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Design of Deep Supported Excavations: Comparison Between Numerical and Empirical Methods

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Abstract. This paper focuses on the derivation of design prop loads for supported excavations in stiff clay with increasing excavation depth and number of prop levels. For multi-propped walls there are a number of empirical graphs to obtain the design prop forces. CIRIA C517 (Twine & Roscoe, 1999) enhancing Terzaghi & Peck's work (Terzaghi & Peck (1967) and Peck (1969)) and making it more relevant in the UK practice, suggests the Distributed Prop Load (DPL) method based on 81 case histories and field measurements of prop loads. Similar guidance and empirical graphs exist in other countries such as the EAB Recommendations in Germany (Recommendations on Excavations: EAB, 3rd Edition, 2014). The design prop loads derived by empirical graphs (both CIRIA and EAB which are widely used in the UK and Germany respectively) and Finite Element methods are compared in the context of Eurocode 7 requirements. The German recommendations give prop loads in better agreement with the numerical analysis results. Suggestions are made to update the CIRIA guidance in line with the German recommendations and give different shapes of pressure distribution for supported walls with different number of prop levels. This can result in more realistic predictions of prop loads for upper layers, particularly in deep excavations, and hence more economic design.

Keywords. Eurocode 7, CIRIA C517, props, numerical analysis, design

1. Introduction

Nowadays, the increasing demand for underground infrastructure and basements in urban environments highlights the need for achieving more economic and safe design of retaining walls. The requirement of limiting ground movements and movements of adjacent structures and utilities (i.e. serviceability limit states) becomes an important factor; however, there is also the need to ensure that no failure of the support system occurs. Failures are rare but do occur (Twine & Roscoe, 1999).

This paper focuses on the derivation of design prop loads for supported excavations in stiff clay with increasing excavation depth and number of prop levels. While, the advantages and disadvantages of different calculation models for multi-propped walls are illustrated, the authors focus more on the results of finite element analysis and empirical methods. The design prop loads derived by empirical graphs (both CIRIA and EAB which are widely used in the UK and Germany respectively) and the finite Element method are compared in the context of Eurocode 7 requirements.

2. Calculation Models

Four different analysis methods have been routinely used for retaining walls and the design of the support system: Empirical, Limit-Equilibrium (LE), Finite Element and other Soil-Structure Interaction (SSI) methods.

Traditionally, empiricism has been used for embedded wall design and, in order to obtain the design prop forces for multi-propped walls, there are a number of empirical graphs (Terzaghi & Peck (1967), Peck (1969)), Twine & Roscoe, 1999) that can be used. The apparent pressure distributions given by Terzaghi & Peck (1967) and Peck (1969) are simple to use and have been widely adopted in practice. They are based on field measurements of prop loads and provide the designer with conservative lateral earth pressures distributions. CIRIA C517 (Twine & Roscoe, 1999) enhancing previous work and making it more relevant in the UK practice, suggests the Distributed Prop Load (DPL). Similar guidance and empirical graphs exist in other countries such as the German EAB guidance (Recommendations on Excavations: EAB, 3rd Edition, 2014).

Limit Equilibrium (LE) methods can be used for cantilever and single propped walls to obtain the embedment depth, the bending moments, shear, and axial forces. These are statically determinate problems and conventional analytical methods are sufficient to calculate the structural forces.

Soil-Structure Interaction methods (SSI) such as sub-grade reaction models (e.g. beam-spring) and pseudo-finite element methods are widely used for simple 2D geometries.

Nowadays, full numerical methods such as the finite element method (FEM) are increasingly employed for retaining wall design as the advances in available software and constitutive models allow for better simulation of the real field conditions. With FEM even complex geometries and supporting systems can me simulated in 2 and 3 dimensions with certain ease.

As this paper addresses the prop design challenges of supported walls with increasing number of prop levels, LE methods are not relevant. For multi propped walls, the stress redistribution might be important and FEM is preferred to other SSI methods. For these reasons, this paper focuses on comparing FEM with empirical methods in terms of design prop loads.

3. Finite Element vs Empirical Methods

In this section, the challenges and limitations of the two calculation models chosen for this study are discussed.

