ASSESSING THE STATIC OF SOIL-STRUCTURE INTERACTION ON THE BEHAVIOR OF REINFORCED CONCRETE STRUCTURES: A MECHANO-FIABILISTIC APPROACH

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Abstract: Assuring the lifespan and safety of reinforced concrete (RC) structures is essential, given the potential risks of malfunctions such as premature failure. To meet this challenge and construct durable, cost-effective structures, consideration of soil-structure interaction and inclusion of soil resistance elements in mechanical evaluations are critical. This study uses a numerical model based on the finite element method to examine the impact of inherent non-linearities in the soil on the performance of a three-span RC beam. The numerical study highlights the crucial role of soil geotechnical parameters. It clarifies the complex static non-linear effects that result from the interaction of the soil and the structure. The work also introduces a mechano-fiabilistic method, emphasizing how soil behavior in traditional RC structure designs is unexpected and non-linear. The sensitivity of structural safety to changes in soil parameters is revealed by integrating static modeling of the soil-structure interaction into the mechanical model of a continuous beam. This study emphasizes how important it is to incorporate soil-structure interaction into RC structure designs for precise, dependable, and economical results.

Keywords: static analysis, nonlinear behavior, soil-structure, soil uncertainties, reliability

1. INTRODUCTION

Ensuring that RC structures operate correctly in real-world scenarios is essential, highlighting the importance of their stability. Project owners and managers of road networks are primarily concerned with investigating and comprehending damage processes in these structures. The problem is made more difficult by the nonlinear

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behavior of the structure and the soil and by different loading circumstances. These elements may hasten deterioration, shorten the structure's life, or cause catastrophic collapse. As a result, the loss of load-carrying capability has emerged as one of the main mechanisms of probable failure. As a result, the loss of load-carrying capability has emerged as one of the main mechanisms of probable failure. This capacity loss is directly impacted by the variability of soil properties, which also influences the types of loads, such as shear pressures or bending moments applied to the structure. The loss in load-carrying capacity is directly related to the variability in soil properties [1]. As a result, this fluctuation affects the loads like shear forces or bending moments applied to the structure.

Soil-structure interaction is essential for ensuring the stability of RC structures. This is due to the significance of the underlying soil parameters [2]. It is important to evaluate how the soil and structure interact, particularly under different load scenarios. Research on the effects of soil-structure interaction was prevalent in the 1990s because it is critical to understand structural issues when they arise [3]. There are many examples in the literature that demonstrate the complexity of the interaction between soil and structure, and the need to consider certain soil features. Jahangir et al. [4] conducted a thorough investigation of the relationship between soil and structure, focusing on settlements in homes built on expansive soils, during dry periods.

The analytical model demonstrated an inverse relationship with load, building rigidity, and foundation embedding depth. Additionally, building length and soil suction were found to directly affect final deflection. Santoso et al. [5] developed a modified version of the Metropolis-Hastings algorithm to improve accuracy and decrease chain correlation for tiny failure probability in subset simulations. To identify mechanical parameters in soil-structure interaction studies, Fontan et al. [6] proposed a numerical non-destructive testing technique based on the particle swarm optimization algorithm. Elachachi et al. [7] further developed this work by considering soil's spatial heterogeneity and focusing on underground pipeline failure using the Monte Carlo approach. Montero et al. [8] suggested an analytical model for soil-structure interaction in creep ground.

They emphasized the importance of conducting specific creep tests and validated the model on a slab and wall. Bezih et al. [9] presented a finite element model of soil-structure interaction for RC structures, addressing the impact of long-term soil deformations on structural safety. The model is applied to real RC structures, considering soil-structure interaction in time. Numerical simulation tests were conducted on different soft soils, revealing the importance of compressibility parameters and heterogeneity soil behavior in safety RC structures assessment. In recent work, Ghorbani et al. [10] developed a theoretical framework for elastoplastic interaction in unsaturated granular soils with a rigid cylindrical object using the mortar-type contact algorithm. This framework allowed for the modeling and verification of stress-induced anisotropy.

Due to the instability of the soil-structure interaction system and its changes over time, predicting the performance and safety of RC structures is difficult. Therefore, it is crucial to include reliability and probabilistic indicators in the design and operation of these systems. Reliability analysis of RC structures is particularly important when studying them in operation, especially when the soil's vast variability affects the mechanical behavior of the superstructure. Several studies based on dependability theory have examined this type of organization. These studies have focused on various failure mechanisms in RC structures, such as corrosion of the reinforcement due to exposure to an aggressive and polluted environment, and damage from concrete creep effects [11]. Guo et al. [12] propose a deflection control strategy for long-span prestressed concrete (PSC) box-girder bridges.

The strategy is based on field monitoring and probabilistic finite element analysis. A three-dimensional finite element model is used to predict bridge behavior, identify uncertainties in long-term deflections, and determine the amount of control required using backup prestressing tendons. Bezih et al. [13] investigated the failure probability of RC bridges resulting from soil-structure interaction using nonlinear elastic soil stiffness. Krishnan et al. [14] explored the impact of soil variability on strip footings under inclined and eccentric loads. They utilized probabilistic analysis and contour charts to demonstrate the correlation between vertical distances and bearing capacity factor. Recently, Yichuan et al. [15] emphasized the significance of comprehending spatial variability in geotechnical engineering projects. They utilized practical expressions and methods such as finite element and dynamic reliability calculation to highlight potential pitfalls in oversimplified model slopes, which could result in erroneous designs.

To address this issue, we propose developing a soil-specific mechano-fiabilistic framework to estimate potential deformations that could impact a structure during soil-structure interaction calculations. We employ one-dimensional spring element modelling to construct the mechanical model for the soil-structure interaction system on a real-life example of a multi-span RC beam girder. We use a finite element approach to account for the nonlinear behavior of the soil. The study integrates the mechanical model and reliability techniques using the first-order reliability method (FORM) and the LIFEREL software for reliability-based analysis. It enables the evaluation of sensitivity factors and the identification of the roles played by different variables in sustaining the operational dependability of RC structures.

