Article

To what extent do software programs comply with Eurocode 7 with regard to the bearing capacity of strip foundations

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Abstract: Software programs are at present the common tool for calculating the bearing capacity of foundations. These programs claim to be in line with Eurocode 7. In this study, a parametric sensitivity analysis is carried out in order to obtain a clear view of the effective conformity between software programs and the analytical method of Eurocode 7 regarding the bearing capacity of strip foundations. In order to carry out this research, a benchmark exercise is carried out, which is the basis of our research model. The research model is dimensioned in the software programs 'spread footings' from *GEO5* and 'D-foundations' from *Deltares*. The overall conclusion is that there is a high degree of conformity between the analytical method of Eurocode 7 and the software programs in question. However, if the reliability is compromised, as is the case with a high angle of shearing resistance value, the user is not notified.

Keywords: Eurocode 7; Spread footings; Strip foundations; Benchmarking; Bearing capacity; *Deltares*; *GEO5*; Meyerhof

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1. Introduction

The ultimate bearing capacity of a foundation has traditionally been evaluated by various analytical methods. The equation proposed by Meyerhof (1963) includes shape factors, inclination factors and depth factors. Other factors, to allow for a sloping ground surface and for any inclination of the base, can also be included when required. Due to the completeness of Meyerhof's equation, it has become the preferred analytical method used in Eurocode 7 [1]. These Eurocodes prescribe all kinds of regulations, rules and requirements concerning the design of structures. Eurocode 7 is one of the ten Eurocodes and focuses on the geotechnical design of structures, such as foundations. In this Eurocode, regulations can be found with regard to the soil characteristics. A complete overview of the Eurocodes can be found in Appendix A.

Considerable effort has been made by research institutes as well as construction companies to design different software programs for the calculation of geotechnical constructions. These programs claim to be in line with Eurocode 7. The question is, however, to what extent is this claim correct and how is it applied in the software programs? In this study, a strip foundation will be elaborated. A strip foundation, often termed a continuous footing, has a length significantly greater than its width (L > 5B) [2]. It is generally used to support a series of columns or a wall. The research question of this study is therefore:

To what extent do software programs comply with Eurocode 7 with regard to the bearing capacity of strip foundations?

On the one hand, this study examines whether the prescribes boundaries mentioned in the Belgian national annex of Eurocode 7 are included in software programs; on the other hand, we investigate whether it is possible to deviate from these prescribed boundaries and how this affects the reliability of the results. In addition, we also investigate how software programs react to parameters for which there are no regulations in Eurocode 7. More specifically, this concerns the geometry and applied loads on the structure. This will be realized by means of a parametric sensitivity analysis.

The software programs which are used in this research are: *'spread footings'* from *GEO5* and *'D-foundations'* from *Deltares*. After performing the research described above, an attempt will be made to answer the research question.

In the second chapter the research methodology of this study is illustrated. This includes a brief literature review, the research model along with the associated influence parameters and the prescribed limitations. The results of the influence parameters are then presented in chapter three. The most important research results are also discussed in this chapter. Finally, the last chapter formulates a conclusion on the research question.

At the end of this study, an addendum is added in which a comparison is made between a slab foundation and a pile foundation. This addendum is made in collaboration with Kristof Dierckx and David Van Camp.

2. Research methodology

2.1. Literature review

In the literature review, sufficient knowledge is acquired in order to carry out this research. First, the physical properties of soil are thoroughly studied in order to distinguish the important parameters. Second, the different theories about the state of stress in soils are studied. It is important to differentiate between the total stress and the effective stress as these two types of stress are frequently used in geotechnical calculations. Another crucial factor in the literature review is Eurocode 7, since the thesis is based on this document. The bearing resistance of a strip foundation can be calculated using different methods. The first method is the analytical method, which will be used in this study. The second method for calculating the bearing resistance is the semi-empirical method. The last method uses presumed measures, which involve conventional and generally conservative rules in the design [3]. From the analytical method used in Eurocode 7 we get two formulas that are used throughout this entire study:

$$R/A' = (\pi+2)\ c_u\ b_c\ s_c\ i_c + q \tag{1}$$

With: R/A' = bearing resistance

c_u = undrained shear strength

b = inclination factors of the foundation base, with subscript c

s = shape factors of the foundation base, with subscript c

i = inclination factors of the load, with subscript c

q = overburden or surcharge pressure at the level of the foundation base

$$R/A' = c' N_c b_c s_c i_c + q' N_q b_q s_q i_q + 0{,}5\, \gamma' B' N_\gamma b_\gamma s_\gamma i_\gamma \quad (2)$$

