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Nonlinear Static Soil-Structure Interaction Analysis of Time-Dependent Soil Deformation Effects on RC Structures

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Abstract
Soil response and superstructure behavior are two major factors influencing the long-term performance of reinforced concrete (RC) structures. Maintaining the structural integrity of these structures over time is crucial due to the complex static interactions between the soil and the structure. This study uses a finite element model to examine the stability of RC structures, considering the long-term static interactions between the nonlinear behavior of the soil and the structure. Numerical simulations are performed on real RC beam constructions at serviceability limit states (SLS) under various loading scenarios in both homogeneous and heterogeneous soil conditions. The parametric study's results indicate that soil heterogeneity and static soil-structure interactions significantly influence the design of RC structures. The nonlinear behavior of the soil over time intensifies these impacts further. This study shows how important it is to think about different types of soil and how they interact with structures when they are not moving. This is especially true when it comes to soil that is easily compressed and changes shape over time in a nonlinear way. By incorporating these factors, the research highlights the critical need to integrate soil heterogeneity and static interaction into the design process to ensure the stability and safety of RC structures. Ultimately, the results demonstrate that accounting for these complex interactions can greatly improve the durability and reliability of RC structures in diverse soil conditions.
Keywords: Soil-structure interaction. Finite element model. Mechanical analysis. RC structure. Nonlinear behavior. Compressibility parameters.

1. Introduction

In engineering studies, soil-structure interaction (SSI) is critical for accurately predicting the behavior of structures subjected to varying soil conditions. Ignoring this interaction can lead to inaccurate assessments of structural performance, potentially resulting in design flaws or safety concerns. By accounting for SSI, engineers can better understand how structures respond to dynamic loads, such as earthquakes or wind, thereby enhancing the resilience and reliability of infrastructure. Studies that overlook SSI may underestimate the impact of soil properties on structural behavior, hindering the optimization of designs and construction practices. Dutta and Roy (2002) found the Winkler (Winkler, 1867) hypothesis to be effective and simple in modeling soil-structure interaction, suggesting it's a more practical approach than fixed base idealizations. Referencing Dasgupta *et al.* (1999) , they discussed a tested way to use computers to account for nonlinear load-settlement characteristics in the process of frame-soil interaction consolidation settlement. Understanding the pressure state at the soil-structure interface is critical for accurately designing RC structures. This requires establishing correlations between pressure states and soil deformation patterns. Agrawal and Hora (2010) investigated a two-bay, two-story plane building frame-soil system and found significant structural differences in comparison to conventional methods.

The non-linearity of the soil mass led to higher vertical settlements and increased forces within the frame members, resulting in a bilinear pattern of variation. Chore *et al.* (2014) investigated the physical modeling of space frame-pile foundations and soil systems using finite element models. They included non-linear soil mass behavior and conducted interaction analysis for parametric and iterative studies. They found that the non-linearity of soil increased top displacement but marginally affected the absolute maximum moment in columns. Loukidis and Tamiolakis (2017) studied Winkler spring stiffness constants over time for mat foundation design, using finite element analysis to create slab deflections and bending moment diagrams and proposing spatial distribution equations. Bezih *et al.* (2020) developed a finite element model to study how soil and RC structures interact with each other. They specifically looked at how long-term changes in the soil affect the safety of the structures. They applied this model to real RC structures, taking into account the soil-structure interaction over time. Numerical simulations were conducted on various soft soils, emphasizing the significance of compressibility parameters and soil heterogeneity in assessing the safety of RC structures. Ai *et al.* (2021) developed a semi-analytical and semi-numerical approach to analyze the interaction between layered soils and raft foundations using elastic-viscoelastic correspondence principles and integral transform methods. In their recent work, Lanes *et al.* (2023) developed a numerical method for analyzing frame structures on footing foundations subjected to slow strains from consolidation settlements. More recently, Liu *et al.* (2024) developed a new methodology to simulate time-dependent soil-structure interaction in superstructures, testing it on a 3D-printed aluminum-framed structure. The study highlights its potential for practical SSI analysis.

This interaction is particularly important in the context of fine soils, where hydromechanical phenomena predominate. Differential settlements, primary consolidation, and secondary consolidation are all made worse by the fact that fine soils don't let much water through. This means that their shear strength is much lower than that of coarse soils (Tian *et al*., 2020; Wang *et al*., 2016; Zhu *et al*., 2018) . Consequently, these factors can precipitate premature deterioration or structural failure in RC structures (Gourvenec *et al*., 2014; Yin and Graham, 1999) . Hence, it is imperative to consider the mechanical properties and heterogeneity of soft soils when designing RC structures to ensure both their longevity and cost-effectiveness (Bezih *et al*., 2020, 2024; Fontan *et al*., 2011) . As a result, the analysis of RC structures at serviceability limit states (SLS) becomes imperative. The complex interplay between soil and structure necessitates the inclusion of SSI in studies to ensure realistic simulations and informed decision-making throughout the engineering process. This underscores the significance of considering SSI in engineering analyses and design processes, as it ultimately impacts the safety, performance, and longevity of structures.

