THREE-DIMENSIONAL EFFECTS IN TEMPORARY EXCAVATIONS IN SOFT CLAY

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KEYWORDS

Excavations, soft clay, design

ABSTRACT

Excavations must always be performed in such a way that the stability conditions are satisfying. For excavations without geometrical constraints in the vicinity a battered excavation may be sufficient. Otherwise, embedded retaining walls are required. Depending on the site conditions the retaining walls may be of cantilever type or supported at one or several levels.

In order to seek to avoid a retaining wall or - when it is needed - optimise it, it may be beneficial to account for "3D-effects". The 3D-effects may be "natural", e.g. an excavation with a limited horizontal extent or working equipment with a limited extent along the crest of the excavation. However, temporary 3D-effects in the construction stage may also be achieved by carefully planning the excavation works in such a way that the extent of the critical section is limited (e.g. a sequential excavation process).

This Paper summarises the results of three R&D-projects with focus on how 3D-effects can be accounted for in the design of temporary excavations in soft clay and thereby contributing to minimising the carbon footprint. The work, which is partly based on 3D finite element analyses, includes suggestions for best practice using extended 2D analyses, as well as design examples, for battered excavations and excavations supported by retaining structures.

1. INTRODUCTION

Temporary works, e.g. excavations, should be planned and designed in order to minimise the costs and the carbon footprint given the site-specific conditions and safety regulations.

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In connection with temporary excavations these aspects may be achieved by accounting for "3D-effects". Such effects may be the result of e.g. the geometry of the excavation, the construction sequence or the horizontal extent of heavy working equipment next to the excavation. Some examples from practice are given in Figure 1 in which a weak section (-) is surrounded by strong sections (+). Ideally, accounting for 3D-effects will result in a battered excavation, but when such a solution is not sufficient the amount of, e.g. the sheet pile walls and/or the loads in the bracing system can be minimised.

Historically, semi-empirical expressions and/or design charts have been developed for assessing 3D-effects in ultimate limit state design for e.g. shallow foundations (bearing capacity), slopes (stability) and retaining walls (basal heave). However, such expressions and charts are developed based on idealised situations. Accounting for 3D-effects in practice requires careful considerations. A possible approach is to perform 3D finite element analyses, but such analyses are time-consuming and are thus mainly carried out in large construction projects or in R&D-projects.

In ultimate limit state design, the 3D-effect may be quantified by a 3D factor of safety, F_{3D}, which always will be larger than the 2D factor of safety for the weak section, $F_{2D,weak}$, but always lower than the 2D factor of safety for the strong sections surrounding the weak section, $F_{2D,strong}$. The 2D safety factors for the weak and the strong sections respectively are fairly easily determined using e.g. design charts or conventional 2D software based on traditional Limit Equilibrium methods or the finite element method. However, in order to account for 3D effects more sophisticated software is needed resulting in considerably longer calculation times.

This article summarises Swedish best practice for estimating F_{3D} in temporary excavations in soft clay with an undrained shear strength in the order of 10-20 kPa and an overconsolidation ratio in the order of 1,0-1,5. The study is limited to idealising and treating soil strength as "undrained", i.e. limited to excavations of short duration in low permeable soils. The importance of considering the effect of dissipation of (stabilising) excess pore pressures after excavation is, however, reported in [1].

Section 2 covers battered excavations while Section 3 covers excavations supported by embedded retaining structures. The suggested methods are generally based on 2D analyses of the weak and the strong sections.

2. 3D-EFFECTS IN BATTERED EXCAVATIONS

The 3D-stability when a weak section is surrounded by infinitely strong sections have been studied by several researchers in the past. In e.g. [2] both plane ends, cf Figure 2, and curved ends have been analysed for a situation where the ground consists of a cohesive soil with constant undrained shear strength and unit weight while the only destabilising actions are the depth and the length of the excavation. If assuming plane ends $F_{3D,plane}$ can be formulated analytically. However, it is not possible to formulate an analytical expression for $F_{3D,curved}$ if assuming curved end. Based on the results reported in [2] an approximate analytical solution accounting for curved ends may be formulated as (cf. [3]):

$$F_{3D,curved} \approx F_{2D,weak} + 0{,}75 \cdot \left(F_{3D,plane} - F_{2D,weak}\right) \qquad \text{(Eq. 1)}$$

The maximum depth of the failure mechanism resulting in the lowest factor of safety accounting for 3D-effects, $F_{3D,critical}$, is always smaller than or equal to the maximum depth of the of the critical failure mechanism for the 2D factor of safety for the weak section, $F_{2D,weak,critical}$. Consequently, several 2D failure mechanisms, with varying maximum depth, must be analysed in order to find the critical 3D-mechanism using Equation 1.

