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Technical Note

Meta-analysis of ground movements associated with deep excavations using a data mining approach

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ABSTRACT

This paper presents a rigorous statistical approach to identify the controlling factors in the development of ground movements associated with deep excavations. It also gives the most suitable definition of support stiffness from many suggested definitions in the literature. The study is based on a newly compiled database from 389 case studies of propped and anchored excavations. Data mining techniques (e.g. principal component analysis and multi-linear regression) were used to identify significant relationships between the parameters under study and to quantify the global trends in the database. The study shows that the main factors controlling the ground movements are those related to ground conditions, confirming the conclusions of previous empirical studies. It is also shown that the definition of Addenbrooke et al. (1994) is the most suitable expression of support stiffness, therefore providing conclusive evidence for its future use.

1. Introduction

Movement occurrence in the ground around deep excavations is related to the movements of the retaining structure. Multiple authors have shown different relationships in this regard, e.g. Peck (1969), Ou et al. (2000), Long (2001) and Gaba et al. (2003). Most of these relationships are based on empirical studies; however, none of these applied advanced statistical techniques. Recent statistical studies have focussed on the development of predictive equations to determine wall displacements for particular ground conditions (Zhang et al., 2015, 2017; 2018; Hsieh and Ou, 2016; Goh et al., 2017a) using assumptions about the controlling variables.

Out of the many parameters influencing ground movements in excavations, support stiffness, defined as the resistance to ground movements provided by the retaining structure, has been identified as greatly relevant (Long, 2001; Goh et al., 2017b; Hsieh et al., 2017). There have been different expressions and terminologies, e.g. system stiffness, defined by the authors to represent support stiffness, but yet no definitive consensus on which is the most appropriate. In this paper, we use support stiffness for all for consistency.

The widely adopted empirical model was first proposed by Peck (1969). He generated a series of plots of the maximum vertical settlement (δ_{vmax}) of the ground behind the retaining wall, and normalised it against excavation depth (H). The case studies used were a combination of soldier pile and sheet pile walls with support through props or anchors. Peck concluded that ground conditions represented the greatest influence on the magnitude of settlements. Following this realisation, Peck split the database into three categories based on the ground conditions. These were: Zone I, sand/soft clay to hard clay; Zone II, very soft to soft clay with either a limited depth of soft clay beneath the excavation or a significant depth of soft clay but with a large factor of safety (FoS) against excavation base heave as defined by Terzaghi (1943); Zone III, very soft to soft clay with a low margin of safety against basal heave. The predicted dimensionless vertical settlements ranged from $\delta_{vmax}/H < 1\%$ for Zone I to $\delta_{vmax}/H > 2\%$ for Zones II/III. Peck also found that the lateral extent of settlements at the ground surface was greater in Zones II/III, reaching up to a distance equivalent to four times the excavation depth, than that in Zone I, which only reached up to a distance of twice the excavation depth. This study was limited to δ_{vmax} with no relationships investigated for the maximum horizontal displacement (δ_{hmax}) of the retaining wall or the effect of wall properties.

Goldberg et al. (1976) expanded the work of Peck (1969) by studying both δ_{vmax} and δ_{hmax}. This study comprised of 63 case

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studies in different soil conditions and demonstrated that ground conditions as well as wall type and support system have an effect on displacements. It was shown that in sands, gravels and stiff clays, which roughly correspond with Peck's Zone I, the maximum vertical settlement was $\delta_{vmax}/H \leq 0.5\%$. This gives values half as large as those predicted by Peck (1969) for the same zone. δ_{hmax} of walls in Zone 1 was found to be $\delta_{hmax}/H \leq 0.35\%$. Goldberg et al. (1976) also proposed a semi-empirical approach to calculate the ratio of $\delta_{vmax}/\delta_{hmax}$. Sand, gravel and semi-solid to solid clays were found to have a $\delta_{vmax}/\delta_{hmax}$ ratio of 0.25–2. Soft to stiff clays, however, were found to display a $\delta_{vmax}/\delta_{hmax}$ ratio of 0.5–2.5.

Clough et al. (1979) focused on the ground movements surrounding deep excavations in soft clays in Oslo, Chicago, Boston and San Francisco. It was found that the maximum horizontal displacements depended on the FoS against basal heave (Terzaghi, 1943). Clough et al. (1979) discovered that excavations with a FoS value less than 1.5 caused the horizontal displacements to increase significantly.