In this study, we utilize a finite element model of SSI, as described by Bezih *et al.* (2020) , to evaluate the stability of RC structures, considering the impact of soil deformations over time. We apply this model to real RC beam structures and analyze the SSI over an extended period. For the mechanical modeling of the soil-structure system, we use a one-dimensional model with spring elements to simulate continuous RC beams in contact with the soil. To account for the time-dependent non-linear behavior of the soil, we employ the soft soil creep model, developed by Vermeer and Neher (1999) . The finite element method addresses the soil's non-linear temporal behavior, calculating consolidation settlements and bending moments in RC beams. Numerical simulations are conducted on compressible soils at the serviceability limit state (ELS) under various loading conditions, considering both homogeneous and heterogeneous soil conditions.

2. Analysis of RC Structures

2.1. Modeling of Soil-Structure Interaction

A structure based on the surface of a homogeneous (elastic solid) and horizontal soil, whose mechanical properties are known and constant, frequently models the SSI. If large deformations of the soil are predictable, it is not necessary to model a structure with perfect embedding at its base (Figure 1-a). For example, in the case of very rigid structures built on a soil with average mechanical strength, the most significant deformations can occur in the soil rather than in the structure. Thus, we carry out the modeling by representing the ground as springs (Figure 1-b) or finite elements (Figure 1-c).

It is standard procedure to model the soil as a homogeneous and isotropic elastic medium and the structure as a beam element defined by its rigidity (EI) in order to simplify the structural actions in the analysis of soil-structure interaction (Elachachi *et al.*, 2012; Frantziskonis and Breysse, 2003; Franzius *et al.*, 2005; Jahangir *et al.*, 2013) . The Euler-Bernoulli theorem, which ignores shear-induced deformations, provides the basis for the majority of beam solutions on elastic foundations (Morfidis and Avramidis, 2002) .

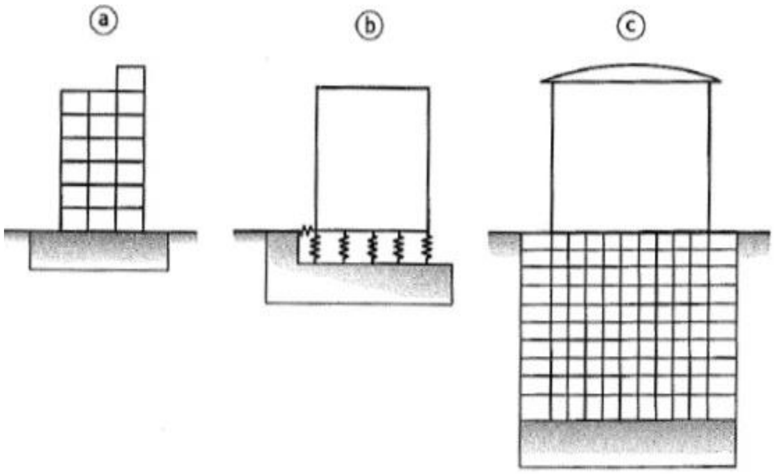


Figure 1 - Modeling of SSI:
a) Perfect fitment; b) Springs; c) Finite elements. From Davidovici (1999).

When a load is applied, it causes deformations and a redistribution of stresses in the soil around the foundation. This redistribution of stresses is dependent on the foundation's rigidity, the interface's properties, and the nature of the soil. Knowledge of the state of stress at the soil-foundation contact is necessary for realistic design that takes into account the soil's bearing capacity threshold. This contact constraint plays a major role in the study of SSI (Jahangir, 2011) . If we model the foundation as a beam resting on a Winkler soil model (see Figure 2), then an element of length dx of the beam can be isolated, as shown in Figure 3. The reaction of the soil and the stresses, such as the bending moment and the shear forces on its two sides, are also represented.

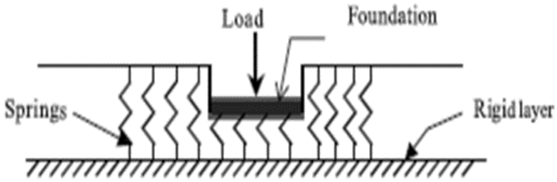


Figure 2 - Winkler foundation.

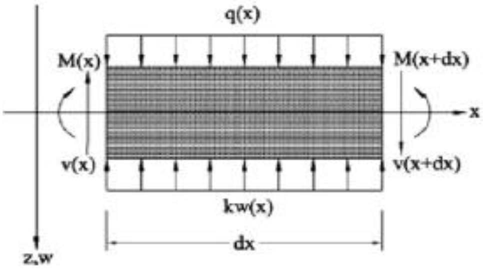


Figure 3 - Single element isolated from a beam.

The relationship between the stress under the foundation and the displacement of this unit element is given by Equation 1:

$$p(x) = k.w(x) \tag{1}$$

with p(x) is the reaction of the unit element of the soil [kN/m], w(x) is the settlement of the unit element of the soil [m].

The soil reaction coefficient k [kPa] is influenced by several factors, such as the load applied, the foundation's geometry, and its stiffness (Denis *et al*., 2007) . This coefficient increases when the foundation is flexible, and the soil is rigid.