With: R/A' = bearing resistance

c′ = effective cohesion

N = bearing capacity factors, with subscripts c, q and γ

b = inclination factors of the foundation base, with subscripts c, q and γ

s = shape factors of the foundation base, with subscripts c, q and γ

i = inclination factors of the load, with subscripts c, q and γ

q′ = effective overburden pressure at the level of the foundation base

γ' = effective weight density of the soil below the foundation level

B′ = effective foundation width

The first formula is used to calculate the bearing resistance in undrained conditions, while the second formula should be used to calculate the bearing resistance in drained conditions. It should be noted that depth factors are excluded in Eurocode 7.

2.2. Research model

In this section, we will shed light on the research model used in this study. The research model is a benchmark exercise found in '*Decoding Eurocode 7*'[4]. It considers the design of a strip foundation on clay, as shown in Figure 1. The footing is required to carry an imposed permanent load V_{Gk} = 250 kN/m and an imposed variable load V_{Qk} = 110 kN/m. Groundwater is at depth d_w. The width B of the foundation is 2.5m, the length L is 50m and the depth d is 1.5m. The footing is founded on a medium strength soil with characteristic undrained shear strength c_{uk} = 45 kPa, angle of shearing resistance φ_k = 25°, effective cohesion c'_k = 5 kPa, and weight density γ_k = 21 kN/m³.

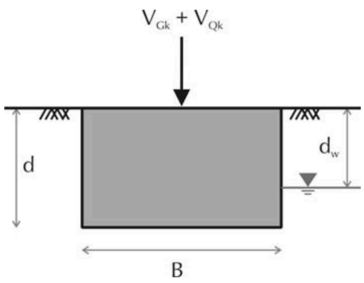

Figure 1: Strip footing on clay [4]

2.3. Prescribed restrictions

In order to establish a qualitative comparison between the analytical method used in Eurocode 7 and the numerical calculations, some restrictions should be introduced. Firstly, we only consider centric loads. Horizontal loads are also excluded in this study. Another restriction is that only the ultimate limit state is considered. Design Approach 1 combination 2 is used for all the calculations: partial factors are applied to ground strengths and variable actions, while permanent actions and resistances are left unfactored. In this design approach, partial factors are used early in the calculation process, close to the source of uncertainty.

2.4. Parametric sensitivity analysis

A parametric sensitivity analysis is performed using the analytical method to obtain the most significant parameters. These parameters can be arranged in three categories. The first category contains parameters regarding soil properties, such as the angle of shearing resistance and the effective cohesion. Another category consists of parameters concerning the load, e.g. the inclination angle of the vertical load. The last category contains all the parameters related to the geometry such as the width of the foundation. An overview of the categories with the various parameters is shown in Table 1.

Table 1: Categories with various parameters

Category I	Category II	Category III
Angle of shearing resistance	Magnitude of load	Width of foundation
Undrained shear strength	Inclination angle of load	Length of foundation
Effective cohesion	Load eccentricity	Thickness of foundation
Weight density		Depth of foundation
Groundwater level		
Multiple soil layers		

3. Results & discussion

After performing the parametric sensitivity analysis stated above, it becomes clear that the most significant results obtained are related to soil properties. In this section, these results are presented and discussed. For each soil property, the Belgian national annex of Eurocode 7 (ANB EN 1997) prescribes an interval that must be respected. Deviation from these values is only possible if justified (e.g. test results) [5]. These intervals are marked in the figures by a box.