Clough and O'Rourke (1990) expanded the database previously constructed by Goldberg et al. (1976) and considered Peck (1969) as the most widely used empirical prediction of ground movements upon deep excavations. Clough and O'Rourke (1990) divided the database into two categories: Category 1, stiff clays/residual soils/sands; and Category 2, soft/medium clays. It was found that the maximum horizontal displacements were largely independent of wall type with an average of $\delta_{hmax}/H = 0.2\%$, while the maximum settlements averaged $\delta_{vmax}/H = 0.15\%$ for Category 1 conditions, giving a $\delta_{vmax}/\delta_{hmax}$ ratio of less than 1. The δ_{hmax} values of Category 2 conditions were found to be greater than those of Category 1 and influenced by their FoS against basal heave and system stiffness of the support.

Long (2001) compiled an extensive database of 296 global case studies of deep excavations with ground movements. The database was divided into propped, un-propped and cantilever walls. The propped walls were then sub-divided by the depth of soft soil and FoS against basal heave (Table 1, where h is the depth of soft soil). Long (2001) plotted the data against the support stiffness expressions, flexibility number (Addenbrooke et al., 1994) and system stiffness (Clough et al., 1979) as well as excavation depth. A description of the expressions for support stiffness is presented in Table 2. Long (2001) found that there was a slight trend of horizontal displacement decreasing with increasing system stiffness; however, this was not significant.

Long (2001) analysed the effect of different support types on δ_{vmax} and δ_{hmax}. It was found that there is a variable response in the ratio of $\delta_{vmax}/\delta_{hmax}$ between different support types and ground conditions. The findings of Long (2001) are summarised in Table 1. This shows that, as the soil conditions deteriorate, the ratio of $\delta_{vmax}/\delta_{hmax}$ changes from less than 1 to greater than 1. Long (2001) did not quantify the relationship between support stiffness and ground movements, despite identifying the possibility that existed.

Long (2001) suggested that there is a linear relationship between H and δ_{vmax} and δ_{hmax} once classification of different ground conditions has been made, although this was not proven in terms of statistical significance. He also identified that there is an increase in δ_{hmax} with a decreasing FoS against basal heave, confirming the conclusions of the earlier study by Clough and O'Rourke (1990).

Table 1
Findings of Long (2001) for magnitudes of ground movement based on split database.

Dataset	δ_{hmax}/H (%)	δ_{vmax}/H (%)	Description of data
1	0.18	0.14	$h < 0.6H$
2	0.38	0.48	$h > 0.6H$, $FoS > 3$
3	0.82	1.1	$h > 0.6H$, $FoS < 3$

Table 2
Support stiffness terms used in past studies.

Support stiffness definition	Source
Bending stiffness, EI Material flexibility, $\ln(EI)$	
Flexibility number, $H^4/(EI)$	Rowe (1952)
Flexibility number, $\log_{10}(H^4/(EI))$	Long (2001)
Wall flexibility, EI/s^5	Addenbrooke et al. (1994)
Displacement flexibility, $s^5/(EI)$	Long (2001)
Wall flexibility, $\log_{10}(s^4/(EI))$	Long (2001)
System stiffness, $EI/(\gamma_w s^4)$	Clough et al. (1979)

Note: E is the Young's modulus, I is the second moment of inertia of support, s is the support spacing, and γ_w is the unit weight of water.

2. Research significance

From the above studies, it is clear that although simple regression analysis has been used in the past, advanced data analytics have not been used to study the different groupings of categories influencing in particular the support stiffness behaviour. As described above, there have been a variety of expressions to attempt to quantify the role that an excavation's support stiffness plays in observed displacements. In total, eight different expressions have been identified in the literature, as shown in Table 2.

The aim of this paper is to apply data mining techniques to an improved updated database of excavations with the purpose of rigorously classifying variables in terms of system performance and assess the most appropriate expression of support stiffness. The study focusses on excavations built using propped and anchored retaining walls as they provide the most extensive number of cases. In order to achieve this, a valuable improved database of case studies is also presented that can be of great use to other researchers in the field.