In Figure 4, part (a) represents an arbitrary load on a beam supported elastically on a soil modeled by Winkler elements, part (b) shows the reaction of the soil p(x) under the beam associated with the curve w=w(x) of the settlement, and part (c) represents a unitary element integrating the reaction of the soil and the load of the structure q.

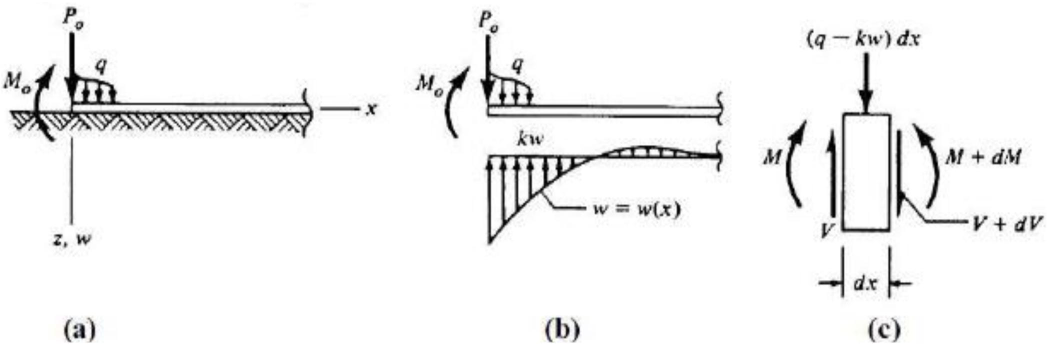


Figure 4 - Soil-beam interaction according to the Winkler model.

Figure 4 illustrates how we can isolate an element of the beam's length dx if we model the foundation as a beam resting on a Winkler soil model.

The following Equation 2 applies because of the equilibrium of vertical forces between the distributed load, the ground reaction, and the shear force in the beam (Figure 1-c).

$$V + dV + (q - kw)dx - V = 0 \quad (2)$$

We deduce (Equation 3) that:

$$\frac{dV}{dx} = -q + kw \quad (3)$$

With the Euler-Bernoulli theorem linking the bending moment to the shear force and the deflection of a beam (Equation 4) :

$$EI\frac{d^4M}{dx^4} + q = kw \quad (4)$$

Houlsby *et al*. (2005) note that the Winkler model (Equation 4) is simple and compatible with both analytical and numerical methods. The primary challenge of this model lies in determining *ks*, the stiffness of the elastic springs representing the soil beneath the foundation. This challenge is twofold because the soil reaction coefficient's numerical value is influenced by both the dimensions of the loaded area and the type of soil (Bowles and Guo, 1996) .

2.2. Model With Finite Elements

One particularly reliable numerical approach for examining SSI issues is the finite element method. Researchers first simulated the unbounded domain of the soil mass, which stretches infinitely in one or both directions, using traditional finite element methods (Ai *et al*., 2014; Neto *et al*., 2021) . Many software programs, such as ROBOT, SAP2000, and others, place a high priority on structural analysis, often simplifying the contribution of foundations and subsoil with basic elastic spring constants. For an accurate numerical analysis of tall structures, it's essential to have well-defined input parameters, incorporating comprehensive constitutive models for all materials, including soil, as well as models for soil-structure interfaces. The mechanical response of the compressible subsoil primarily governs the interaction between the structure and the soil system. In practice, the stress-strain behavior of the soil mass is nonlinear, necessitating the use of numerical techniques for accurate modeling. Differential settlement of the soil mass leads to a redistribution of forces within the frame members. It's important to understand how these kinds of interaction systems behave structurally because settlements change the shear forces and bending moments in the superstructure in big ways (Kacprzak *et al*., 2023; Tamayo and Awruch, 2016) .

To evaluate the settlement at the supports and the maximum bending moment of the RC structure, we utilized the finite element model developed by the second author. This model incorporates an analytical expression for the vertical stress applied to the soil, derived using the methodologies proposed by Vermeer *et al*. (1998) and Bjerrum (1967) . These methodologies assume the time-dependent nature of all inelastic strain and the influence of accumulated strain from prior creep stages on the pre-consolidation stress.

Their framework breaks down the total strains into elastic and inelastic strains, also known as visco-plastic or creep strains. Specifically, the consolidation phase integrates the inelastic strains, which manifest under constant effective stresses. Furthermore, Bjerrum (1967) found a close relationship between the pressure prior to consolidation and the creep strain that accumulates over time. Therefore, Vermeer *et al*. (1998) calculate the total strain ε_c when they apply an effective stress to the soil sample (Equation 5) :

$$\varepsilon_c = \varepsilon_c^e + \varepsilon_c^c = A\, ln\frac{\sigma'}{\sigma_0'} + C\, ln\frac{\tau_c+t'}{\tau_c} \quad (5)$$

where, ε represents the logarithmic strain, σ_0' denotes the initial effective pressure before loading, and σ' signifies the final effective pressure after loading. The parameter τ_c is a model constant, and t' refers to the actual time.

