A FRAMEWORK FOR THE USE OF RELIABILITY METHODS IN DEEP URBAN EXCAVATIONS ANALYSIS

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Abstract

Deep excavations in urban areas impose deformation to adjacent structures; hence the reliability of deformation analysis for the real deep excavation projects is very important to be assessed. In this study a framework is presented for the use of reliability methods in deformation analysis of deep urban excavations. The suggested framework is applied for 5 real deep excavation projects implemented during last 10 years. All studied cases were recognized as projects of high importance in urban areas, and were monitored during the excavation process. A non-probabilistic reliability analysis procedure, Random set method, in combination with finite element numerical modeling is applied to obtain the probability of unsatisfactory performance for each case. The reliability analysis results are confirmed by field observations and measurements. Typical results for the probability of analytical deformations exceeding the acceptable values along with the site observations and measured displacements for 5 real deep excavation projects show that the reliability analysis could be a beneficial tool for designer. It is concluded that applying the suggested framework in the design stage of deep excavation projects may lead to design more appropriate systems compared to common deterministic design methods.

DOI https://doi.org/10.18690/actageotechslov.18.1.2-14.2021

Keywords

deep excavation, random set finite element method, reliability analysis, system performance; uncertainty

OKVIR ZA UPORABO METOD ZANESLJIVOSTI PRI ANALIZAH GLOBOKIH IZKOPOV V URBANIH OKOLJIH

Ključne besede

globoki izkop, metoda naključnih nizov s končnimi elementi, analiza zanesljivosti, zmogljivost sistema, nezanesljivost

Izvedek

Izvedbe globokih izkopov v urbanih območjih povzročajo deformacije na sodobnih konstrukcijah; zato je zelo pomembna ocena zanesljivosti analize deformacij za dejanske projekte globokih izkopov. V tej študiji je predstavljen okvir za uporabo metod zanesljivosti pri analizi deformacij globokih izkopov v urbanih okoljih. Predlagani okvir je bil uporabljen za 5 dejanskih projektov globokih izkopov, izvedenih v zadnjih 10 letih. Vsi preučeni primeri so bili prepoznani kot projekti velikega pomena v urbanih območjih in so bili spremljani med izvedbo izkopov. Za verjetnostno analizo uspešnosti izvedbe izkopov se je za vsak od primerov uporabil postopek verjetnostne analize zanesljivosti, temveč metoda naključnih nizov v kombinaciji z numeričnim modeliranjem končnih elementov. Rezultate analize zanesljivosti potrjujejo terenska opazovanja in meritve. Tipični rezultati za verjetnostno analizo zanesljivosti izvedbe izkopov se za vsak od primerov ni uporabil postopek verjetnostne analize zanesljivosti, temveč metoda naključnih nizov v kombinaciji z numeričnim modeliranjem končnih elementov. Rezultate analize zanesljivosti potrjujejo terenska opazovanja in meritve. Tipični rezultati verjetnosti analitičnih deformacij, ki presegajo sprejemljive vrednosti, skupaj z opazovanji na lokaciji in izmerjenimi premikmi za pet dejanskih projektov globokih izkopov kažejo, da bi bila analiza zanesljivosti lahko koristno orodje za projektante. Ugotovljeno je bilo, da uporaba predlaganega okvira v fazi načrtovanja projektv globokih izkopov lahko privede do zasnovne ustreznih sistemov v primerjavi s splošnimi metodami determinističnega načrtovanja.
1 INTRODUCTION

As a result of the extensive development of urban areas, deep excavation design has become an increasingly pursued issue in engineering analyses in recent years. Because of the great effects of deep excavation-induced ground movements on the nearby structures, the assessment of the effects of deep excavations on ground movements has been the subject of interest of several studies [1-6]. Ignoring the deformation caused by excavating process in the design stage can cause significant damage to adjacent structures and utilities. Excessive movements can occur without a failure mechanism occurring [7], hence it should be considered in the design stage as long as the failure control. In other words, both the serviceability and ultimate limit state of the system should be evaluated in order to design sufficient support plan for a deep excavation wall. Structure failure events pose a significant threat not only to human life but also to the environment and in general to economic development. Sources of ground movement are lateral displacement of excavation wall and displacement due to support system installation [8]. Hence, in the presented study the horizontal displacement of the excavation top point (as a significant system response affecting the nearby facilities) is considered as the main system response to be controlled.

