ANALYSIS OF WALL AND GROUND MOVEMENTS DUE TO DEEP EXCAVATIONS IN SOFT SOIL BASED ON A NEW WORLDWIDE DATABASE

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ABSTRACT

This study is based on an extensive database of more than 530 current international case histories on deep excavations mostly in soft soils. The measured retaining wall and ground movements of all excavations were analysed, taking into account the subsurface and groundwater conditions, the geometric boundary conditions as well as the support system and the excavation method used in each case. By means of the database an empirical analysis of the behaviour of excavation support systems is performed and the main factors affecting the behaviour of deep excavations are examined. Special focus is set on identification of relationships between wall and ground movements, the support system employed and the excavation method used. The results are compared with previous empirical studies.

Key words: database, deep excavation, empirical study, ground movements, retaining walls (IGC: H2)

INTRODUCTION

The performance of deep excavations depends on a large number of geotechnical and geometrical boundary conditions and influential factors that are interdependent to different degrees. A proven approach to identify the significant parameters affecting the deformation behaviour of deep excavations is the empirical analysis of the measured displacements in a large number of case histories. Peck's (1969) well-known state-of-the-art-report has initiated a number of similar empirical studies. As each case is also influenced by subordinate parameters such as workmanship or time effects, a large number of case histories is required to obtain reliable results and general trends by this approach. Taking previous studies into account, a new extensive database of more than 530 recent case histories taken from worldwide experience of deep excavations mainly in soft and stiff cohesive, but also in non-cohesive ground was collected and analysed empirically. The study presented here concentrates on excavations in soft soils characterised by undrained shear strengths $c_u \leq 75$ to $100$ kN/m$^2$ (example, Photo 1). The notation of the symbols used is defined in Fig. 1. The database was used to analyse current trends in retaining wall performance and to examine the main parameters influencing wall and ground displacements. Special focus is set on the identification of relationships applied in practice between measured wall and ground movements and the support system and excavation method used. It is pointed out that the approach to evaluate the performance of deep excavations on the basis of empirical studies does also have some weaknesses. First of all, the task is multi-dimensional owing to the great number of factors influencing the behaviour of any excavation project. So it is unlikely that linear dependencies between single influence factors and measured deformations are encountered. Furthermore, each excavation is influenced by parameters and incidents such as workmanship or deviations from design, factors generally not mentioned in the reports evaluated in the empirical study; all the more as they are impossible to quantify, such parameters may well be relevant to the measured deformations. These aspects have been considered in a sense that as many case histories as possible are included in the database, further that geometrical and geotechnical boundary
conditions for each case history are documented in great detail, including all indications and notes about damages or specific experiences gained during construction (Moormann, 2002, 2003).

PREVIOUS EMPIRICAL STUDIES

For strutted and tied-back soldier pile walls and sheet pile walls Peck (1969) developed plots of ground settlements $u_s$ normalized by the excavation depth $H$ against distance from the excavation (Fig. 2). The ground conditions were identified as the main influence factor by defining three zones. The settlements varied between $u_s/H < 1.0\%$ for zone I (sand and soft to hard clay) and $> 2.0\%$ for zone III (very soft to soft clay down to significant depth). In soft to very soft soils the lateral extent of settlements at the ground surface can reach approx. four times the excavation depth $H$, whereas in sand and clay the extent of settlements is limited to $2 \cdot H$. As criterion for the classification of soft soils the stability number $N_s$ was introduced. The approach often used in practice was confirmed by Lambe (1970), Lambe et al. (1970) and O'Rourke (1976, 1981) in their analysis of additional case histories. Goldberg et al. (1976) analysed 63 case histories in different types of soil, demonstrating the influence of ground conditions, but also of the wall type and supporting system on the measured movements. The analysis indicates that in sands and gravels as well as in stiff clays the maximum horizontal wall displacements amount to $u_{\text{max}}^W/H \leq 0.35\%$ and the maximum settlements to $u_{\text{max}}^S/H \leq 0.5\%$, half as much as indicated by Peck (1969) for his zone I. The study shows that the maximum settlements $u_{\text{max}}^S$ behind excavations are 0.5 to 1.5 times the maximum horizontal wall displacements $u_{\text{max}}^W$, in soft clays the factor $u_{\text{max}}^S/u_{\text{max}}^W$ may also lie above 2.0 (Fig. 3(a)). The visualization of settlement profiles of the ground surface behind different excavations shows that the greatest settlements occur within a horizontal distance corresponding to the excavation depth $H$ (Fig. 3(b)). In clays, the settlements can extend laterally to distances of more than $2 \cdot H$.

