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Benchmarking analytical and software calculation methods for designing slab foundations according to Eurocode 7

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Abstract: This study examines prescription of Eurocode 7 in terms of designing slab foundations. The calculations of the load-bearing capacity are made with two different methods, namely an analytical method and one with software programs such as *GEO5* and *Deltares*. The main purpose of this paper is benchmarking these methods to indicate where the differences are and if the results are reliable. In order to analyze this, first, a parametric study is conducted on the various parameters, e.g. the cohesion, the unit weight and the angle of shearing resistance of the soil. Subsequently, several cases are worked out more in detail. Finally, it is concluded that there are indeed differences between the calculation methods and that some design/material parameters have a major impact on the final result. For example, for the calculation of the load-bearing capacity we are safe up to an angle of shear resistance of 35°, because the results of the different calculation methods remain the same. If the angle of shear resistance exceeds this value, differences in the calculation methods can be noticed.

Keywords: Benchmarking; Eurocode 7; slab foundations; load-bearing capacity; *GEO5*; *Deltares*

1. Introduction

1.1 General problem and research question

It is important to create a building process that is as efficient as possible. It all starts with a good preparation, because this will save us a considerable amount of work and money and that is what it is all about in civil engineering.

One of the most important aspects of the construction process is the design of the foundation. The entire building and all the related loads must be properly transferred to the ground and the whole structure must remain stable and safe throughout its service life. Hence, the European Committee for Standardization (CEN) developed a standard or guideline that specifies how geotechnical design should be conducted within the European Union. This guideline, also known as Eurocode 7, ensures compliance with the requirements for mechanical strength, stability and safety established by the European Union law.

Benchmarking is a method to compare results or performances with a reference. Different software programs claim to work in compliance with Eurocode 7, which means in a simple model, we should be able to get the same output results. But is this really the case? Therefore, the research question is as follows:

“ What is the difference between the analytical model of Eurocode 7 and other calculation methods, when designing slab foundations? “

This paper will examine what Eurocode 7 prescribes, more specific in terms of slab foundations. Subsequently, the practical implementation of this standard will be benchmarked with software programs, such as *GEO5* and *Deltares*. The purpose of this paper is to show the reader in which domains results are reliable and where we have to pay attention.

2. Theoretical base

2.1 Literature research

A geotechnical design can be made in three different ways. [1]

First of all, there is the deterministic method. This method simply asserts that the design value of the action (Ed), or its characteristic value (Ek), must be smaller than the design value of the resistance (Rd), or its characteristic value (Rk) divided by a global safety coefficient (S). (Equation 1) This method has several disadvantages; e.g. it is not in accordance with applicable Belgian standards and it is unclear what the global safety coefficient exactly means for the individual parameters. [1]

Equation 1: Deterministic method

$$Ed\ (= Ek) \leq Rd\ \left(= \frac{Rk}{S}\right) \qquad (1)$$

The second method is the semi-probabilistic method. This method introduces different Design Approaches (DA's) in order to take account of the safety on all the different parameters separately. The Design Approaches differ in the way in which they use partial safety factors. These factors are, depending on which Design Approach is used, applied to the actions, materials and resistances. This allows designers to make a better assessment of the safety on the individual parameters.

- DA 1-1 has partial safety factors applied to the actions, e.g. forces and loads.
- DA 1-2 has partial safety factors applied to the material properties, e.g. the soil characteristics.
- DA 2 has partial safety factors applied to the resistances and to the actions.
- DA 3 has partial safety factors applied to both the actions and the material properties.

Because this study focuses on the different soil parameters, this paper only uses DA 1-2 as the most relevant Design Approach. This DA shows how to design the foundation when the strength of the soil is worse than expected. The partial safety factors provided in Eurocode 7 for DA 1-2 are shown in Table 1.

Table 1: DA1-2 Partial safety factors [2]

DA1-2 Partial safety factors			
Actions/Effects	Permanent loads unfavorable	γg	1,00
	Variable loads unfavorable	γq	1,30
Material properties	Angle of shearing resistance	$\gamma \varphi$	1,25
	Effective cohesion	γc	1,25
Resistances	Bearing resistance	γRv	1,00

The last method is the probabilistic method. This method is based on statistical processing and analyzing the evolution of the results. A good probabilistic analysis requires a great amount of data and energy (processing power). All possible situations need to be taken into account before a good judgement can be made. That is why this method is not used very often in practice because it takes a considerable amount of time.

