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RELIABILITY ANALYSIS OF RC STRUCTURES CONSIDERING SOIL STIFFNESS VARIABILITY AND SOIL-STRUCTURE INTERACTION

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ABSTRACT: This study investigates the reliability of reinforced concrete (RC) structures under variability in soil parameters, modeled using random fields. Numerical simulations with OPTUM G2 software and Monte Carlo methods evaluate the effects of spatial soil stiffness variability on internal forces, deformations, and settlement patterns, emphasizing soil-structure interaction (SSI). Key results indicate that even small differential settlements induced by SSI effects can generate bending moments and shear forces that impact structural stability. Random fields of Young's modulus, modeled with a mean of 10 MPa and a coefficient of variation (COV) of 30%, reveal significant spatial variability. Stiffer soil zones exhibit reduced settlement, whereas softer areas undergo greater deformation, affecting load redistribution. Failure probability (P_f) analysis highlights high sensitivity to correlation distances, peaking at 12.5% for intermediate distances (4–12 m) and diminishing at shorter or longer values. These findings underscore the importance of considering SSI and soil heterogeneity in structural design to avoid underestimating deformation and stress responses. By integrating realistic variability in soil properties, this research offers insights into optimizing RC structure reliability under geotechnical uncertainties.

Keywords: Spatial soil variability, Reliability analysis, Soil structure interaction, Numerical modeling, Monte Carlo simulations

1. INTRODUCTION

The performance of reinforced concrete (RC) structures throughout their lifespan is significantly influenced by both the superstructure and the foundation soil. Accurate modeling of soil-structure interaction (SSI) is crucial for designing safe and cost-effective structures, necessitating its integration into mechanical analyses. While previous studies have examined SSI's effects on RC structures, many relied on simplified soil behavior models. The research employed non-linear models to address variations in contact forces, emphasizing the importance of non-linear material behavior for predicting SSI accurately [1-3]. More recent work underscores the necessity of considering both soil properties and structural stiffness to prevent premature degradation of RC structures[4-6]. Additionally, studies have highlighted the complexity of SSI and the need for comprehensive consideration of these factors [7-11].

These uncertainties related to soil variability must be accounted for to ensure accurate modeling of soil-structure interaction (SSI) and to prevent premature degradation of reinforced concrete structures. In geotechnical engineering, soil variability is a complex characteristic influenced by various sources of uncertainty. These uncertainties mainly stem from intrinsic variabilities, measurement errors, and transformation uncertainties, such as correlations between properties and rheological models [12-13]. Reliability analysis developed for sizing structures under random conditions highlights the importance of reliability as a key indicator of operational safety. Many authors have addressed the unknowns of soil parameters, making probabilistic and reliable analysis in geotechnics possible [10, 13-20].

Despite these improvements, most research to date has focused solely on the interactions between soil, foundations, and structures without examining how changes in soil strength parameters can affect outcomes [21-24]. These differences arise from many unknown sources and contribute to the uncertainty in the results of soil-structure interaction analyses [25-27].

Building on these foundational insights, several studies have employed advanced methods to further investigate the complexities of soil variability and its impact on reinforced concrete structures, particularly concerning the effects of differential settlement.

The study [28] conducted a reliability analysis on foundation settlements and differential settlements of paired footings utilizing the random finite element method, treating Young's modulus as a spatial random variable modeled as a lognormal random field. Meanwhile, another study [29] examined the variability in settlement and differential settlement of a pair of foundations situated on a random heterogeneous medium. They predicted the stochastic differential settlement by integrating the Monte Carlo Simulation (MCS) with the deterministic finite element method. In the study [30], the finite element code Cast3M was used to analyze the problem of an isolated footing and two adjacent footings resting on a heterogeneous elastic soil. The spatial variability of the soil properties was represented using the theory of rotating bands in conjunction with a Monte Carlo method. The numerical simulations focused on absolute settlement and differential settlement. These simulations confirmed the existence of a critical range for the ratio between the soil's correlation length and the distance between footings, which is influenced by the spacing and size of the footings. It was also shown that the characteristic differential settlements are capped at a value that is a multiple of the average individual settlement.

Additionally, the behavior of shallow foundations under complex loading conditions using probabilistic methods, employing improved subset simulation for the reliability analysis of differential settlement between two footings [31]. In [17], SRSM was used to assess the reliability of elastic differential settlement between two footings of the same size and equal loading. Another study, documented in [18, 32], examined how differential settlement affects framed structures. The results of this research helped improve the combined design of geotechnical and structural elements.

In this regard, the effect of soil variability on the performance of a statically indeterminate single-span, single-story frame structure was studied in [27]. They examined differential settlement between footings as a factor influencing the internal forces within the frame. The study utilized the empirical method developed by [33], which estimates footing settlement in granular soils based on standard penetration test results. This method considers factors such as the increase in effective stress at the foundation level, the width of rectangular footings or the diameter of circular footings, the shape factor, the depth of influence correction factor, and the compression index.

In this context and building on the work of [27], this paper investigates how soil stiffness variability and soil-structure interaction affect the performance of a three-span, four-story frame structure. Specifically, the study evaluates the differential settlement between the footings and its impact on the internal forces within the frame. The primary objective is to understand how spatial variability in soil stiffness, modeled using stochastic fields, influences the reliability of RC structures by generating internal forces such as bending moments, normal forces, and shear forces. This work also aims to provide a methodological framework for integrating stochastic soil properties into geotechnical and structural analyses, enhancing reliability assessments under geotechnical uncertainties.