Figure 1. Some typical situations where 3D-effects have been incorporated in design in order to achieve satisfying stability conditions in temporary excavations. Upper left: A battered excavation with a limited horizontal extent. Upper right: A cantilever sheet pile wall next to trafficked railway tracks. Lower left: A cantilever sheet pile wall supporting an excavation that progresses sequentially from right to left while simultaneously casting a concrete slab. Lower right: A sheet pile wall supported by struts while excavating and casting a concrete slab sequentially.

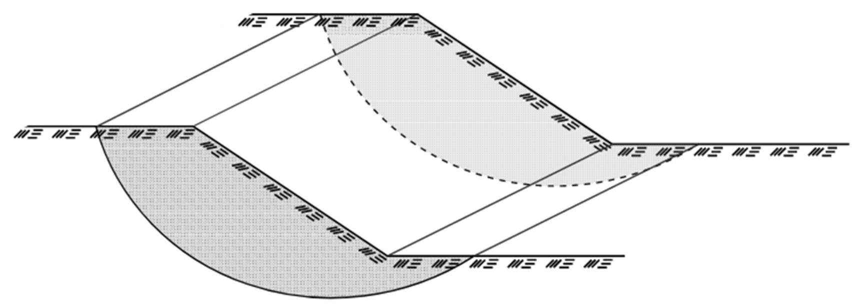

Figure 2. The 3D failure mechanism for a weak section surrounded by infinitely strong sections if assuming plane ends.

In reality, the strong sections surrounding the weak section are rarely infinitely strong. In such situations Equation 1 may overestimate F_{3D}. In order to overcome this, several scenarios, frequently occurring in practice, have been analysed. The study is briefly described below (see [3] for details).

The study focuses on four main scenarios (see Figure 3):

- A long excavation subdivided in short segments in which excavating, pipe installation and backfilling are made sequentially
- An excavation for a manhole (the length of the excavation is limited, but equal to the width of the excavation)
- An excavation for a bridge foundation (the length of the excavation is limited, but larger than the width of the excavation)
- A long excavation with heavy machinery locally located behind the crest of the excavation

Each main scenario has been further subdivided when it comes to the undrained shear strength of the soil, the geometry of the excavation and the adjacent load leading to a total of 66 scenarios being analysed. Each scenario has been studied using 3D finite element analyses (PLAXIS 3D), using the Mohr-Coulomb model, resulting in a value for F_{3D} considered to be the benchmark for that specific scenario. In a few scenarios (3 out of 66) the critical failure mechanism turns out is to be "local bearing capacity", i.e. the critical mechanism does not involve the excavation. The 63 scenarios have also been studied using conventional limit equilibrium analyses (Slope/W) and 2D finite element analyses (PLAXIS 2D) of both the weak and the strong sections.