![Figure 1](image.png)

**Figure 1.** Schematic figure for effects of deep excavation on ground movement and adjacent buildings.

The uncertainty caused by soil and rock properties such as cohesion and elastic modulus poses a major challenge in geotechnical problems. Soils are variable, whether such variability is recognized in design or not. Addressing uncertainty does not increase the level of safety, but allows a more rational design as the engineer can calibrate the decisions on a desired or required performance level of a structure [9]. Reliability analysis methods represent the most important aspect of performance, namely the probability of unsatisfactory performance of a system. Using deterministic methods, excavations are designed based on the stability safety factor, deformation of excavation walls and adjacent buildings, ignoring the existing uncertainties in soil properties. The main advantage of reliability analysis over deterministic methods in terms of safety lies in the fact that, the designer is able to provide more complete and realistic information regarding the level of safety of design.

In recent years, the technology for implementing deep excavations in Iran has improved considerably. Using simple reliability analysis methods is encouraged in the design stage of the projects in order to propose optimum support system plans. In this study a framework is represented for the use of reliability methods in deep urban excavations analysis. Due to the great effect of deformation induced by deep urban excavations on the nearby facilities, the framework is based on controlling the horizontal displacement of the excavation top point as the main system response. The Random Set Method (RS) is selected for performing reliability analysis and a finite element software was used to model the deep excavations. The main reason to choose RS method is that it works well with the limited soil data available in real deep excavation projects and it takes the soil input variables in the form of intervals.

Being able to select and communicate the level of performance and reduce undesired conservatism, in turn, is beneficial in the economic sense [9]. It also reduces the risk of incorrect decisions due to unintentionally optimistic modeling [10]. In order to estimate the probability of unsatisfactory performance of the system, a threshold value is considered for horizontal displacement of the excavation top point as a target value and the probability of having displacement more than this value is compared to the acceptable probability of excessive deformation.

The presented framework is based on applying the previously published research findings. The Innovation is (I) to combine these methods in order to present a simple and practical framework and (II) applying it for 5 important deep excavation projects implemented during the last 10 years. The results were compared to the site measurements and field observations on the problems encountered in reality. The selected cases have been implemented in Tehran during 2010 to 2018. The support system plans for all cases were implemented based on deterministic analysis methods and no reliability analysis had been performed at the design stage. All studied cases were recognized as projects of high importance in urban areas, and were therefore monitored during the excavation process.
2 THE METHODOLOGY OF PRESENTED FRAMEWORK

The steps to implement the presented framework for reliability analysis of deep excavations in urban areas are summarized below:

[Step 1]: Performing the reliability analysis for the selected deep excavation projects.

[Step 2]: Selecting the target value for horizontal displacement of the excavation top point (as the main system response) and the acceptable probability of excessive deformation.

[Step 3]: Comparing the probability of excessive deformation to the acceptable value and evaluating the performance of proposed support system to find out whether any revision is required or not.

3 USED RELIABILITY ANALYSIS METHOD

Although various mathematical methods have been proposed and investigated for reliability analysis [11-23], applying these methods to geotechnical problems presents certain difficulties. It highlights the importance of proposing methods that draw on limited input data which are available in real geotechnical project such as deep excavations in order to represent an appropriate system uncertainty when the exact input variable values are not available. Since 2000, the random set method has been applied to a certain extent in geotechnical studies, and has mostly been used in tunnel studies. Peschl [25] and Schweiger and Peschl [26] combined the random set theory with the finite element method (FEM), it is possible to obtain more than one response focal element obtained from each deterministic FE calculation is equal to the product of probability of excessive deformation to the acceptable value and evaluating the performance of proposed support system to find out whether any revision is required or not.

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Tehran was considered in each study, which was not sufficient for a practical conclusion. Momeni et al. [31] evaluated the random set method for reliability analysis of deep excavations using Monte Carlo technique.