For the same strain, we can express the following Equation 6:

$$\varepsilon_c = \varepsilon_c^e + \varepsilon_c^c = A\, ln\frac{\sigma'}{\sigma_0'} + B\, ln\frac{\sigma_{pc}}{\sigma_{p_0}} \quad (6)$$

Before loading, the initial effective pressure is represented by σ_0', and after loading, the final effective pressure is represented by σ'. The preconsolidation pressure prior to loading and at the end of consolidation are denoted by the quantities σ_{p0} and σ_{pc}, respectively. There are two material parameters: A and B. You can express the elastic deformation component in terms of the consolidation pressure using the following Equation 7:

$$\sigma_{pc} = \sigma_{p0}\, exp\left(\frac{u}{Bz}\right) \quad (7)$$

The relevant variables represent the footing's vertical displacement (u) and the depth of the stress-influenced zone (z), which is believed to be 1.5 times the footing's breadth. Therefore, we can express the deformation in the time-dependent creep phase as follows using the ultimate effective load pressure as given by Equation 8:

$$\sigma' = \sigma_0'\, exp\left(\frac{\frac{u}{z} - C\, ln\left(\frac{\tau_c+t'}{\tau_c}\right)}{A}\right) \quad (8)$$

This study integrates soil-structure interaction by utilizing a logarithmic relationship (Equation 9) to model the soil behavior beneath the structure's footings.

$$\sigma = \sigma_{p0}\, exp\left(\frac{u}{Bz}\right) + \sigma_0'\, exp\left(\frac{\frac{u}{z} - C\, ln\left(\frac{\tau_c+t'}{\tau_c}\right)}{A}\right) \text{ for: } t' > 0 \quad (9)$$

For normally consolidated soil (OCR = 1), where $\sigma'_0=\sigma_{p0}$ and τ_c is exactly one day, the relationship below (Equation 10) can be used to indicate the total applied vertical stress:

$$\sigma = \sigma_0'\left(exp\left(\frac{u}{Bz}\right) + exp\left(\frac{\frac{u}{z} - C\, ln(t'+1)}{A}\right)\right) \text{ for: } t' > 0 \quad (10)$$

Here, Equation 10 represents the logarithmic relationship governing the applied vertical stress σ'_0 over time t', considering the consolidation time τ_c. This equation accounts for the change in effective stress caused by time-dependent soil consolidation processes.

2.3. Case Study Presentation

There are two main sections to this study. Firstly, the second author develops a finite element model and uses MATLAB software to carry out the numerical modeling of SSI. This way of modeling, which looks at both how the soil interacts with the structure and how the soil changes over time, will make it easier to design an RC structure at the SLS. Furthermore, we will look into how various soil compressibility characteristics affect the stress and deformation behavior of the structure. We must build the beam's mechanical model, as shown in Figure 5, to compute the total soil settlement and the maximum bending moment within the beam girders' cross-section. This model includes vehicles and trucks as consequences of traffic. The structural analysis will consider the combination of loads at the Serviceability Limit State (SLS). In this case, X represents the last axle's position in relation to the first support, A.

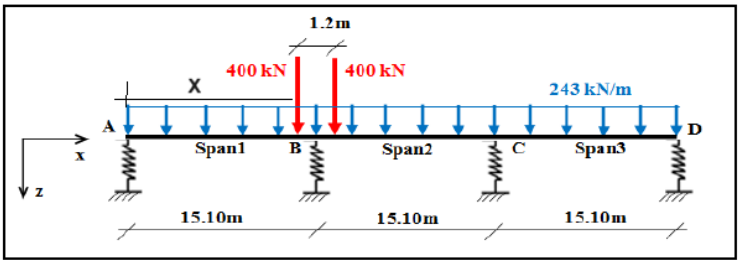


Figure 5 - RC beam mechanical model with three similar spans.

3. Results and discussions

The numerical SSI model created by second author was used to figure out how nonlinear behavior and different types of soil affect the ability of RC beams to deform. This model enabled us to calculate the bending moments and support displacements of RC beams. The numerical simulation results, as presented in this section, depict the mechanical interaction between the soil and the structure, as seen in Figure 5.

3.1. Vertical Strain Over Time in Compressible Soil

To conduct a thorough assessment of the soil's impact on the construction's safety, we have chosen to look at compressible soil. We have determined the compression index (*Cc* = 0.05*)* and the initial void ratio (*e0* = 0.80*).*

It is important to note that the soil's actual compressibility properties influence the calculated vertical strain. Throughout the day, we apply initial effective and isotropic preconsolidation pressures of 45 kPa and 85 kPa, respectively, to the compressible soil. Furthermore, the beam girder's supports A, B, C, and D apply stresses of 100 kPa, 98 kPa, 160 kPa, and 136 kPa, respectively, causing the soil to creep under this restriction. We consider one day to be the duration required for 100% primary consolidation. We applied consolidation time to numerical simulations on low-compressible soil with similar compressibility properties. To counteract the creep effect, we subjected the soil to continuous loads for 1, 100, 1000, 3000, 6000, and 12000 days in this case to counteract the creep effect. This period is usually considered adequate to complete primary consolidation and detect the beginning of creep (Al-Shamrani and Al-Mashary, 2003*)* .