Groundwater level can have a significant effect on the bearing capacity, yet it is not taken into account in the following discussion. This is because results are only re-scaled, and do not undergo any further significant modification. Calculations including groundwater can be found in Appendix B.

3.1. Angle of shearing resistance

When analysing the bearing capacity of the foundation as a function of the angle of shearing resistance, we see that for the analytical method of Eurocode 7, *Deltares* and *GEO5*, there is a nonlineair evolution of the bearing capacity (Figure 2). This is caused by the angle of shearing resistance, that occurs in the tangent in the bearing capacity factors within Eq. (2). From these results, we can conclude that both *Deltares* and *GEO5* deliver reliable results within the prescribed interval of the Belgian national annex of Eurocode 7, i.e. 15° - 40° [5]. For larger angles, the results diverge at a faster rate and further research is required. It is noteworhy to mention that this analysis can only be executed in drained conditions, as the angle of shearing resistance in undrained conditions is equal to zero.

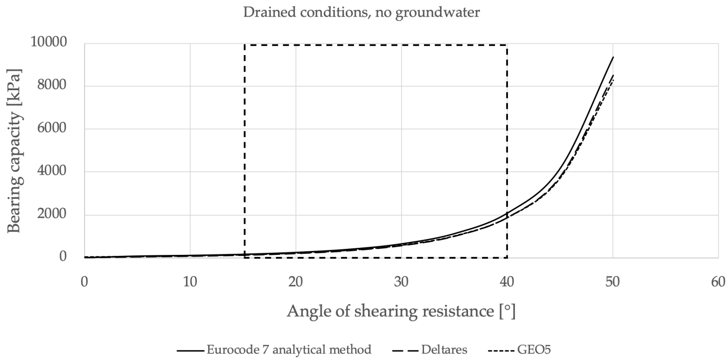

Figure 2: Angle of shearing resistance - bearing capacity

3.2. Cohesion

Effective cohesion is a soil property which is used in drained conditions. Undrained cohesion, also called undrained shear strength on the other hand, is used to calculate the bearing capacity in undrained conditions. When the results of these two soil properties are analysed, we can see that the three calculation methods result in a linear relationship between the bearing capacity and the cohesion. The analytical method used in Eurocode 7 contributes to a slightly higher value of the bearing capacity (Figure 3 and 4). This is due to the fact that all three calculation methods use different values for shape factors, since the width and length of the foundation differ for the three methods: in *Deltares*, the length is considered to be infinite while in the other two calculation methods, the length is taken as 50m. In *GEO5*, the width of the foundation cannot be adjusted and is set to 2m, while in the other two methods, the width is equal to 2.5m.

We can conclude that the results obtained by *Deltares* and *GEO5* provide reliable results within the prescribed limits, i.e. 0 kPa – 15 kPa for the effective cohesion and 10 kPa – 200 kPa for the undrained shear strength.

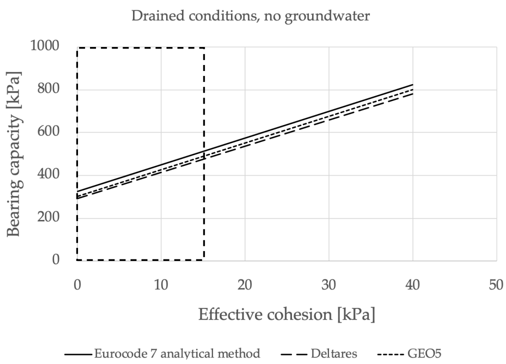

Figure 3: Effective cohesion - bearing capacity.