Based on case histories in Chicago O'Rourke (1981) analysed the wall and ground movements of strutted excavations in medium dense to dense sands and soft clays and evaluated an empirical relationship between the settlements at the ground surface and the horizontal wall displacements. In order to reduce the horizontal wall displacements O'Rourke recommended that excavation works be limited to $h \leq 5\ m$ below the lowest strut, O'Rourke discussed the time-dependent movements of excavations in cohesive soils and, in accordance with Burland et al. (1979), called for the installation of struts as soon as possible after excavation.

Clough et al. (1979) analysed mainly deep excavation in soft clays in Oslo, Chicago, Boston and San Francisco. Their analysis shows that horizontal wall movements depend significantly on the factor of safety against base heave $FOS_{\text{base}}$, as introduced and defined by Terzaghi (1943) and Bjerrum and Eide (1956) (refer to the definitions in Fig. 4). For $FOS_{\text{base}} < 1.5$, the wall movements increase distinctively.

The database of Goldberg et al. (1976) was expanded by Clough and 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 $u_h^{\text{max}}$ were found to be largely independent of the wall type with on average 0.2% $H$, while the maximum settlements $u_s^{\text{max}}$ were on average about 0.15% $H$ (Fig. 5), even smaller than mentioned by Goldberg et al. For soft to medium clays (category II) Clough et al. (1989) produced a plot (Fig. 4) showing the maximum horizontal wall displacements $u_h^{\text{max}}/H$ dependent on the factor of safety against basal heave $FOS_{\text{bas}}$ and the system stiffness $K_1$ of retaining wall and support defined as:

$$K_1 = EI/(\gamma_a \bar{h})$$  \hspace{1cm} (1)

where $EI$ is the flexural rigidity per unit width of the retaining wall, $\gamma_a$ the unit weight of water and $\bar{h}$ the average support spacing as defined in Fig. 1. Figure 4 shows that the horizontal wall movements increase rapidly as the risk of failure due to base heave increases and the safety factor $FOS_{\text{bas}}$ reaches unity. The influence of the system stiffness, i.e. the influence of the stiffness of the retaining wall and support system on the wall movements becomes less relevant with increasing value of $FOS_{\text{bas}}$ but is of major importance in cohesive soils with $FOS_{\text{bas}} < 1.5$. Figure 4, based on preliminary studies of Mana and Clough (1981), shows that with a safety factor of $FOS_{\text{bas}} = 1.4$ for sheet pile walls in soft clays the horizontal wall movements lie at $u_h^{\text{max}}/H \leq 2\%$ whereas for diaphragm walls the horizontal wall movements reduce to $u_h^{\text{max}}/H \leq 0.5\%$. Besides several national reports (e.g. Ou et al. (1993) for Taiwan, Carder (1995) as well as Fernie and Sucking (1996) for Great Britain, Masuda (1996) for Japan and Yoo (2001) for Korea), a number of studies pertaining to specific soil conditions exist (e.g. Burland et al. (1979) for London Clay, Karlsrud (1986 and 1997) for Soft Oslo Clay, Wong and Paton (1993) for Taipei Basin, et al. (1997) for Singapore Marine Clay). Based on the empirical study by Goldberg et al. (1976), but updated by 117 additional case histories for the period of 1976-1989, Duncan and Bentler (1998) presented an analysis of the evolution of deep excavation technology. Long (2001) analysed 296 case histories from Peck (1969) up to date, so far being the most current and comprehensive empirical study. Long's study largely validates the results of Clough and O'Rourke (1990) for stiff soils with $u_h^{\text{max}}/H = 0.05-0.25\%$ and $u_s^{\text{max}}/H = 0-0.20\%$. For soft clays with low factors of safety $FOS_{\text{bas}}$, large movements of up to $u_h^{\text{max}}/H = 3.2\%$ may occur, broadly following the trends in Clough's chart (Fig. 4). Long stated that the deformations of deep excavations in...
non-cohesive soils as well as in stiff clay are largely independent of the stiffness of the wall and the support as well as of the kind of support. The system stiffness has a significant influence on the observed deformations only for deep excavations in soft clays with low factors of safety \( FOS_{\text{base}} \), whereas for excavations in soft clays with an adequate factor of safety against basal heave the dependency on the system stiffness becomes less relevant (Fig. 4).