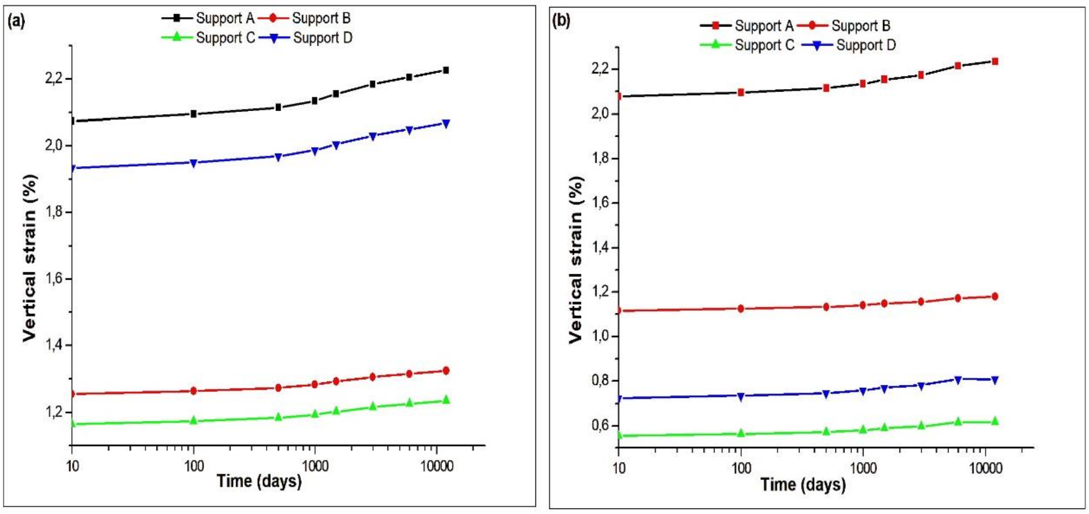


Figure 6 - RC Vertical strain curves in the beam for:
(a*)* **homogeneous and (b***)* **heterogeneous soil type.**

Especially when comparing creep rate models of the compressible soil layer, the applied vertical stress affects the observed vertical strain. For a homogeneous soil with an initial void ratio of $e0$ = 0.80 and a compression index of Cc = 0.05, the creep rates at supports B and D are 1.40% and 2.10%, respectively. We use these values as a reference to assess the effects of soil heterogeneity. Interestingly, a heterogeneous soil with a compression index of Cc = 0.11 and an initial void ratio of $e0$ = 0.51 reduces these values to 1.18% and 0.82%, respectively. The cross sections at supports A and D show a similar trend, but with a more rapid rate of increase. This demonstrates that the soil compressibility parameters' heterogeneity has a significant impact on the system's response heterogeneity. In this case, the soil's heterogeneity causes the deformation capacity at the internal support cross sections of the RC beams to decrease by almost two times. Structural analysis generally accepts that soil heterogeneity has a particular impact on support cross sections.

3.2. Impact Of Secondary Consolidation Time on Soil Behavior

The most useful and commonly used metric to describe secondary compression is the secondary compression coefficient (Handy, 2002; Yin, 1999) . This is important because, for some soils, the coefficient remains almost constant with increasing loading. Therefore, researchers have conducted several studies to explore the long-term soil behavior of engineering works (Hu and Yang, 2017; Mesri and Vardhanabhuti, 2005) . We conducted a numerical study for various values of the soil compressibility parameters to elucidate their impact on the secondary consolidation of the beam. Figure 7 depicts secondary consolidation as a function of time.

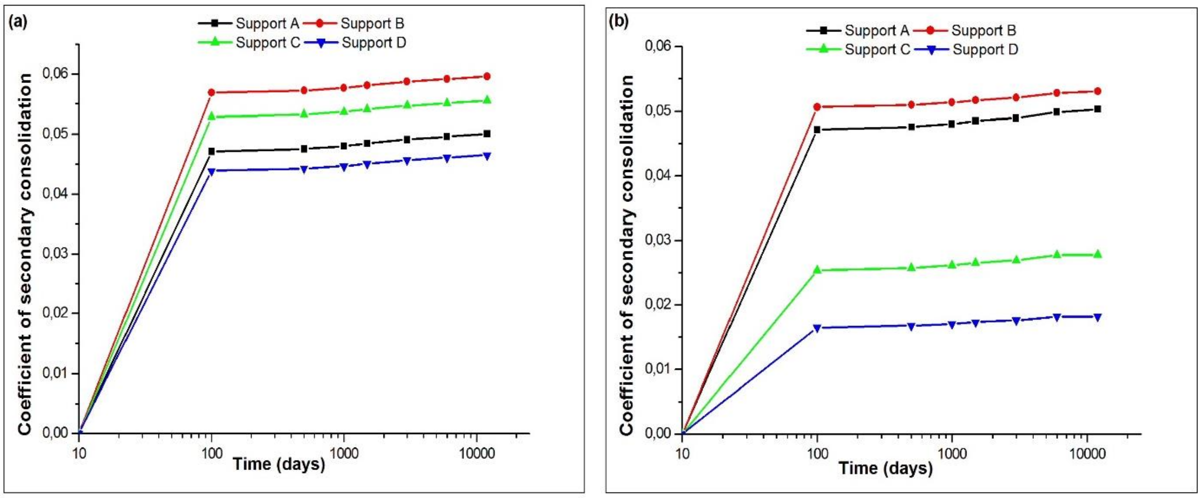


Figure 7 - Secondary consolidation plots for two soil types: (a) homogeneous and (b) heterogeneous soil type.