2.2 Terminology

As previously mentioned, Eurocode 7 (also written as EN 1997-1) is a standard that specifies how geotechnical design should be conducted within the European Union. This standard is based on the semi-probabilistic method, which means it uses the different Design Approaches and their partial factors in order to design geotechnical structures, such as slab foundations.

When countries of the European Union format national standards based on the principles of the Eurocode, they must also add a National Annex in order to ensure that the safety of a design remains a national and not a European responsibility. This annex contains specific information on those parameters, so-called Nationally Determined Parameters, which are left open in the Eurocode for national choice. This means that the Eurocode that is used in Belgium is called 'NBN EN 1997-1 + ANB'. [2]

An important part of this standard is the calculation of the ultimate load-bearing capacity. The ultimate load-bearing capacity is the theoretical maximum contact pressure between the foundation and the soil which can be supported without shear failure in the soil. Section '*2.3 State of the art*' will explain how this is calculated exactly.

'Spread Footing' from *GEO5* is a simple but reliable tool for solving geotechnical problems and designing different types of foundations that are used in this study to calculate the vertical load-bearing capacity. This program designs slab foundations subjected to a general load according to the Belgian Eurocode NBN EN 1997-1 + ANB.

The other software program that is used in this research is called '*D-foundations*' from *Deltares*. This program is also able to determine the vertical load-bearing capacity for a given foundation, but this calculation is based on the Dutch Eurocode NEN 9997-1 + C2.

Both of these programs claim that it is possible to implement standards such as Eurocode 7 and their corresponding partial factors. This will be examined in the following chapters.

2.3 State of the art

One of the most important formulas in this study to calculate the ultimate load-bearing capacity of a slab foundation, is the Meyerhof formula (Equation 2). Meyerhof is known for his sustainability formulas, which have also found their way into various standards, such as Eurocode 7. This formula is used for drained conditions and a vertical load working on the foundation. A complete derivation of this equation is given in the references. [3]

Meyerhof's formula is based on the formula of Terzaghi [4], with the difference that he introduced further coefficients, such as depth and inclination coefficients. In this way, Meyerhof ensured that the three major parts that are related to a foundation design, were considered.

First of all, the load-bearing capacity depends on the mechanical properties, as well as the original stresses and the water conditions in the ground. Secondly, it depends on the geometrical characteristics of the foundation. And finally, the load-bearing capacity depends on the loads that are working on the foundation. These three parts will be the common thread throughout this research.

The formula itself consists of three main terms. The cohesion term refers to the effective cohesion c' of the type of soil that is used. The depth term consists of a value q', which stands for the depth of the foundation multiplied by the unit weight of the soil (γ). Finally, the surface term refers to the (effective) surface breadth B' of the foundation.

In conclusion, the three main terms are multiplied with other factors. Table 2 shows the description of all the individual factors in Meyerhof's formula for load-bearing capacity of shallow foundations.

Equation 2: Meyerhof formula for calculation the load-bearing capacity

$$\frac{R}{A'} = \boxed{\begin{matrix} c'Nc\ sc\ ic\ dc\ (bc) \\ \text{Cohesion term} \end{matrix}} + \boxed{\begin{matrix} q'Nq\ sq\ iq\ dq(bq) \\ \text{Depth term} \end{matrix}} + \boxed{\begin{matrix} 0{,}5\ B'\gamma'N\gamma\ s\gamma\ i\gamma\ d\gamma\ (b\gamma) \\ \text{Surface term} \end{matrix}} \qquad \left[\frac{kN}{m^2}\right] \qquad (2)$$

Table 2: Different factors of the Meyerhof formula

	Name	Relates to	Why
c′	Effective cohesion	Soil	It is a soil characteristic.
γ'	Effective unit weight	Soil	It is a soil characteristic.
Ni	Bearing capacity factors	Soil	Standard factors which depend on the internal friction angle.
ii	Load inclination factors	Load	Factors to take inclination of the load into account.
A′	Effective base area	Load	As a result of any eccentric load.
si	Shape factors	Geometry	Factors to take the shape of the foundation into account.
di	Depth factors	Geometry	Factors to take the depth of the foundation into account.
(bi)	Base inclination factors	Geometry	Factors to take inclination of underside of the base into account.