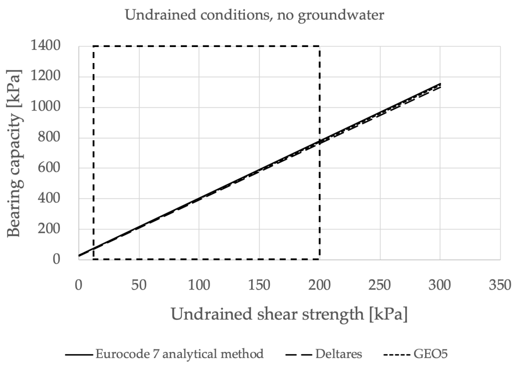

Figure 4: Undrained shear strength - bearing capacity

3.2. Two-layer soil

The analytical model of Eurocode 7 along with the two software programs are used to calculate the bearing capacity of the strip footing, founded in a two-layer soil, shown schematically in Figure 5. Eight different cases are examined: a soft clay underlain by a stiff clay and a stiff clay underlain by a soft clay, both in drained and undrained conditions, and both with and without groundwater. The properties of the two soils used in this analysis are summarized in Table 2. As with the previous parameters discussed above, groundwater does not have a major role to play in the calculations. As a result, it is not included in the discussion.

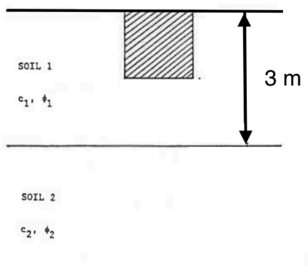

Figure 5: Two-layer soil [6]

Eurocode 7 states that analytical methods are often not applicable when multi-layer soils are considered. However, to correlate with the numerical calculations, analytical calculations have been carried out, with soil properties of both the soft and stiff layer.

Table 2: Soil properties of the two layers

Soil properties	**Soft clay**	**Stiff clay**
Angle of shearing resistance [°]	18	25
effective cohesion [kPa]	2	45
Undrained shear strength [kPa]	2	45
Weight density [kN/m3]	21	21

3.2.1 Undrained conditions

When a soft layer underlain by a stiff layer is modelled in the software programs, both *Deltares* and *GEO5* perform the calculation using the soil properties of the soft layer (Figure 6). But when we shift the layers, the two software programs respond differently: *Deltares* does not differentiate from the previous calculation, while *GEO5* is now using the soil properties of the stiff clay to calculate the bearing capacity (Figure 7). This difference can be easily understood by adjusting the thickness of the upper layer, i.e. stiff clay: If we increase the thickness in *Deltares* to 4.5m we get a bearing capacity of 193.90 kPa. If we decrease the thickness in *GEO5* to 1.5m, we get a bearing capacity of 38.9 kPa.

This means that for a stiff layer underlain by a soft layer, both software programs have the same approach: if the thickness of the upper layer is below a certain value, the soil properties of the soft layer are taken for calculation. However, this certain value differs in both software programs.

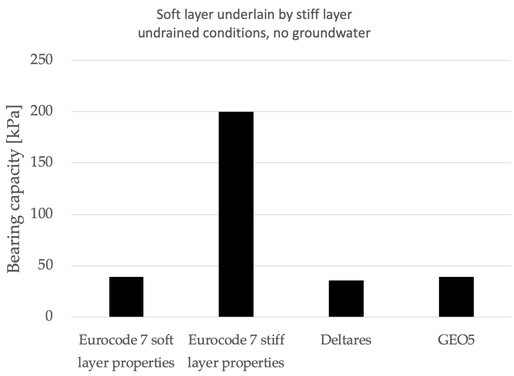

Figure 6: Soft layer on stiff layer, undrained conditions

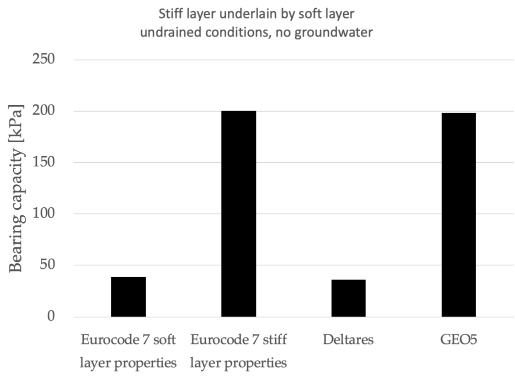

Figure 7: Stiff layer on soft layer, undrained conditions

3.2.2 Drained conditions

For cohesive soils such as the soft clay and the stiff clay from this example, both the undrained and drained conditions needs to be verified. However, bearing capacity calculations in drained conditions for multi layer soils are not as straightforward as calculations in undrained conditions, as discussed in paragraph 3.2.1. Analytical calculations are not applicable in these conditions. If we compare the results of both software programs, we can deduce that the difference between *Deltares* and *GEO5*, as in the undrained conditions discussed above, is due to the thickness of the upper layer. From a thickness of 4.5m and above, in the case of a soft layer underlain by a stiff layer, both the calculations from *Deltares* and *GEO5* would result in a similar bearing capacity (Figure 10).

