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A study of wall and ground movements due to deep excavations in soft soil based on worldwide experiences

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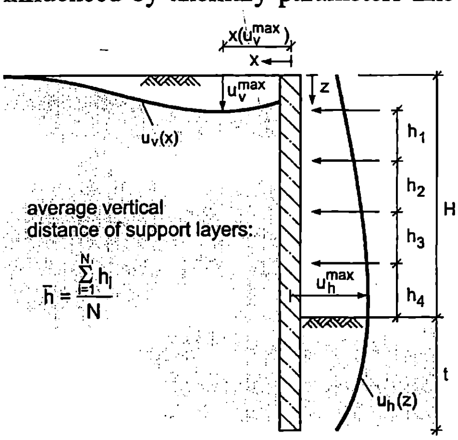
ABSTRACT: An extensive database of more than 530 actual international case histories of deep excavations mainly in soft ground is the basis of this study. The measured retaining wall and ground movements of all excavations were analyzed taking into account the soil and groundwater conditions, the geometric configuration as well as the support system and the excavation method used in each case. The database is used to analyze empirically the behaviour of retaining wall systems and to examine the main parameters influencing the performance of deep excavations. Special focus is set to identify relationships between wall and ground movements and the kind of retaining system and excavation method used. The results are compared with previous empirical studies.

1 INTRODUCTION

The behaviour of deep excavations depends on a great number of geotechnical and geometrical boundary conditions and influence factors that partly eclipse each other. A methodical approach to identify the main factors decisively influencing the deformation behaviour of deep excavations is the empirical analysis of the movements observed by measurements at a great number of case histories. Peck's (1969) well-known state-of-the-art-report has been an initial for several other similar empirical studies. As each case is influenced by ancillary parameters like workmanship



H [m] : max. depth of excavation (final stage)
t [m] : static relevant embedded length
h_i [m] : vertical spacing of support (struts, anchor)
u_h^{max} [m] : maximum horizontal wall displacement
u_v^{max} [m] : maximum vertical displacement at ground surface
N [-] : number of support layers

Figure 1. Definition of symbols used in analysis.

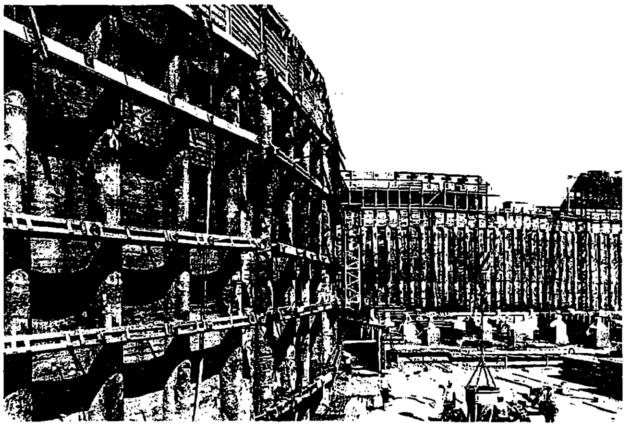


Figure 2. Example of a 14 m deep building pit in urban area excavated in soft soil.

or time effects, a large number of case histories are required to gain reliable results and general trends by this approach. Taking previous studies into account, a new extensive database of more than 530 actual case studies taken from worldwide experiences of deep excavations mainly in soft and stiff ground is collected and analyzed empirically. The study presented here concentrates on excavations in soft soil characterized by the undrained shear strength $c_u \leq 75$ kN/m² (example in Fig. 2). The notation of the symbols used is defined in Figure 1. The database is used to analyze actual trends in retaining wall performance and to examine the main parameters influencing wall and ground movements. Special focus is set to identify state-of-the-art-relationships between wall and ground movements and the retaining system and excavation method used.