2. NUMERICAL MODEL OF THE SOIL-STRUCTURE INTERACTION

2.1. Model for simulating soil behavior

This study examines the impact of non-linearities in natural soils on the behavior of RC structures using a numerical finite element model created with MATLAB software. The model calculates the bending moment and support displacement of an RC beam. To accurately represent the non-linear behavior of the soil prior to failure, the numerical model incorporates a nonlinear elastic hyperbolic soil model [16, 17]. The hyperbolic relationship provided by Kondner [16] is expressed below:

$$q_1 - q_3 = \frac{\varepsilon_1}{\frac{1}{E_i} + \frac{\varepsilon_1}{(q_1 - q_3)_{ult}}} \tag{1}$$

In this scenario, the main and minor primary stress, are represented by q_1 and q_3, respectively; the axial strain is indicated by ε_1; E_i represents the initial tangent Young's modulus; and the asymptotic value of the deviatoric stress is defined by is $(q_1 - q_3)_{ult}$. Kondner's law was extended by Duncan [17] by introducing Janbu's [18] original tangent modulus:

$$E_i = K.P_a \left(\frac{q_3}{P_a}\right)^n \tag{2}$$

where P_a is the air pressure, K and *n* are parameters changed during drained triaxial compression experiments at different confining pressures q_3. The model incorporates a hyperbolic stress-strain relationship that is dependent on the soil volume's deformation properties and stress history. The authors introduced a parameter R_f represented as ratio of the maximum asymptotic stress $(q_1 - q_3)_{ult}$ divided by the failure deviatoric stress $(q_1 - q_3)_f$:

$$R_f = \frac{(q_1 - q_3)_f}{(q_1 - q_3)_{ult}} \tag{3}$$

As the rupture occurs before reaching the asymptotic curve, the value is always less than one R_f. Moreover, we assume that the stress state at failure meets the Mohr-Coulomb plasticity criterion.

$$(q_1 - q_3)_f = \frac{2(c \cos\varphi + q_3 \sin\varphi)}{1 - \sin\varphi} \tag{4}$$

where c denotes the cohesion, and φ represents the internal friction angle of the soil. Consequently, the ultimate expression for the tangent Young's modulus, characterized as Et, is:

$$E_t = K.P_a \left(\frac{q_3}{P_a}\right)^n \left[1 - \frac{(1 - \sin\varphi)(q_1 - q_3)}{2(c \cos\varphi + q_3 \sin\varphi)}\right] \tag{5}$$

This work examines soil-structure interaction using a hyperbolic relationship applied to the soil beneath the structure's foundations.:

$$q = q_3 + \frac{v}{\frac{z}{K_0} + \frac{v}{(q_1 - q_3)_{\text{ult}}}} \tag{6}$$

Within the formula, v represents the settlement of the soil below the footing, q is the applied vertical stress, q_3 is the confinement stress at the center of the stress effect zone above the footing, κ_0 is the initial stiffness of the soil, and$(q_1 - q_3)_{ult}$ is the ultimate deviatoric capacity of the soil. The initial stiffness of the spring model may be obtained by computing the initial elastic modulus of the soil beneath the footing at a depth of z=1.5 times the footing width (B).

The ultimate deviatoric stress can be stated as follows, according to Bezih et al., [13]:

$$(q_1 - q_3)_{\text{ult}} = m_{(q_1-q_3)_{\text{ult}}}\left(1 + 1.85\left(\frac{\varphi}{m_\varphi} - 1\right)\right) \quad (7)$$

In this case, φ stands for the friction angle random variable, m_φ for its mean value, and $m_{(q_1-q_3)_{\text{ult}}}$ for the ultimate deviatoric stress mean value. This relationship allows us to find the random ultimate deviatoric stress as a dependent variable on the soil's random friction angle. This connection is helpful when utilizing the FORM approach to determine the failure probability of the structure.

The formula uses the mean ultimate deviatoric stress as a foundation, which facilitates the scaling of statistics concerning friction angles. This scaling process makes it easier to assess changes in soil strength. We incorporate the interaction between soil and structure into this model by incorporating a hyperbolic relationship that characterizes the soil's behavior beneath the structure's footings. This connection is described as follows:

$$q = q_3 + \frac{v}{\frac{z}{K_0} + \frac{v}{m_{(q_1-q_3)_{\text{ult}}}\left(1+1.85\left(\frac{\varphi}{m_\varphi}-1\right)\right)}} \quad (8)$$

The hyperbolic model parameters for the sandy soil under consideration in this investigation are taken from Table 1.

Table 1. Parameters of the hyperbolic model of the soil.

Type soil	q_3 (kPa)	Pa (kPa)	φ (°)	c (kPa)	K	n	R_f
Sandy	260	100	30	0	200	0.25	0.7

2.2. Mechanical model for RC structure

The findings of the numerical simulation model evaluating the static soil-structure interaction impact on the behavior of an RC bridge are shown in this section. It comprises three span girders with a combined length of 45.30 meters; each span is 15.10 meters long and has a constant moment of inertia (Figure 1). This bridge's architecture is examined in light of [19] and [20].

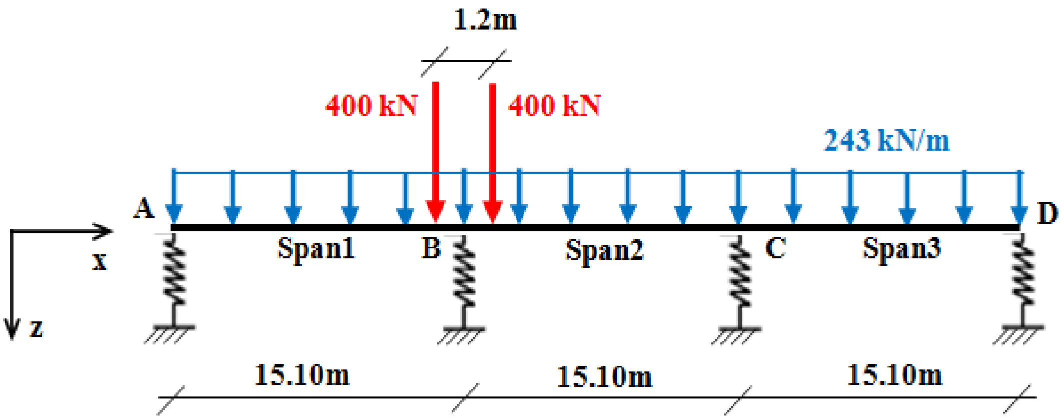


Fig. 1. Mechanical model of an RC structure with three similar spans.

Nonetheless, the load model (LM1) in Eurocode1 defines the traffic on the bridge by considering wheel loads TS and concurrently uniformly distributed loads G and UDL on each conventional lane. Almost all of the consequences of truck and vehicle traffic are included in this model. As seen in Figure 1, the bridge's mechanical model must be defined to compute the bending moment in the bridge girders. Over a depth of 1.5 times the footing width, the initial stiffness of the spring model is calculated in terms of the initial elasticity modulus of the soil under the footings in the influence zone.

3. RESULTS AND DISCUSSION

3.1. Deterministic analysis

The goal of the deterministic research is to examine how various factors affect the behavior of the structure, with special attention to the interaction between the soil and the structure. The soil behavior model and its parameters are the primary focus of this investigation. The stability evaluation, and in particular the ultimate limit state (ULS), is the main emphasis of the criteria applied in this work. To evaluate the results of soil-structure interaction computations, the influence of soil properties is analyzed. The loads are determined by the most important basic combination at the ULS. Understanding how differences in soil variables affect the interaction between the soil and the structure is made easier by this study.