The literature survey of existing empirical studies based on different data bases yields contradictory results with regard to the influence of some factors relevant to the deformation behaviour of deep excavations. The study presented in the following aims at bringing together the present experiences gained in different nations and regions as well as in different types of soils, assessing the new results in view of existing experience.

NEW DATABASE
Data Collection and Classification
For the new database, 536 international case histories were collected, of which some 300 case histories date from the decade 1991–2001 and about 160 from the decade 1980–89. For the period prior to 1980 only a few selected case histories were considered. So the database
may be one of the most comprehensive and current studies so far. Aside the author’s data, the information was mainly extracted from all pertinent geotechnical journals and international conference proceedings. In each case the measured retaining wall and ground movements were analysed, 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. Extensive, detailed tables with all specifications and full references are given by Moormann (2002) and are also easily available, e.g. for further research activities (Moormann, 2003). The case histories were classified according to ground conditions, whereby the following five classes were defined:

- deep excavation in cohesive soils of very soft to soft consistency ($c_u < 75$ kN/m$^2$),
- in cohesive soils of at least stiff consistency ($c_u \geq 75$ kN/m$^2$),
- in non-cohesive soils,
- in layered soils and
- in rock.

The subsoil conditions are characterized as ‘layered soils’ when the part of any type of soil amounts to less than 60% of the subsoil profile along the retaining wall’s height. Relevant for the subdivision of the case histories are the subsoil conditions in the depth between the excavation level and the base of the retaining wall (embedding depth).

In the following the analysis of data will concentrate on 153 case histories dealing mainly with excavations in soft clay characterized by an undrained shear strength of $c_u \leq 75$ kN/m$^2$.

**Analysis and Interpretation of Data for Soft Soil**

In order to examine the main parameters influencing the performance of excavations in Fig. 6 the maximum horizontal wall displacement is plotted against the excavation depth $H$ for all five classes of soil types. The wall and support type is, as in all other diagrams, identifiable for each case history by the corresponding symbol chosen. As listed in the legend in Fig. 6, for each case history, the wall type is indicated by the type/shape of the symbol chosen, whereas the filling of the symbol represents the type of support used in the particular case. That means for example that there are case histories with sheet pile walls (shape: circle) that are tied back (shape: circle; filling: empty/white), braced (shape: circle; filling: solid) or constructed top/down (shape: circle; filling: crossed) and so on. The analysis in Fig. 6 exhibits the following main features:

- The values $u_{h}^{\text{max}}(H)$ scatter in a wide range, indicating no simple linear dependency on the horizontal wall displacements $u_{h}^{\text{max}}$ on the excavation depth $H$. However, on neglecting some case histories with extraordinary movements, each type of soil displays a clear tendency that the horizontal wall displacements increase with increasing excavation depth $H$.
- The soft clays exhibit the largest scatter in the $u_{h}^{\text{max}}(H)$ values, indicating the dependency on further significant factors. For 40% of the excavations in soft soil, the displacements lie at $0.5\% \leq u_{h}^{\text{max}}/H \leq 1\%$ whereas for 27% of the case histories the wall displacements are even greater (on average $u_{h}^{\text{max}}/H = 0.87\%$). Only in 33% of the excavations in soft clay are the horizontal wall displacements smaller than 0.5% $H$.
- For excavations in at least stiff clays the horizontal wall displacements are significantly smaller. Only in 8% of the cases in stiff clay are the displacements $u_{h}^{\text{max}}/H > 1\%$, the average value being $u_{h}^{\text{max}}/H = 0.25\%$.
- For 65% of all case histories in non-cohesive soils the measured wall displacements are smaller than $u_{h}^{\text{max}}/H = 0.25\%$, the average value is $u_{h}^{\text{max}}/H = 0.27\%$.
- In layered soils the magnitude of the wall displacements is similar to the excavations in non-cohesive soils.
- The type of wall seems to have an influence on the horizontal wall displacements regardless of the soil type: the greatest displacements were measured for sheet pile walls whereas for diaphragm walls and secant pile walls the horizontal displacements tend to be significantly smaller.
- With regard to the support system chosen, it is difficult to identify a clear influence on the measured displacements. A comparison of tied back walls and braced walls astonishingly shows no significant differences. The excavations executed by a top/down method tend to show relatively small wall movements, which may be a consequence of the fact that the walls are braced by the underground floors being installed prior to excavating the next step.