3. Compilation and preparation of the database

The database is compiled from case studies from published literature, based on the cases by Long (2001) using the same variables. In total, 389 case studies have been compiled, with 235 from the database constructed by Long (2001), and additional 154 cases added by this study, dating from 2002 to 2016. The database is attached in the Appendix. It should be noted that only the propped or anchored excavation case studies from the database of Long (2001) were included.

The information from the case studies included the excavation depth (H), depth of soft soil (h), support spacing (s), bending stiffness (EI), soil shear strength (St), FoS against basal heave and maximum horizontal displacement (δ_{hmax}). Fig. 1 shows an illustration of the geometrical parameters described above. For the statistical analysis, H, h, s, EI and St have been considered as the

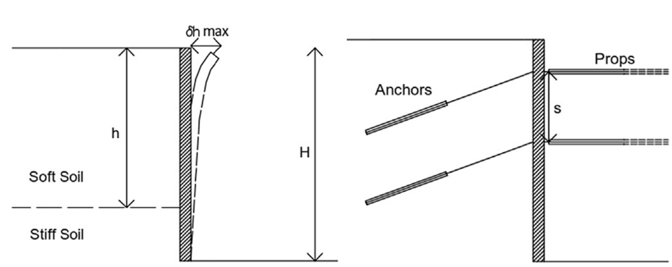


Fig. 1. Illustration of parameters collected in database.

independent variables or covariates, while δ_{hmax} is the response variable correlated to the above parameters. Although the FoS against basal heave has been identified by previous studies, such as Clough and O'Rourke (1990), as being particularly influential in the magnitude of δ_{hmax}, its value was not reported in all case studies used to compile the database. Therefore, it could not be explicitly considered in the analysis. This missing information was expected to have a negative impact on the predictive capacity of any equations that could be derived from the statistical analysis. However, this limitation affects neither the evaluation of the relative effect that the other variables in the database have on δ_{hmax}, nor the structure of correlations between them. In other words, the fact that basal heave based FoS values could not be accounted for in all cases is not detrimental in assessing the influence of the other variables considered on δ_{hmax} values from an statistical point of view.

The shear strength of soil at dredge level (St) was collected for all case studies. The way in which this value was presented in the literature varied between units of kilopascal (kPa), standard penetration test (SPT) (N value) and notes on consistency. It was necessary to convert these values into the same unit, i.e. the unit of kPa.

To convert the SPT-N value to kPa, empirical relationships were used. The relationships between SPT-N value and kPa vary for fine- and coarse-grained soils. From Sivrikaya and Togrol (2006), a standard conversion for fine-grained soils was shown in Eq. (1). Although Eq. (1) did not accurately represent the variations between soil types and geographical locations, given the insufficient data to support more detailed relationships, it was considered to be an appropriate approximation.

$$St = 5N \tag{1}$$

where N is the SPT number.

Table 3 shows the relationship of consistency with a range of shear strengths for fine-grained soils.

For coarse-grained soils, relationships between the density of material and its internal friction angle were used, as shown in Table 4. The internal friction angle, combined with a characteristic value for the unit weight of the formation and the excavation depth, was used to derive the shear strength using the following equation:

$$St = \sigma' \tan\phi + c \tag{2}$$

where σ' is the effective vertical stress (dry conditions were assumed), ϕ is the internal friction angle, and c is the cohesion (0 for coarse-grained soils).

The depth of soft soil was normalised against H in order to apply the parameter across a range of excavation depths. This value was set at 1 for $h \geq H$. This prevents any very deep layers of soft soil from being overly dominant within the data.

4. Overview of the methodology of analysis

Analysis of the database was undertaken using data mining techniques (Hair et al., 2010). Principal component analysis (PCA) was applied to the independent variables (H, h, s, EI and St) in order to reformulate the same information into a reduced number of new variables, called principal components or factors, by grouping closely statistically-related variables. Application of this technique offers two important benefits: it reduces the number of independent variables without losing a significant part of the information, which makes the database easier to be analysed and modelled by means of multiple linear regression; and it reveals not only the variables correlated with each other but also the structure of these correlations. The principal components or factors obtained from the PCA relied upon independent variables for the multiple linear regression analysis. By doing so, multicollinearity problems in the database are overcome and as a result, more robust and stable regression equations can be obtained than using the raw data. A full explanation of PCA is available in Wold et al. (1987) and Browne (2001).