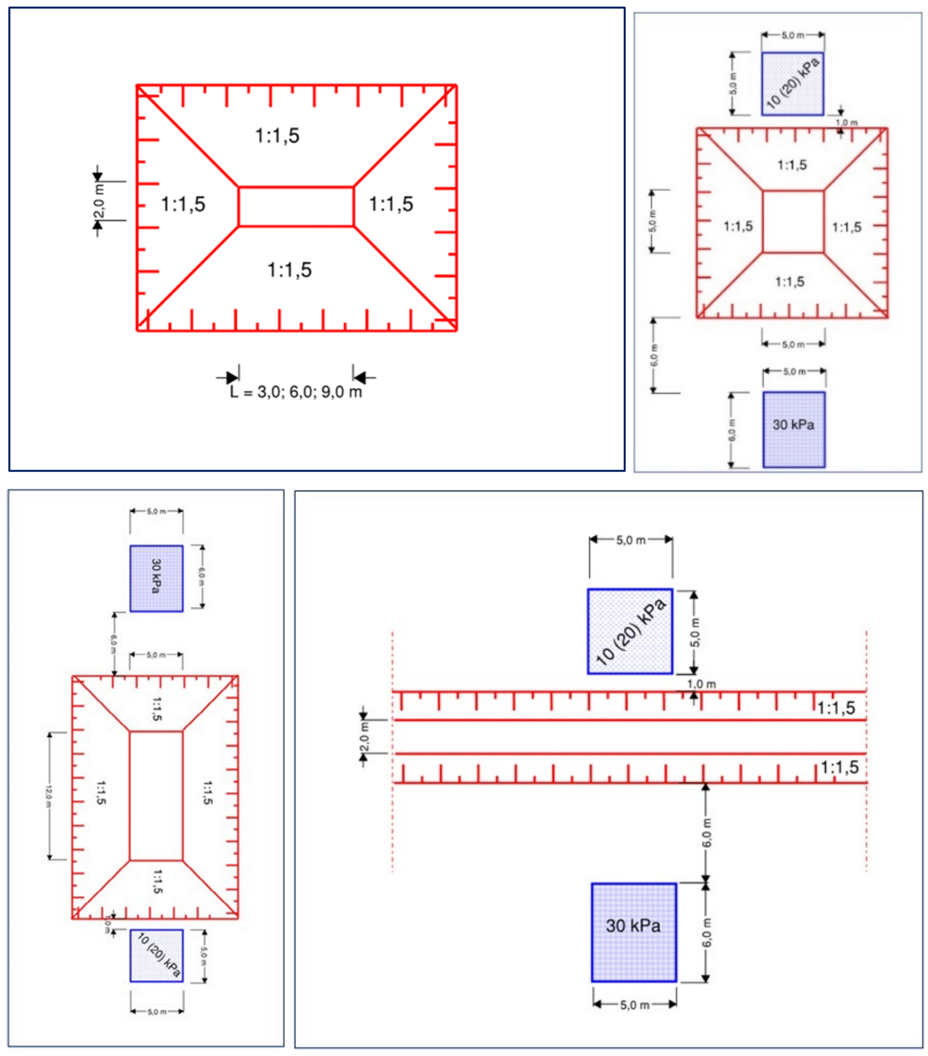

Figure 3. Upper left: A long excavation subdivided in short segments in which excavating, pipe installation and backfilling are made sequentially. Upper right: An excavation for a manhole. Lower left: An excavation for a bridge foundation. Lower right: A long excavation with heavy machinery locally located behind the crest of the excavation.

Various ways of combining $F_{2D,weak}$ and $F_{2D,strong}$ for estimating F_{3D} were formulated and compared to the benchmark (i.e. the 3D finite element analyses). The resulting suggested expression for F_{3D} is:

$$F_{3D} \approx F_{2D,weak} + \left(1 - \frac{F_{2D,weak}}{F_{2D,strong}}\right) \cdot 0{,}75 \cdot \left(F_{3D,plane\ ends} - F_{2D,weak}\right) \quad \text{(Eq. 2)}$$

Similar to Equation 1, several 2D failure mechanisms, with varying maximum depth, must be analysed in order to find the critical 3D-mechanism using

Equation 2. The resulting estimated $F_{3D,critical}$ is, with a few exceptions, within ± 10% compared to using 3D finite element analysis, cf. Figure 4.