The soil is modeled as a continuous medium following an elastic behavior law with a randomly distributed Young's modulus (E). Using OPTUM G2 software [34], soil-structure interaction, settlements, and internal forces are analyzed. The study employs Monte Carlo simulations to calculate the probability of failure concerning differential settlement thresholds, with stochastic fields generated based on log-normal distributions. Parameters such as the mean elastic modulus, coefficient of variation (COV = 30%), and horizontal and vertical correlation lengths are incorporated, reflecting realistic spatial variability.

The approach enables the determination of vertical displacements, including differential settlements, and their effects on internal forces. It demonstrates how harmful forces arise due to spatially distributed soil properties, even in unloaded and weightless frames. By focusing on the soil-foundation-structure system's response, this study highlights the influence of soil heterogeneity on structural reliability and failure probabilities.

To generate a random field for a specific material parameter, four input parameters are required: the mean value of the parameter, the coefficient of variation (COV) expressed as a percentage, the horizontal correlation length (Dx) in meters, and the vertical correlation length (Dy) in meters. Typically, the vertical correlation length is less than the horizontal correlation length. The coefficient of variation of the soil's elastic modulus COV (E) is approximately 30%. To evaluate the response of the numerical model, we conducted simulations using the Monte Carlo method and numerical modeling with OPTUM G2 (2D) finite element software. The analysis of soil and structural deformation utilized spatially distributed values for the soil modulus. Harmful internal forces, such as bending moments and normal and shear forces, are generated in the structure due to differential settlements in an unloaded and weightless frame. This analysis aimed to assess the response of the soil-foundation-structure system and calculate the probability of system failure while considering the spatial variability of soil properties.

The subsequent sections of this article will be organized as follows: first, we will outline the modeling procedure for the structural frame and soil using OPTUM G2 software. Next, we will examine the effects of soil-structure interaction in a deterministic context. This will be followed by a reliability assessment of RC structures, considering the variability of soil stiffness, with a focus on log-normal distribution and random field distributions. We will then analyze the influence of spatial soil variability on structural response, specifically regarding differential settlements and detrimental internal forces. Finally, the paper will conclude with appropriate remarks summarizing the key findings.

2. RESEARCH SIGNIFICANCE

This research investigates the reliability of RC structures under the influence of soil variability, a factor often oversimplified in prior studies. By using OPTUM G2 software, the soil is modeled as a continuous medium with an elastically varying Young's modulus (E) that better reflects real-world soil behavior. The study demonstrates the importance of accounting for soil stiffness variability in structural design to avoid underestimating potential deformations and stresses. These insights are particularly relevant for engineers involved in the design of foundations, as they underscore the need to incorporate soil heterogeneity to improve safety margins and optimize structural performance. Practically, this research can guide the development of more reliable design codes, contributing to the creation of more resilient infrastructure. It also highlights the necessity of incorporating soil-structure interaction (SSI) effects in geotechnical assessments, particularly for projects in areas with heterogeneous soil conditions. This approach will allow for better predictions of foundation performance under varying soil conditions, reducing the risk of structural failures due to unexpected settlement or stress distributions.

3. NUMERICAL MODELLING PROCEDURE

This paper employs numerical analysis to examine the reliability of adjacent footings of a frame structure settling differently due to random variation in the stiffness of the underlying foundation soil. The study looks at how changes in space affect the frame structure. The analysis uses a plane deformation approach. The structure comprises three bays, each 6 meters long, and four stories, each 4 meters high. Shallow, rigid foundations, with widths B1 and B2 for the outer and inner foundations, respectively, and a height of 0.5 meters, support the frame. The frame is built on loose sand defined by Young's modulus (E) and Poisson's ratio (ν). The frame's columns and beams are elastic, represented by plate elements (see Table 1). A special element known as a rigid plate connects the columns to the rigid foundation. After preliminary calculations, we established the study domain to minimize boundary effects, resulting in a domain with a length of 5B1 + 3L + 5B1 and a height of 5B2, as shown in Fig.1.

Fig.1 shows the fixed lower boundary and the vertical boundary's horizontal constraint.

We use the academic version of OPTUM G2 computer code (2D), a commercially available finite element program that lets us do stochastic analyses, especially random-field modeling of how material parameters change over space. The study focuses on initial elastic settlements due to service loads, by assigning an elastic behavior model to the soil. In this study, Young's modulus (E) is randomized, while Poisson's ratio (ν) remains constant.

This study is modeled using a two-dimensional (2D) plane strain approach. For structures that extend significantly in the out-of-plane direction, the 2D elastic modulus field is interpreted as an average over this dimension. For finite dimensions, the 2D model serves as an approximation. However, it is important to acknowledge the limitations of using a 2D model for soil-structure interaction (SSI) analysis. This approach does not capture three-dimensional effects, such as out-of-plane forces, anisotropic soil behavior, or complex boundary conditions. While computationally efficient, the 2D assumption may be less accurate in cases where significant 3D interactions occur. Future studies could extend this work to a 3D framework, allowing for a more comprehensive assessment of SSI and further validation of the findings presented here.