3.1.1. Effect of soil confinement stress

Separate soil confinement forces of 32, 135 and 260 kPa were used during simulations to represent various degrees of embedment depth for the structural foundation. Figures 2, 3, and 4 display diagrams illustrating the maximum bending moments discovered in the structural beam components. Prominent conclusions are demonstrated by a detailed comparison between the numerical model (i.e., spring model) results using nonlinear elastic analysis and the results from rigid support analysis. Specifically, it is discovered that, under different loading situations at the ULS, the bending moments in spans 1 and 2 increase with the type of soil model. However, the bending moments for support B decrease under different load conditions. Regardless of the soil model used, there is a considerable moment reduction by 17% at support B and 12% in span 2 compared to the rigid support scenario. However, the changes in moments are small for span 1. These findings unequivocally demonstrate how soil and structure interaction influences the structural behavior at support B and in span 2.

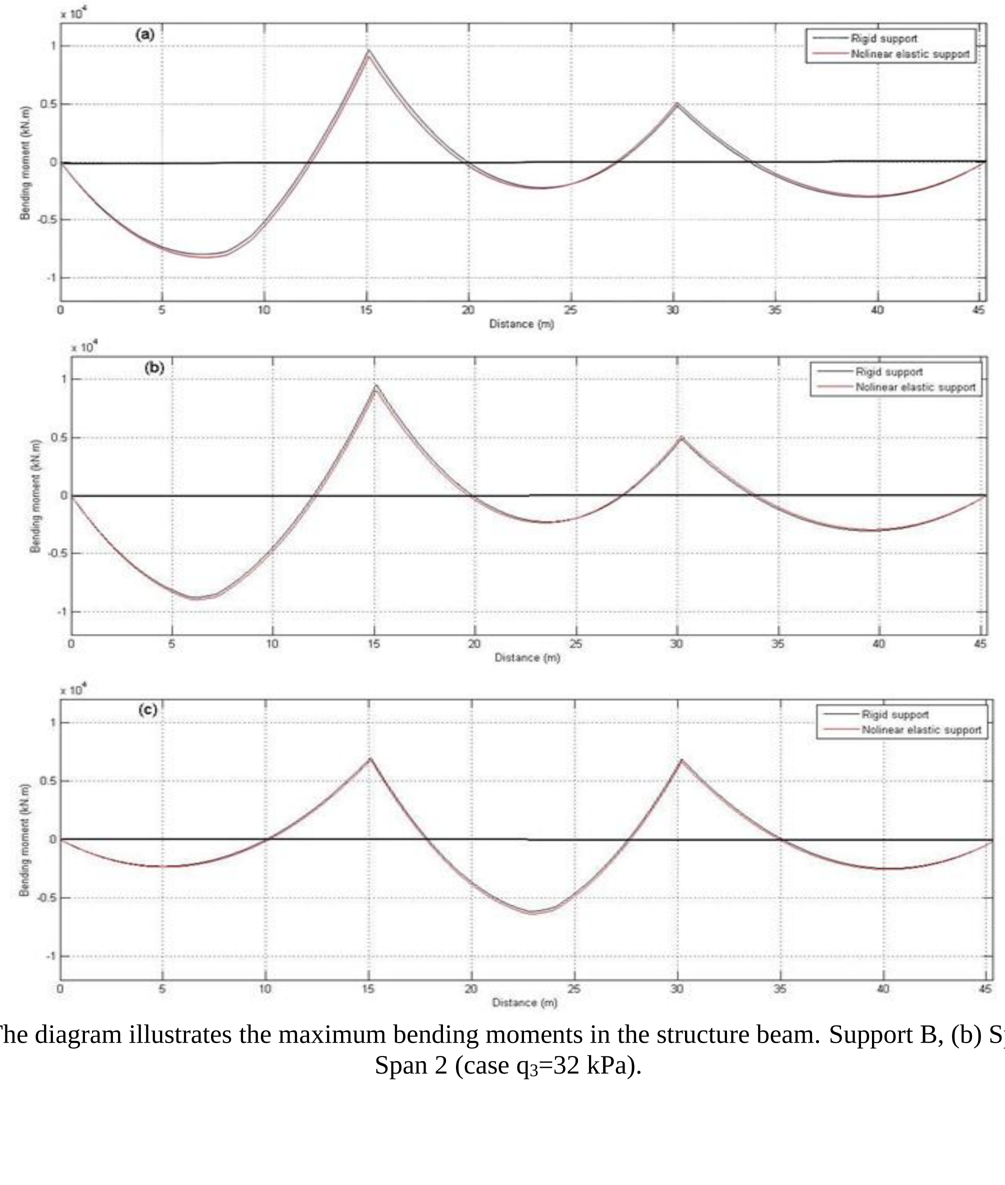


Fig. 2. The diagram illustrates the maximum bending moments in the structure beam. Support B, (b) Span 1, (c) Span 2 (case q_3=32 kPa).

Furthermore, the results show that the maximum moments are overestimated when considering rigid support conditions compared to the actual behavior of the structure. It is crucial to consider this since the behavior of the soil itself has a significant influence on the soil-structure interaction. Therefore, the study must take soil-structure interaction into account.

