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ALIGNING ECONOMIC AND SUSTAINABILITY GOALS: TRADE-OFFS FROM A GEOTECHNICAL PERSPECTIVE

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ABSTRACT

The construction industry's extensive use of steel and concrete contributes significantly to greenhouse gas emissions. Meeting the Paris Agreement's goal of limiting global warming requires the industry to reduce its climate impact by optimizing material use. Geotechnical engineers play a crucial role in designing structures that minimize material consumption while maintaining structural integrity. Accurate knowledge of soil conditions, obtained through sufficient soil sampling, is essential for this task. However, current incentives in the construction process often lead to insufficient soil sampling, as developers aim to minimize costs. With limited data, geotechnical engineers are inclined to overdesign structures to minimize failure risks, resulting in excessive material use and higher costs. This paper explores the balance between the cost of additional soil sampling and the environmental and economic gain of an optimized design. It discusses the dilemmas facing the geotechnical engineer trying to align economic and safety in an era of increasing demands for sustainable designs.

Keywords: sustainability and soil sampling.

INTRODUCTION

Buildings contribute significantly to CO₂e (CO₂ equivalents) emissions and are part of a highly resource-intensive industry.

The focus of this paper is the foundation, a critical element of all buildings. Foundations are primarily constructed using concrete and steel - materials that contribute significantly to CO₂e emissions due to the energy-intensive processes involved in cement production, steel manufacturing, and raw material extraction. At present, no CO₂e-free alternatives can fully replace these materials while maintaining the necessary strength, durability, and structural performance.

To reduce CO₂e emissions from groundwork, optimizing material use is essential. Geotechnical engineers play a key role in designing foundations that minimize material consumption while ensuring structural integrity. This will become increasingly important as more countries implement regulations aimed at reducing CO₂e emissions across the entire life cycle of buildings.² A significant share of these emissions comes from the production of materials.

This paper focuses on the design of concrete piles used in foundations. It examines how knowledge of soil conditions influences design optimization and, ultimately, material usage and CO₂e emissions.

GEOTECHNICAL INVESTIGATION

The design of all foundations is based on geotechnical investigations. Usually, the investigation program is planned before the layout of the building is fully defined.

According to Eurocode DS/EN 1997-2 + AC:2011, the spacing of investigation points should be between 15 and 40 m for an industrial structure. It is stated in the standard that the spacing should be used as guidance.

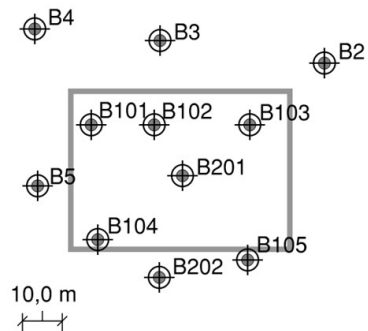


Figure 1 Situation plan of investigation points. The outline of the building is shown as a grey line

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² In Denmark, a life cycle assessment (LCA) is required for all new buildings (except for critical infrastructure and unheated buildings under 50 m²). Starting July 1, 2025, new buildings must meet an emissions threshold of no more than 7.1 kg CO₂e/m²/year on average, which will be further reduced to 5.8 kg CO₂e/m²/year by 2029. These limits vary depending on the building type (The Ministry of Social Affairs and Housing (2024)).

In Figure 1, a simplified situation plan is shown. The situation plan shows the location of boreholes at a new industrial structure on Zealand, Denmark. The building measures 55 x 40 m. The boreholes are placed with a spacing of 15 - 30 m.

Based on the boreholes the soil stratigraphy is estimated and shown in Figure 2. From Figure 2 it is seen that the soil layers consist of fill, after which peat with varying thickness is found. Thereafter, clay till with varying thickness is found till the full depth of the boreholes. The layer of peat will cause settlements of the higher soil layers resulting in downdrag on the piles.

FOUNDATION DESIGN

Due to the soil condition, the foundation of the industrial building will include concrete piles.

The pile base resistance is calculated from ground test results according to DS/EN 1997-1 and the corresponding national annex DS/EN 1997-1 DK NA.

Based on the geotechnical investigation and prior experience, relevant soil parameters have been determined. These parameters are presented in Table 1.

Table 1 Soil parameters for pile design

Soil type	Unit weight γ/γ' [kN/m³]	Friction angle, φ_k [°]	Undrained shear strength, c_{uk} [kPa]
Fill	18/8	28	-
Peat	16/6	26	60
Clay till	21/11	-	250

Driven concrete piles measuring 35 x 35 cm are used, spaced at 4 x 4 m intervals. Each pile must have a minimum load-bearing capacity of 1250 kN in the ultimate limit state (ULS). The top elevation of the piles is set at +0.0 m.

Based on the soil stratigraphy shown in Figure 2, the foundation is divided into two zones with different pile lengths. The required pile lengths and the delineation of these two zones are indicated in Figure 3.

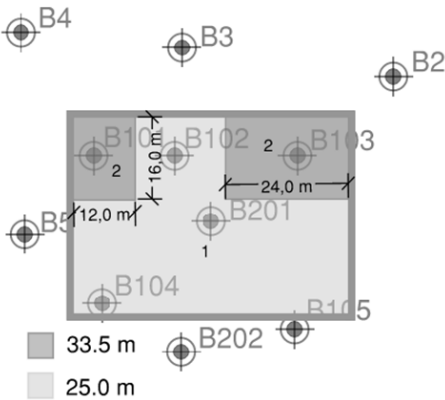


Figure 3 Required pile length in the ultimate limit state (ULS)

CO₂e EMISSIONS FROM FOUNDATION

With a building footprint of 2,200 m², a total of 138 piles are required. According to Figure 3, 36 piles are placed in Zone 2 and 102 piles in Zone 1. This results in a total of 3,756 meters of 35 x 35 cm concrete piles.