We perform the finite element calculations using 2000 elements, choosing the 6-node Gauss element type for its suitability for this analysis. We use a log-normal distribution for Young's modulus (E) for loose sand, with a mean value of 10 MPa and a coefficient of variation (COV) of 30%, as reported by. We perform the finite element calculations using 2000 elements, choosing the 6-node Gauss element type for its suitability for this analysis. We use a log-normal distribution for Young's modulus (E) for loose sand, with a mean value of 10 MPa and a coefficient of variation (COV) of 30%. These values are widely used in scientific literature. For example, Bowles [35] reports a range of Young's modulus values for loose sands between 10 and 25 MPa. Regarding the coefficient of variation of (E), it is reported in [36], citing [37], report a range of COV between 2% and 42%, with a standard value of 30%.

The horizontal correlation length is a variable parameter, ranging from 0.5 m to 100 m. To focus on the differential settlement between the two footings, only the horizontal correlation length (Dx) is considered. A vertical correlation length (Dy) of 200 m is assigned to minimize its effect on the numerical simulations, meaning that the modulus E will vary randomly only in the horizontal direction and not with depth, to capture the differential settlements between neighboring footings. We apply uniform vertical pressures of q1 = 300.0 kPa and q2 = 330.0 kPa to the tops of the outer and inner foundations, respectively, to represent the typical stress for sand soil with an elastic modulus of 10 MPa. We assume in this study that the frame does not support any permanent or operational load. We perform 1000 Monte Carlo realizations (a statistical method used to simulate a wide range of possible outcomes by generating random samples based on predefined probabilities) for each correlation distance and analyze the resulting foundation settlements and other internal forces in the structural frame.

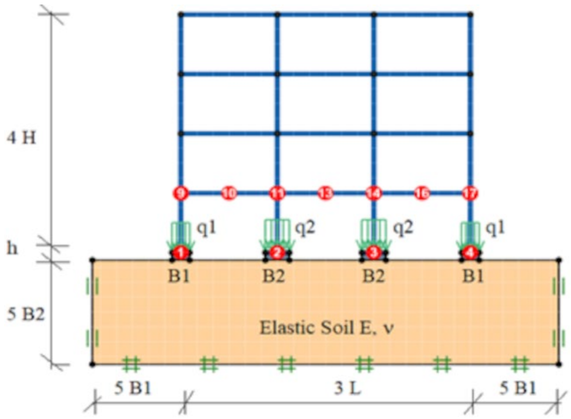

Fig.1 Model dimensions and boundary conditions

Table 1 Soil and Structural Frame used parameters

Designation	Material	Properties
Soil	Elastic	E = 10 MPa; ν = 0.30; COV(E) = 30%; Distance correlation Horizontal Dx = 0.5 to 100 m and Vertical Dy = 200 m (fixed)
Foundation	Rigid	B1 = 1.1 m; B2 = 1.5 m; h = 0.5 m
Frame	Plate	L = 6 m; H = 4 m; E = 30000 MPa; EI = 160000 kN/m^2
Connection Foundation/Frame	Rigid Plate	-
Surcharge	-	q1 = 300 kN/m^2 (on B1); q2 = 330 kN/m^2 (on B2)

4. EFFECT OF SOIL STRUCTURE INTERACTION

Soil-structure interaction (SSI) plays a significant role in the response of structures to external loads. In this context, real-time monitoring systems offer a valuable tool for improving the reliability and safety of reinforced concrete (RC) structures. By monitoring parameters such as soil displacement, foundation settlement, and structural strain, these systems can detect early signs of potential issues. This early detection allows for timely intervention, preventing significant structural damage and ensuring long-term stability. Such systems, incorporating technologies like accelerometers and strain gauges, can therefore play a critical role in managing SSI and mitigating risks in real-time.

Additionally, fluctuations in the groundwater table are an important factor influencing soil stiffness and differential settlements. When the water table rises, soil stiffness decreases, leading to increased compressibility and settlement under the foundation. Conversely, a drop in the water table can cause soil consolidation and differential settlements. These fluctuations directly affect the long-term behavior of foundations, making it essential to account for them in the design phase to maintain the reliability and performance of RC structures.

Finally, construction practices, including foundation design and material selection, can significantly influence the interaction between soil and structure. The choice of deep or shallow foundations, along with high-quality materials, can reduce differential settlement and improve the structural response to loading. Ensuring proper construction practices further enhances the soil-structure interaction and ultimately the safety and longevity of RC structures.

To better illustrate the effect of the soil-structure interaction, the following will focus on the present case study. Before delving into the probabilistic study related to the spatial variation of the soil's Young's modulus, let us first consider the deterministic case. Under the influence of loads, there is a slight differential settlement between the edge foundation and the central foundation, measuring exactly 0.0024 m, which corresponds to an inclination of 0.04%. This differential settlement has induced bending moments in the lightweight structure under unloaded conditions, as depicted in Fig. 2. These bending moments would be overlooked if the soil-structure interaction (SSI) were not considered.