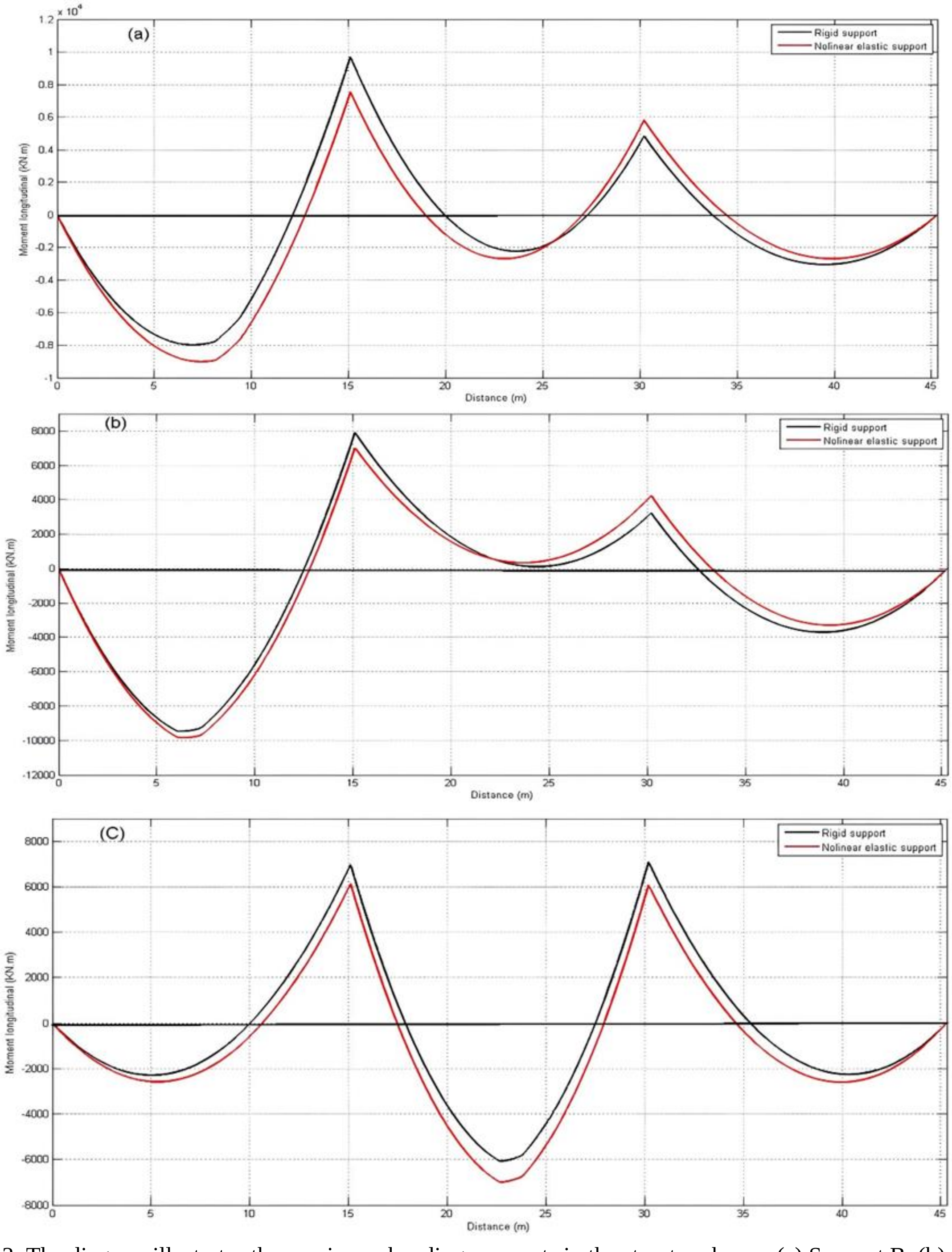


Fig. 3. The diagram illustrates the maximum bending moments in the structure beam. (a) Support B, (b) Span 1, (c) Span 2 (case q_3=135 kPa).

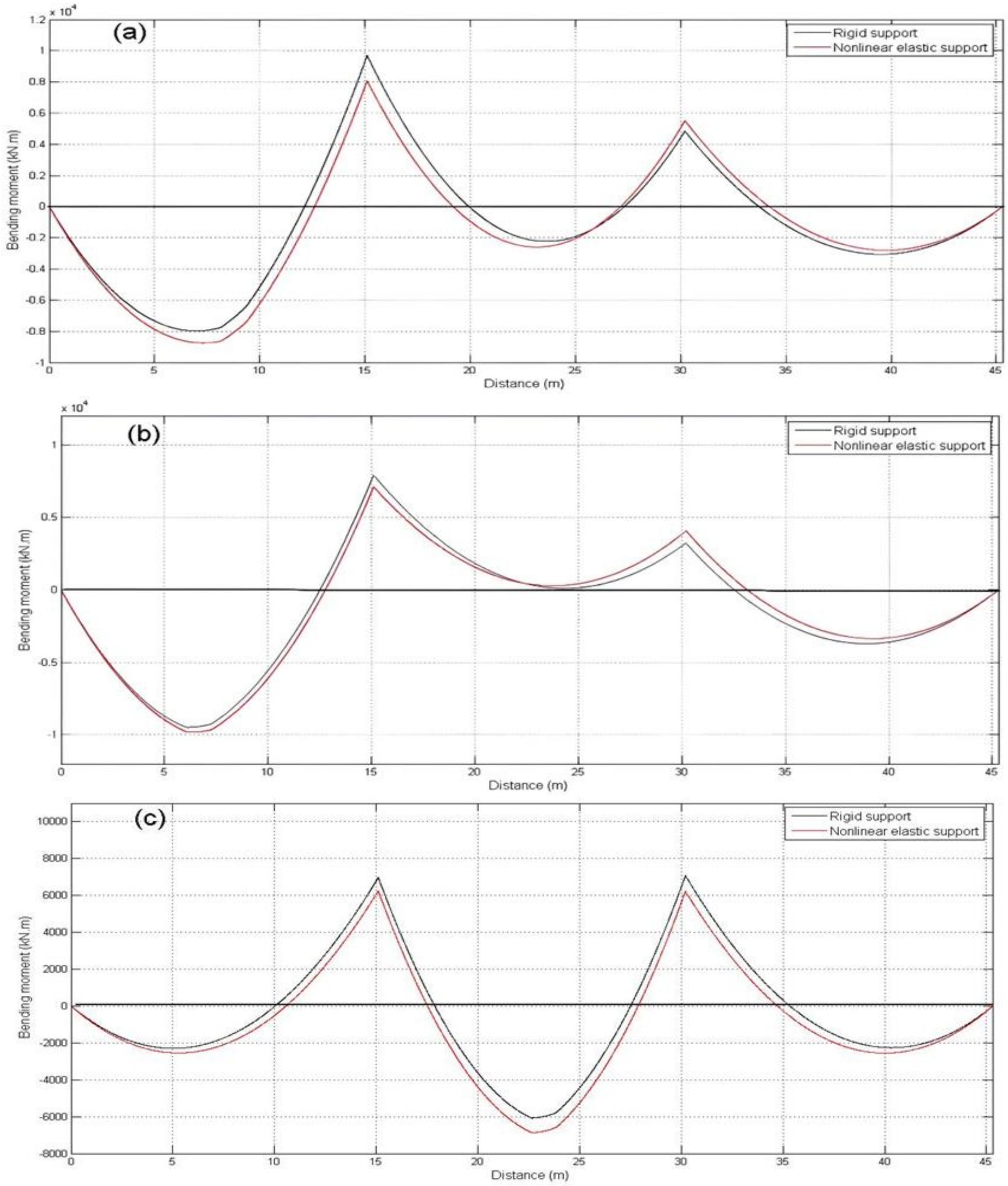


Fig. 4. The diagram illustrates the maximum bending moments in the structure beam. (a) Support B, (b) Span 1, (c) Span 2. (case q_3=260 kPa).