For deep excavations in soft and stiff cohesive soils, the maximum horizontal wall displacement $u_{h}^{\text{max}}$ is usually observed at the final depth of excavation ($z = 1.0H$) or, as in 67% of the case histories, at a depth $z$ of $0.5H$ to $1.0H$ below ground surface (Fig. 7). For 21% of the case histories $u_{h}^{\text{max}}$ was measured near the top of the wall.

Analogous to Fig. 6 displaying $u_{h}^{\text{max}}$ as a function of $H$, Fig. 8 shows the relationship between the maximum vertical displacement $u_{v}^{\text{max}}$ at ground surface behind an excavation and the excavation depth $H$ for different soil types, dependent on the type of retaining wall and support system used as marked by the symbol used in each case. The maximum settlement at ground surface normalized against the excavation depth $H$ was measured for different soil types as follows:

- soft clays: $u_{v}^{\text{max}}/H = 0.1\% \pm 10.1\%$, on average 1.07%,
- stiff clays: $u_{v}^{\text{max}}/H = 0.0\% \pm 0.90\%$, on average 0.18%,
- non-cohesive soils: $u_{v}^{\text{max}}/H = 0.0\% \pm 2.43\%$, on average 0.33%,
- layered soils: $u_{v}^{\text{max}}/H = 0.0\% \pm 0.89\%$, on average 0.25%.

Thus, the empirical study confirms the supposition that for deep excavations in at least stiff clays the settlements behind a deep excavation are significantly smaller than for deep excavations in soft clays.

It should be noticed that settlements were consistently
reported to be measured even in stiff clays, apart from a few exceptions reported by Clough and O’Rourke (1990). However, long-term observations e.g. in the slightly over-consolidated stiff Frankfurt Clay show that—due to unloading effects of the subsoil during excavation—a heave of the ground surface is usually measured up to a distance of twice the excavation depth $H$ (Moormann, 2002). In this context it is to be pointed out that the measured settlements result from different deformation mechanisms caused by horizontal displacements of the retaining walls, the effect of a groundwater-drawdown as well as of unloading due to excavation.

For deep excavations in soft clay Fig. 9 illustrates the relationship between the maximum vertical displacement $u_{v}^{\text{max}}$ measured behind a retaining wall and the maximum horizontal wall displacements $u_{h}^{\text{max}}$. In agreement with the results of Goldberg et al. (1976, Fig. 3(a)), the ratio $u_{v}^{\text{max}} / u_{h}^{\text{max}}$ varies for excavations in soft clay as well as for all soil conditions generally between 0.5 and 1.0, at most 2.0. The postulate of Peck (1969) of a constant volume displacement ($u_{v}^{\text{max}} / u_{h}^{\text{max}} = 1.0$) is thus not confirmed.

For 70% of all case histories the maximum settlement $u_{v}^{\text{max}}$ is measured at a horizontal distance $x$ from the retaining wall that is smaller than half the excavation
Fig. 7. Deep excavations in cohesive ground: vertical distance $z$ of the point of max. horizontal wall displacement $u_{h}^{\text{max}}$ below ground surface depending on the depth of the excavation $H$ (legend in Fig. 6)

Fig. 8. Max. vertical displacement (i.e. settlement) $u_{v}^{\text{max}}$ measured behind retaining wall vs. excavation depth $H$ depending on type of soil, retaining wall and support system used (legend in Fig. 6)
depth \((x(u^\text{max}_v) \leq 0.5H, \text{Fig. 11})\), confirming the evaluation performed by Goldberg et al. (1976); however, in soft clays the distance can also increase to \(x \geq 2.0H\), illustrating the potential hazard of a far reaching impact on adjacent urban structures.