3. Research design

3.1 Procedure and parameters

To start this study, it was of utmost importance to define the boundaries. As previously mentioned, only slab foundations are considered in this research paper. For strip and pile foundations, the reader is referred to other papers in the literature. [5-6]

Subsequently, in order to be able to make a good comparison afterwards, specific boundaries are defined, for example the type of soil and range of parameters that will be used. An overview of the soil parameters and their ranges can be found in Table 3.

Table 3: Soil parameters and the ranges

	Name	Range
Φ′	Eff. Angle of shearing resistance [°]	1 - 50
c′	Effective cohesion [kPa]	0 - 20
γ'	Unit weight [kN/m³]	1 - 50

Prior to the parametric study and because of different possible scenarios, it was important to first work out a simple model and understand the calculation process. In this case the simple model is a slab foundation just below the ground level, with a centric permanent load, resting on a homogeneous soil (sandy clay). (Figure 1) An overview of the required input parameters is shown in Table 4.

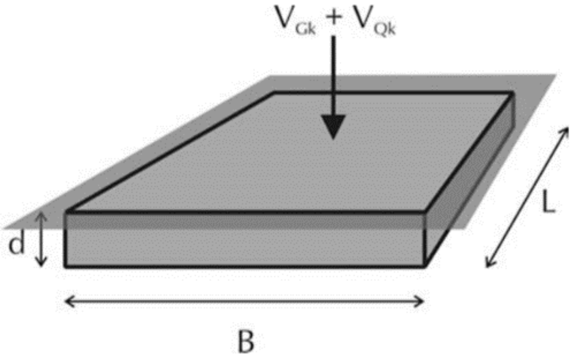


Figure 1: Schematic representation of the slab foundation for the analytical calculation [11]

Table 4: The required input parameters for the analytical calculation

Plate	Length	L	20,00	m
	Breadth	B	10,00	m
	Thickness	t	0,50	m
	Depth	d	0,50	m
Load	Permanent	VGk	2500	kN
	Variable	VQk	0	kN
		VQh	0	kN
Soil (Sandy Clay)	Eff. angle of shearing resistance	φ'k	24,5	°
	Effective cohesion	c'k	14	kPa
	Unit weight	γk	18,5	kN/m³
Reinforced Concrete	Unit weight	γc	25	kN/m³

The next step is to calculate the ultimate vertical load-bearing capacity of the simple model. This analytical calculation is made in the program Excel and is based on Eurocode 7 and the corresponding formulas. Because Eurocode 7 is an established law, the output results obtained will be our reference values. Then, the benchmark value is evaluated by working out the same case in the software programs *GEO5* and *Deltares*.

Once the calculation process of this model is understood, a study of the different soil parameters and their ranges, as mentioned before in Table 3, can be conducted. This section finds out which parameters are sensitive and which do not affect the load-bearing capacity, both in terms of the analytical calculation as well as in the programs.

Finally, other cases will be worked out, which will also relate to the three main parts (soil, geometry and loads). This will allow us to understand what happens in other situations. All the calculations can be consulted in Appendix A.

Not all cases are discussed in this paper, only the ones where something remarkable has been noticed. For example, what is the effect if we introduce a second, dense layer of sand. And what will happen with the load-bearing capacity if the load is applied eccentrically on the plate.

3.2 Limitations and assumptions

In order to define boundaries, a number of limitations and assumptions have been established in this study.