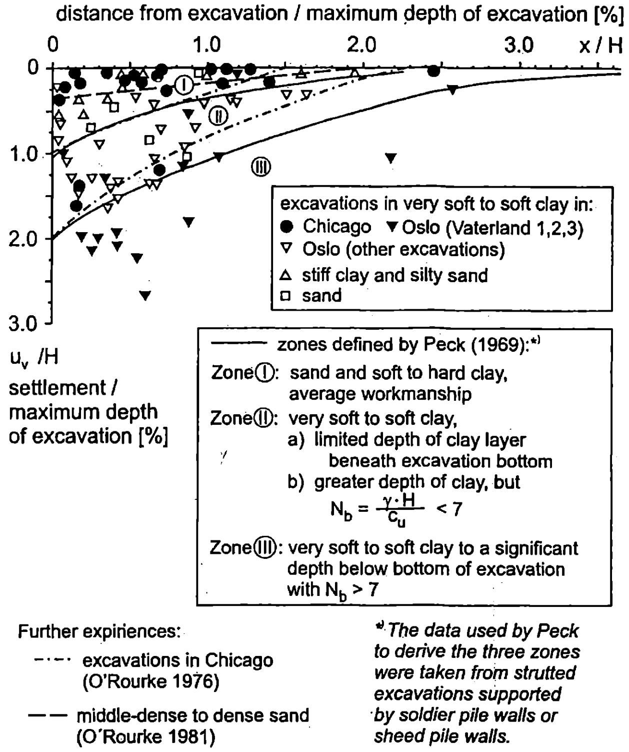


Figure 3. Summary of measured settlements adjacent to deep strutted excavations (according to Peck 1969, supplemented).

2 PREVIOUS EMPIRICAL STUDIES

Peck (1969) developed plots of ground settlements u_v normalized by the excavation depth H against distance from the excavation (Fig. 3). The ground conditions are identified as the main influence factor by defining three zones. The settlements varied between u_v / H < 1.0% for zone I and > 2.0% for zone III. The approach often used in practice was confirmed by Lambe et al. (1970) and O'Rourke (1976, 1981) analysing additional case histories.

Goldberg et al. (1976) analysed 63 case histories in different soils demonstrating the influence of ground conditions, but also of the kind of the wall and supporting system on the movements measured. The study shows that the maximum settlements u_v^{max} behind excavations are 0.5 to 1.5 times the maximum horizontal wall displacements u_h^{max}, in soft clay the factor u_v^{max} / u_h^{max} may also be greater than 2.0 (Fig. 4).

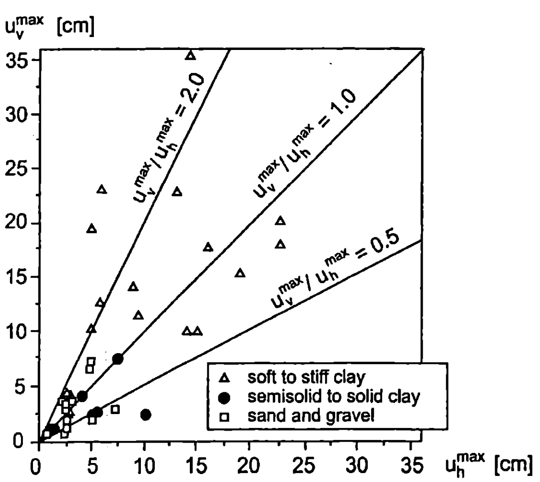


Figure 4. Comparison of max. vertical settlements u_v^{max} behind a retaining wall with max. horizontal displacement of the wall u_h^{max} (Goldberg et al. 1976).

Goldberg's database was expanded by Clough & O'Rourke (1990), who divided the case histories in two categories. For stiff clays, residual soils and sand (category I) the maximum horizontal wall displacements u_h^{max} was found to be quite independent from the wall type with 0.2%H in average, whereas the maximum settlements u_v^{max} are 0.15%H in average (Fig. 5). For soft to medium clay (category II) Clough et al. (1989) produce a plot (Fig.13) showing the maximum horizontal wall displacements u_h^{max}/H in dependency of the factor of safety against basal heave FOS_{base} and of the system stiffness K_1 of retaining wall and support defined as:

$$K_1 = EI/(\gamma_w \bar{h}^4) \quad (1)$$

whereas EI is the bending stiffness of the retaining wall, γ_w is the unit weight of water and $\bar{h}$ is the average support spacing as defined in Figure 1. Figure 13 shows that the horizontal wall movements increase rapidly as the risk of base heave increases and safety factor FOS_{base} reaches unity. The influence of the system stiffness on the wall movements becomes less relevant with increasing value of FOS_{base}.