It was found that using the natural log of δ_{hmax} provided a more homoscedastic distribution of residuals, which is an important requirement in linear regression analysis, and therefore, $\ln\delta_{hmax}$ was considered as the response variable rather than δ_{hmax}. The regression is used to assess both the relevance of different variables and the appropriateness of different support stiffness definitions.

Table 3
Relationship of soil consistency with shear strength (adapted from Das, 2015).

Consistency	Shear strength (kPa)	Adopted value (kPa)
Very soft	0–25	12.5
Soft	25–50	37.5
Medium	50–100	75
Stiff	100–200	150
Very stiff	200–400	300
Hard	>400	400

Table 4
Relationship between sand/gravel density and internal friction angle (adapted from Das, 2015).

Density	Internal friction angle (°)	Adopted angle (°)
Loose	30–35	32.5
Medium	35–40	37.5
Dense	40–45	42.5
Very dense	45	45

5. Results and discussion

The results of the analyses are summarised in Table 5. Since there are alternative definitions for the support stiffness, an alternative analysis was carried out for each of them, with H, h and St common to all of them. For each of these analyses, the first two principal components ($PC1$ and $PC2$) were retained, and the equations that relate each of these to the original variables are presented. To define the principal components, the example of wall flexibility (EI/s^5) in Table 5 is used. It is shown that there are two clear groupings of variables for the principal components in Eq. (17): St and h/H are combined to create principal component 1 ($PC1$), and H and wall flexibility (EI/s^5) to create $PC2$. The components will be called soil properties ($PC1$) and wall properties ($PC2$) after their input variables are described. The explained variance, expressed as a percentage of the total variance in the database, informs about the success of the principal components in summarising the information contained by all the original variables in the dataset. The adequacy of each of the definitions of support stiffness can be assessed by comparing the explained variance for the different analyses in the table.

The response variable $\ln\delta_{hmax}$ was related to $PC1$ and $PC2$ by means of multiple linear regression. The resulting equations are shown in Table 5, together with the R^2 values, which are a measure of the accuracy of these equations in fitting the original data.

Figures in the last column of Table 5 show the independent variables (H, h, s, St, and support stiffness) plotted on the new feature space defined by the principal components $PC1$ and $PC2$. The calculation of the principal components is performed using standardised values, meaning that any input values need to be converted before being used to create the components. The

Table 5
Comparison of analyses of databases created using different support stiffness definitions.