- The soil of the simple model consists of maximum two soil types, namely clay and sand. We consider that the soil is only in drained condition. This means all the soil parameters are 'effective'. [1]

- The load-bearing capacity of the slab foundations will only be calculated with the Meyerhof formula. (Equation 2)

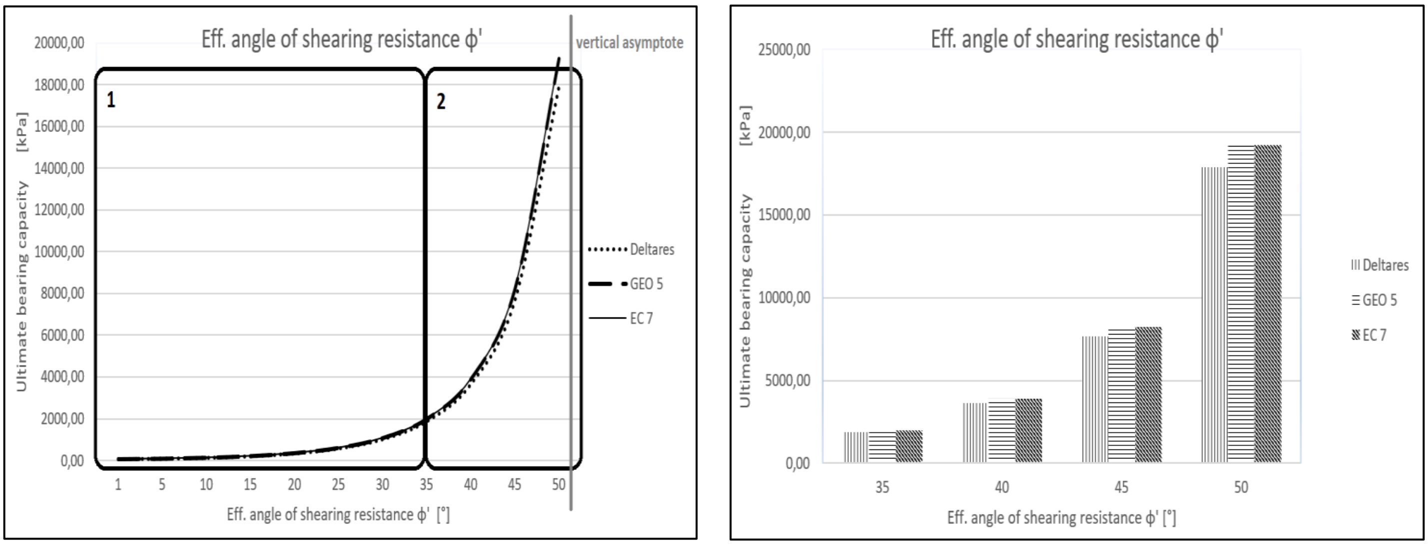
- The slabs are made of reinforced concrete with a unit weight of 25 kN/m³.

- In the cases mentioned in this paper, the slabs are always just below the ground level, so the effect of overburden is omitted.

4. Results & Discussion

4.1 Soil

4.1.1 Parameter study



(a) (b)

Figure 2: Results of the parameter study of the effective angle of shearing resistance

The first soil parameter that will be discussed is the effective angle of shearing resistance or internal friction angle. This angle describes the friction shear resistance of soils and it can be found using experimental tests such as the triaxial test or correlated using empirical formulas. [7] Since this study assumes that the soil is in a drained state, the effective shear resistance parameters will be used.

As previously mentioned, the effective internal friction angle varies between 1° and 50°. Figure 2 (a) shows the course of the parameter study. For the course of this graph, it can be noticed that there is a rather linear course up to a friction angle of 25° and at a friction angle higher than 35°, there is a very steep gradient. In other words, a vertical asymptote becomes apparent. This is due to the fact that when determining the different load-bearing capacity factors, a tangent always occurs in the formulas. To verify this, a fictitious value of 85° has also been tested. With this value, a very high value for the load-bearing capacity is obtained but it remains in the trend of the vertical asymptote.

Another thing that can be determined from this graph is that two zones can be separated from each other. Zone 1 is called the safe zone. This means if the soil has an internal friction angle of up to 30°, the results of the calculation of the load-bearing capacity are definitely reliable. The reason is that all calculation methods, analytical and both *GEO5* and *Deltares*, give the same results in this zone.

