Computers and Geotechnics 100 (2018) 203–215

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Evaluating random set technique for reliability analysis of deep urban excavation using Monte Carlo simulation

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ARTICLE INFO

Keywords:
Random set
Finite element
Monte Carlo
Deep excavation
Reliability analysis

ABSTRACT

Over the last few years, the importance of non-deterministic techniques in Geotechnical engineering is highlighted in literature. Random set (RS) theory is recently being utilized for reliability analysis of geotechnical problems, however, its application in deep urban excavation is not yet investigated for a real case study. Hence, in this paper, an attempt is made to investigate the feasibility of the RS method in determining the reliability of deep excavations. For this reason, a 27-meter-deep urban excavation in Tehran, Iran is considered as a case study. The excavation is numerically modelled. Subsequently the reliability analysis is performed. Findings indicate that the probability of collapse of excavation is as low as 10^{-7} which suggests that the project is safe against collapse. The aforementioned conclusion is confirmed when RS results were compared with site observation. Additionally, RS results were evaluated using Monte Carlo (MC) technique. Although further studies for more real case studies are recommended, good agreement between the results of MC and RS methods suggests the feasibility of RS technique for estimating the reliability of deep urban excavations.

1. Introduction

In recent past years the rate of underground construction *i.e.* deep excavation has been increased rapidly. It is generally attributed to high cost of land, lack of sufficient space for urban development as well as regulation requirements. Precise stability analysis of deep excavation is crucial due to the fact that failure of such excavations can lead to catastrophic consequences. There are various methods for analysis of deep excavation projects; however, they can be categorized into deterministic and non-deterministic approaches. Although implementation of conventional deterministic methods is usual practice, in recent past years, the use of non-deterministic techniques has drawn considerable attention. As underlined in the 55th Rankin lecture [1], non-deterministic methods work better compared to deterministic methods in highlighting the likelihood of failures of geotechnical problems. In fact, non-deterministic techniques deal with reliability analysis. They suggest the probability of failure (P_f) and indicate how reliable a deep excavation project is. Many studies have shown the feasibility of non-deterministic techniques in reliability analysis of different geotechnical structures. The application of random field theory in performing reliability analysis of deep excavations is underlined in study conducted by Luo et al. [2].

Some researchers reported the workability of fuzzy methods in conducting reliability analysis of Geotechnical problems [3]. Other methods include the first order second moment and the second order second moment [4]. The former utilizes the first terms of a Taylor series expansion of the performance function to approximate the expected value and variance of the performance function while the latter uses the terms in the Taylor series up to the second order. Furthermore, these methods provide values of the reliability index, and as a disadvantage to them, a further assumption about the performance function is necessary to obtain the probability of failure [5–8]. The use of random set theory coupled with numerical techniques in solving geotechnical problems is highlighted in literature. The main advantage of this technique over other similar methods is the point that random set (RS) method works well with limited soil data and it takes the soil parameters in the form of intervals. This is of interest for deep excavation problems as compiling numerous data is a difficult task to be accomplished. A number of researchers including Tonon [9], Schweiger and Peschl [10] and Nasekhian and Schweiger [11] merged RS theory with Finite element method to perform reliability analysis of geotechnical problems.

RS-FEM modelling procedure starts with selection of input parameters

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https://doi.org/10.1016/j.compgeo.2018.03.012
Received 2 December 2017; Received in revised form 15 March 2018; Accepted 27 March 2018

(soil parameters like friction angle, φ, or unit weight, γ) in the form of intervals. Subsequently, a sensitivity analysis is performed for identifying the most important input parameters. 2^N finite element analysis are conducted where N is the number of input parameters. Finally, two optimistic and pessimistic limits are determined using a p-box representation. RS-FEM results are displayed in terms of cumulative probability distribution functions of lower and upper bounds. Different limit states can be introduced for quantifying the unfavorable serviceability function of an excavation. More details on RS-FEM procedures is provided in Section 4. A review on related works shows that the first study, which suggests the feasibility of RS-FEM in deep excavation projects, was performed by Scheweiger and Peschl [10]. Nevertheless, their study was not based on a real case study. Other scholars [12–15] also mentioned that RS-FEM is a feasible tool in dealing with urban excavation problems. For the purpose of brevity details of their works is not presented here, however, a brief description of the excavation projects studied in their paper can be found in study conducted by Momeni et al. [14].

Overall, this paper is mainly aimed to analyze the reliability of a real deep excavation project using a relatively new technique called random set finite element method (RS-FEM). To the best of authors' knowledge, its application in reliability analysis of a real excavation project is not investigated in well-established papers and therefore, this study attempts to introduce the application of RS-FEM as a feasible and practical tool for determining the reliability of deep urban excavations. The technique is relatively new, simple and requires relatively few analysis. Additionally, for evaluation purpose, Monte Carlo (MC) simulation, which is a well-respected and widely spread technique, is utilized.