3.1 Concept of Random Set Method

The random set theory provides a general framework for dealing with set-based information and discrete probability distributions [26].

Assume that $X$ is a non-empty set containing all possible values of a variable $x$. Dubois and Prade [32] defined a random set on $X$ as a pair ($\mathcal{A}, m$), where $\mathcal{A} = \{A_i : i = 1, ..., n\}$ and $m$ is a mapping, $\mathcal{A} \rightarrow [0,1]$, so that $m(\phi) = 0$ and

$$\sum_{\phi \in \mathcal{A}} m(\phi) = 1 \quad (1)$$

In the above, $\mathcal{A}$ is known as the support of the random set, the sets $A_i$ are the focal elements, and $m$ is known as the basic probability assignment. Each set contains certain possible values for the variable $x$, and $m(A_i)$ can be viewed as the probability that $A_i$ is the range of $x$. Because of the imprecision of this formulation, it is not possible to calculate the precise probability of a generic $x \in X$ or generic subset $E \subset X$, but only the lower and upper bounds of this probability.

With numerical modeling based on the finite element method (FEM), it is possible to obtain more than one system response without making any changes to the model. Therefore, the random set in combination with the FEM will be a sufficient reliability analysis method.

Assume that function $f(A_i)$ represents a numerical model in the RS-FEM framework. The number of system input variables is $N$ and $n$ information sources are available. Hence, $n^N$ FE runs are required to consider all possible combinations of input variables based on the input sources of information. Because only extreme values of input random sets are considered, $2^N$ FE runs are also required to perform interval analysis.

The number of all calculations $n_s$ required to determine the bounds of the system response are:

$$n_s = 2^N \prod_{i=1}^{n} n_i \quad (2)$$

Assuming that input variables $(A_1, ..., A_n)$ are stochastically independent, the joint probability for the system response focal element obtained from each deterministic FE calculation is equal to the product of probability assignment $m$ for each input focal element as:

$$m(A_1 \times ... \times A_N) = \prod_{i=1}^{n} m_i(A_i) \quad (3)$$
3.2 Random Set Finite Element Method

With numerical modeling based on the finite element method, it is possible to obtain more than one system response without making any changes to the model. Therefore, in this study, reliability analysis is accomplished by using the random set in combination with the finite element method.

The steps to implement random set reliability analysis in combination with numerical modeling are summarized below:

[Step 1]: Define the geometry of the system, prepare the finite element model and select the appropriate constitutive model for material.

[Step 2]: Provide available sources of information to define different input random sets for the basic system variables. In the case that two sources of information are available, the probability of each basic variable can be set to 0.5. In this way, almost all sources of uncertainties are taken into consideration in the modeling procedure.

[Step 3]: Consider spatial variability in order to reduce uncertainty over the input random sets.

[Step 4]: Determine the most influential input variables using sensitivity analysis to reduce the number of required FE runs.

[Step 5]: Generate all possible combinations of input variables for the FEM and calculate the relevant probability share for each individual run. Each combination (set) is keyed into a finite element model, the model is run and the desired output is recorded. This process is repeated \( n_c \) times (Eq. 2) and the model outputs are recorded. The probability share assigned to the model output for each combination is calculated from multiplying the probability of each basic variable (Eq. 3).

[Step 6]: Perform FE calculations and represent the main system responses in terms of the lower and upper bounds of discrete cumulative probability functions (CDF). The resulting CDF are fitted using a best-fit method (Easyfit software [34] in this study) to achieve a continuous distribution function.

[Step 7]: Define suitable performance functions which can be evaluated using the reliability analysis results (bounds on continuous distribution functions of the system response) to obtain a range for the probability of failure or unsatisfactory performance. In this study an acceptable value is defined for horizontal displacement of the excavation top point as a target value and the probability of having displacement more than this value which indicates the probability of unsatisfactory performance of the system can be determined.