The second, so-called danger zone (2), is represented graphically in Figure 2 (b). From the moment that the internal friction angle is in the range of 35° - 50°, there are visible differences. On the one hand, the value of the load-bearing capacity increases quickly, due to the tangential function mentioned earlier. On the other hand, not all methods obtain the same results as the reference value of the analytical model (EC7).

For example, *Deltares'* results are always smaller. This is because in this program the load-bearing capacity is calculated according to article 6.5.5.2 from the Dutch Standard NEN 9997-1 + C2 and it applies not only a safety factor on the internal friction angle and the cohesion, but it also applies a safety factor of 1.1 on the unit weight of the soil (γ). This means that the program underestimates the value, even compared to the European standard. This indicates that *Deltares* is a rather conservative program.

GEO5 on the other hand, always obtains exactly the same results as the reference value of the analytical calculation (EC7). Therefore, it can be concluded that this program works in accordance with Eurocode 7 and that there are no differences between the analytical model and this calculation method.

Not only the internal friction angle has been examined. A parameter study was also performed on the other soil parameters, such as the effective cohesion c′ and the unit weight γ. These graphs both showed a linear course. This means that if these values vary within the predetermined range, we simply obtain a proportionate relationship with the load-bearing capacity and that is not interesting to analyse in this paper.

4.1.2 Two-layered soil

In this chapter another layer will be introduced in the soil profile, namely a dense sand layer. This allows us to analyze the effect of what happens when we have a loose layer on a dense layer and vice versa. The characteristics of this layer of sand is shown in Table 5.

Table 5: Soil characteristics of sand with trace of fines

Soil (Sand with trace of fines)	Eff. angle of shearing resistance	φ'k	29,5	°
	Effective cohesion	c'k	0	kPa
	Unit weight	γk	17.5	kN/m³

The load-bearing capacity of the two-layered soil is related to the relative average strength of the two layers, the load-bearing capacity of the under layer, the thickness of the top layer and the width of the foundation (B). The following graph is obtained by calculating the load-bearing capacity of a dense sand layer on a loose layer, with the thickness of the dense layer varying. (Figure 3)

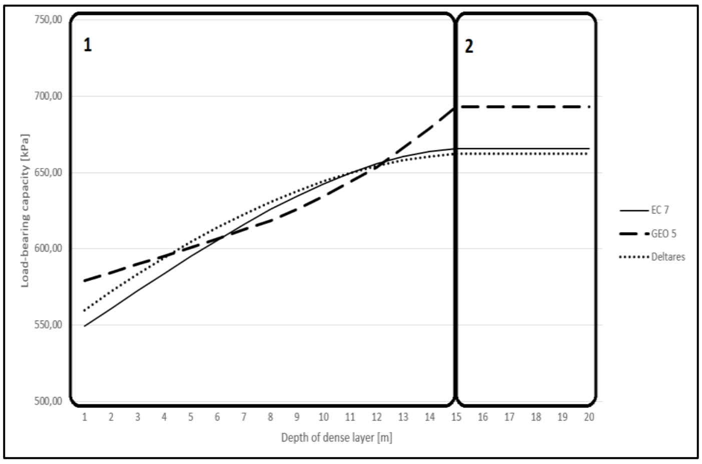


Figure 3: Depth of dense layer in function of the load-bearing capacity

In the course of this graph, again two zones can be distinguished from each other. Zone 2 starts from a depth equal to 1,5 times the width of the sole (B), which is 15m. It can be concluded that from this depth, the effect of a two-layered soil has virtually no influence anymore, because the load-bearing capacity from that moment on remains constant at a value equal to the ultimate load-bearing capacity of an infinitely thick sand layer. This conclusion is in accordance with Tcheng. [8]

In the other zone (Zone 1), the depth of the top layer is less than 1,5 times the width of the sole (B). When this is the case, it depends on how thick the top layer is before it can be determined that we are dealing with punching shear failure. With punching shear, the shearing surface is slightly different in contrast to general shear failure.