However, if we look at the case where a stiff layer is underlain by a soft layer, we see that the bearing capacity calculated by *GEO5* stabilises from an upper layer thickness of 4.5m, while in the case of *Deltares* it only stabilises from 6m onwards (Figure 11). This can be explained by the fact that *Deltares* also takes into account punching shear failure. This is a downward movement of the foundation caused by soil shear failure only occurring along the boundaries of the wedge of soil immediately below the foundation.

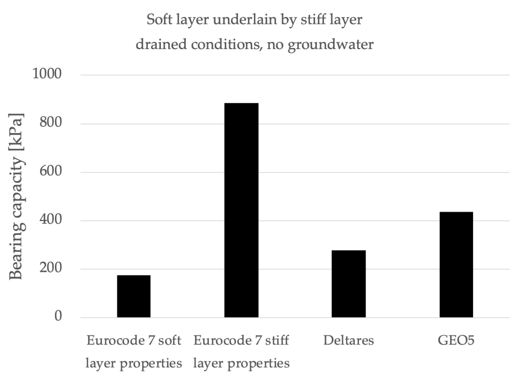

Figure 8: Soft layer on stiff layer, drained conditions

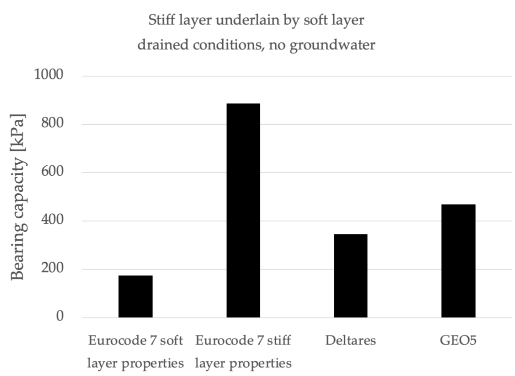

Figure 9: Stiff layer on soft layer, drained conditions

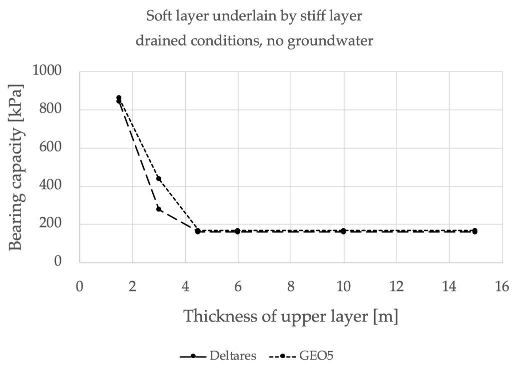

Figure 10: Soft layer on stiff layer - layer thickness, drained cond.

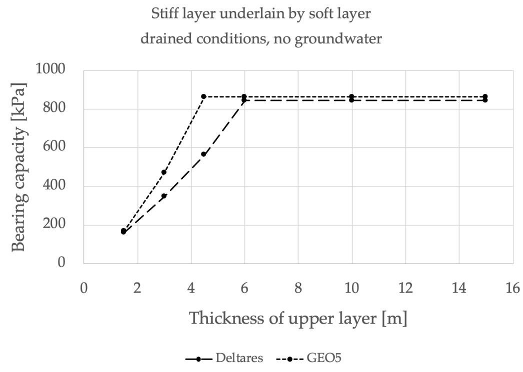

Figure 11: Stiff layer on soft layer - layer thickness, drained cond.