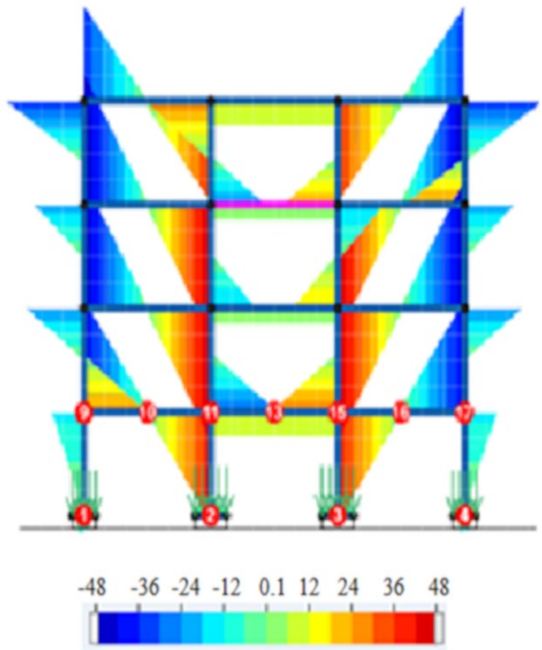

Fig. 2 Deterministic bending moments in an unloaded, lightweight frame due to differential settlement with a constant soil modulus. Moments are expressed in kN·m.

5. RELIABILITY ASSESSMENT OF RC STRUCTURES

In addition to considering the variability of soil stiffness and its effects on soil-structure interaction, it is important to also account for the long-term performance and degradation of RC structures. Over time, soil conditions such as compaction, moisture content, and differential settlement can significantly affect the behavior of the foundation and structure. These changes may lead to increased settlements or altered load distributions, potentially compromising the structural integrity of the RC foundation.

To mitigate these effects, effective maintenance strategies are required. Regular monitoring of soil behavior, such as through real-time sensors or periodic inspections, can help detect early signs of deformation or settlement. Ground improvement techniques like soil stabilization or underpinning may be necessary to address significant soil degradation. Adaptive design approaches, which take into account the long-term variability of soil properties, also play a crucial role in ensuring the continued reliability of RC structures throughout their lifespan.

To further explore these concepts, the following section presents a comprehensive reliability assessment of RC structures, taking into account the variability of soil stiffness and the interactions between the soil and structure. Understanding the statistical properties of soil parameters is essential, particularly the Young's modulus, which is modeled using a lognormal distribution. This approach helps evaluate the impact of soil variability on structural behavior.

5.1 Lognormal distribution of Young's modulus

The Young's modulus E of the elastic soil follows a probability distribution characterized by a mean value and standard deviation. The variability in this modulus is modeled using the lognormal distribution, meaning that the natural logarithm (ln) of E is normally distributed. If the mean and standard deviation of the soil Young's modulus are denoted as μ_E and σ_E, respectively, then the standard deviation and mean of the normal distribution of ln E are given by:

$$\sigma_{\ln E} = \sqrt{\ln\left(1 + \left(\frac{\sigma_E}{\mu_E}\right)^2\right)} \quad (1)$$

$$\mu_{\ln E} = \ln\mu_E - \frac{1}{2}\sigma_{\ln E}^2 \quad (2)$$

And the probability density function of the lognormal distribution is given by:

$$f(E) = \frac{1}{E\sigma_{\ln E}\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln E - \mu_{\ln E}}{\sigma_{\ln E}}\right)^2\right] \quad (3)$$

The characteristics of the lognormal distribution can be summarized based on the properties of the normal distribution as follows:

$$\mu_E = \exp\left(\mu_{\ln E} + \frac{1}{2}\sigma_{\ln E}^2\right) \quad (4)$$

$$\sigma_E = \mu_E\sqrt{[\exp(\sigma_{\ln E}^2) - 1]} \quad (5)$$

The lognormal distribution based on equation (3) with mean μ_E = 10 MPa and standard deviation σ_E = 3 MPa (COV_E =30%) is shown in Fig. 3. From equations (1) and (2) it is easily shown that: $\mu_{\ln E} = 2.2595$ and $\sigma_{\ln E} = 0.2396$.

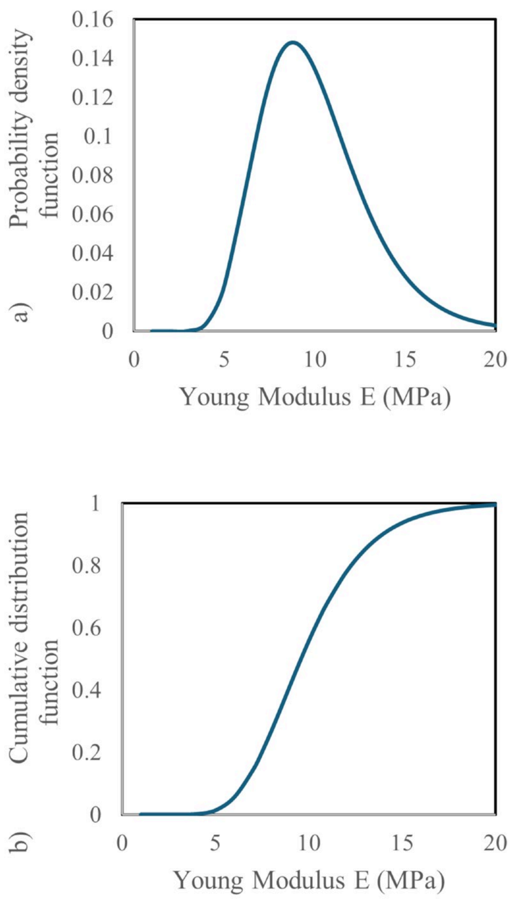

Fig. 3 Lognormal distribution of Soil Young Modulus E (MPa) with a mean of 10 MPa and a COV of 3 MPa (30%): a) Probability density function, b) Cumulative distribution function