3.1. FEMs and ULS challenges

EC7 suggests three different Design Approaches (DAs) and each National Standard Body has chosen which approach is preferable. DA1, which is adopted in the UK, has two different combinations (sets of partial factors), namely DA1-1 and DA1-2. In general, we could say that DA1-1 and DA2 are Load Factoring Approaches (LFAs) as the factors are applied to actions or action effects while DA1-2 and DA3 are Material Factoring Approaches (MFAs) as the soil strength parameters have to be factored. All the calculations in this paper are performed according to the DA1 requirements.

In staged construction problems, for DA1-2 there are two different ways to factor soil strength within FEM, both strategies have arisen from the lack of guidance in the code (Katsigiannis et al, 2014). These are called: Strategy 1, where the material parameters are factored from the beginning so the analysis is performed with the design values of soil strength; on Strategy 2, calculations are performed with characteristic values and at critical stages the material parameters are reduced to their design values. A good description of the two strategies has been given by Simpson (2012). Katsigiannis et al. (2014) have also discussed the advantages and disadvantages of the two strategies which are summarized in Table 1. For DA1-1 when using FEMs to derive the design prop loads, a load factor of 1.35 is applied to the effect of actions (i.e. prop loads) at the end of the analysis. Moreover, a factor of 1.5/1.35=1.1 is applied to the variable unfavourable loads such as the surcharge at the beginning of the analysis.

Table 1. Advantages and disadvantages of the two material factoring strategies

	Strategy 1		Strategy 2
✓	It is straightforward and easy	✓	More critical in terms of design structural forces
✓	It can be applied in many situations, not only in staged construction problems	✓	It can be used in conjunction with SLS and DA1-1.
X	In some cases it might yield design structural forces with inadequate margins of safety	X	It requires many extra construction stages
		X	Additional computational effort and time

3.2. Empirical Methods for deriving prop loads

As mentioned in section 2, for retaining walls with many prop levels there are a number of empirical graphs to obtain the prop forces. These empirical methods (Terzaghi & Peck (1967), Peck (1969)) are easy to use and have been. widely adopted in practice. They are based on case studies and provide the designer with conservative lateral earth pressures distributions. Peck (1969) considered case studies in stiff clays, supported only by flexible walls, so he gave only tentative apparent pressure graphs, for excavations in stiff clays, supported by stiff walls He stated at an ASCE conference in 1990 that these graphs might not be conservative (Twine & Roscoe, 1999).

CIRIA C517 (Twine & Roscoe, 1999), enhancing Terzaghi & Peck's work (1967) and making it more relevant to the UK practice, suggests the Distributed Prop Load (DPL) method based on 81 case histories and field measurements of prop loads. Soils are classified in 4 classes named A for normally consolidated and slightly overconsolidated clays; B for heavily overconsolidated clays; C for granular soils and D for mixed soils. A distinction is also made between flexible (sheet pile) and stiff (diaphragm, bored pile) walls. DPL is not the real lateral stress distribution but gives values of prop forces unlikely to be exceeded for any temporary system in a similar excavation (Twine & Roscoe, 1999). CIRIA C517 gives characteristic values of prop loads in accordance with the Eurocode's definitions and adopts the limit state approach. This means in order to obtain the design values of prop loads a load factor of 1.35 should be applied to the values derived from the graphs. The DPL given for stiff walls supporting stiff clays is uniform with depth and equal to 0.5γH where γ is the average unit weight of the soil layers in kN/m^3 and H is the excavation depth in metres.

According to Twine & Roscoe (1999), there are also a number of conditions that the designer should check before using the empirical graphs (geometry, surcharge, sufficient toe embedment etc.). For example, the graphs take into account a surcharge of 10kPa applied at the ground surface. This allows for comparisons with the FEM analysis as presented in section 3 where a surcharge of 10kPa is also considered.

Other British documents, such as BS8002 (1994) recommends the use of Peck's diagrams (1969) for multi-propped walls without mentioning how they should be used for ULS and SLS calculations, while CIRIA C580 (Gaba et al., 2003) clearly encourages the use of C517's DPL method. C580 is included in the EC7 UK National Annex as Non Contradictory Complementary Information document (NCCI) and it encourages the use of soil-structure interaction methods (beam-spring, beam continuum, FEM etc.) for multi-propped wall design, mentioning that SSI method results should be checked with comparable experience and making reference to CIRIA C517 and the DPL method. This means that both documents are still in use together with EC7 and many designers still refer to the CIRIA DPLs for the design of supported walls.