4. Conclusion

The aim of this study was to assess the conformity between Eurocode 7 and software programs. In order to carry out this research, a benchmark exercise is carried out. It concerns a strip foundation founded in clay. Influence parameters are then formulated for this research case. The research case in combination with all the influence parameters form the research model that is dimensioned in the software programs, which are *'spread footings'* from *GEO5* and 'D-*foundations'* from *Deltares*. By means of an analytical calculation, a parametric sensitivity analysis is carried out. Out of the three calculation methods, and for every influence parameter, it appears that *Deltares* is slightly more conservative compared to the other two calculation methods considered.

The overall conclusion is that there is a high degree of conformity between the analytical method of Eurocode 7 and the software programs in question. However, if the reliability is compromised, as is the case with a high angle of shearing resistance value, the user is not notified. The user must then have sufficient knowledge to classify the results as unreliable. One way of avoiding this could be to notify the user when values are entered which are not within the limits of the values indicated in the Eurocode 7.

Addendum

In this addendum, a brief study regarding the comparison of three foundation types, namely strip foundations, plate foundations and pile foundations, is disclosed. The same setup is used in all three calculation methods: the analytical calculation method of Eurocode 7, *Deltares* and *GEO5*. This setup is shown in Figure AD1.

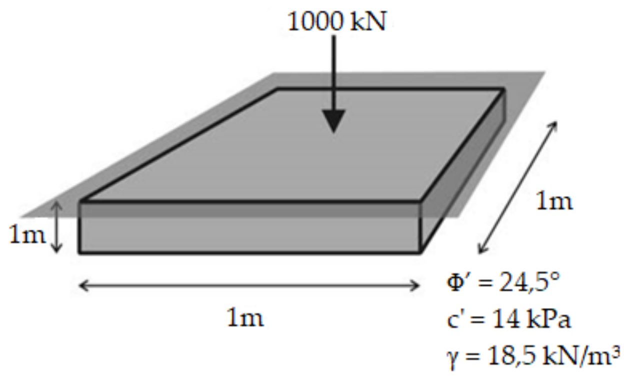

Figure AD1: setup with parameters for comparison

Table AD1: Bearing capacity of different foundation types

	Eurocode 7 analytical method [kPa]	Deltares [kPa]	GEO5 [kPa]
Strip	419.03	307.66	419.03
Plate	419.03	402.21	419.03
Pile	463.00	/	570.00

When we compare the bearing capacity of strip foundations and plate foundations, we can deduce that both for the analytical calculation of Eurocode 7 and the numerical calculation of *GEO5*, the results are identical. The bearing capacity calculated for the two foundation types in *Deltares* differs considerably. This is due to the fact that in *Deltares*, an infinitely long strip foundation is used, which results in shape factors equal to 1 (the length appears in the denominator in the formula). As a result, the bearing capacity of the strip foundations is lower than the bearing capacity of the plate foundation.

For the comparison of the pile foundation with the other two foundation types, the difference is found in the fact that pile foundations don't use ground safety coefficients, resulting in a higher bearing capacity. Another aspect that is causing this difference is the shaft resistance: when calculating the bearing capacity of pile foundations, a shaft and base resistance is taken into account, while the other two types of foundation only take into account the base resistance.

Appendix A

Table A1: overview of Eurocodes

Eurocode 0	Basis of structural design (EN 1990)
Eurocode 1	Actions on structures (EN 1991)
Eurocode 2	Design of concrete structures (EN 1992)
Eurocode 3	Design of steel structures (EN 1993)
Eurocode 4	Design of composite steel and concrete (EN 1994)
Eurocode 5	Design of timber structures (EN 1995)
Eurocode 6	Design of masonry structures (EN 1996)
Eurocode 7	Geotechnical design (EN 1997)
Eurocode 8	Design of structures for earthquake resistance (EN 1998)
Eurocode 9	Design of aluminium structures (EN 1999)