4 SELECTED PROJECTS SPECIFICATION

In order to assess the presented framework for reliability analysis of deep excavation projects, a number of monitored case studies must be undertaken. Tall buildings are common in northern Tehran. In order to supply sufficient space for parking, multi-story basements are constructed for these buildings; thus major deep excavation projects are performed to construct the basements. The routine depth of a deep excavation is 20 to 40 m. The soil layers generally consist of fill materials near the ground surface (1.5 to 3 m in depth), with clayey gravel and clayey sand being mostly frequently observed in succession. In order to consider the mentioned specifications of general deep excavations in Tehran, five excavation walls from 3 important monitored projects were selected as summarized in Table 1. The excavation areas of the selected projects are large and the inclination of the ground surface causes different excavation depths at different parts of the same project.

<table>
<thead>
<tr>
<th>Project</th>
<th>Excavation depth (m)</th>
<th>Fill material depth (m)</th>
<th>Excavation area (m²)</th>
<th>Support system</th>
<th>Main type of soil layers</th>
<th>Number of walls investigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Atlas Plaza, Commercial center</td>
<td>23 and 25</td>
<td>3</td>
<td>32000</td>
<td>nail-anchor combination</td>
<td>clayey gravel and clayey sand</td>
<td>2</td>
</tr>
<tr>
<td>Shiraz Street, Golestan Administrative-commercial building</td>
<td>34 and 36.5</td>
<td>1.5</td>
<td>8500</td>
<td>nail-anchor combination</td>
<td>clayey gravel and stiff clay</td>
<td>2</td>
</tr>
<tr>
<td>North Atlas, Hotel</td>
<td>36.5</td>
<td>1.5</td>
<td>16000</td>
<td>nail-anchor combination</td>
<td>clayey gravel and clayey sand</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 1. General specifications of selected projects.
Fig. 2 shows the excavation location and neighboring facilities, including buildings and roads for intended excavation projects. In the first project, as illustrated in Fig. 2(a), two walls were selected for the study because of the differences in horizontal displacements and surcharges. It should be noted that, according to the monitoring reports, several small cracks were observed on the ground surface near wall 2. The second excavation project (Fig. 2(b)) was launched in 2012. As activities proceeded, several cracks were observed around the northern part of the excavation, leading to anxiety in residents of nearby buildings; thus, excavation activities were suspended for a period in order to revise the stabilization plan. The soil profile that appeared during the excavation process indicated that the primary geotechnical investigations were not consistent with real soil conditions. Several residential buildings exist adjacent to the street located on the north side of the project, and according to the monitoring reports, the majority of horizontal displacements occurred in the northwestern part of the excavation; hence, reliability analysis is performed for walls nos.3 and 4 located in this region. The third excavation project is located in the northern half of the first deep excavation project site as illustrated in Fig. 2(c). This project was being carried out in order to construct a hotel, and during the excavation process, a building located in the southern half of the current excavation was being built.

The excavation support system implemented for all projects was a nail-anchor combination. Support systems were designed by geotechnical engineers applying deterministic methods. In the presented study the effect of uncertainty in soil properties on reliability of deep excavations has been taken into account applying RS-FEM. The support system is considered to be equal in all finite element runs performed for reliability analysis of each intended wall. Hence for the sake of brevity the details of support systems are not explained in detail.

5 IMPLEMENTATION OF RS-FEM

Numerical modeling was done using finite element software [35]. Fig. 3 plots the system model cross-section for intended walls.

For each soil variable, according to the geotechnical reports and engineering judgment, along with expert knowledge, two ranges with a weight of 0.5 each are suggested.

In order to consider the spatial variations in soil parameters, the primary values of the variables are modified slightly, using a variance reduction technique. In this study, the method proposed by Schweiger and Peschl [26] is applied. For the purpose of brevity, details of this method are not presented here and can be found in other studies [26, 31].

The modified upper and lower bounds of the suggested ranges, and the reference values for each soil variable, are represented in Tables 2-5.
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Figure 3. Cross section of the system for investigated case studies.

Table 2. The ranges of random sets and reference values for soil variables considering spatial variation (case studies 1, 2).