General shear failure involves total rupture of the underlying soil. At failure the entire soil mass within the failure wedge participates and well-defined failure surfaces develop (Figure 4). [9]

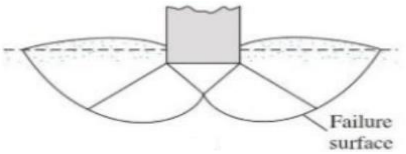


Figure 4: General shear failure surface

When punching shear occurs, the soil outside the loaded area remains relatively uninvolved and there is minimal movement of soil on both sides of the footing (Figure 5). In other words, the foundation penetrates deeper into the ground as a result of the compression of the underlying layers. This form of shear failure creates vertical failure. [9]

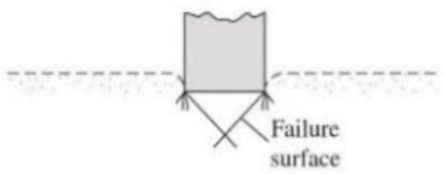


Figure 5: Punching shear failure surface

If the footing rests on a relatively thin dense layer (sand) above a soft cohesive layer (clay), it may punch through the top layer into the underlying layer, which undergoes a general shear failure. [10] In such a case, the ultimate bearing capacity behavior of the footing will be governed by the strength characteristics of the clay layer. On the other hand, if the top layer is relatively thick, the failure surface will be fully contained in the top clay layer and there will be only general shear failure.

In addition, there is also an analysis of what happens when we exchange the two ground layers, loose and dense, with each other. This simply inverted the graph and the same two zones could be separated.

4.2 Load

This chapter looks at the effects of increasing and displacing the vertical force acting on the slab foundation. First, if the vertical load increases, this does not directly affect the value of the load-bearing capacity but only decreases the overdesign factor (ODF). This factor is the ultimate load-bearing capacity divided by the total vertical force. If the value of the ODF is less than 1, the design of the slab foundation is unacceptable.

Secondly, an eccentric load is examined. Due to an eccentricity of the load, a complex distribution of the contact stress between the ground and the slab develops. To minimize this complexity, we use the 'effective surface or area' to calculate the load-bearing capacity.

The original surface of the slab is reduced to a centrically loaded 'effective surface', on which the load-bearing capacity is then evenly developed.

Because a soil cannot take any tension and in order to prevent contact with the ground being lost at the slab edges, there is a rule made up to avoid this situation. This rule is called the 'middle-third' rule. [11] It means that the vertical load should always act in the middle third of the foundation. In other words, the eccentricity of the action from the center of the foundation is kept within the following limits:

$$eb \leq \frac{B}{6} \text{ } and \text{ } el \leq \frac{L}{6}$$

where B and L are respectively the breadth and length of the slab foundation and eb and el are eccentricities in the direction of B and L. (Figure 6)

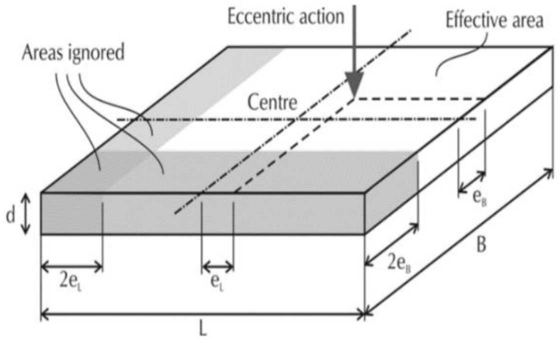


Figure 6: Schematic representation of the effective area [11]

Subsequently, the results itself (Table 6). It can be concluded that there is a difference between the different calculation methods. First of all, there is a difference between the centric and eccentric value. This is due to the fact that at the calculation of the eccentric load the effective lengths and breadths are used in the Meyerhof formula, which reduces the load-bearing capacity.

Table 6: Results centric vs. eccentric load

EC7 centric - qu [kPa]	EC7 eccentric - qu [kPa]	GEO 5 eccentric - qu [kPa]	Deltares - Rd [kN]	Deltares eccentric - qu [kPa]
580,5	487,3	491,75	45167,2	460,89

In addition, *GEO5* gives an almost similar value. It can be concluded that *GEO5* is well adapted to the analytical model and is in compliance with Eurocode 7.

Deltares, on the other hand, obtains a different value. Again, this small difference is due to the safety factor of 1.1 which is set on the density of the soil.