5.2 Modeling Soil Stiffness Variability Using Random Fields

Regarding the random fields to be generated by OPTUM G2 software, it must be said that the Young's modulus of the soil will vary between simulations and will not maintain a constant value across the entire domain considered. Indeed, the concept of random fields enables the generation of more realistic spatial distributions of soil parameters, which better reflect natural variability. In addition to the probability distribution referenced in the equations above and in Fig. 3, vertical and horizontal correlation distances are introduced, such that a value of a soil parameter measured at one point will exhibit some correlation with the value measured at an adjacent point, depending on the distance between the two points (both vertically and horizontally). The correlation distance describes the range over which the measured values are likely to be significantly correlated, helping to capture the spatial continuity of soil properties.

A larger correlation distance results in a more smoothly varying random field, leading to more gradual transitions in soil properties, while a small correlation distance will indicate that the random field has an irregular distribution, with abrupt changes between neighboring points. Fig. 4 illustrates the random fields for the Young's modulus of the soil, with a mean value of 10 MPa, and a coefficient of variation of 30%, but for different horizontal and vertical correlation distances, highlighting the effect of varying these distances on the spatial distribution of the soil properties.

5.3 Number of Monte Carlo Simulations

The number of Monte Carlo simulations needed to derive the required statistical values, to ensure that the results are not dependent on the number of simulations conducted, should be determined through preliminary analyses. Fig. 5 indicates that an average value of differential settlement can be obtained with acceptable accuracy using just 300 simulations. However, to reliably estimate the probability of failure, a minimum of 1000 simulations is essential. Fig. 5 illustrates the statistical results obtained in relation to the number of Monte Carlo simulations conducted.

6. INFLUENCE OF SOIL SPACIAL VARIABILITY ON STRUCTURAL RESPONSE

Fig. 6 illustrates the variation of Young's modulus (E) across the random field, highlighting significant soil spatial variability. Fig. 7 displays the vertical displacement isoclines, demonstrating the differential settlement between the two foundations. Additionally, Fig. 7 indicates that the study area is appropriate, as the boundaries remain unaffected by the largest displacements, which decrease as one moves away from the foundations.

In this study it has been considered that the acceptable service limit state for the structure corresponds to a differential settlement not exceeding the value of $|\delta| = 1.2$ cm corresponding to the ratio:

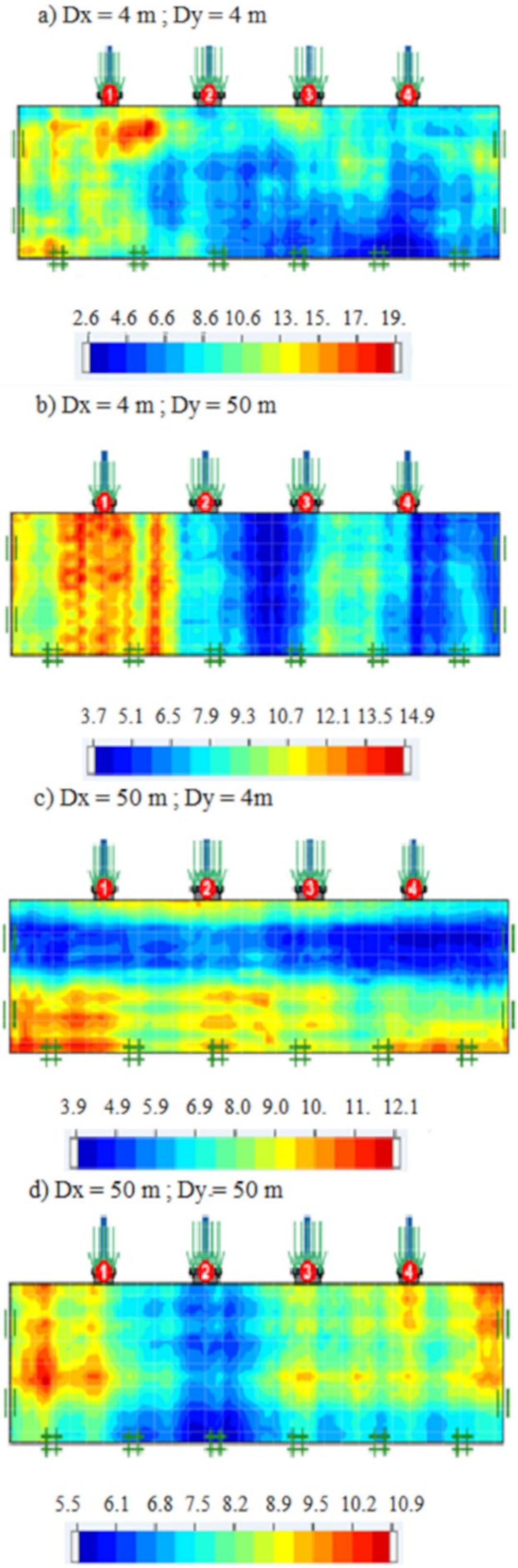

Fig. 4 Random fields of soil Young modulus E (MPa) with a mean of 10 MPa and a COV of 3 MPa (30%): a) Dx=4; Dy=4 m b) Dx=4; Dy=50 m c) Dx=50; Dy=4 m d) Dx=50; Dy=50 m.

$$\frac{|\delta|}{L} < \frac{1}{500} \quad (6)$$

As such, a factor called probability of failure was introduced which can be evaluated as follows:

$$P_f = P(|\delta| \geq 1.2 \text{ cm}) = \frac{N_f}{N_s} * 100 \quad (7)$$

where, P_f represents the probability of failure as defined above, N_f is the number of simulations in which the differential settlement exceeds 1.2 cm, and Ns is the total number of simulations, totaling 1000 Monte Carlo simulations for this study.