The settlement profiles and the classification into three zones as introduced by Peck (1969, Fig. 2) can broadly be confirmed also by this new database with the current case histories (Fig. 11). In the case of deep excavations in soft clay retained by means of sheet pile walls settlements were reported to lie within the zones II and III. For deep excavations in stiff clay the new database shows that the settlements are clearly smaller than \(u^\text{max}_v/H = 0.5\). The influence of the dimensions of an excavation on its displacements was investigated in several cases. For example in Fig. 12, the maximum horizontal wall displacement \(u^\text{max}_h\) is plotted versus the excavated soil volume \(V\), representing the overall size of an excavation. In these cases no impact or dependencies between the dimension of an excavation and its displacements are apparent.

**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. The stiffness of a retaining system is represented mainly by means of the bending stiffness \(EI\) of the retaining wall, the stiffness of

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**Fig. 9.** Deep excavations in soft ground: max. vertical displacement \(u^\text{max}_v\) of the ground surface behind the wall depending on the max. horizontal wall displacement \(u^\text{max}_h\) (legend in Fig. 6).

**Fig. 10.** Deep excavations in cohesive soil: Horizontal distance \(x\) of the point of max. vertical displacement \(u^\text{max}_v\) of the ground surface from the retaining wall depending on the depth of excavation \(H\) (legend in Fig. 6).

**Fig. 11.** Settlements of the ground surface depending on the type of soil (new database) in comparison with the settlement zones by Peck (1969, Fig. 2).
the support, by the configuration, location and distance between support layers and by the embedment length of the retaining wall.

As a first approach, shown in Fig. 13, the influence of the average vertical support spacing \( \tilde{h} \) (as defined in Fig. 1) and of the embedment length \( t \) related to the excavation depth \( H \) on the maximum horizontal wall displacement \( u^\text{max}_h \) is investigated. In soft clays, the average vertical support spacing \( \tilde{h} \) varies mainly between 2 m and 4 m; the average deduced from the 153 case histories was \( \tilde{h} = 3.65 \) m. The diagram in Fig. 13(a) shows that the horizontal wall displacements are not affected by the average vertical support spacing \( \tilde{h} \).

Furthermore, the wall displacements seem to be independent of the magnitude of the embedded length \( t \) of the wall (Fig. 13(b)). The embedded length \( t \) of retaining walls in soft clay varies between 0.1\( H \) and 2.0\( H \), on average at \( t = 0.92 \)\( H \). Several approaches exist for the representation of the stiffness of a retaining system (retaining wall, supporting system) within a single parameter. Based on a dimensional analysis, Addenbrooke (1994) defined a 'displacement flexibility' number as:

\[
K_I = \log (\tilde{h}^2/EI)
\]  

Addenbrooke postulated that for excavations with similar \( K_I \) values comparative movements should be expected. But the analysis in Fig. 14 shows that there is a wide scatter in the measured displacements for each flexibility number. In Fig. 15, the maximum horizontal wall displacement \( u^\text{max}_h \) related to the excavation depth \( H \) is plotted versus the system stiffness \( K_I \) as defined by Clough et al. (1989, Eq. 1). Again the data for deep excavations in soft clay scatter in a wide range without a clear dependency of the wall displacements on the system stiffness, although there are signs that the diagram developed by Clough et al. (1989, Fig. 4) may be broadly confirmed with regard to the influence of the factor of safety against basal heave. A slight influence of the system stiffness on the horizontal wall displacements of deep excavations in soft soils is only partly discernible for excavations with low factors of safety against basal heave (\( FOS_{bas} \) smaller \( \approx 1.5 \)). The fact that the wall movements are mainly independent from the stiffness of the retaining wall and the supporting system even in soft clay could also be shown to pertain to other ground conditions (Moermann, 2002). Similar results were recently gained by Long (2001).

This result is of great practical and economical relevance for the design of deep excavations. It suggests that there is no direct or at least no linear correlation between the system stiffness and the movements: an increase in the system stiffness does not result in a corresponding decrease in the displacements. This result of the
empirical study is in some way contrary to the approach often used in practice to limit excavation displacements by means of very stiff retaining systems.