3.1.2. Effect of the angle of soil friction

The impact of the soil friction angle on the RC structure displacement in the numerical model was examined using a constant confinement stress of 260 kPa and an initial stiffness modulus of 19 MPa. Building on the findings presented in the previous sections, it is now possible to examine the relationship between the friction angle and the soil's ultimate stress and failure stress (Table 2).

Table 2. The impact of the friction angle on the soil's failure and ultimate stress.

Friction angle φ^0	Type of support soil-structure interaction	The ultimate stress $(q_1 - q_3)_{ultim}$ kPa	The failure stress $(q_1 - q_3)_r$ kPa
25	Nonlinear elastic supports	380.61	543.43
30		520.00	742.85
35		699.44	999.20
40		935.00	1336.70

An investigation has been conducted on the effects of varying the friction angle from 25 to 40 degrees. It has been shown that the friction angle highly influences the displacement of RC structures. Specifically, as Figure 5 shows, a 20% increase in soil deformation occurs when the friction angle is reduced from 25 to 40 degrees.

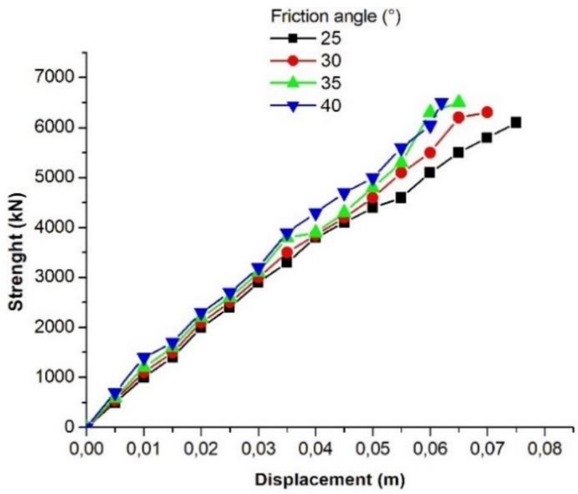


Fig. 5. Effect of friction angle on displacement in RC structures.

3.2. Reliability analysis

To guarantee the safe design of RC structures, reliability analysis is essential. It entails evaluating the structure's dependability concerning different possible forms of failure, each denoted by a limit state function. This evaluation takes into account the intrinsic variability of the input random variables, which are distinguished by their probability distributions. The primary aim is to ascertain the failure probability (P_f) of the structure, denoted by equation (9), which signifies the possibility of the applied load effect (*S*) beyond the structural resistance (*R*):

$$P_f = P(S > R) \quad (9)$$

Since the failure probability P_f for realistic structures is typically quite small, it makes more sense to express it as a reliability index (β). This conversion is achieved using the standard Gaussian distribution function, represented by the symbol Φ. Equation (10) defines this function with a zero mean and a unit standard deviation.

$$\beta = -\Phi^{-1}(P_f) \quad (10)$$

This reliability research focuses on the ultimate limit condition of the structure deck concerning the bending capacity of the RC girders. Equation (11) provides the following expression for the limit state function, or G(X):

$$G(X) = R - S \quad (11)$$

Here, the girder's ultimate bending resistance (R), the applied moment (S), the vector of random variables (X), and the complex interactions between the soil and the structure (G(X)) are all taken into consideration. This comprehensive approach guarantees the structural deck's reliability and safety by allowing a thorough assessment of its structural integrity under various loading situations.

The likelihood of structural collapse is ascertained by evaluating the limit state function G(X), as detailed in equation (11). This inquiry uses the FORM technique, which is included in the LIFEREL software. The final moments in the girder cross-sections are computed in each cycle for each load scenario linked to the ULS. These moment computations are performed using a modified MATLAB numerical model that carefully considers soil-structure interaction.

3.2.1. Variability in soil constitutive behavior

Soils are characterized by a constitutive rule derived from empirical parameters obtained by in situ and laboratory studies. In the case of sandy soil, the tangent modulus of Duncan's law equation (5) is most affected by the angle of friction and the confining stress, according to preliminary research [13]. It is crucial to emphasize that the parameters that form the basis of Duncan's model are not fixed values; instead, they are closely related to the properties of the soil, namely the angle of friction in sandy soils and the confining stress.

Figures 6, 7 and 8 display stress-strain curves for various samples with coefficients of variation set at 5%, 10%, and 15% for the friction angle and 15% for the confining stress. These figures demonstrate the significant impact that soil properties have on soil capacity and settling. Put differently, settlement dispersion is evident at a given deviatory stress level, especially at high lead levels (e.g., above 40 to 200 kPa, as depicted in Figure 7). The coefficient of variation (COV$\boldsymbol{\varphi}$) fluctuates at 5%, 10%, and 20%, respectively, with a confining stress of 135 and 260 kPa. Conversely, excess lead levels are around 60 kPa, 80 kPa, and 100 kPa at confining strains of 32 kPa, with corresponding COV$\boldsymbol{\varphi}$ values of 5%, 10%, and 20%, respectively.