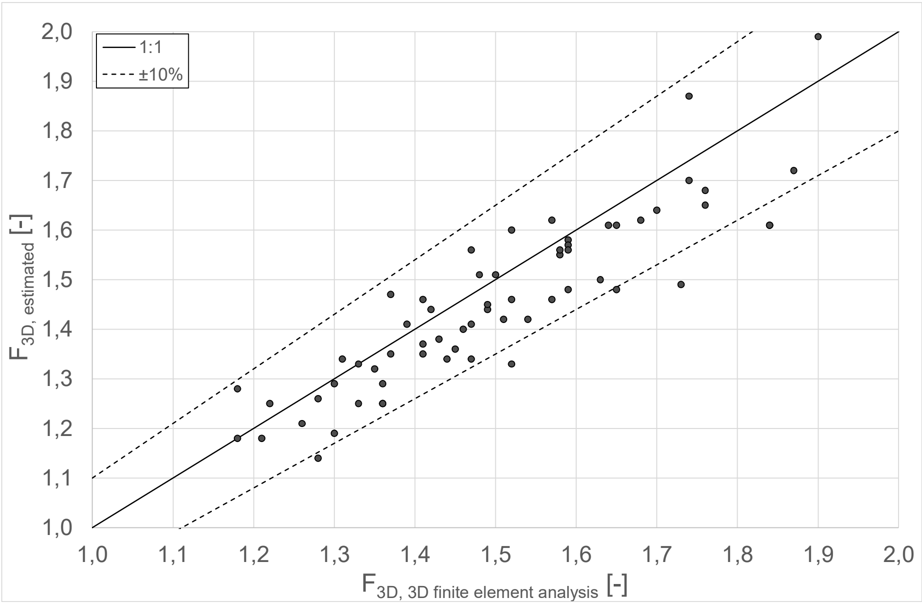

Figure 4. Comparison of F_{3D} according to 3D finite element analysis and Equation 2.

3. 3D-EFFECTS IN EXCAVATIONS SUPPORTED BY EMBEDDED RETAINING WALLS

This section covers consideration of sequential excavation processes in the design of excavations supported by embedded retaining walls, specifically braced excavations. A complete description is given in [1], that also reports the design and monitoring results of two projects where sequential excavation was carried out. Accounting for the 3D-effect in excavations supported by a cantilever wall, which is described in more detail in [4], may be considered to be a special case of the more general cases of embedded retaining walls described in [1].

In the following paragraphs, some highlights from an idealised example involving a braced sheet pile wall covered in [1] is reported to illustrate the benefit of a sequential excavation and support process.

Figure 5 illustrates the idealised example involving a 3.5 m deep excavation in a clay characterised by an undrained shear strength c_u of 20 kPa. If the critical cross section "B" would be carried out and analysed as a 2D situation with an internal bracing system, the structural loads (considering partial factors) in the retaining system would be as in the right-hand illustration in Figure 5. Furthermore, the net earth pressure on the wall $(N_a+N_p)c_u$ - $(\sigma_{va}-\sigma_{vp})$ considering analytical limiting (Rankine) earth pressures is shown. The net pressure is calculated based on the earth pressure coefficients on the excavated and retained side of the sheet pile wall set to N_a=N_p=2.57 (i.e. according to Janbu [5] and assuming full roughness) and, in accordance with Swedish guidelines [6], considering a water-filled crack on the retained side of the wall. The latter governs the net earth pressure above a depth of 5.5 m where the water pressure is larger than the active earth pressure.

A sequential excavation process is considered in this example to avoid an internal bracing system (rather the waler beam and the soil transfers loads between the weak cross section "B" and the strong neighboring sections "A" and "C"). The example resembles the real case "Knutpunkt Gamlestaden" reported in [1]. The simplest consideration of the 3D-effect is to consider transfer of loads between the sections in the waler beam only. Transfer of loads will, however, also take place via mobilisation of soil strength. Hence, compared to a 2D situation the active earth pressure is reduced in section "B" while it increases in sections "A" and "C". On the contrary, the passive earth pressure is increased in section "B" while it decreases in sections "A" and "C" The distribution of the forces in the waler beam and the earth pressure against the sheet pile wall are sketched in Figure 6.