Similar guidance and pressure graphs exist in many European countries. The German EAB guidance (Recommendations on Excavations: EAB, 3rd Edition, 2014) has been recently published and included in the EC7 German National Annex as an NCCI. The pressure distributions for different geometries of supported walls are given in Figure 1.

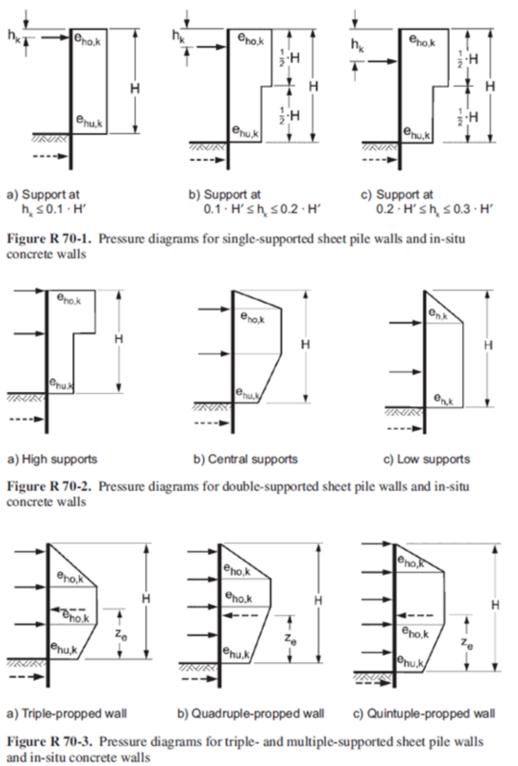

Figure 1. German EAB pressure diagrams (Recommendations on Excavations: EAB, 3rd Edition, 2014)

4. Comparing the design prop loads

4.1. Analysis Description

The computer software PLAXIS V12.01 was used for the analysis in its two-dimensional version. A simple elastic-perfectly plastic model, namely a Mohr Coulomb criterion with φ' = 0 was used while undrained conditions were assumed, essentially performing a total stress analysis employing a Tresca failure criterion. However, the water pressures are explicitly included in the model at the initial stage of the analysis allowing for the K_0 value to be defined in terms of effective stresses. In all the analyses, typical stiff highly OC clay total stress parameters were used which are listed in Table 2. Hollow steel props with external diameter of 406.4 mm and width 12.5mm were simulated in all cases with EA=3100000 kN/m. Five different geometries were analysed: (1) one prop wall with H equal to 8m and embedment depth of 4m; (2) 2 prop wall with an H equal to 12m and embedment depth of 4m; (3) 3 prop wall with an H equal to 16m and embedment depth of 4m; (4) 4 prop wall with an H equal to 20m and embedment depth of 4m; (5) 5 prop wall with an H equal to 24m and embedment depth of 7.5m (see Figure 2). The following modeling sequence was analysed (an overdig of 0.5m is considered):

- Stage 0 Initial State
- Stage 1 Install wall and apply 10kPa surcharge
- Stage 2 Excavate 4m of soil
- Stage 3 Install Strut 1 (-2m)
- Continue the process of excavation and installation of struts until the end of the excavation.

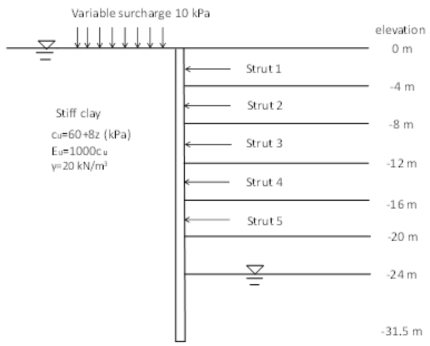

Figure 2. Geometry of the supported wall with 5 strut levels

Table 2. Mohr-Coulomb parameters

Total stress parameters	
γ_{sat} (kN/m^3)	20
c_u (kPa)	60+8z
E_u (kPa)	1000c_u
	ν (Poisson's ratio) = 0.495

4.2. Prop load comparison

In Figure 3, the maximum prop loads from different factoring methods for K_0=1.2 are presented for the 5 prop geometry. DA1-1 governs in terms of prop loads and DA1-2 Strategy 2 is more critical than Strategy 1. While only the results for the 5 prop geometry are presented here, ongoing research shows that the difference between the two DA1-2 Strategies become more apparent as the excavation depth increases.