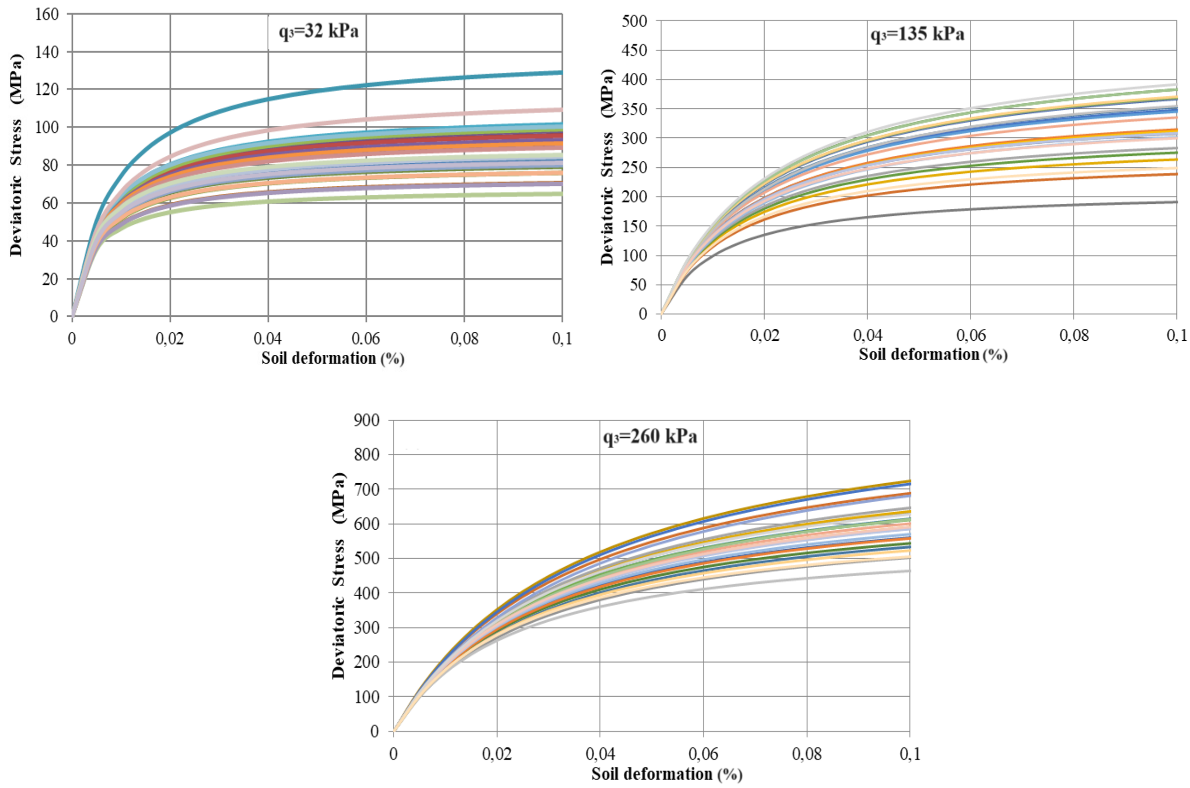
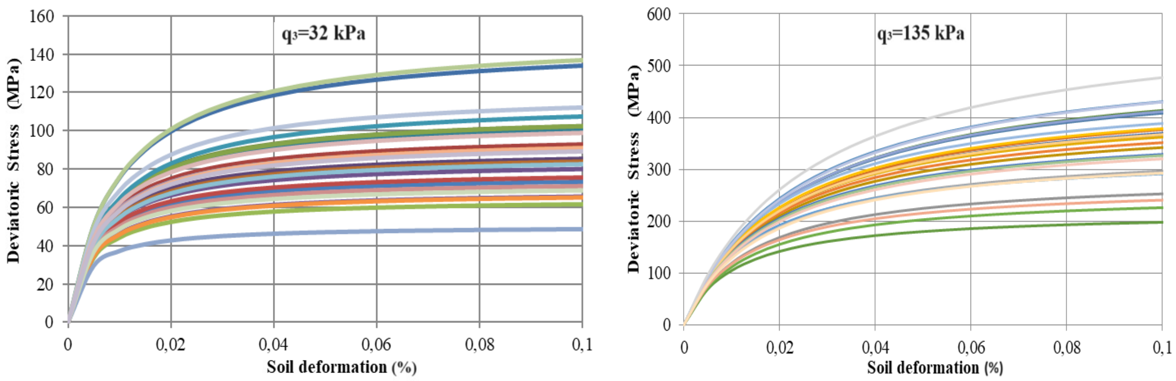


Fig. 6. Stress–strain curves for random sampling of soil parameters with COV$\boldsymbol{\varphi}$ = 5%.



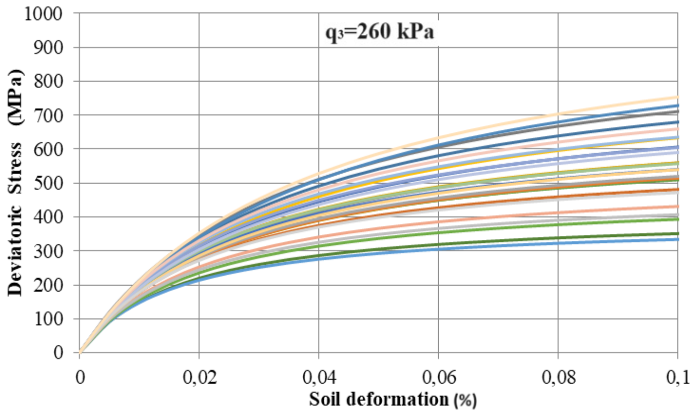


Fig. 7. Stress–strain curves for random sampling of soil parameters with COV$\boldsymbol{\varphi}$=10 %.

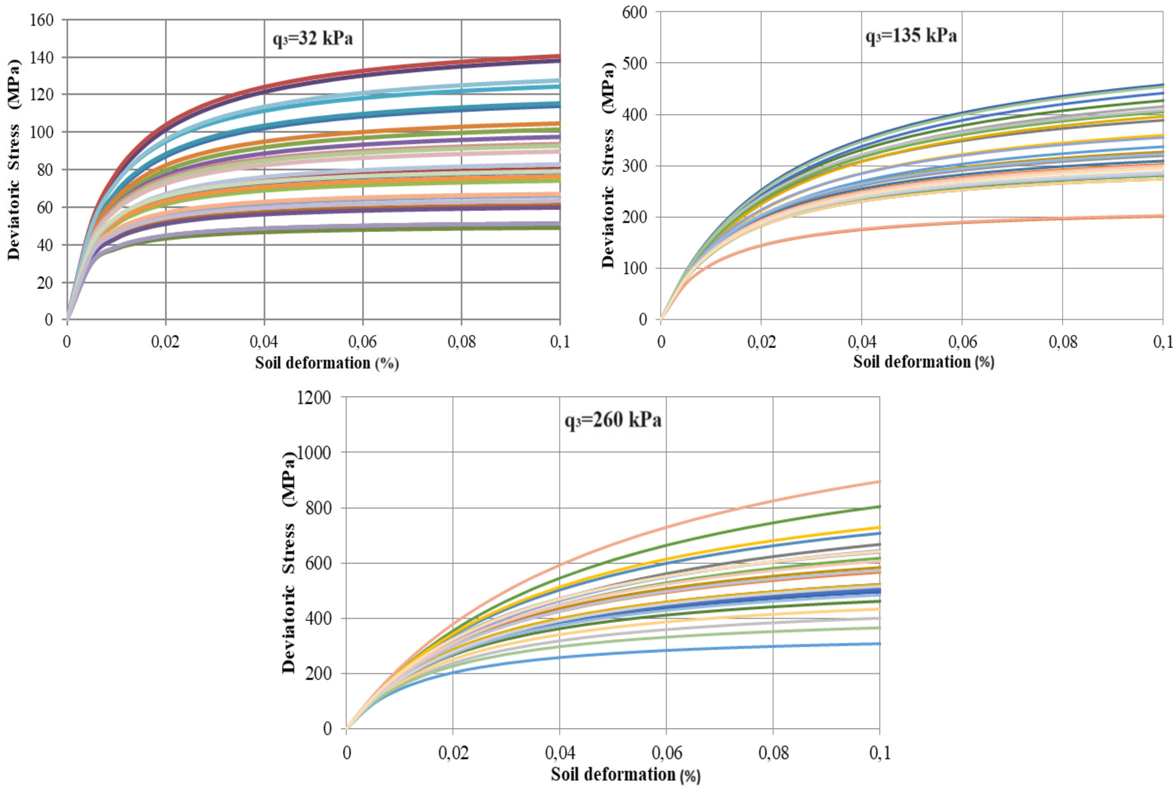


Fig. 8. Stress–strain curves for random sampling of soil parameters with COV $\boldsymbol{\varphi}$=15 %.