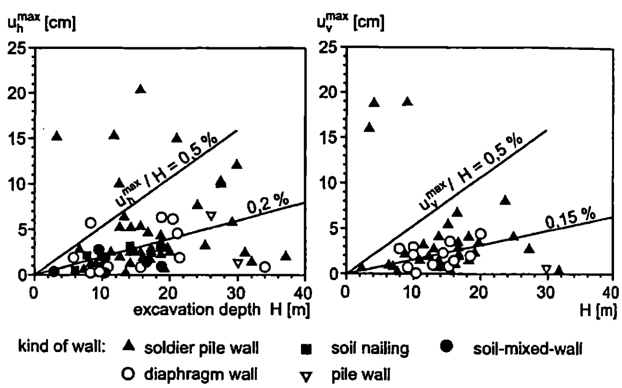


Figure 5. Influence of depth of excavation H on the max. horizontal wall displacement u_h^{max} and on the max. vertical displacements u_v^{max} of the ground surface behind the wall of excavations in stiff clay and sand (Clough & O'Rourke 1990).

Besides several national reports and studies for specific soil conditions (e.g. Burland et al. 1979, Karlsrud 1986, Wong et al. 1997), Duncan & Bentler (1998, 117 additional case histories) and Long (2001, 296 case histories) present actual and comprehensive empirical studies. Long's study proofs for stiff soil with u_h^{max}/H = 0.05-0.25% and u_v^{max}/H = 0-0.20% largely the results of Clough & O'Rourke (1990). For soft clay where there is a low factor of safety FOS_{base} large movements up to u_h^{max}/H = 3.2% occur, but follow broadly the trends in Clough's chart (Fig. 13).

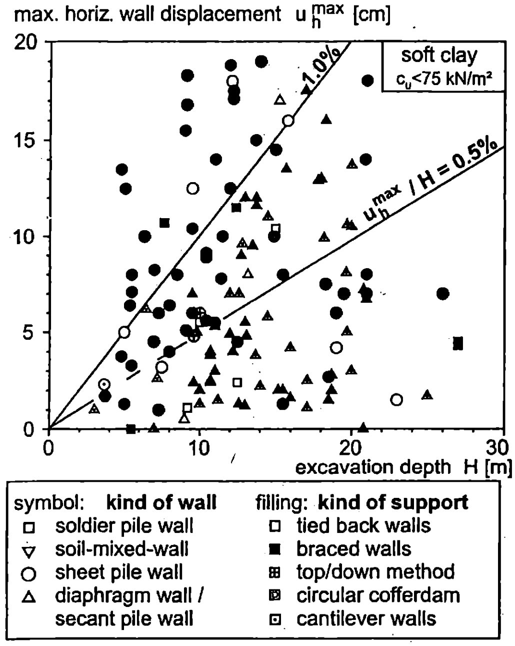


Figure 6. Deep excavations in soft ground: max. horizontal wall displacement u_h^{max} vs. excavation depth H depending on retaining wall and support system used.