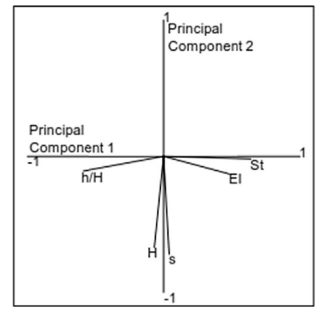
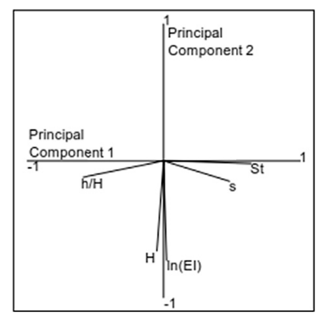
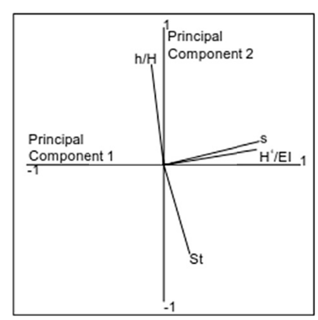
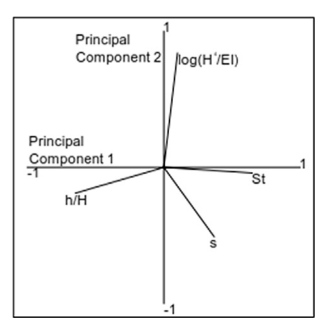
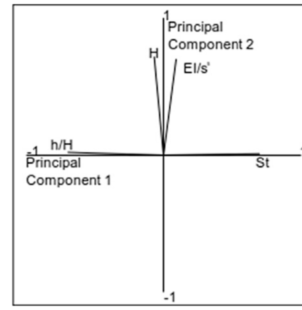
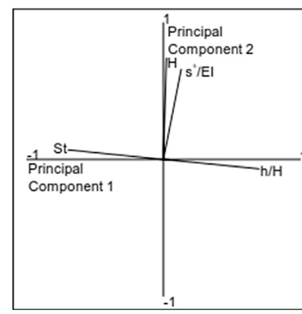
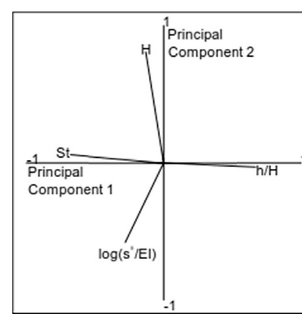
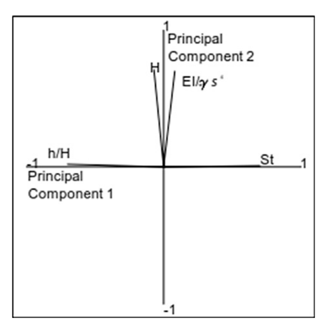
Support stiffness definition	Principal components and regression model for support stiffness definition	Significance test	Representation of principal components
Bending stiffness (EI)	Principal component 1: $PC1 = 0.64St - 0.07H - 0.59h/H + 0.04s + 0.48EI$ (3) Principal component 2: $PC2 = -0.02St - 0.67H - 0.11h/H - 0.72s - 0.13EI$ (4) Regression model: $\ln\delta_{\text{hmax}} = 3.35 - 0.51PC1 - 0.19PC2 - 0.05PC1PC2 - 0.09(PC2)^2 \pm 1.58$ (5)	Variance = 65% $R^2 = 0.44$	
Material flexibility ($\ln(EI)$)	Principal component 1: $PC1 = 0.64St - 0.05H - 0.59h/H + 0.48s + 0.02\ln(EI)$ (6) Principal component 2: $PC2 = -0.02St - 0.66H - 0.12h/H - 0.15s - 0.73\ln(EI)$ (7) Regression model: $\ln\delta_{\text{hmax}} = 3.29 - 0.51PC1 - 0.08PC2 - 0.1PC1PC2 \pm 1.5$ (8)	Variance = 66% $R^2 = 0.43$	
Flexibility number ($H^4/(EI)$)	Principal component 1: $PC1 = 0.19St - 0.09h/H + 0.7s + 0.68H^4/(EI)$ (9) Principal component 2: $PC2 = -0.65St + 0.73h/H + 0.17s + 0.11H^4/(EI)$ (10) Regression model: $\ln\delta_{\text{hmax}} = 3.29 - 0.2PC1 + 0.44PC2 \pm 1.6$ (11)	Variance = 84% $R^2 = 0.39$	
Flexibility number ($\log_{10}(H^4/(EI))$)	Principal component 1: $PC1 = 0.65St - 0.65\frac{h}{H} + 0.37s + 0.1\log_{10}\left(\frac{H^4}{EI}\right)$ (12) Principal component 2: $PC2 = -0.04St - 0.19\frac{h}{H} - 0.51s + 0.84\log_{10}\left(\frac{H^4}{EI}\right)$ (13) Regression model: $\ln\delta_{\text{hmax}} = 3.11 - 0.47PC1 + 0.25PC2 + 0.09(PC1)^2 \pm 1.59$ (14)	Variance = 75% $R^2 = 0.44$	

Table 5 (*continued*)