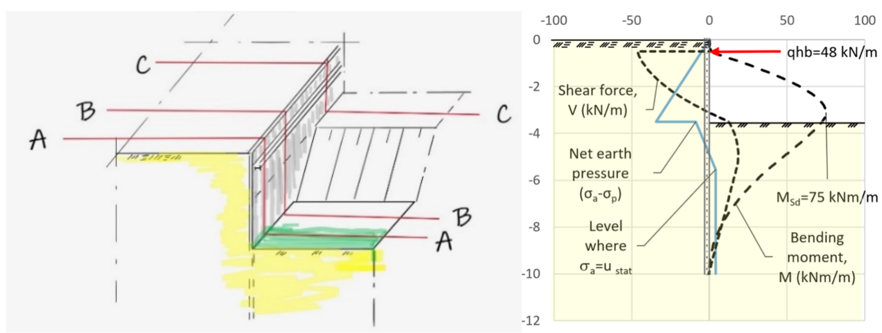

Figure 5. Left: Illustration of an idealised sequential excavation: "A" previously excavated and supported (by a concrete slab) section, "B" critical cross section, and "C" partially excavated section. Right: Structural design loads and earth pressure if analysing section "B" as a 2D situation.

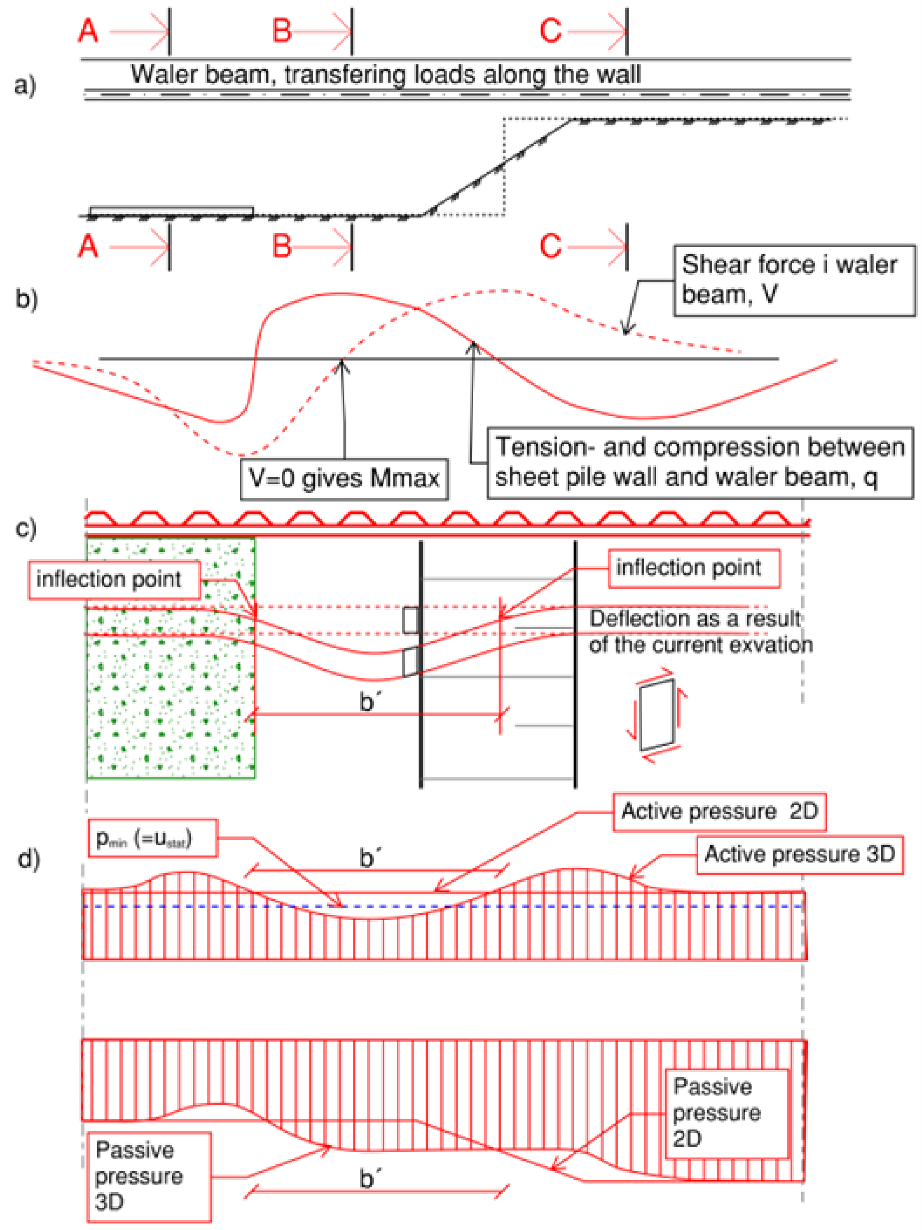

Figure 6. Sketches of the loads in waler beam and soil during sequential excavation. a) Geometrical front view corresponding to Figure 5, b) Sketch of load transfer via waler beam, c) Geometrical top view with sketch of soil deformation, d) Sketch of idealised (re)distribution of earth pressure against the retained (top) and excavated (bottom) side of the retaining wall.

Considering load transfer in the waler beam and the soil, the structural loads in the retaining system during excavation of section "B" is illustrated in Figure 7. A detailed description of the design is provided in [1]. One of the important aspects that are outlined in [1] is, e.g., that the integrated "arching effect" and load transfer in the soil in the interfaces between the weak section and the strong sections must not exceed the design soil shear strength.

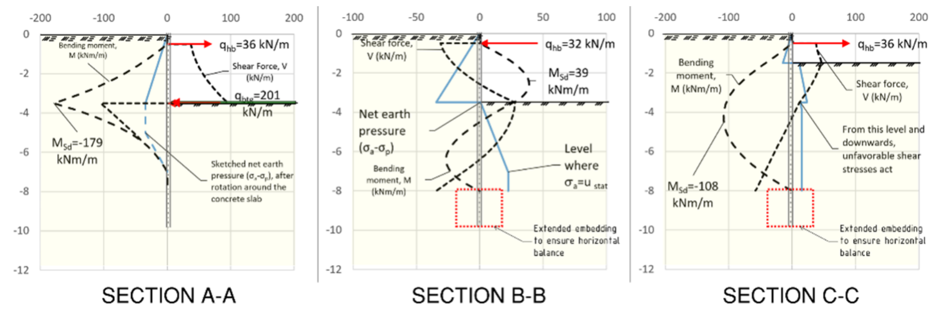

Figure 7. Structural design loads in retaining system for sections A", "B" and "C" considering sequential excavation (illustrating excavation in "B").

By sound design consideration of the effect of sequential excavation and support process, internal bracing can be avoided and still conventional sheet piles (due to the limited bending moment) can be used in this example. This is summarised in Table 1. It would, conversely, be possible to keep the internal bracing system but then consider 3D-effects in design to reduce the design load and/or length of the retaining wall.

Table 1. Summary of the structural design loads in the idealised example (wall length 10m).