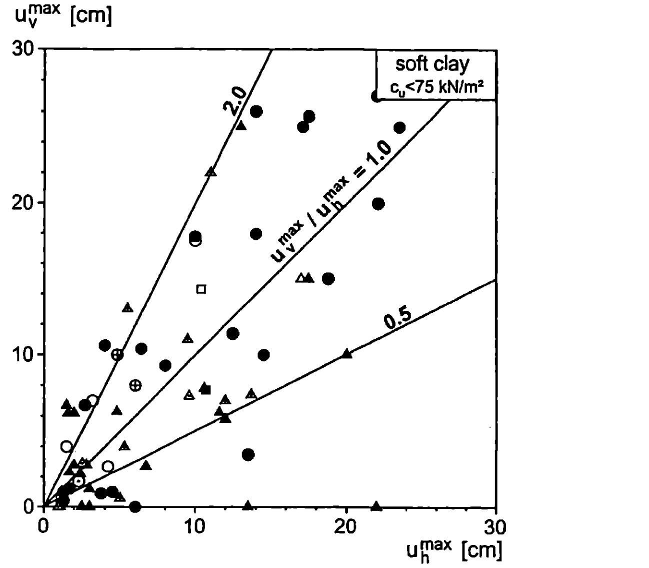


Figure 8. Deep excavations in soft ground: max. vertical displacement u_v^{max} of the ground surface behind the wall depending on the max. horizontal wall displacement u_h^{max} (legend in Fig. 6).

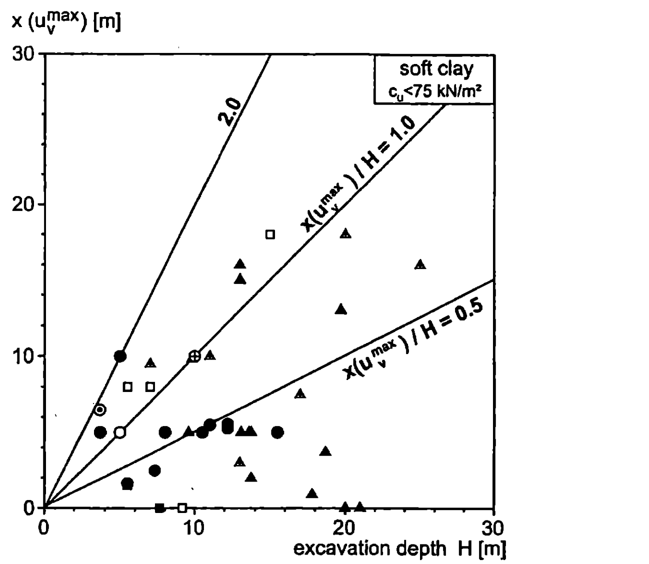


Figure 9. Deep excavations in soft ground: Horizontal distance x of the point of max. vertical displacement u_v^{max} of the ground surface from the retaining wall depending on the depth of excavation H (legend in Fig. 6).

3 NEW DATABASE

3.1 Data collection and subdivision

For the new database 536 international case histories were collected whereby some 300 case histories are of the decade 1991-2001. So the database may be one of the most comprehensive and actual studies so far. Besides own data the information were mainly extracted from all relevant geotechnical journals and conference proceedings. The measured retaining wall and ground movements of each case was analyzed taking into account the soil and groundwater conditions, the geometric configuration as well as the retaining wall and support system and the excavation method used. Very detailed tables with all specifications and full references are given by Moormann (2001) and are also easily available e.g. for further research activities (Moormann 2002). The case histories were subdivided depending on ground conditions. In the following the analysis of data will concentrate only on excavations in soft clay (153 case histories).

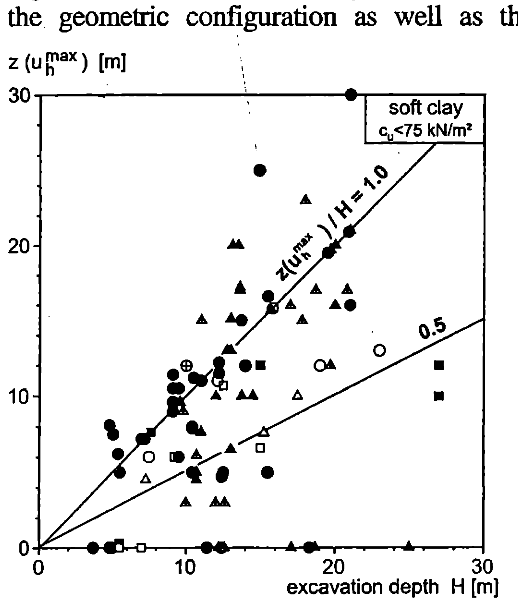


Figure 7. Deep excavations in soft ground: vertical distance z of the point of max. horizontal wall displacement u_h^{max} below ground surface depending on the depth of the excavation H (legend in Fig. 6).