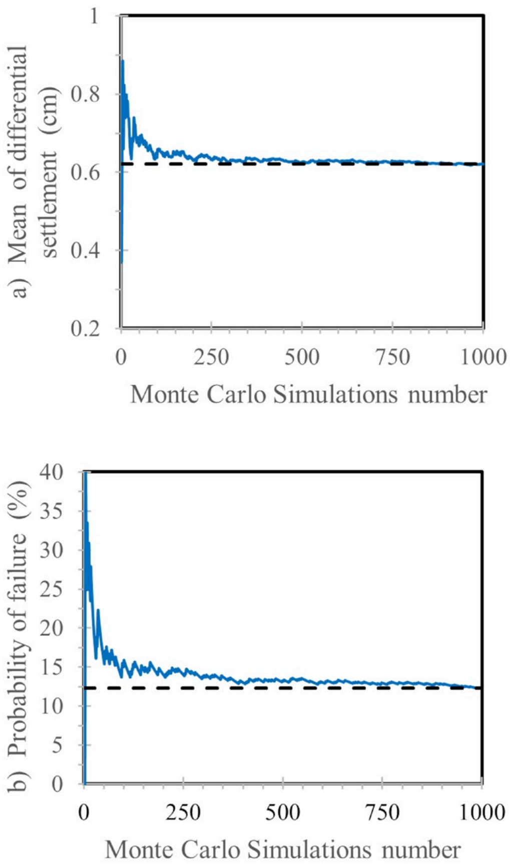

Fig. 5 Statistical results as a function of the number of Monte Carlo simulations: a) Mean differential settlement b) Probability of failure.

Fig.8 and Fig.9 illustrate the variation of the P_f with correlation distance (Dx). As Dx increases from 0.5 m to 5 m, P_f rises from 1% to a peak of 12.5%, then decreases to 0.9% at Dx = 100 m. The highest P_f values, ranging from 10.5% to 12.5%, occur for Dx values between 4 and 12 m. When Dx is less than 2 m or greater than 25 m, P_f falls below 6%, indicating the high sensitivity of structural frames to soil spatial variation. Fig. 9 specifically demonstrates how differential settlement between neighboring foundations influences P_f, with all three curves following a similar trend. Notably, P_f values for differential settlement between two adjacent foundations are lower than those between exterior and interior foundations.

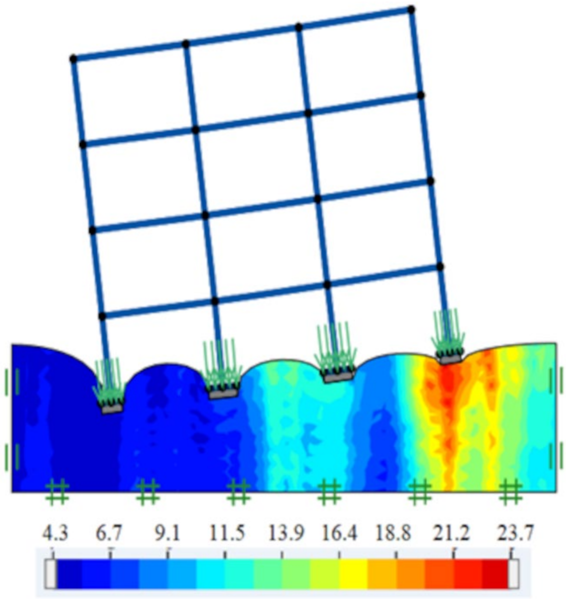

Fig. 6 Deformed soil and structure with spatially distributed values of soil modulus E (MPa).

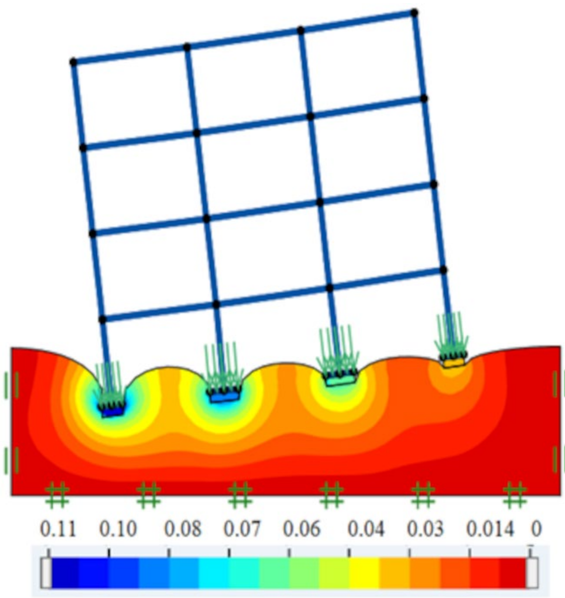

Fig. 7 Deformed soil and structure showing distributed values of vertical displacement y (m).