Situation	Max bending moment [kNm/m]	Waler beam [kN/m] section forces	Concrete working platform max [kN/m]
2D	75	48	-
2D after bracing removed	70	-	120
3D considering waler beam only [a)]	244	-58/+48/-58	242
3D considering waler beam and soil [b)]	179	-36/+32/-36	201

The excavation length of the weak section is limited to [a)] 3.7m and [b)] 5.0m respectively. In this example this is governed by the structural capacity of the chosen waler beam.

4. CONCLUSIONS

Sequential excavation processes can in some situations be a means to create "3D-effects" and avoid the need for retaining structures, minimising the amount of steel or concrete in retaining structures, or reduce the deformations in the surroundings. However, when 3D-effects are accounted for in design the complexity increases as there is a need to analyse several neighboring cross-sections and in particular to consider their intricate interaction. Accordingly, the design must be based on sound conceptual models and considerations. This paper, which is a summary of [1, 3 and 4], provides guidance and best practice for industry when excavating in soft clays. The design should, as always, be well-documented and thoroughly checked by an independent reviewer with adequate theoretical knowledge and experience. Furthermore, the design and restrictions must be transferred to clear-cut drawings. Also, a close collaboration is needed with the personnel at site so that the work is executed as intended. Finally, monitoring excavation-induced displacements should be done in order to ensure that the stability of the excavation is satisfying.

ACKNOWLEDGEMENTS

The financial support provided by The Development Fund of the Swedish Construction Industry and Skanska Sverige AB is gratefully acknowledged. The authors would also like to thank their colleagues at Skanska Teknik for valuable discussions and comments.

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