3.2 Analysis and interpretation of data for soft soil

To examine the main parameters influencing the performance of excavations in Figure 6 the max. horizontal wall displacement u_h^{max} is plotted versus the excavation depth H. The kind of wall and support is,

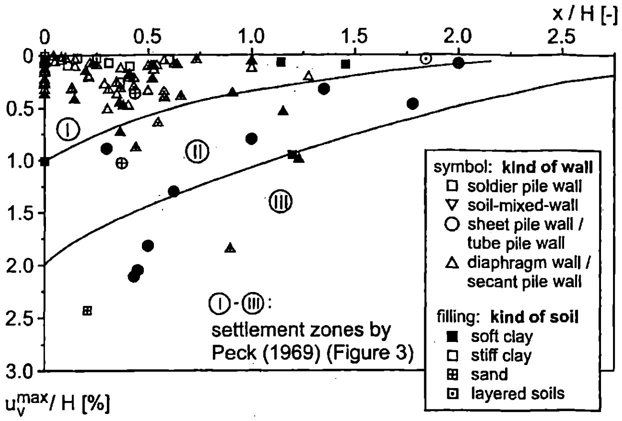


Figure 10. Settlements of the ground surface depending on the type of soil (new database) in comparison with the settlement zones by Peck (1969, Fig. 3).

as in all other diagrams, identifiable for each case history by the symbol used (legend in Fig. 6). In soft clay the values $u_h^{max}(H)$ scatter in a wide range indicating the dependency on further factors. For 40% of the excavations it is $0.5\% \leq u_h^{max}/H \leq 1\%$ whereas for 27% of the case histories the wall displacements are even greater (in average $u_h^{max}/H = 0.87\%$. The greatest displacements were measured for sheet pile walls. The chosen support system is without a clear influence.

The max. horizontal wall displacement u_h^{max} is usually observed at the depth of the final excavation bottom ($z = 1.0H$) or, as by 67% of the case histories, in a depth z of $0.5H$ to $1.0H$ below ground surface (Fig. 7). For 21% of the case histories u_h^{max} was measured at wall head.

Figure 8 shows a comparison of the max. vertical settlements u_v^{max} behind a retaining wall with the max. horizontal wall displacements u_h^{max}. In agreement to results of Goldberg et al. (1976, Fig. 4) the quotient u_v^{max}/u_h^{max} varies mainly between 0.5 to 1.0, max. 2.0. The postulate of Peck (1969) of a volume-constant movement ($u_v^{max}/u_h^{max} = 1.0$) is not confirmed. For deep excavations in soft clay the max. settlement at ground surface is found to be in dependency of the excavation depth $u_v^{max}/H = 0.1$-10%, in average 1.1%.

For 70% of all case histories the maximum settlement u_v^{max} is measured in a horizontal distance x from the retaining wall that is smaller than half the excavation depth ($x \leq 0.5H$, Fig. 9), but in soft clay the distance can also increase to $x \leq 2.0H$ indicating the potential danger of a far reaching impact on adjacent urban buildings.

The settlement profiles and the subdivision in three zones as introduced by Peck (1969, Fig. 3) can broadly be confirmed also by this new database with actual case studies (Fig. 10). Especially for deep excavations in soft clay retained with sheet pile walls settlements were reported which lie within the zones II and III. For deep excavations in stiff clay the new database shows settlements which are clearly smaller than $u_v^{max}/H = 0.5$.