Appendix B

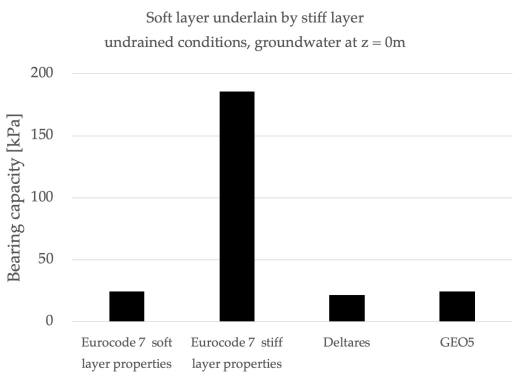

Figure B1: Soft layer on stiff layer in undrained conditions, z=0m

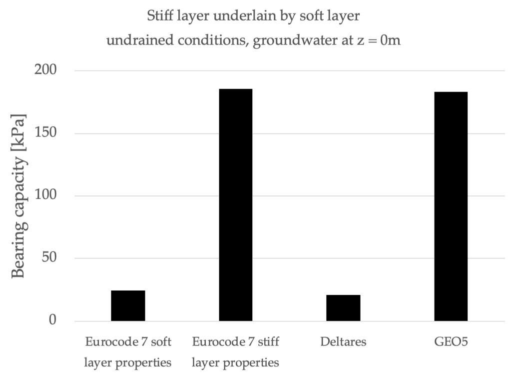

Figure B2: Stiff layer on soft layer in undrained conditions, z=0m

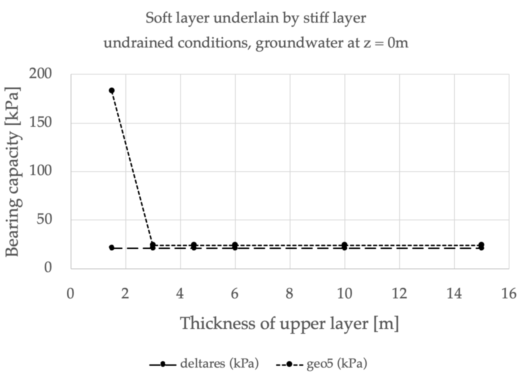

Figure B3: Soft on stiff - thickness of upper layer, undr. cond., z=0m

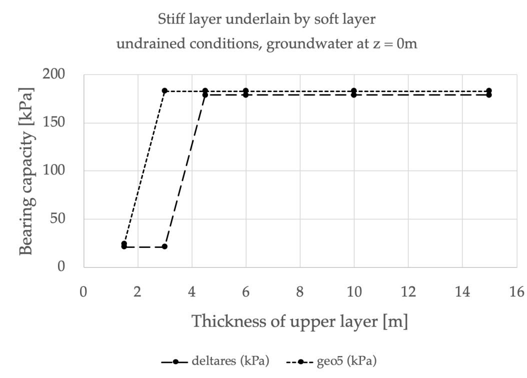

Figure B4: Stiff on soft - thickness upper layer, undr. cond., z=0m

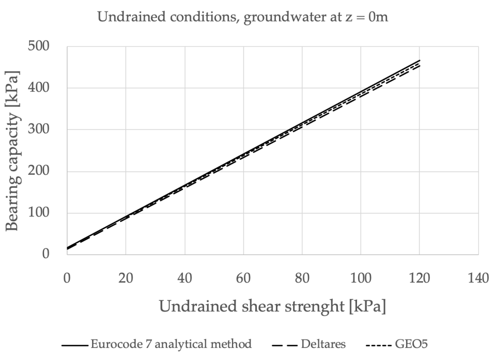

Figure B5: Undrained shear strength - bearing capacity, z=0m

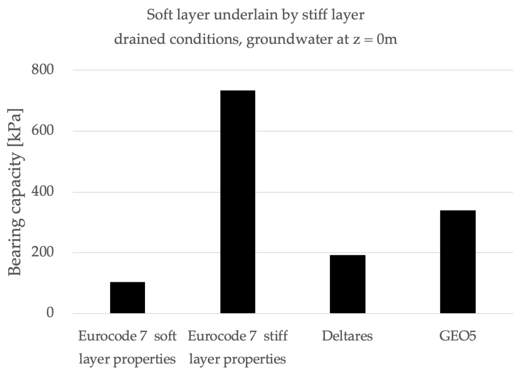