Additionally, the study [27] investigated differential settlement in soils with spatially varying properties using different methods and found that neighboring interior foundations yield similar results. The findings indicate that differential settlement, primarily due to variations in the soil's modulus of elasticity, significantly affects the generation of forces within the frame, even when the frame initially carries no load, resulting in substantial bending moments. The study [27] reached similar conclusions.

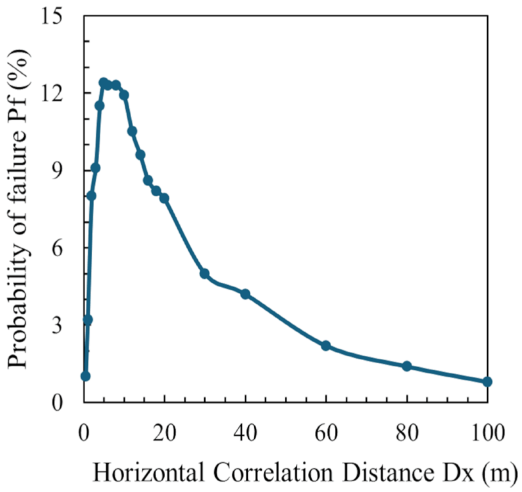

Fig. 8 Variation of the probability of failure P_f with the correlation distance considering the differential settlement between foundations 3 and 4.

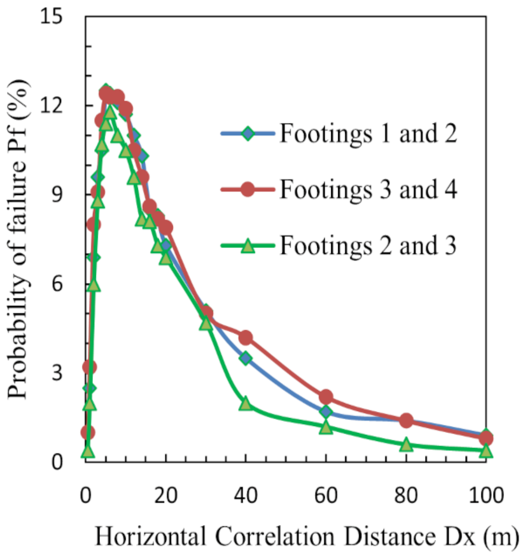

Fig. 9 Variation of the probability of failure Pf with the correlation distance considering the differential settlement between pairs of neighboring foundations.

Fig. 10 shows the internal forces (bending moments, shear forces, normal forces) in the frame structure caused by differential settlement. It clearly illustrates how variations in the soil's modulus of elasticity due to spatial variability generate significant internal forces, even in the absence of external loads or applied pressures. This strongly underscores the importance of considering soil property variability in structural stability analyses. Similar studies have confirmed that soil variability leads to notable internal forces, which must be accounted for in design considerations [27, 30].

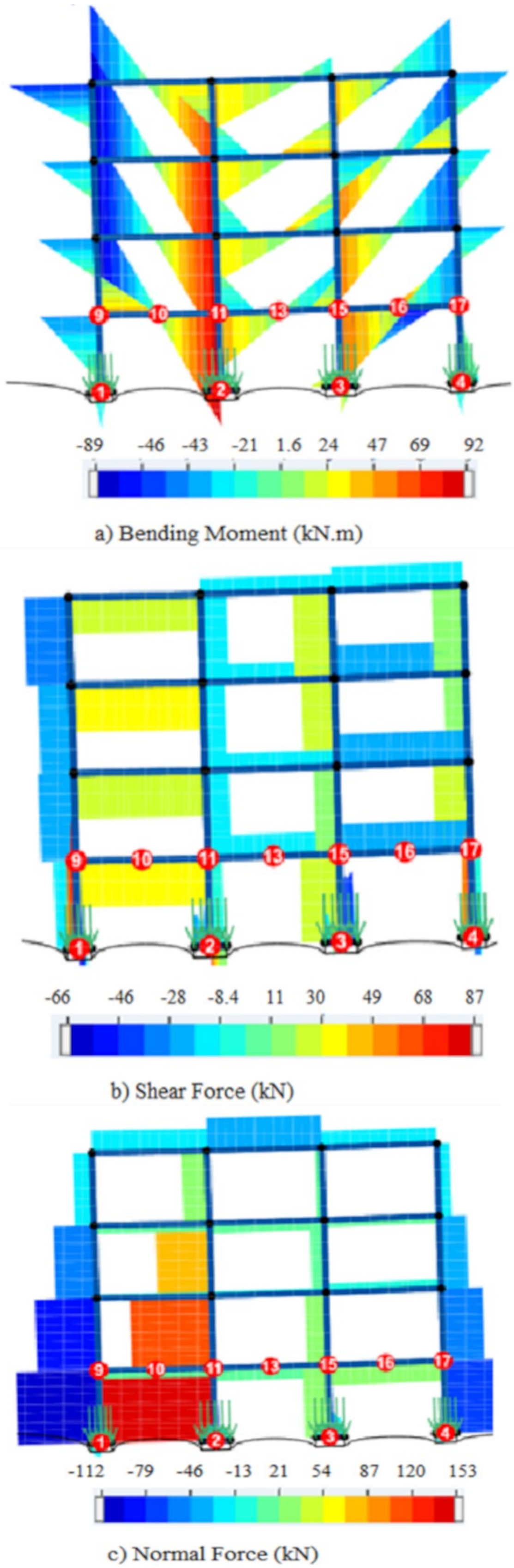

Fig. 10 Forces in the frame caused by differential settlement for a weightless and not loaded frame: a) Bending Moments b) Shear Forces c) Normal Forces.