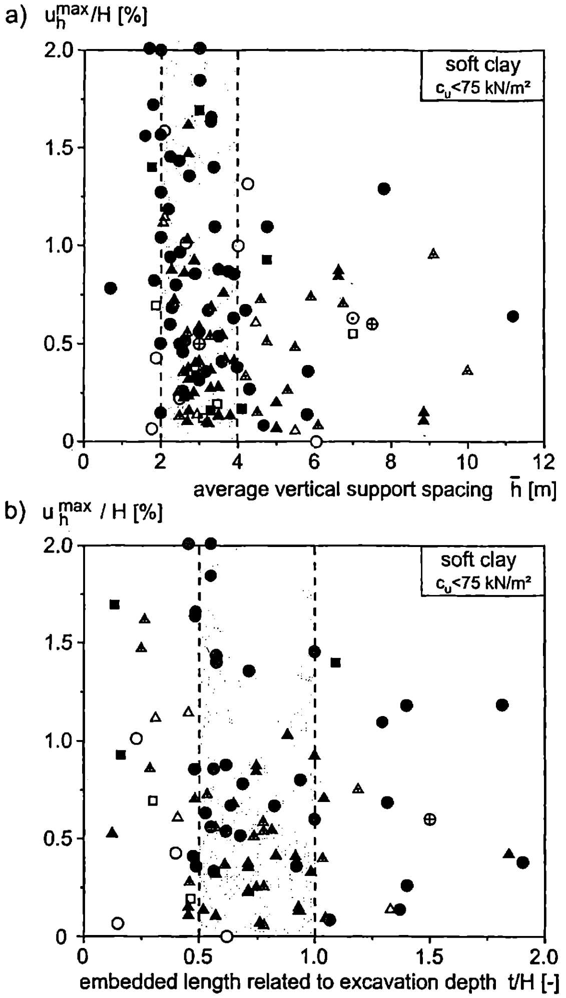


Figure 11. Deep excavations in soft ground: a. Influence of the average vertical support spacing $\bar{h}$ on the related max. horizontal wall displacement u_h^{max}/H. b. Influence of embedded length t related to the depth of excavation H (legend in Fig. 6).

3.3 *Influence of the stiffness of the retaining system*

In many previous studies the stiffness of the retaining system was identified as an important influence factor for the performance of deep excavations.

As a first approach in Figure 11 the influence of the average vertical support spacing $\bar{h}$ and of the embedded length t related to the excavation depth H on the max. horizontal wall displacement u_h^{max} is investigated. In soft clay the average vertical support spacing $\bar{h}$ varies mainly between 2 m and 4 m, in average of the 153 case histories $\bar{h}$ is 3.65 m. The diagram in Figure 11a shows no influence of the average vertical support $\bar{h}$ on the horizontal wall displacements.

As well there seems to be no dependency of the wall displacements on the magnitude of the embedded length t of the wall (Fig. 11b). The embedded length t of retaining walls in soft clay varies between $0.1H$ and $2.0H$, in average t is $0.92H$.

There exist different approaches to summarize the stiffness of a retaining system (retaining wall, supporting system) within a single parameter. Based on

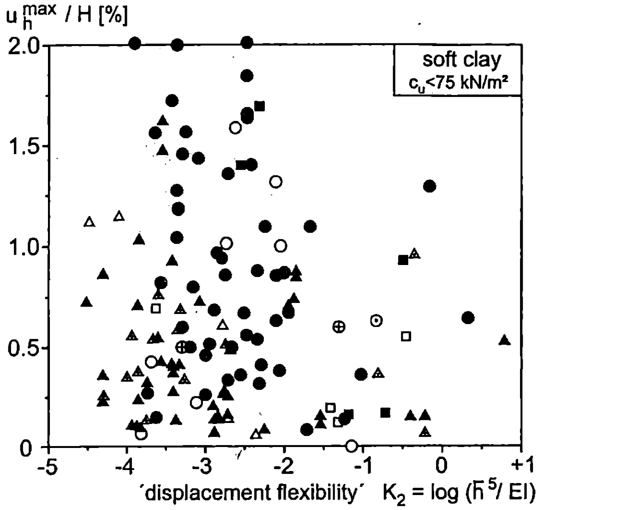


Figure 12. Related max. horizontal wall displacement u_h^{max}/H depending on the flexibility number K_2 by Addenbrooke (1994) (legend in Fig. 6, K_2 as defined by Eq. 2).