Figure B6: Soft layer on stiff layer in drained conditions, z=0m

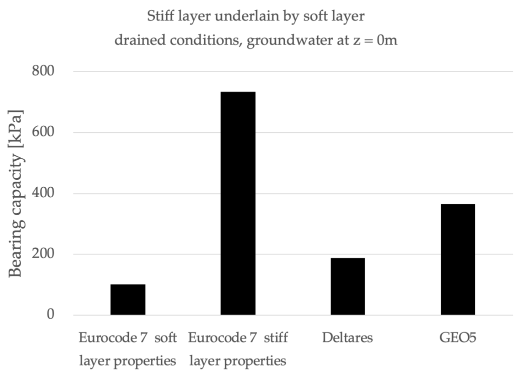

Figure B7: Stiff layer on soft layer in drained conditions, z=0m

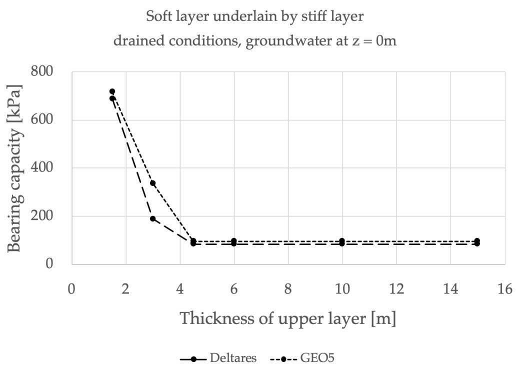

Figure B8: Soft on stiff - thickness of upper layer, dr. cond., z=0m.

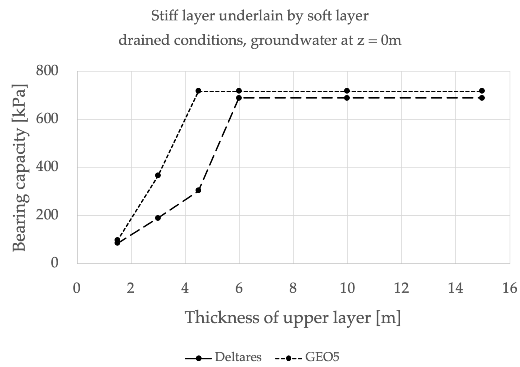

Figure B9: Stiff on soft - thickness of upper layer, dr. cond, z=0m

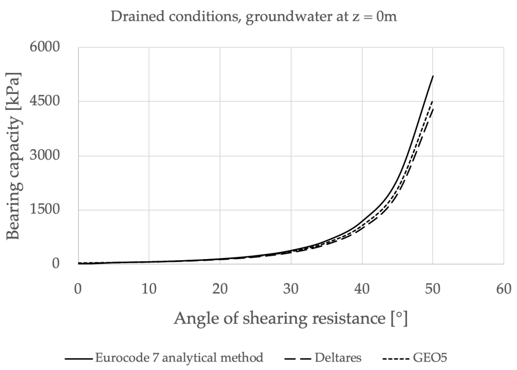

Figure B10: Angle of shearing resistance - bearing capacity, z=0m

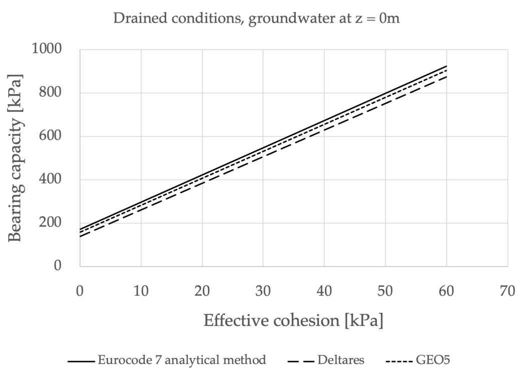

Figure B11: Effective cohesion - bearing capacity, z=0m

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