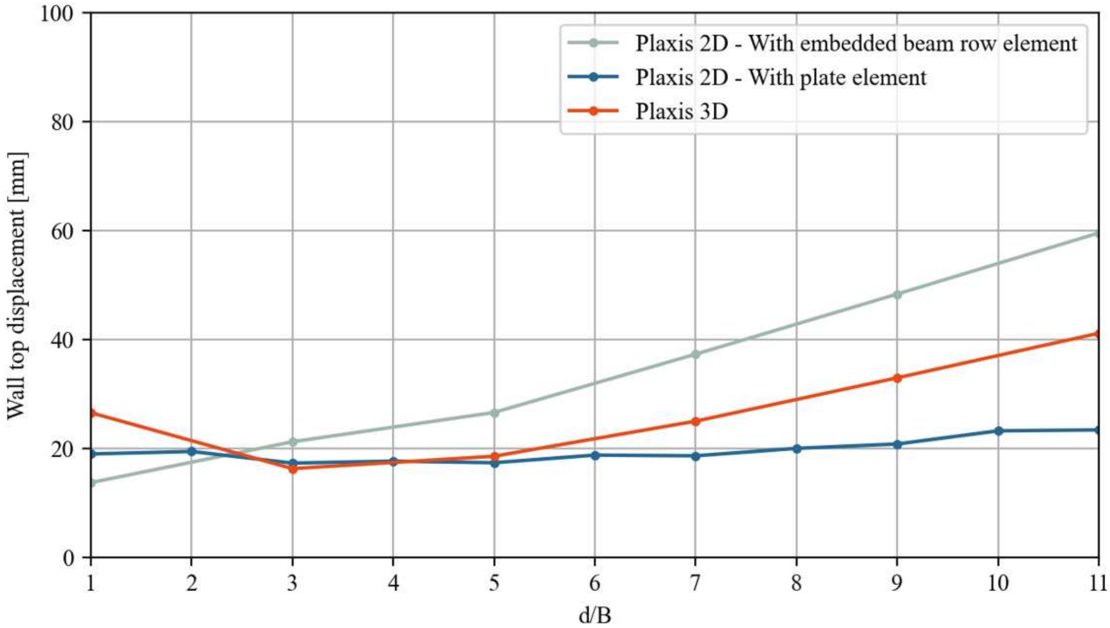

Figure 8. Comparison of the displacement at the top of the wall for varying pile spacing using the considered approaches in Plaxis

5 DISCUSSION

The results presented here only applies for a single case of granular soils. However, the results provide positive indications that the approach of using embedded beam row elements below excavation depth constitutes a good compromise between simplified earth pressure calculations and full 3D analysis.

As stated previously the main motivation behind designing a soldier pile wall with FEM rather than through the use of traditional earth pressure theory is the abilities of FEM to handle complex geometries and load scenarios. In order to perform a comparison, naturally a simple case needed to be considered in the present paper. The approach in Plaxis 2D can however be extended to various other more complex scenarios. As the functionality of the embedded beam row element is independent of how the surrounding model is set up, it seems that the behaviour shown in the present paper would also be valid for more complex situations.

The results indicate that using the Plaxis 2D approach with embedded beam row elements may result in a slightly less conservative design when compared to the traditional Danish approach in Spooks. However, the approach can be expected to result in a much safer design compared to the one obtained from using only plate elements. When considering a d/B-ratio below 3 the wall is seen to behave much like a full wall. Consequently, modelling a soldier pile wall using only plate elements can be justified in this area. However, for a d/B-ratio above 3 a model consisting solely of plate elements should be expected to yield results which is on the unsafe side. In this case using the embedded beam row element is a much more accurate and safe approach.

The results from using Plaxis 2D with embedded beam elements indicates higher safety level with increasing d/B-ratio when compared to Spooks. The main reason why this tendency is observed is believed to be due to the different ways active earth pressure is handled between the two approaches. In Spooks, active earth pressure is distributed along the entire plane (Geo, 2003) while the lateral resistance of the embedded beam row element only considers active earth pressure on the pile i.e. a limited section of the plane. As the d/B-ratio increases this difference is expected to increase. Entirely different results may be achieved by considering other ways of defining the lateral resistance of the embedded beam rows e.g. using the p-y curve expressions like the ones presented by Reese et al. (1974).

Based on the observations presented in the present paper, it seems that applying the embedded beam row for analyses of discrete, but plane-strain elements can be justified. The approach may be further extended to the analyses of e.g. anchor plates for anchored sheet pile walls.

6 CONCLUSIONS

From the presented comparison of reached safety level, it is evident that the approach of using Plaxis 2D with embedded beam row element constitute a viable alternative to full 3D analysis in situations where traditional earth pressure calculations do not suffice.

The formulas given by Brinch Hansen (1961) may be used to define the lateral resistance of the embedded row element. Through this approach the design of a soldier pile wall can generally be expected to be safer than simply using solely plate elements. However, at a d/B-ratio below 3 the soldier pile wall can be expected to behave largely like a full wall, justifying a simplified approach where only plate elements are used in this case.

Deformations can generally be expected to be overestimated i.e. on the safe side when using the default parameters given for the embedded beam elements. Using only plate elements will, however, underestimate deformations when compared to a full 3D analysis.

7 ACKNOWLEDGEMENTS

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