a dimensional analysis Addenbrooke (1994) defined a 'displacement flexibility' number as:

$$K_2 = log\left(\bar{h}^5 / EI\right) \qquad (2)$$

Addenbrooke postulated that for excavations with same K_2-value nearly the same movements should be expected. But the analysis in Figure 12 shows that there is a wide scatter in the measured displacements at each flexibility number.

In Figure 13 the max. horizontal wall displacement u_h^{max} related to the excavation depth H is plotted versus the system stiffness K_1 as defined by Clough et al. (1989, Eq. 1). Again the data scatter in a wide range without a clear dependency of the wall displacements on the system stiffness. This result, that the wall movements are mainly independent from the stiffness of the retaining wall and the supporting

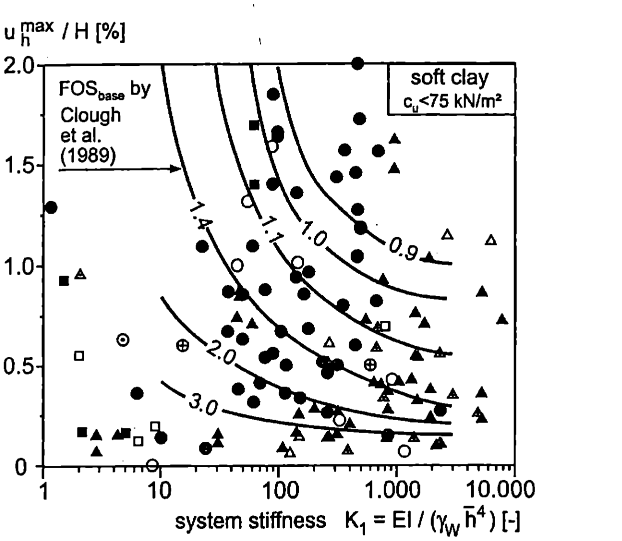


Figure 13 Deep excavations in soft ground: max. horizontal wall displacement vs. system stiffness defined by Clough et al. (1989) (legend in Fig. 6).

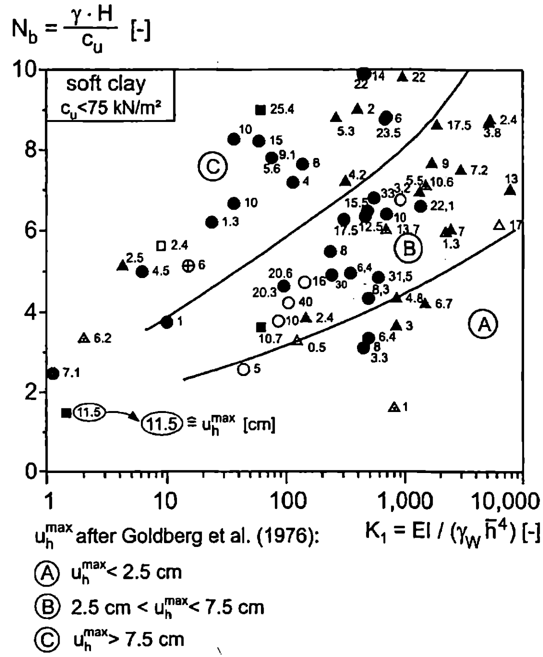


Figure 14. Influence of the system stiffness and stability number on wall displacements in soft clay by Goldberg et al. (1976) in comparison with the results of the new database (legend in Fig. 6).

system, could also be shown for other ground conditions (Moormann 2001). Similar results were actually also gained by Long (2001). The result is of great practical and economical relevance for the design of deep excavations. Firstly it proofs that there are further relevant factors that influence the performance of deep excavations beside the retaining system and the ground condition. In addition it suggests that there is no direct or at least no linear correlation between the system stiffness and the movements: An additional increase of system stiffness does not effect an appropriate additional decrease of movements. This result of the empirical study is in some way contrary to the approach often used in practice to limit movements due to excavations by very stiff retaining systems .