Support stiffness definition	Principal components and regression model for support stiffness definition	Significance test	Representation of principal components
Wall flexibility (EI/s^5)	Principal component 1: $PC1 = 0.7St - 0.07H - 0.7\frac{h}{H} + 0.09\left(\frac{EI}{s^5}\right)$ (15) Principal component 2: $PC2 = 0.01St + 0.72H + 0.02\frac{h}{H} + 0.7\left(\frac{EI}{s^5}\right)$ (16) Regression model: $\ln\delta_{hmax} = 3.34 - 0.51PC1 + 0.31PC2 + 0.19PC1PC2 - 0.06(PC2)^2 \pm 1.56$ (17)	Variance = 67% $R^2 = 0.45$	
Wall Flexibility ($s^5/(EI)$)	Principal component 1: $PC1 = -0.7St + 0.02H + 0.7\frac{h}{H} + 0.13\left(\frac{s^5}{EI}\right)$ (18) Principal component 2: $PC2 = 0.07St + 0.74H - 0.07\frac{h}{H} - 0.66\left(\frac{s^5}{EI}\right)$ (19) Regression model: $\ln\delta_{hmax} = 3.25 + 0.52PC1 + 0.16PC2 - 0.02PC1PC2 + 0.03(PC2)^2 \pm 1.62$ (20)	Variance = 68% $R^2 = 0.41$	
Wall flexibility ($\log_{10}(s^4/(EI))$)	Principal component 1: $PC1 = -0.68St - 0.13H + 0.67\frac{h}{H} - 0.28\log_{10}\left(\frac{s^4}{EI}\right)$ (21) Principal component 2: $PC2 = 0.06St + 0.81H - 0.03\frac{h}{H} - 0.58\log_{10}\left(\frac{s^4}{EI}\right)$ (22) Regression model: $\ln\delta_{hmax} = 3.2 + 0.46PC1 + 0.13PC2 - 0.09PC1PC2 + 0.07(PC1)^2 \pm 1.64$ (23)	Variance = 77% $R^2 = 0.4$	
System stiffness ($EI/(\gamma_w s^4)$)	Principal component 1: $PC1 = 0.7St - 0.07H - 0.7\frac{h}{H} + 0.08\frac{EI}{\gamma_w s^4}$ (24) Principal component 2: $PC2 = 0.01St + 0.71H + 0.02\frac{h}{H} + 0.7\frac{EI}{\gamma_w s^4}$ (25) Regression model: $\ln\delta_{hmax} = 3.34 - 0.51PC1 + 0.31PC2 + 0.19PC1PC2 - 0.06(PC1)^2 \pm 1.56$ (26)	Variance = 67% $R^2 = 0.45$	

variable that is positioned close to a principal component, shown by the axes, indicates that the variable is loaded mostly onto a single principal component, meaning that it dominates the behaviour.

By reducing the number of variables in the dataset, using PCA, it is inevitable that some of the original information would be lost, and that is why the percentage of explained variance is always less than 100%. This is in the very nature of a meta-analysis such as this one, and it explains why the R^2 values are never high. By definition, R^2 values range between 0 and 1, where 1 corresponds to perfect correlation between estimates and observations (Hair et al., 2010). This statistic appears simple in principle; however, in practice, the expected value of R^2 relies on the quality of the original data. The analysis of well-constrained data, such as those from laboratory scientific studies, generally yields remarkably high values of R^2, while datasets which are intrinsically more scattered, such as those in social sciences or in meta-analyses like this case, generally yield lower R^2 values since accurate predictions cannot be expected under those circumstances. While the goal of this study is not to predict movements, these significance tests will indicate which expression of support stiffness is the most suitable in terms of characterising the horizontal displacement.

Table 5 shows that the alternative regression models yield comparable R^2 values. The models where the support stiffness was represented by wall flexibility (EI/s^5) and system stiffness ($EI/(\gamma_w s^4)$) achieved the highest R^2, although both had lower variance scores. This difference in results of the significance tests can be explained by examining the figures in Table 5. The datasets having higher variance also present a greater collinearity between the principal components, with variables plotted further from the axes, which has a negative effect on the regression analysis. The last four figures in Table 5 show the least collinearity between the principal components, allowing a more robust and stable regression analysis. Hence, wall flexibility (EI/s^5, Eq. (17)) and system stiffness ($EI/(\gamma_w s^4)$, Eq. (26)) are the best to represent support stiffness.

System stiffness contains γ_w, which after normalisation will be effectively removed from the variable. Therefore, these two variables are similar in their composition, with EI divided by s raised to a power. It can be deduced that the greater the influence of the support spacing parameter on the support stiffness variable, the more suitable the expression of support stiffness. This is intuitive as widely spaced supports would be expected to provide less resistance to displacement than closely spaced supports.

Although Eqs. (17) and (26) were found to be similarly effective in representing support stiffness, the diagnostics of the regression model leading to Eq. (17) were better in terms of the distribution of the residuals. Therefore, it was conclusive that wall flexibility (EI/s^5) was the best definition of support stiffness in order to characterise horizontal displacements based on this database.