<table>
<thead>
<tr>
<th>Layer</th>
<th>Cohesion $c$ (kN/m²)</th>
<th>Friction angle $\phi$ (°)</th>
<th>Elastic modulus $E_{50}^{ref}$ (MN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range of sets</td>
<td>Ref</td>
<td>Range of sets</td>
</tr>
<tr>
<td>Fill Material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 1</td>
<td>6.93-13.21</td>
<td>9.65</td>
<td>29.29-33.29</td>
</tr>
<tr>
<td>Set 2</td>
<td>6.07-11.79</td>
<td></td>
<td>28.71-32.71</td>
</tr>
<tr>
<td>Clayey gravel (dry)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 1</td>
<td>72.86-102.86</td>
<td>85</td>
<td>38.57-43.29</td>
</tr>
<tr>
<td>Set 2</td>
<td>67.14-97.14</td>
<td></td>
<td>37.43-42.71</td>
</tr>
<tr>
<td>Clayey gravel (saturated)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 1</td>
<td>62.86-92.86</td>
<td>75</td>
<td>31.29-35.29</td>
</tr>
<tr>
<td>Set 2</td>
<td>57.14-87.14</td>
<td></td>
<td>30.71-34.71</td>
</tr>
<tr>
<td>Clayey sand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 1</td>
<td>46.43-66.43</td>
<td>55</td>
<td>29.93-33.93</td>
</tr>
<tr>
<td>Set 2</td>
<td>43.57-63.57</td>
<td></td>
<td>29.07-32.07</td>
</tr>
</tbody>
</table>

Table 3. The ranges of random sets and reference values for soil variables considering spatial variation (case study 3).

<table>
<thead>
<tr>
<th>Layer</th>
<th>Cohesion $c$ (kN/m²)</th>
<th>Friction angle $\phi$ (°)</th>
<th>Elastic modulus $E_{50}^{ref}$ (MN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range of sets</td>
<td>Ref</td>
<td>Range of sets</td>
</tr>
<tr>
<td>Fill Material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 1</td>
<td>5.75-13.13</td>
<td>9.81</td>
<td>26.75-30.75</td>
</tr>
<tr>
<td>Clayey gravel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 1</td>
<td>53.77-73.77</td>
<td>65</td>
<td>32.75-36.75</td>
</tr>
<tr>
<td>Set 2</td>
<td>56.23-76.23</td>
<td></td>
<td>33.25-37.25</td>
</tr>
</tbody>
</table>
Table 4. The ranges of random sets and reference values for soil variables considering spatial variation (case study 4).

<table>
<thead>
<tr>
<th>Layer</th>
<th>Cohesion $c$ (kN/m$^2$)</th>
<th>Friction angle $\varphi$ (˚)</th>
<th>Elastic modulus $E_{50}^{ref}$ (MN/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range of sets</td>
<td>Ref</td>
<td>Range of sets</td>
</tr>
<tr>
<td>Fill Material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 1</td>
<td>5.77-13.15</td>
<td>9.81</td>
<td>26.77-30.77</td>
</tr>
<tr>
<td>Clayey gravel (dry)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 1</td>
<td>33.83-67.66</td>
<td>53.09</td>
<td>32.77-36.77</td>
</tr>
<tr>
<td>Set 2</td>
<td>36.17-72.34</td>
<td></td>
<td>33.23-37.23</td>
</tr>
<tr>
<td>Clayey gravel (saturated)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 2</td>
<td>16.17-36.17</td>
<td></td>
<td>33.23-37.23</td>
</tr>
<tr>
<td>Stiff Clay</td>
<td></td>
<td>94.04</td>
<td>8.77-12.77</td>
</tr>
<tr>
<td>Set 2</td>
<td>79.26-112.34</td>
<td></td>
<td>9.23-13.23</td>
</tr>
</tbody>
</table>

Table 5. The ranges of random sets and reference values for soil variables considering spatial variation (case study 5).