2. Case study

The deep urban excavation project presented in this paper is stabilized with the aid of soil anchors. The project is located near Chitgar lake, Tehran, Iran. The plan area of the project is 9000 m^2 and the maximum depth of excavation is 27 m. The western side of the excavation is adjoined to a number of high-rise buildings. Similarly, the northern side of the project is adjoined with a street and a bus station. The southern and eastern sides of the excavation are adjoined with Chitgar national park. Fig. 1 shows the deep excavation project and the adjacent utilities.

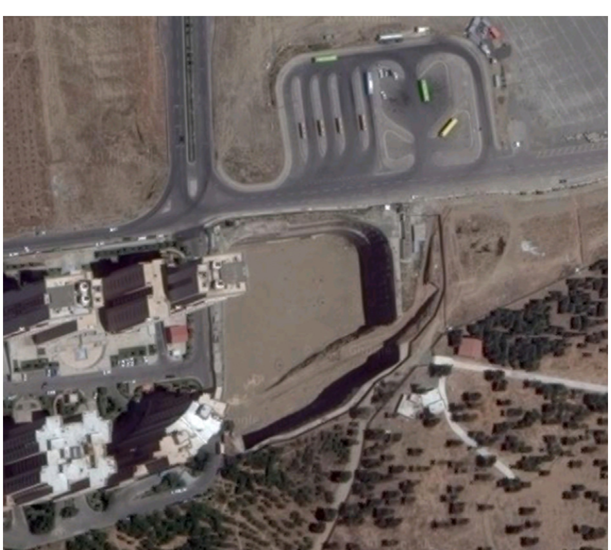

Fig. 1. SABA project location.

Different layers of soils were identified with the aid of site investigation (SI). According to the SI report, the first two meters was a low quality mixture of sand, clay and gravel. The underlying layers were mainly cohesive gravel soils. The observed ground water level was far below the ground surface. As shown in Fig. 2 soil anchors were used for stabilizing the excavation. These tendons are often installed at low angles. Soil anchors, which have a number of strands, are grouted in partial lengths allowing them to have both a fixed zone and free stressing zone. The bar within the fixed zone develop a bond to the surrounding soil. The free stressing zone is subsequently tensioned, which as a consequence leads to immediate resistance mobilization. In the presented project, 6-strands anchors were installed in six levels with average vertical and horizontal distances of 3 m and 4 m, respectively. The fixed length of anchors was set to be 6 m and the unbound length of anchors was within the range of 4.5–14 m. It is worth mentioning that the northern side of the project is considered for analysis in this paper. Details on engineering properties of soil as well as mechanical properties of anchors are presented in Section 4.2.

3. Random sets theory

In order to counteract situations when there are ranges of data at designer's disposal, random set theory can be used [16–18]. The concept of random set theory is an extended concept of random variable and random vector. Random set is defined on imprecise data [19–21]. The following paragraphs provide brief explanations on random set theory and its related keywords; more details on the theory is beyond the scope of this paper and can be found in classic books *e.g.*, Foundations of Random Sets [22].

Nevertheless, let X be an imprecise interval variable *e.g.* cohesion of soil (C). Random set can be defined on X as a pair ($\Im$,m) where $\Im = \{A_i: i = 1. \ldots .n\}$ and m is a mapping, $\Im \to [0.1]$, so that $m(\varnothing) = 0$ and

$$\sum_{A \subseteq \Im} m(A) = 1 \tag{1}$$

where $\Im$ contains all the possible values of a variable $\boldsymbol{x}$ and A_i are the focal elements *i.e.* all possible subsets in the range of X, and $m(A)$ can be defined as the probability that A is in the range of x. For example, suppose that possible values for the cohesion are between 15 and 65 kN/m^2 and there are four different Geotechnical reports for a specific site which suggest different values for the cohesion of soil. According to the first report, the cohesion is between 20 and 40. In the random set context, the subset (A_1) is between 20 and 40 (see Fig. 3). Similarly, suppose the second subset (A_2) is between 22 and 32; the third subset (A_3) ranged from 20 to 47 and the fourth subset (A_4) is between 27 and 60. Their relative frequency, m, in this example would be 0.25 for each subset. Overall, the number of subsets (i) can vary from i = 1 to i = n, where n is the number of available sources [10,11,23]. Owing to imprecision, only lower and upper bounds of probability of a total event $Z \subset X$ can be drawn in RS theory. That is to say, in random set theory, imprecise probabilities are defined by the intervals $[Bel(Z). Pl(Z)]$ where the belief function, Bel, of a subset Z is a set function acquired by means of the summation of basic probability assignments of subsets A_i included in Z; and the plausibility function, Pl, of a subset Z is a set function acquired by means of the summation of basic probability assignments of subsets A_i having non-zero intersection with Z [24] (see Fig. 4).

The random set theory can be presented in a P-box representation system as shown in Figs. 3 and 4 [9]. For a closed interval of a focal element $A_i = \{x | x \in [l_i. u_i]\}$, Bel (x) and Pl (x), the lower and upper cumulative probability distribution functions, respectively, can be determined using equations from 2 to 5.

$$\text{Bel(x)} = \sum_{i:x \geqslant u_i} m(A_i) \tag{2}$$