Figs. 2 and 3 show how the non-standardised variables influence the principal components. In Fig. 2, St and h/H have a similar influence on the value of $PC1$. An increase in the value of the principal component for soil properties is related to an increase in the soil strength or a decrease in the depth of soft soil. Simply, better ground conditions can lead to a larger, more positive value of the soil properties principal component.

Fig. 3 shows that H has a more significant effect on the component than EI/s^5. An increase in the excavation depth and wall flexibility will result in an increase in the principal component of wall properties. This indicates that excavations which have a greater depth have support with a greater value of wall flexibility. This is an expected outcome that stiffer support and closer spaced props are likely to be used for deeper excavations.

Fig. 4 shows a contour plot created from Eq. (17) which is converted to δ_{hmax}, and indicates how δ_{hmax} is influenced by the principal components as illustrated in Figs. 2 and 3. It shows that as soil properties increase, indicating improved ground conditions, the magnitude of displacements decreases. The rate of reduction in δ_{hmax} decreases as soil properties increase. The relationship between the wall properties component and δ_{hmax} shows an increase in displacement as this component increases at positive values of

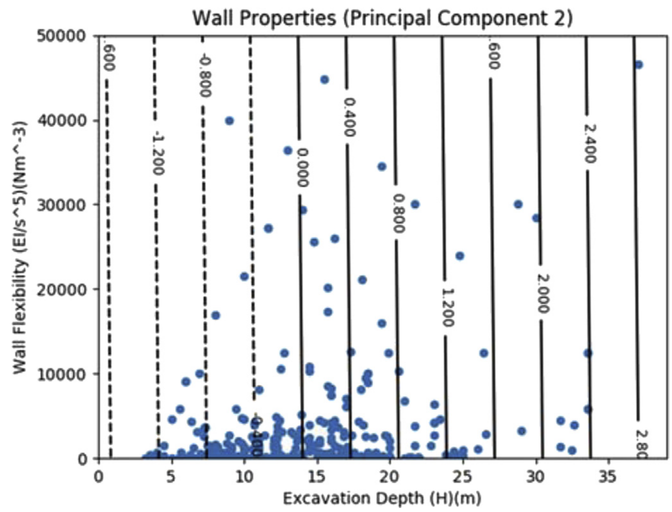


Fig. 3. Contour plot of wall flexibility (EI/s^5) against H for calculating wall properties ($PC2$) overlain by data from database.

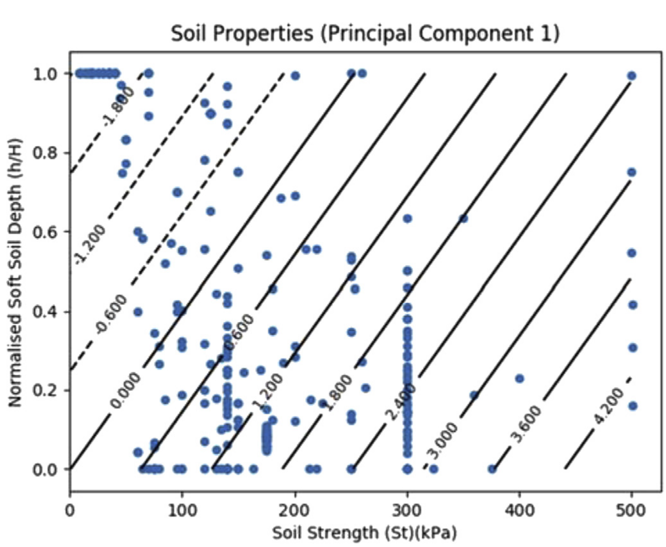


Fig. 2. Contour plot of h/H against soil strength (St) at dredge level for calculating soil properties ($PC1$) overlain by data from database.