<table>
<thead>
<tr>
<th>Layer</th>
<th>Cohesion $c$ (kN/m$^2$)</th>
<th>Friction angle $\varphi$ (˚)</th>
<th>Elastic modulus $E_{50}^{ref}$ (MN/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Range of sets</td>
<td>Ref</td>
<td>Range of sets</td>
</tr>
<tr>
<td>Fill Material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 1</td>
<td>3.75-8.75</td>
<td>6.5</td>
<td>30.75-34.75</td>
</tr>
<tr>
<td>Set 2</td>
<td>4.25-9.25</td>
<td></td>
<td>31.25-35.25</td>
</tr>
<tr>
<td>Clayey gravel (dry)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 1</td>
<td>48.77-66.89</td>
<td>58.44</td>
<td>32.75-36.75</td>
</tr>
<tr>
<td>Set 2</td>
<td>51.23-68.11</td>
<td></td>
<td>33.25-37.25</td>
</tr>
<tr>
<td>Clayey gravel (saturated)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set 1</td>
<td>38.77-60.66</td>
<td>51.56</td>
<td>32.75-36.75</td>
</tr>
<tr>
<td>Set 2</td>
<td>41.23-64.34</td>
<td></td>
<td>33.25-37.25</td>
</tr>
</tbody>
</table>

Sensitivity analysis is carried out to identify which variables exert the most influence on the system response, and subsequently reduces the number of required finite element runs. In this study, the method provided by the U.S. Environmental Protection Agency (EPA) [36] generalized and made compatible with the random set approach by Peschl [25], is used.

According to the sensitivity analysis conducted based on the horizontal displacement of the excavation top point, the variables listed in Table 6 were selected as the most influential ones for each case study.

In order to establish belief and plausibility functions (for example, upper and lower bounds) for a specific system response obtained from finite element calculations; the probability box (p-box) of model output has been constructed. A p-box is a pair of cumulative probability distribution functions (CDFs) that represents the imprecise probability distribution of a random variable [37]. The discrete cumulative probability functions are fitted by means of best-fit methods; to obtain a continuous distribution function matched with each of the upper and lower bounds of the reliability analysis results.

5.1 Acceptable value for horizontal displacement of the excavation top point

Considering an acceptable (Threshold) value for horizontal displacement of the excavation top point for each
case study, one can estimate the probability of unsatisfactory performance of the system. The acceptable displacement depends on national codes and engineering judgment to some extent [38].

Depending on project constraints, requirements with respect to control of wall and ground movements will vary. Estimates of wall and ground movements are typically made using semi-empirical relationships developed from past performance data. According to federal highway administration manual [39] the maximum horizontal deformation, $\delta_{\text{max}}$, for anchored walls constructed in sands and stiff clays average approximately 0.002 H with a maximum of approximately 0.005 H where H is the height of the wall. Navy design manual DM 7.2 [40] suggests that walls in sands and silts might displace laterally up to 0.002 H. This value for stiff and soft clay was recommended to be 0.005 H and 0.002 H, respectively. PSCG [41], based on the importance of utilities adjacent to excavation, set some criteria for excavation protection levels in Shanghai, China. According to these criteria, $\delta_{\text{max}}$ should be less than 0.003 H in the case that important infrastructure or facilities exist within a distance of 1-2 H from the excavation. If no important infrastructure and facilities exist within a distance of 2 H from the excavation, then $\delta_{\text{max}}$ should not exceed 0.007 H.

According to the above-mentioned references the acceptable value of horizontal displacement for the intended deep excavation walls are presented in Table 7.

<table>
<thead>
<tr>
<th>Case study NO.</th>
<th>Excavation depth (m)</th>
<th>Neighboring situation</th>
<th>Acceptable $\delta_{\text{max}}/H$ (%)</th>
<th>Threshold value considered for horizontal displacement of the excavation top point (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23</td>
<td>No important facility and building</td>
<td>0.5</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>No important facility and building</td>
<td>0.5</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>36.5</td>
<td>Several residential buildings</td>
<td>0.2</td>
<td>65</td>
</tr>
<tr>
<td>4</td>
<td>34</td>
<td>No important infrastructure and facilities within a distance of 2 H from the excavation</td>
<td>0.2</td>
<td>65</td>
</tr>
<tr>
<td>5</td>
<td>36.5</td>
<td>No important facility and building</td>
<td>0.5</td>
<td>150</td>
</tr>
</tbody>
</table>