In this context a numerical study of deep excavations in London Clay by Potts & Day (1991) is interesting, who showed that the maximum bending moment of a retaining wall could be reduced by 80% by using a sheet pile wall instead of a diaphragm wall resulting in only a slight increase of movements. Similar results of analytical and numerical investigations are also presented by Wong & Broms (1989).

For strutted excavations in soft ground the dependency of the related horizontal wall displacement u_h^{max}/H on the safety factor against basal heave FOS_{base} were also investigated by Mana & Clough (1981). The limits indicated by them can broadly be confirmed by the new database (Fig. 15).

The approach by Goldberg et al. (1976) to predict the horizontal wall displacements in dependency of the system stiffness K_1 and the stability number N_b (Fig. 14) seems to be not a reliable method as the scattering results of the new database indicate.

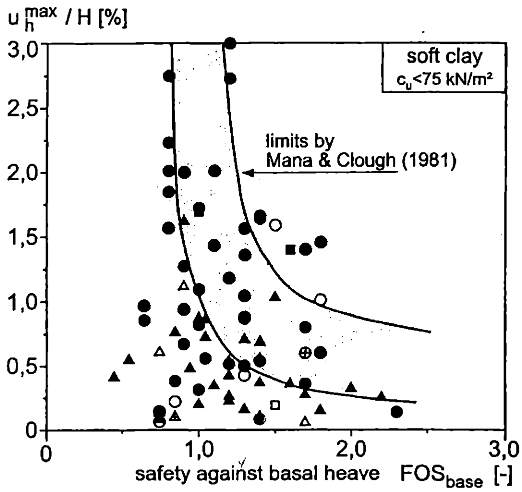


Figure 15. Deep excavations in soft clay: u_h^{max}/H depending on the safety factor FOS_{base} against basal heave in deep excavations – comparison of the approach by Mana & Clough (1981) with the results of the new database (legend in Fig. 6).

4 CONCLUSIONS

An extensive database of more than 530 mainly very actual worldwide case histories is the basis for the empirical study of retaining wall and ground movements due to deep excavations presented in this paper. The database was used to examine the main parameters influencing the performance of deep excavations in soft soil ($c_u \leq 75$ kN/m²). The main results are:

- The max. horizontal wall displacements u_h^{max} are frequently between 0.5%H and 1.0%H, in average equal to 0.87%H. The max. horizontal displacement u_h^{max} is usually measured in a depth of $z = 0.5H$ to $1.0H$ below ground surface.
- The max. vertical settlements at the ground surface behind a retaining wall u_v^{max} are frequently between 0.1%H and 10%H, in average equal o 1.1%H. The settlement u_v^{max} appears usually in a distance x of ≤0.5H behind the retaining wall, but there are cases with x up to 2.0H. The quotient u_v^{max}/u_h^{max} varies mainly but without clear trends between 0.5 and 1.0.
- As relevant influence parameters the ground conditions and the excavation depth H are identified.
- There is no empirically provable influence of the kind of support system (anchored, propped or top/down method) on the performance of deep excavations also top/down systems tend to show the smallest movements.
- The retaining wall and ground movements seem to be widely independent of the system stiffness of the retaining system. This lack of dependency indicates that, once sufficient stiffness is available, movements are determined by other relevant factors, but an additional increase of system stiffness does not effects an appropriate additional decrease of movements.

This result, that should be further investigated and verified by additional empirical and numerical or analytical studies, indicates a potential for a redesign of retaining systems and more economic solutions with retaining systems of reasonable stiffness.

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