Furthermore, the study [27] also found that significant bending moments occur in frames that are initially unloaded. These findings emphasize the importance of numerous simulations and careful consideration of soil variability for accurate structural behavior assessments, aligning with previous research conclusions.

The Coefficient of Variation (COV) of the Monte Carlo Simulations estimator for the probability of failure (P_f) is given by [38] as the following equation:

$$COV(P_f) = \sqrt{\frac{1-P_f}{P_f N_s}} \quad (8)$$

where P_f is the probability of failure as defined above, and Ns is the total number of simulations, which was 1000 Monte Carlo simulations for this study. The variation of COV as a function of P_f is shown in Fig. 11.

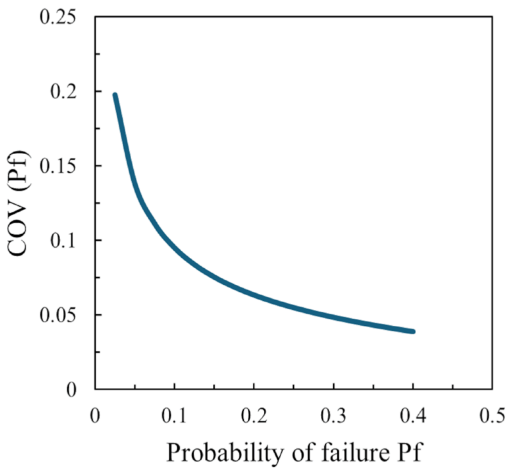

Fig. 11 COV of failure probability estimates for P_f varying from 2.5% to 40% and 1000 Monte Carlo simulations.

The curve in Fig. 11 demonstrates that the coefficient of variation (COV) decreases as P_f increases. As indicated by a lower COV, higher failure probabilities lead to more precise estimations of P_f. When P_f is low (around 2.5%), the COV is high, indicating greater uncertainty in the estimate. As P_f rises, the COV decreases, reflecting reduced uncertainty and a more reliable estimation of the probability of failure. Conducting a high number of simulations (1000) helps to lower the COV, thereby enhancing the reliability of the results. The larger the number of simulations (Ns), the more precise the P_f estimation becomes.

7. CONCLUSION

This study investigated the potential differential settlements of elastic soil with spatially varying Young's modulus using reliability analyses and Monte Carlo simulations through the OPTUM G2 finite element software. The results show that soil stiffness variability, characterized by the elastic modulus correlation distance, significantly impacts the differential settlements between the foundations of a framed structure. A critical correlation distance ranging from approximately 4 to 12 meters was identified. Furthermore, when the horizontal correlation distance Dx is less than 2 m or greater than 25 m, the probability of failure P_f falls below 6%, indicating the high sensitivity of structural frames to soil spatial variation.

The analysis also revealed that variations in soil stiffness can induce significant bending moments, shear forces, and normal forces, even in the absence of external loads. These internal forces, generated by seemingly minor fluctuations in the mechanical properties of the soil, influence the overall structural behavior. This underscores the crucial importance of considering not only the average soil parameters but also their spatial variability when designing and analysing reinforced concrete (RC) structures, where soil-structure interaction plays a pivotal role.

Understanding the effects of soil stiffness variability, combined with soil-structure interaction, is essential for ensuring the safety and stability of structures. This research enhances our understanding of the probabilistic nature of differential settlement and its impact on the reliability of RC structures, while demonstrating the effectiveness of Monte Carlo simulations in making robust predictions and quantifying uncertainties in structural reliability analyses.

In conclusion, while this study focuses on relatively simple structural and geotechnical design concepts, the interaction between such a straightforward structure and spatially varying soil stiffness proves to be particularly complex. The results demonstrate that differential settlements and internal forces can significantly compromise the safety and reliability of RC structures. Future research will concentrate on more realistic assumptions, including the adoption of nonlinear models for both soil and structure. Special attention will be given to the preliminary simulation phase to rigorously calibrate our model based on experimental and numerical data available in the scientific literature.

Moreover, moving forward, we acknowledge the value of incorporating real-world data to validate the findings presented in this study. Such future work would enhance the reliability and practical relevance of the conclusions, thereby improving the pertinence and applicability of probabilistic approaches in soil-structure interaction analyses.

The results of this study can have direct applications in real-world construction projects, providing crucial insights to improve the design and construction of RC structures. Specifically, engineers can apply these findings on soil stiffness spatial variability and its interaction with structures to optimize foundation design and minimize risks associated with differential settlements. Furthermore, integrating probabilistic simulation techniques, as used in this study, could enhance design practices by accounting for uncertainties in soil properties, thereby strengthening the safety and durability of structures.

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