4.3 Geometry (addendum)

In this addendum, a brief study about the comparison of three foundation types, namely strip foundations, slab foundations and pile foundations, is disclosed. In this comparison the exact same setup is used in the analytical calculation method of Eurocode 7 and both software programs, *GEO5* and *Deltares*.

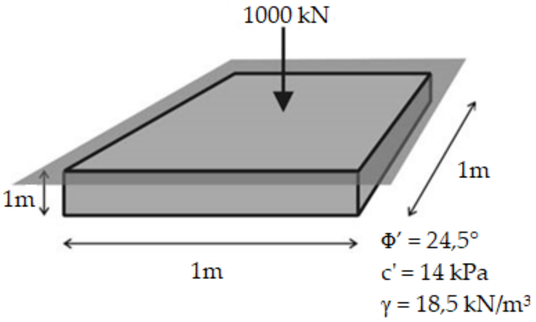


Figure 7: Schematic representation for the comparison between the different foundation types

Table 7: Results comparison strip, slab and pile foundation

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

When the load-bearing capacity of strip foundations and slab foundations are compared, we can deduce that both for the analytical calculation of Eurocode 7 and the numerical calculation of *GEO5*, the results are identical. The load-bearing capacity calculated for the two foundation types in *Deltares* differs considerably. This is due 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 load-bearing capacity of the strip foundations is lower than the load-bearing capacity of the slab foundation.

For the comparison of pile foundations with the two other foundation types, the difference is found in the fact that pile foundations do not use ground safety coefficients, resulting in a higher load-bearing capacity. When calculating the load-bearing capacity for pile foundations, a shaft and base resistance is considered, while the two other type of foundations only take into account the base resistance, resulting in a higher load-bearing capacity as well.

5. Conclusions

In this section several conclusions are described. First, from all the design and material parameters the effective angle of shearing resistance is the most important one. Up to a value of 35 ° we are safe, because the results of the different calculation methods remain the same. As soon as the value increases, the program *GEO5* still provides exactly the same results as the analytical model (EC7), but *Deltares* obtains a lower value. This is due to the fact that *Deltares* works with the Dutch standard NEN 9997-1 + C2 and it applies not only a safety factor on the internal friction angle and the cohesion, but it also applies a safety factor of 1.1 on the unit weight of the soil (γ).

Secondly, when a second layer is introduced, the thickness of the top soil layer has a marked influence on the load-bearing capacity. The load-bearing capacity decreases steadily with the increase of the top layer thickness when this layer is weaker than the bottom layer, and vice versa. The load-bearing capacity attains a steady value at a specific top-layer thickness, depending on the width of the foundation (B) and the characteristics of the two soils.

In general, we can conclude that *GEO5* is in close compliance with Eurocode 7 when designing slab foundations. This is because it always provides exactly the same results as the analytical method for all of the different cases that have been calculated. On the other hand, *Deltares* works with the Dutch version of the Eurocode and provides more conservative results. This program makes underestimates, even against the European standard. These underestimates have been integrated and are based on the assumption that this is the safest approach. (Table 8)

Table 8: Conclusion

Parameter		Reliable results in range	Safest calculation method
Φ'	Eff. Angle of shearing resistance [°]	1 - 35	*Deltares – D-foundations*
c'	Effective cohesion [kPa]	0 - 20	*Deltares – D-foundations*
γ	Unit weight [kN/m³]	1 - 22	*Deltares – D-foundations*
e	Eccentricity of the load [m]	$eb \leq \frac{B}{6}$ and $el \leq \frac{L}{6}$	*Deltares – D-foundations*

6. Future work

This research can be repeated when horizontal loads acting on the foundation are introduced. Then more criteria will have to be checked, such as the gliding resistance.

In order to improve the programs, a kind of "input check" can be introduced. This means that when we give in the different parameters, it will check automatically if we are in a safe zone and whether we can obtain reliable values.

In addition, there should also be some kind of alarm function in the programs. It should warn us that we have entered an unrealistic value and that we are in the danger zone.

Appendix A

This appendix contains all the calculations of the different cases and can only be consulted digitally.

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