The soil compressibility characteristics significantly influence the overall behavior of the soil-structure system, even when accounting for soil heterogeneity. This impact is particularly pronounced at supports C and D, where changes in compressibility parameters during secondary consolidation have a substantial effect, aligning with the findings in Section 3.1. The interaction effect between the soil and the structure intensifies by almost a factor of two for each cross section, especially at supports A and B. These results clearly indicate that secondary consolidation increases markedly when compressibility characteristics are considered, underscoring the need to account for potential long-term settlements and differential movements in structural design to ensure stability and integrity in heterogeneous soil conditions.

3.3. Bending Moments Diagram

It looks at the worst possible mix of SLS under three different contact conditions: rigid supports, linear and nonlinear elastic soil behavior as shown in Equation 10, and homogeneous versus heterogeneous soil conditions. We conduct this assessment through a series of numerical simulations of soil-structure interaction, providing a comprehensive understanding of the beam's performance across diverse load scenarios. The continuous beam's uniform spans, each of equal length, serve as the backdrop for these load scenarios, as shown in Figure 5. The first loading case occurs at X = 8.15 m, while the second is at X = 14.50 m. Figures 8 and 9 show the maximum bending moment diagrams for the beam girders under homogeneous and heterogeneous soil conditions for the first and second loading cases, respectively.

When you compare fully rigid support scenarios under SLS loading instances for both homogeneous and heterogeneous soils, adding nonlinear elastic soil behavior changes the results. This addition causes the positive moment in span 2 to increase by about 16%, and the negative moment at support B to decrease by 14% for homogeneous soil. The bending moment in span 1, however, stays constant, indicating that we can ignore the influence of SSI in this span.

Conversely, in the heterogeneous soil scenario, the results are equally significant. There is a significant 22% reduction in the negative moment at support B, a significant 15% reduction in the interaction effect for the section in span 2 and a significant 10% reduction for the section in span 1. These findings highlight the substantial influence of SSI on structural behavior and, crucially, highlight the potential for underestimating maximum bending moments when assuming rigid support conditions.

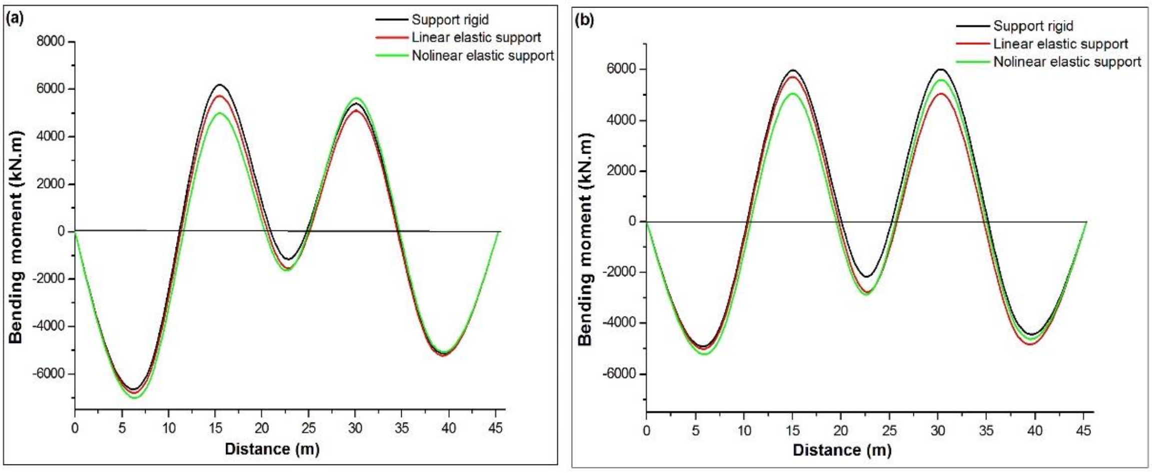


Figure 8 - Diagrams showing the bending moments in the beam girder for the first loading scenario: (a) in homogeneous soil and (b) in heterogeneous soil.