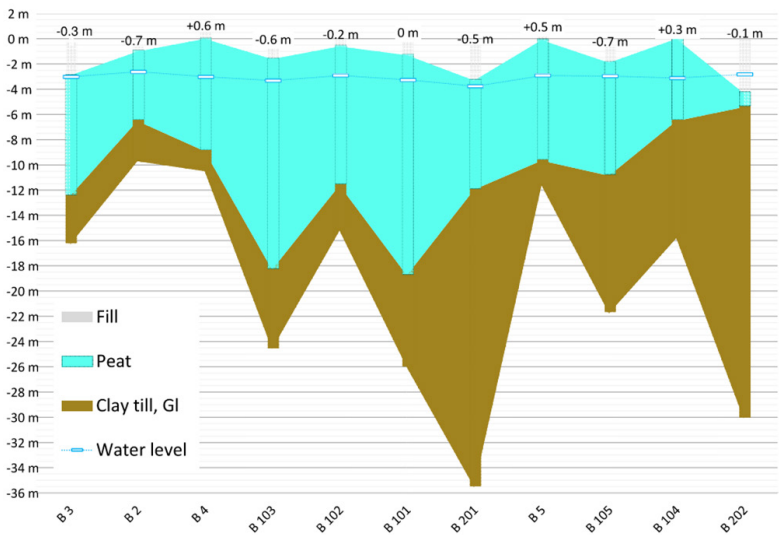


Figure 2 Soil stratigraphy based on the investigation points shown in Figure 1. Elevations are referenced relative to borehole B101.

Centrum Pæle, the main supplier of piles in Denmark, states in an Environmental Product Declaration (EPD) that total CO₂e emissions are 50.8 kg CO₂e per meter of pile produced (see Centrum Pæle A/S (2021)).

Consequently, the piles for the new industrial building in Zealand result in total CO₂e emissions of approximately 191 tonnes.

BOREHOLE SPACING AND CO₂E EMISSIONS

If the spacing between the geotechnical investigations had been 40 meters (instead of 15 - 30 meters), for instance, borehole B102 could have been omitted. This would likely have resulted in ordering longer piles for the entire northern section of the building, even though this would not have been necessary. Based on the results of the geostatic pile design, such a decision would have led to approximately 4% higher CO₂e emissions than required.

Although the client would have saved money by reducing the number of boreholes, this would have led to the use of unnecessarily long piles. While it is not guaranteed during the planning phase that additional investigation points will result in shorter piles, more investigation points do increase the possibility of making localized optimizations by providing a better understanding of the subsurface conditions.

The greater the number of investigation points available as a basis, the more reliable the resulting design will be, thereby minimizing the risk of failure. Investigation points do not necessarily have to be boreholes - they can just as well be CPTs used to determine layer boundaries.

FIELD TESTS

Another decision available to the client is to require pile testing during the construction phase.

According to DS/EN 1997-1 DK NA section A.3.2.2, the correlation factor ξ is set to 1.5 when the pile base resistance is determined solely from ground investigation data. However, if representative field tests (PDA-measurements) are carried out, the correlation factor may be reduced to 1.4 for all applicable piles.

The national annex to DS/EN 1997-1 suggests that a minimum of 5-10 percent of the piles should be tested.

In the case of the industrial building in Zealand, this would correspond to testing 7-14 piles. By reducing the correlation factor through field testing, it is possible to shorten the total pile length by approximately 207 meters, resulting in CO₂e reductions of about 10.5 tonnes. The reduction of total pile length is only based on the reduction of the correlation factor to 1.4 in the pile base resistance. Thus, effects of the pile base resistance calibrated with the field tests are not included.

Based on industry experience, the cost of installing a pile is approximately EUR 100 per meter pile, while the cost of testing a pile is around EUR 1,000. The investment in pile testing can be offset by the savings in both the purchase and installation of shorter piles. However, since the potential savings cannot be guaranteed upfront, the decision to conduct testing requires the client to weigh risk, cost, and sustainability objectives.

DISCUSSION

The foundation design process presents a clear trade-off between short-term cost savings and long-term environmental impact. As demonstrated in the case of the industrial building in Zealand, the total CO₂e emissions from the pile foundations alone amount to approximately 191 tonnes. These emissions are directly influenced by decisions made during both the investigation and execution phases of the project.

Key design choices — such as borehole spacing and field testing — can impact both project costs and CO₂e emissions. Reducing the number of boreholes saves money but often leads to conservative designs with longer piles, as seen in this case where emissions could have increased by 4%.

Fewer investigation points mean less site-specific data, limiting opportunities for optimization. The number of geotechnical investigation points should be assessed on a case-by-case basis, as additional investigations may not always provide added value to a project.

Similarly, testing piles in the field is costly but can reduce pile length by improving design accuracy. For the Zealand project, this could have avoided 10.5 tonnes of CO₂e. Though savings aren't guaranteed, the potential benefits in both cost and CO₂e emissions make it a valuable option.

It is important to account for the tests in the planning of the execution, as the most reliable PDA-measurements are obtained by allowing the soil to regenerate.

To lower emissions, clients must look beyond short-term costs and invest in better data and testing. This shift enables more sustainable, climate-conscious design without necessarily increasing total project costs.

CONCLUSION

Reducing CO₂e emissions from building foundations requires early and informed design choices.

As shown in this study, key decisions —such as borehole spacing and field testing — significantly impact both material use and emissions.

While cost-saving measures like fewer investigation points or skipping field tests may seem attractive, they often lead to conservative designs with higher environmental impact.

To support climate-driven construction, clients and engineers should prioritize data quality and optimization over short-term savings.

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