Empirical and FEM calculations provide different prop force values for the geometry and material considered (see Figures 4-7). In Figures 4-7, the maximum prop loads are given from empirical and numerical methods with varying K_0 for the geometries with more than one strut level.

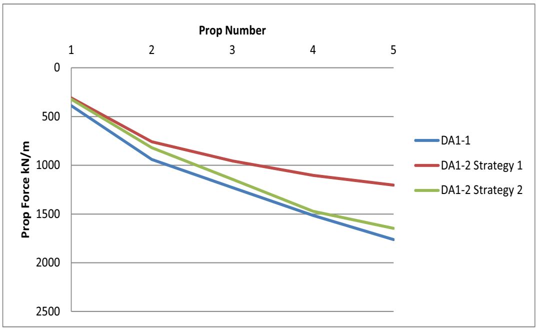

Figure 3. Maximum Prop Loads from different factoring strategies for supported excavation with 5 prop levels

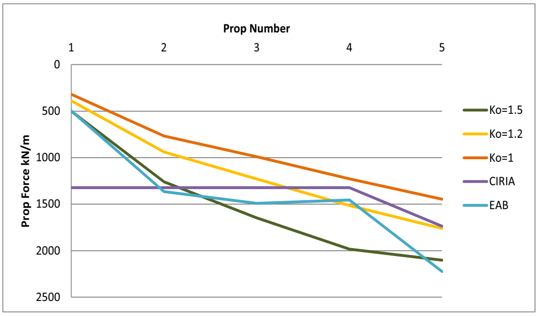

Figure 4. Maximum Prop Loads from empirical and numerical methods with varying K_0 for supported excavation with 5 prop levels

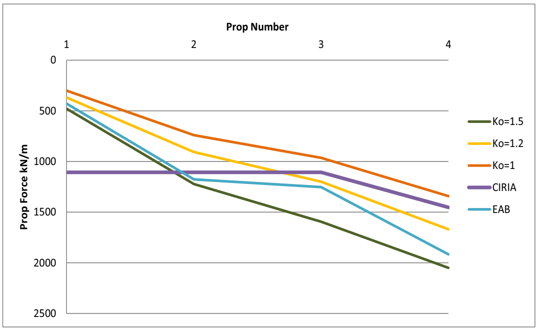

Figure 5. Maximum Prop Loads from empirical and numerical methods with varying K_0 for supported excavation with 4 prop levels

CIRIA C517 and FEMs provide different design prop loads for the geometries and materials considered with the differences becoming particularly apparent for the upper prop levels. On the other hand, the German EAB guidance gives prop force values closer to the FEM results. This raises the question whether CIRIA's uniform lateral pressure distribution is realistic or a different approach in line with the German suggestions could have advantages and result in more economic design.

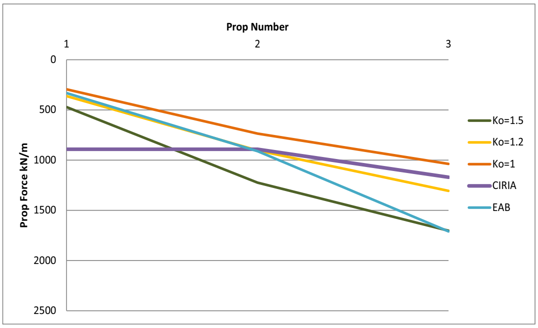

Figure 6. Maximum Prop Loads from empirical and numerical methods with varying K_0 for supported excavation with 3 prop levels

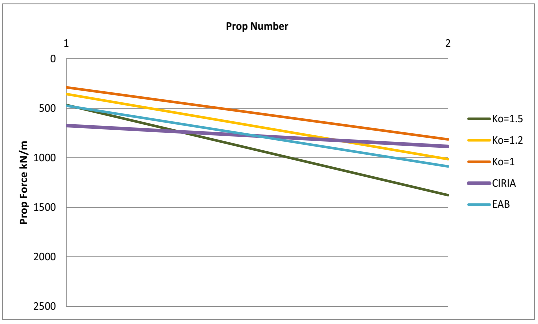

Figure 7. Maximum Prop Loads from empirical and numerical methods with varying K_0 for supported excavation with 2 prop levels