6 ACCEPTABLE PROBABILITY OF EXCESSIVE DEFORMATION

As mentioned earlier, excessive movements can occur without a failure mechanism occurring [7], and should be considered in the design stage as long as the failure control. It is worth mentioning that the probability of excessive deformation for a deep excavation is different from probability of ultimate failure or collapse. In order to decide whether the determined values for aforementioned probabilities are acceptable, a target value should be considered for each one. The acceptable range for the probability of failure reported in many researches is from 10^{-6} to 10^{-4} [42-45]. The acceptable probability of excessive deformation (APED) is certainly higher than these values because of the catastrophic consequences of deep excavation collapse compared to excessive deformation which might cause serviceability failure. In this study the value of 0.1 is considered for APED as proposed by Momeni et al. [38].

7 RESULTS

Figures 4 to 8 represent the reliability analysis results in comparison with the acceptable horizontal displacement value and in-situ measurements for the excavation top point in all studied cases. Such figures could be used as a tool for engineers to discuss on reliability of the system and improve the decision making procedure in order to represent proper support system plans.

7.1 Comparison and discussion for case study 1

![Figure 4. Reliability analysis results compared to threshold value and in-situ measurements for case study 1.](image-url)
Fig. 4 shows that:

- The site measurement values (19 mm) fall within the upper and lower bounds. This observation is indicative of the appropriateness of the soil variable input values and shows the validity of the selected reliability method in estimating the deformation of system for case study 1.
- Even in the most unfavorable circumstances (upper bound), the horizontal displacement of the excavation top point does not exceed 57 mm, which is considerably less than the threshold value (100 mm); hence, it can be concluded that the support system implemented for the investigated wall was designed conservatively during the deterministic design stage.

7.2 Comparison and discussion for case study 2

Fig. 5 shows that:

- The site measurement value of the horizontal displacement at the end of the excavation process is equal to 65 mm, which falls within the lower and upper bounds of the results.
- Under the least favorable circumstances (upper bound), the probability that the horizontal displacement of the excavation top point will exceed the threshold value is equal to 0.22 which is more than the APED value of 0.1. This result is in line with the small cracks observed on the ground surface near the excavation.

The walls investigated in case studies nos. 1 and 2 are designed by the same designers, based on identical safety factors and displacement criteria for the deterministic approach. However, according to the field observations, the probabilities of unsatisfactory performance of these two walls were different. This issue is in line with the reliability analysis results and may indicate the applicability of non-deterministic methods to predicting deep excavation system performance compared to the common deterministic methods.

7.3 Comparison and discussion for case study 3

As mentioned in Section 4, due to incorrect investigation of soil conditions considered during the deterministic design stage, the horizontal displacement calculated by means of numerical modeling was less than the threshold value. This inaccuracy led to the proposal of an inappropriate support system and subsequently the appearance of large cracks around the project location during excavation.

Fig. 6 shows that:

- The site measurement value is 189.5 mm, which exceeds the threshold value (65 mm). This indicates that the implemented support system, designed based on the deterministic approach, was not safe.
- The site measurement data is not placed within the range between the lower and upper bound of reliability analysis results. This is because of the significant differences between the geotechnical site investigation data and actual condition of the soil layers. However, the horizontal displacement threshold value falls within the upper and lower bounds, and is very close to the lower bound of the reliability analysis results. The threshold value position may be considered as a warning of the possibility of inappropriate system performance; hence, even in such
circumstances, the non-deterministic approaches may provide more reliable results than deterministic analysis methods.

- According to the lower bound of the results, the probability of the horizontal displacement being more than the threshold value (65 mm) is approximately 0.2. However, when considering the upper bound of the reliability analysis results, the probability of displacements being more than the threshold value is equal to 1. This demonstrates the large difference between the lower and upper bounds of the reliability analysis results, and may serve as a significant warning to the designer regarding the input data and considered support system.

7.4 Comparison and discussion for case study 4

Fig. 7 shows that:

- Although the geotechnical site investigation was not implemented correctly and did not represent the actual soil conditions, the field measurement of the horizontal displacement (152 mm) falls within the lower and upper bounds of the reliability analysis results.

Fig. 7. Reliability analysis results compared to threshold value and in-situ measurements for case study 4.