It is difficult to identify the reasons why the wall stiffness and supporting system have such an insignificant effect on the wall and ground movements. Firstly, the results indicate that there are further relevant factors to consider that may influence the performance of deep excavations besides the general ground conditions and the rigidity of the retaining system. A careful examination of single case histories indicates that these may lie in the soil conditions at the embedment portion, the pertinent groundwater-conditions, surrounding buildings or geometrically irregularities. So too the workmanship, especially the diligence and care taken during construction, unforeseen events and the excavation sequence chosen (height of excavation steps, the temporal succession of excavation steps and installation of struts/anchors etc.) seem to be of significant importance to the displacements as is the pre-stressing of struts and anchors. In addition, time-dependent effects influence the wall and ground movements in cohesive soils (Holt and Griffiths, 1992, Ng, 1999). For deep excavations in soft clay in Taipei (Ou et al., 1998), Calcutta (Som and Gupta, 1994) as well as in Frankfurt (Moormann, 2002) measurements display a time-dependent increase of wall and ground movements after reaching a constant excavation level. A precise identification and quantification of the relative importance of all these factors is difficult, despite the large extent of the case studies, mainly because these factors are not reported and documented in detail in most cases.

Furthermore, the observation that the stiffness of retaining wall and support systems has less of an effect on the movements as expected, may lead to the conclusion that the increasing stiffness of current retaining systems may have reached such a high level, that it hardly influences the relatively small deformations. In this context attention is drawn to a numerical study of deep excavations in London Clay by Potts and Day (1990, 1991), where it was shown 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. Comparative results of analytical and numerical investigations are also presented by Wong and Broms (1989).

As already mentioned, the diagram developed by Clough et al. (1989, Fig. 4) is broadly confirmed in the present study as an approach to roughly estimate the horizontal wall displacements in soft cohesive soils. Figure 15 indicates that in soft soils the wall displace-
ments are influenced by the factor of safety against basal heave whereas in at least stiff cohesive soils this criterion is insignificant due to the high $FOS_{base}$-values to the extent which system stiffness has no impact.

For strutted excavations in soft ground the dependency of the normalised horizontal wall displacement $u_{h}^{max}/H$ on the safety factor against basal heave $FOS_{base}$ was also investigated by Mana and Clough (1981). The limits indicated by them can generally be confirmed by the new database (Fig. 16). The approach proposed by Goldberg et al. (1976) to predict the horizontal wall displacements dependent on the system stiffness $K_t$ and the stability number $N_b$ (Fig. 17) does not seem to present a reliable method, as indicated in the large scatter in the results of the new database.

CONCLUSIONS

An extensive database of more than 530 generally very recent 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 data evaluated were used to examine the main parameters influencing the performance of deep excavations in soft soil ($c_u < 75 \text{kN/m}^2$). The main results obtained include the following:

- The maximum horizontal wall displacements $u_{h}^{max}$ frequently lie between 0.5% $H$ and 1.0% $H$, on average at 0.87% $H$. The maximum horizontal displacement $u_{h}^{max}$ is usually measured at a depth of $z = 0.5H$ to $1.0H$ below ground surface.
- The maximum vertical settlements at the ground surface behind the retaining wall $u_{v}^{max}$ frequently lie in the range of 0.1% $H$ to 10% $H$, on average at 1.1% $H$. The settlement $u_{v}^{max}$ usually occurs at a distance $x$ of $\leq 0.5H$ behind the retaining wall, but there are cases in soft soils with $x$ up to 2.0$H$. The quotient $u_{v}^{max}/u_{h}^{max}$ varies mainly between 0.5 and 1.0, but without clear trends.
- The ground conditions and the excavation depth $H$ are identified as being the most significant influence parameters.
- There is no empirical proof of the influence of the kind of support system (anchored, propped or top/down method) on the performance of deep excavations, although, as expected, top/down systems tend to show the smallest movements.
- The retaining wall and ground movements seem to be largely 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, and an additional increase of system stiffness does not result in a corresponding additional decrease of movements. This last result, that should be further investigated and verified by additional empirical and numerical or analytical studies, illustrates the potential for a redesign of retaining systems and more economic solutions with retaining systems with reasonable stiffness.

REFERENCES