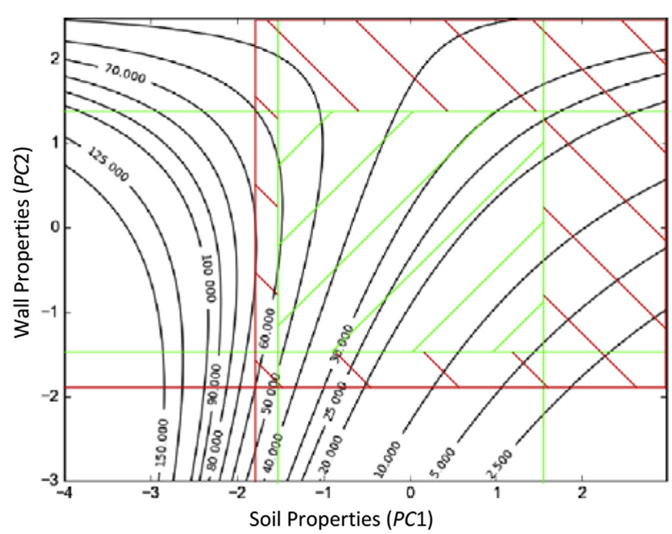


Fig. 4. Contour plot of wall properties ($PC2$) against soil properties ($PC1$) for predicting δ_{hmax} from Eq. (5). Contours are for δ_{hmax} (mm). Red hatch indicates the limit of possible relationships, and green hatch denotes the limit of accurate relationships.

soil properties. However, illogically, when the soil properties component is negative, which is mainly caused by very poor soil conditions, an increase in the wall properties component will result in a decrease in δ_{hmax}. In other words, in very poor ground conditions, increasing the excavation depth and reducing the support stiffness will lead to reduced displacements. However, this clearly does not hold in reality. This highlights the problem with extrapolating trends from case studies further than the range covered by the data in the case studies. Therefore, it is necessary to indicate in Fig. 4 the range of data which show accurate trends, because they are covered by information from the database.

Figs. 2 and 3 show that it is unlikely for the values of the principal components to be less than about −1.8, as this would equate to a soil shear strength very close to zero or a wall flexibility and excavation depth close to zero. When each component is less than −1.8, the trends observed in Fig. 4 are extrapolated inaccurately, indicated by the red hatching.

The most accurate area in Fig. 4 can be further refined by calculating the range of most probable values of each principal component, indicated by green hatching. In this instance, Eqs. (5) and (6) are employed to calculate the values of the principal components in Fig. 4 from standardised values of each variable. Standardisation can represent the values which are within ±1 standard deviation of the mean value. Therefore, the most accurate area in Fig. 4 is in between ±1.56 for *PC*1 and ±1.45 for *PC*2.

Predictions were not the aim of this study and are likely to show a significant error even in the most probable, green hatched portion of the graph, due to three-dimensional effects and/or time-dependent movements as highlighted by Fuentes et al. (2018).

6. Conclusions

An extended database of excavations has been introduced compiling 154 additional case studies presented by Long (2001). This study demonstrates the capability of multivariate statistical techniques to identify trends in large databases of geotechnical data, and illustrates the potential hazards associated with extrapolating data beyond the limits of the data used for the analysis. Soil conditions and excavation depth have been found to be the main influencing factors on the horizontal displacement of deep excavations, confirming the findings of previous studies.

Wall flexibility, as defined by Addenbrooke et al. (1994), has been found to be the most significant interpretation of the expressions of support stiffness for characterising the horizontal displacement of deep excavations which have been suggested by previous studies. Wall flexibility is shown to have little influence on the magnitude of the displacement of deep excavations, a response identified by Long (2001).

The major influences on the horizontal movement of deep excavations have been identified as being soil strength (*St*), normalised depth of soft soil (h/H) and excavation depth (H). This is in agreement with the findings of Long (2001).

Conflicts of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Notations

St	Shear strength of soil at dredge level
H	Excavation depth
h	Depth of soft soil
h/H	Normalised depth of soft soil
s	Support spacing
FoS	Factor of safety
EI	Bending stiffness
δ_h, δ_v	Horizontal and vertical displacements, respectively
δ_{hmax}	Maximum horizontal displacement
δ_{vmax}	Maximum vertical displacement
N	SPT number
σ'	Effective vertical stress
ϕ	Internal friction angle
c	Cohesion

Appendix. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jrmge.2018.12.006.

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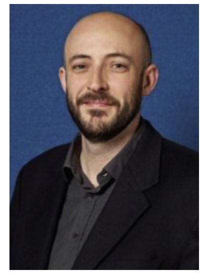

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