- The site measurement value (152 mm) exceeds the horizontal displacement threshold value (65 mm). As per the conclusion for the third case study, incorrect investigation of the soil condition resulted in the proposal of an inappropriate support system, and consequently, large cracks appeared around the project location during excavation activities.

- The probability of excessive deformation for both the upper and lower bounds of the results are equal to 1 and more than the APED; hence, in case study 4, the reliability analysis results demonstrates the inappropriateness of the support system, which was not recognized during the deterministic design stage.

7.5 Comparison and discussion for case study 5

Fig. 8 shows that:

- The site measurement value (71 mm) falls within the upper and lower bounds of the reliability analysis results.

- The threshold value is greater than the values of the upper and lower bounds of the reliability analysis results; hence, the reliability analysis results demonstrate that even in the least favorable circumstances (upper bound), the probability of inappropriate system performance is zero.

Fig. 8. Reliability analysis results compared to threshold value and in-situ measurements for case study 5.

8 OVERALL DISCUSSION ON PROBABILITY OF UNSATISFACTORY PERFORMANCE OF STUDIED CASES

The threshold values for horizontal displacement of the excavation top point for case studies 1 to 5 are displayed in Table 8, along with the reliability analysis results, in order to evaluate the performance of the studied cases.

The conclusions drawn from the data presented in Table 8 are:

For case studies 1 and 5, which encountered no problems in practice, the probability of unsatisfactory system performance for both the lower and upper bounds of results is equal to zero. The reliability of the system in case study 2 is worse than those of nos. 1 and 5, as
small cracks were observed on the ground surface near the excavation. According to the upper bound of the results for case study 2, the probability of the horizontal displacement exceeding the threshold value is equal to 0.22 which exceeds the APED of 0.1 and is in line with the field observations. The system performance for case studies 3 and 4 become significantly worse. For case study 3, in which excavation activities were suspended because of large cracks being observed around the excavation, the lower bound of the results was very close to the threshold value, and when the upper bound of results are considered, the probability of unsatisfactory system performance is equal to 1. For case study 4, in which excavation activities were suspended as in case 3, even in the most favorable circumstances (lower bound of results) the probability of unsatisfactory support system performance is equal to 1 and exceeds the acceptable value of 0.1. Hence, the reliability analysis results and actual field observations are in good agreement for all of the studied cases.

9 CONCLUSION

In this paper the performance of 5 real deep excavation projects were evaluated by a suggested framework and the following conclusions were drawn.

- When applying deterministic analysis methods, inaccurate site investigations may lead to the design of unsafe support systems for deep excavation. However, when using the reliability analysis method, the large difference between the upper and lower bounds of the results (as concluded for case studies 3 and 4) could be considered as a warning to evaluate the geotechnical site investigation process and revise the support system plan for deep excavation. This would prevent problems that may occur as a result of improper system design.
- When a system is designed very conservatively, the reliability analysis results could reveal it. For example in the case studies 1 and 5, the probability of unsatisfactory performance of system is equal to zero according to both lower and upper bounds of the results. This observation is indicative of the conservative design of the system in the deterministic design stage. Applying reliability analysis method for such cases may lead to optimize the plan.
- The results of reliability analysis could be used to predict unsatisfactory performance of deep excavation systems. For the five studied cases, wherever large cracks were observed on the ground surface near the deep excavation (case studies 3 and 4), in the least favorable circumstances, the probability of unsatisfactory system performance was equal to 1 which was more than the APED of 0.1. For the cases that encountered no problems in reality (1 and 5), the probability of unsatisfactory system performance was equal to zero according to both lower and upper bounds of the results. For the situation in which small cracks were observed on the ground surface near the excavation (case study 2), in the least favorable circumstances the probability of unsatisfactory system performance was equal to 0.22 and more than 0.1.

The suggested framework was applied for 5 real deep excavation projects implemented during the last 10 years. The combination of field observations and site measurements with the probability of unsatisfactory performance determined using reliability analysis, and the APED showed that the presented framework is an applicable tool to help the designer improve the decision making procedure and represent more proper support system plans compared to deterministic analysis methods.

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