5. Discussion

The prop loads derived from CIRIA C517 and FEM are different for the case considered in this study. The discrepancy is particularly apparent for the upper prop levels where CIRIA's assumption of a uniform distribution of the earth pressure with depth results in significantly higher design prop loads. FEM results in lower values of strut forces at the top of the wall, increasing with excavation depth for geometries with two or more props considered here. This raises the question of how good is the C517 assessment that the force in the upper struts will be equal to that in lower struts for multi propped geometries. On the other hand, FE methods and the German EAB guidance give prop force values that are in better agreement.

As previously discussed CIRIA C517 does not give the real lateral stress distribution but values of prop forces unlikely to be exceeded for any temporary system in a similar excavation. For excavations in stiff clays (B soils) supported by stiff walls and props the CIRIA assessment is based on 10 case studies most of them in London clay. Five of the ten case studies are supported by only one level of props, one case study by two levels of props and the last four by three prop levels. Singly propped geometries give as expected uniform pressure distributions (e.g. CIRIA case studies BS1, BS3, BS5 etc.). As the number of prop levels increases, the pressure distribution becomes non-uniform, increasing with depth. However, when the pressure distributions from all the case studies are plotted in a single graph, the resulting characteristic (i.e. cautious estimate) DPL is uniform with depth and equal to $0.5\gamma H$. This uniform diagram might be sufficient for a single or even a double layer of props to support excavations, but can be too conservative for walls supported by more prop levels.

On the other hand, the German EAB guidance give different shapes of pressure distribution for supported walls with different numbers of prop levels. The distribution is uniform (rectangular) for single propped walls and becomes trapezoidal as the number of prop levels increases. Note that the guidance gives the shapes of the redistributed pressure diagrams but not the dimensions. The dimensions are problem dependent (based on lateral earth coefficient values) as the area of the trapezoid should be equivalent to the area of the classical triangular earth pressure distribution. This assessment seems more reasonable and results in design prop loads in better agreement with FEM results for the example considered here. In this study, the area of the EAB trapezoid was taken to be equal with the area of the CIRIA rectangular to allow for comparison.

Single supported excavations are statically determinate problems and conventional analytical methods are sufficient to calculate the structural forces. However, for multi-supported excavations, where the analytical methods are not relevant, empirical pressure distributions based on field measurements and good practice can be of great value. It might be worth adopting the German approach and considering separately the CIRIA C517 case studies. This would result in different characteristic DPLs for different numbers of prop levels and more realistic predictions of the upper prop load values, particularly in deep excavations. It might be also worth including more case studies (with large excavation depths and many prop levels). Conventionally, one or two levels of props used to be sufficient for supported excavations in the greater London area. However, in the last few years, in many projects (including the Crossrail station boxes), excavations are much deeper and more prop levels are needed to satisfy SLS and ULS requirements. CIRIA guidance should be in line with current practice in deep excavations.

6. Conclusions

While a broader study is needed, some useful conclusions can be drawn from the work done in this article:

- In most cases under consideration for the stiff clay, DA1-1 gives the highest values of prop forces. The soil strength seems not to be critical for design. The difference between DA1-2 strategies 1 and 2 of material factoring becomes more apparent as the excavation depth (and hence the number of excavation stages and props) increase with DA1-2 Strategy 2, giving higher values of prop loads in all simulations.
- CIRIA C517 and FEM calculations provide different prop force values for the geometries and materials considered. The difference is more significant for the upper prop levels. FEM results in lower values of strut forces at the top of the wall, increasing with excavation depth. Note that there is not much difference in the total force supporting the wall in the two cases. The difference is in the pressure distribution.
- The German EAB guidance gives prop force values closer to the FEM results. The authors suggest that CIRIA should adopt the German guidelines and provide different

DPLs for different number of prop levels. This could result in more realistic predictions of the upper prop load values, particularly in deep excavations.

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