3.2.2. Assessment of structure reliability

Within the framework of this investigation, assessing the structure's dependability is an essential component of evaluating its structural soundness in various scenarios. Based on a set of random variables described in Table 3, the analysis yields loading mean values that are ULS optimized. Emphasizing that every random variable considered in this analysis is presumed to follow a lognormal distribution is essential, as this is a commonly recognized and tested assumption in engineering practice. This decision stems from the realization that many real-world variables, especially those associated with structural performance, tend to display lognormal properties because the underlying elements are multiplicative. Moreover, the coefficients of variation associated with these random variables are determined by reviewing previously published literature or by applying recognized techniques in civil engineering systems. These coefficients of variation are essential for describing the uncertainty and variability present in the examined parameters. This thorough modeling and analysis of the random variables guarantees a solid and realistic evaluation of the structure's reliability, enabling a more precise assessment of its performance and safety in compliance with the ULS.

Table 3. Random variables for the RC structure girder analysis at ULS.

	Elements of the beam			COV (%)
	Mean			
	Support B	Span 1	Span 2	
Bending resistance MR (kN.m)	12048	10956	7674	6-10%
Internal friction angle (φ)	30			5-20%
Confinement stress q_3 (MPa)	135			15%
	260			
Dead load G (kN/m)	135			8%
Uniform live load UDL kN/m)	108			8%
Wheel live load TS (kN/m)	400			15%

In the reliability analysis, a coefficient of variation of 6% is applied to the resistance moment, equivalent to the steel strength dispersion. Figures 9 and 10 illustrate the importance of the model variables on the cross-section safety margins for q_3=135 kPa and q_3=260 kPa.

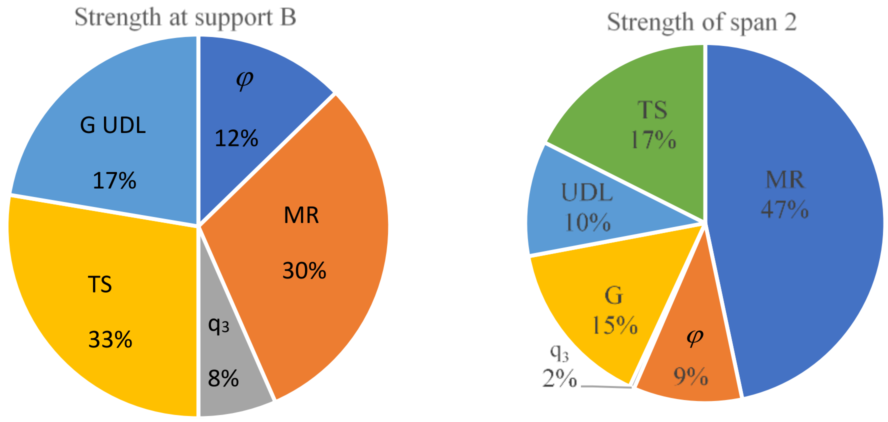


Fig. 9. Importance factors associated with the model parameters (q_3=135 kPa).

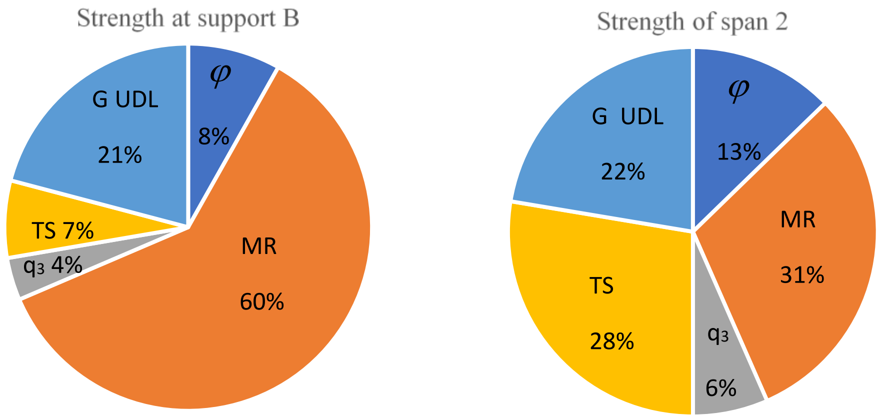


Fig. 10. Importance factors associated with the model parameters (q_3=260 kPa).

The significance of confinement stress in preserving the security of RC cross-sections is evident. Its Effect is particularly apparent for span 1 (8%), as opposed to the piers at support B (12%). Moreover, it is demonstrated that these two cross-sections have corresponding failure probabilities of 3.98×10^{-3} and 3.6×10^{-4} at span 1 and support B. These probabilities must be compared to the results obtained by disregarding soil properties' unpredictability, yielding a failure probability of 1.6×10^{-4} for the cross-section at span1 and 6.5×10^{-12} for the cross-section at support B. The failure probability has increased noticeably, more than double for the cross-section at span 1 and more than twice for the cross-section at support B.

This study shows that the impact of soil uncertainty is much more significant for the positive bending moment at the terminal span. The significance factor diagram further demonstrates that, although there are significant uncertainties associated with this parameter (i.e., 15%), the confinement stress contributes very little to structural safety, between (8 and 2% for q_3=135 kPa) and (4 and 6% for q_3=260 kPa). The total importance of the soil characteristics is around 20%, according to the reliability study, when compared to the effects of dead and living loads. This is a crucial matter. In both cross-sections, the resistance moment has a significant impact.

3.2.3. Variable dispersion impact

To understand the impact of the dispersion of random variables on structural dependability, a reliability study is conducted on various coefficients of variation for the angle of friction and bending resistance. The study focuses on two random variables, the resistance moment, which has a constant coefficient of variation of 10%, and the angle of friction, which has different coefficients of variation, to assess soil's effect on structural safety.

Based on the assumption of nonlinear elastic and stiff soil properties, Figures 11 and 12 illustrate how dispersion influences the probability of failure at critical cross-sections. The results demonstrate that the danger of failure is significantly increased when the friction angle is treated as a random variable, mainly when non-linear soil behavior is involved. As the friction angle's coefficient of variation increases, this effect becomes more evident.

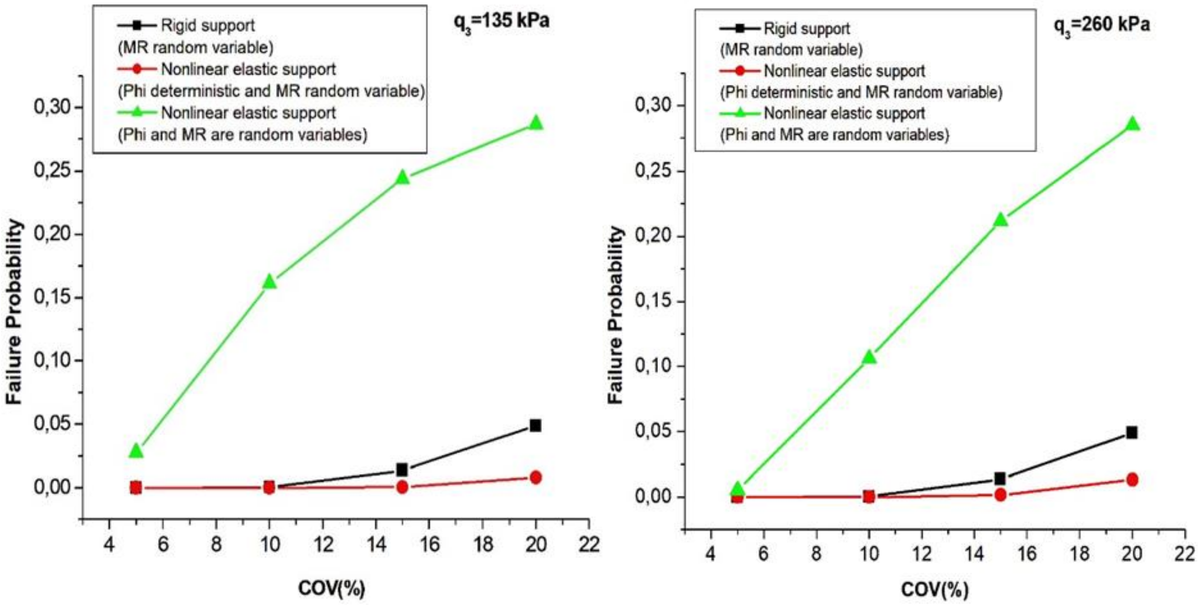


Fig. 11. Evolution failure probability is due to the standard deviation of the internal friction angle of the soil and bending resistance of support B.

The data analysis provides insightful information about the system's activity. First, a higher friction angle coefficient of variation (COV) is associated with a higher risk of failure, mainly when non-linear elastic support is used, with values approaching significance. This emphasizes the importance of comprehending the friction angle probabilistic character to guarantee structural safety, especially considering how strongly it affects the likelihood of failure. Second, it is essential to recognize that slight variations in the COV of the friction angle significantly impact the chance of failure. It is interesting to note that differences in flexural strength have minimal Effect in this case. Therefore, it is critical to acknowledge the probabilistic nature of the friction angle and its pivotal function in spreading moments throughout the structure. Finally, in light of non-linear elastic behavior, the influence of the friction angle dispersion on mid-span reliability is shown to be more significant than that on support reliability. This result highlights the complex effects of the fluctuation of the friction angle on many facets of structural integrity, highlighting the necessity of a thorough comprehension of these dynamics for efficient risk management.

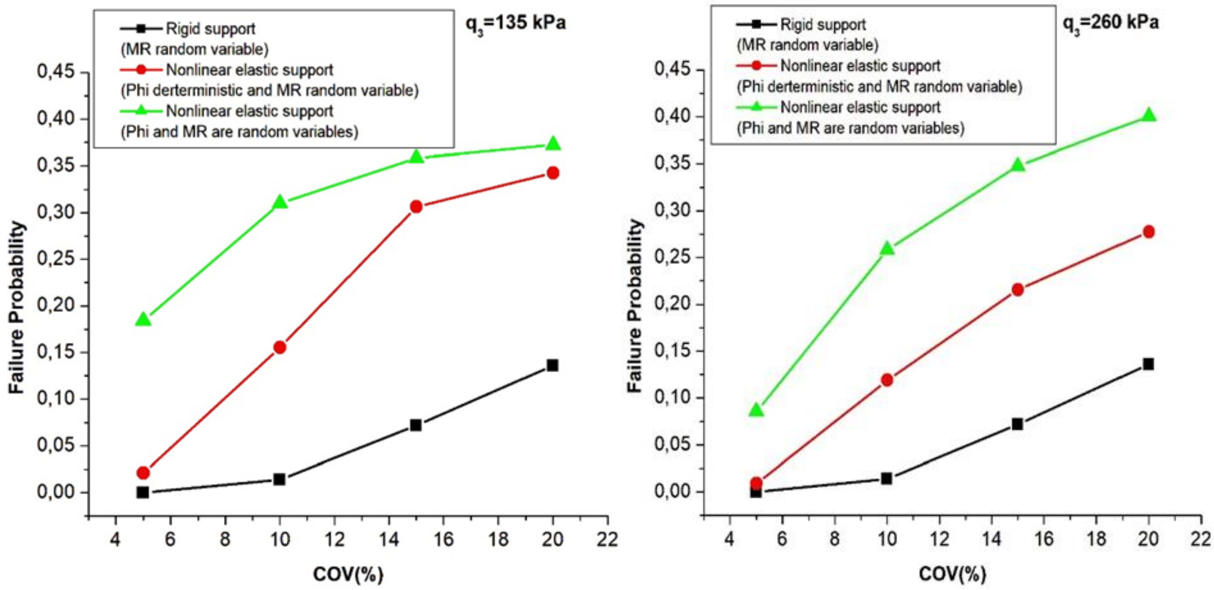


Fig. 12. Evolution failure probability is due to the standard deviation of the internal friction angle of the soil and bending resistance of the span 2.

4. CONCLUSIONS

The purpose of this extensive study was to assess the impact of unknown soil shear parameters on the static soil-structure interaction and how it would affect the dependability of RC structures. Using finite element software for continuous beams supported by nonlinear elastic foundations coupled with a MATLAB-based numerical model, the FORM was utilized to calculate the failure probability of critical cross-sections.

The findings demonstrate how much static soil-structure interaction affects structure dependability, especially in terms of soil non-linearity. Specifically, a substantial overestimation of the structure's dependability resulted from the widely recognized rigid support, which went against the robustness and precautionary principles. Thus, reliable modeling of soil behavior that takes non-linearities and variances into account is crucial. Some noteworthy results were reached as a result of the parametric study's identification of the critical factors affecting the behavior of the RC structures:

The most significant characteristic that affected stability, deformation, and load-bearing capacity was soil confinement. It is crucial in assessing how resistant to deformation the structure is.

Variations in the friction angle: the significance of the friction angle for safety and structural integrity is shown by the significant impact that it has on structure settlements. Because this soil characteristic influences the redistribution of moments inside the structure, it must be taken into account.

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