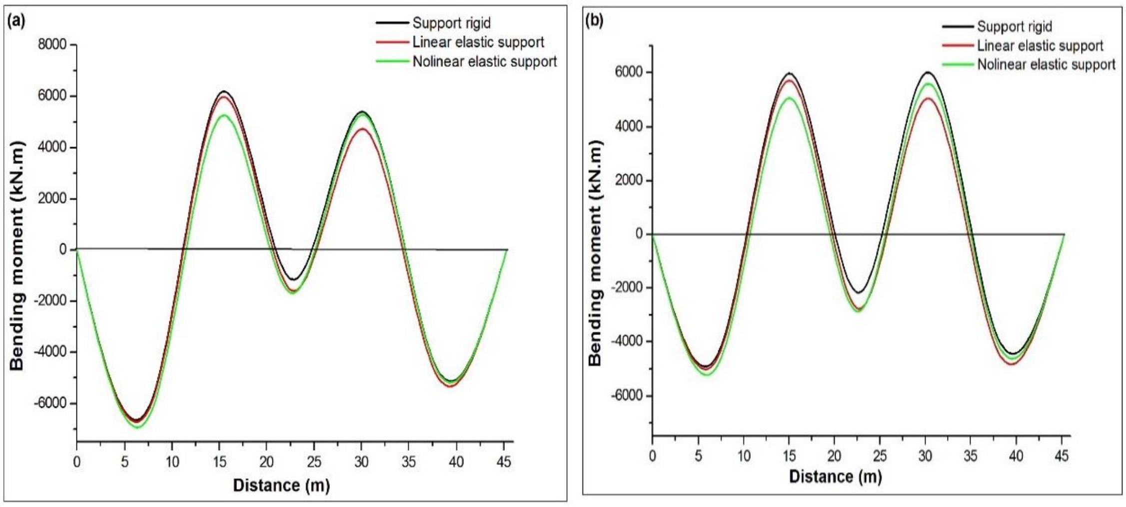
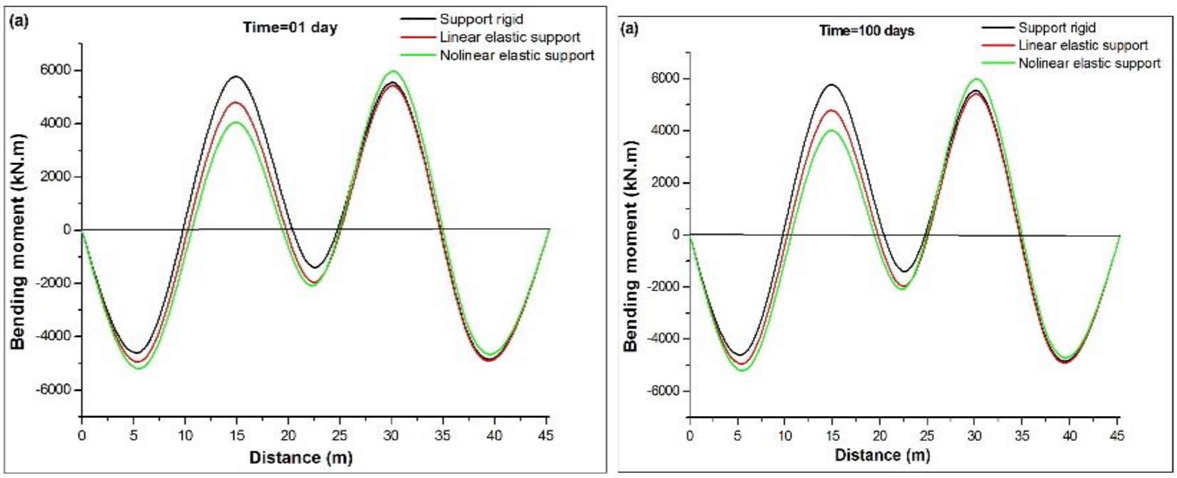


Figure 9 - Diagrams showing the bending moments in the beam girder for the second loading scenario: (a) in homogeneous soil and (b) in heterogeneous soil.

3.4. Bending Moment Time-Curve

Analyzing the variation in bending moments observed at 1, 100, 1000, 3000, 6000, and 12000 days following the application of respective loads can provide further insight into the bending moment-time curve. Figures 10 and 11 depict the bending moment-time curves recorded in the beam girders under three distinct contact conditions. We draw a comparison between the fully rigid support scenario under SLS loading over 1 to 12000 days and the nonlinear elastic behavior of moderately compressible soil. Upon examination of the results, significant differences emerge in the distribution of moments at internal supports and span cross-sections, taking into account SSI. For homogeneous soils, the computational outcomes demonstrate a 39% reduction in the negative moment at support B and an approximately 32% decrease in the positive moment within the second span. Additionally, there is a 17% reduction in positive moments within the first span and an 11% decrease in negative moments at support C, all attributable to the moderately compressible soil. Furthermore, we observe a reduction in the interaction effect, resulting in a 31% decrease in the second span cross-section and a 14% reduction in the first span cross-section. Notably, the bending moment increases, particularly at support B in the first span, and more than doubles for the second span cross-section with soft soil. These findings clarify the impact of SSI on structural behavior and highlight the underestimation of maximum bending moments due to rigid support assumptions:



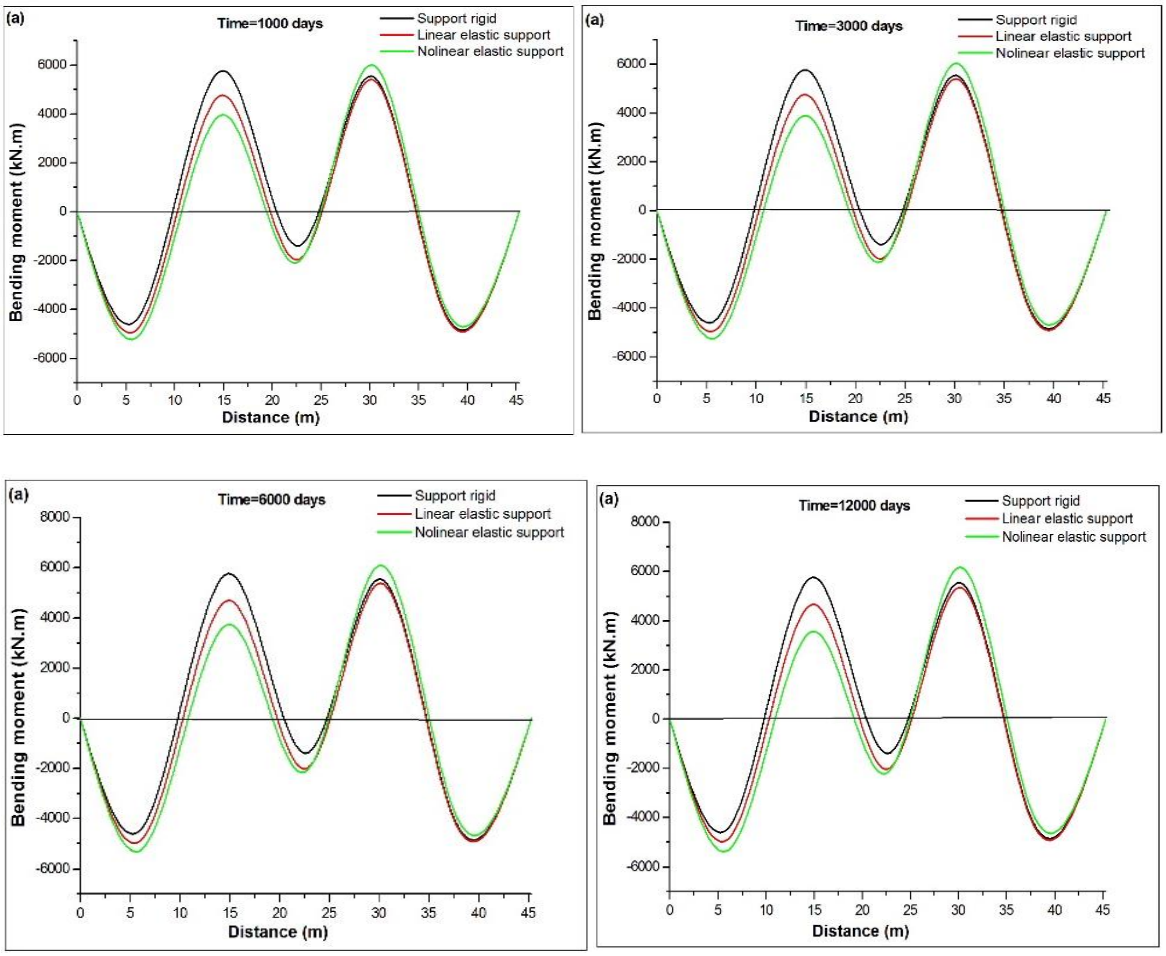
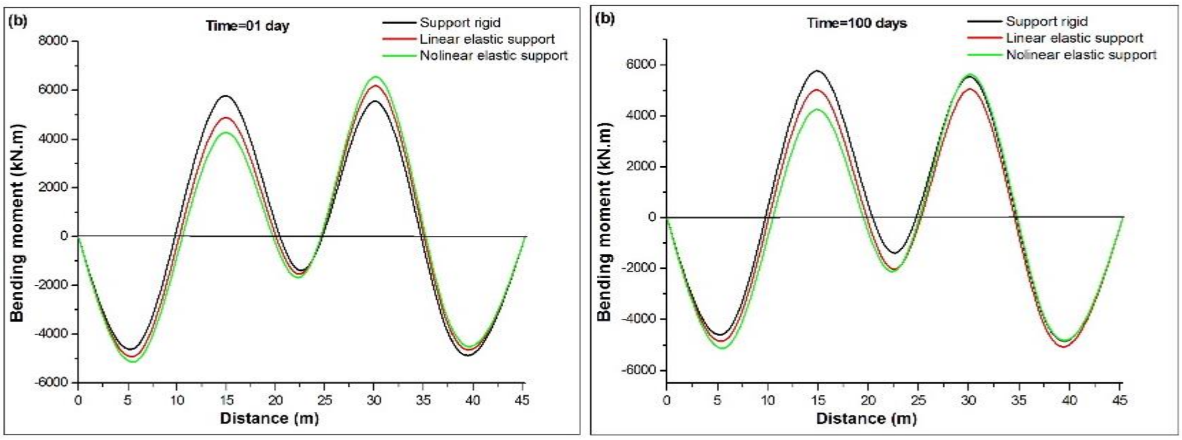


Figure 10 - Bending moment-time diagrams in beam girders with compressible soil under various soil conditions, (a) homogeneous soil.



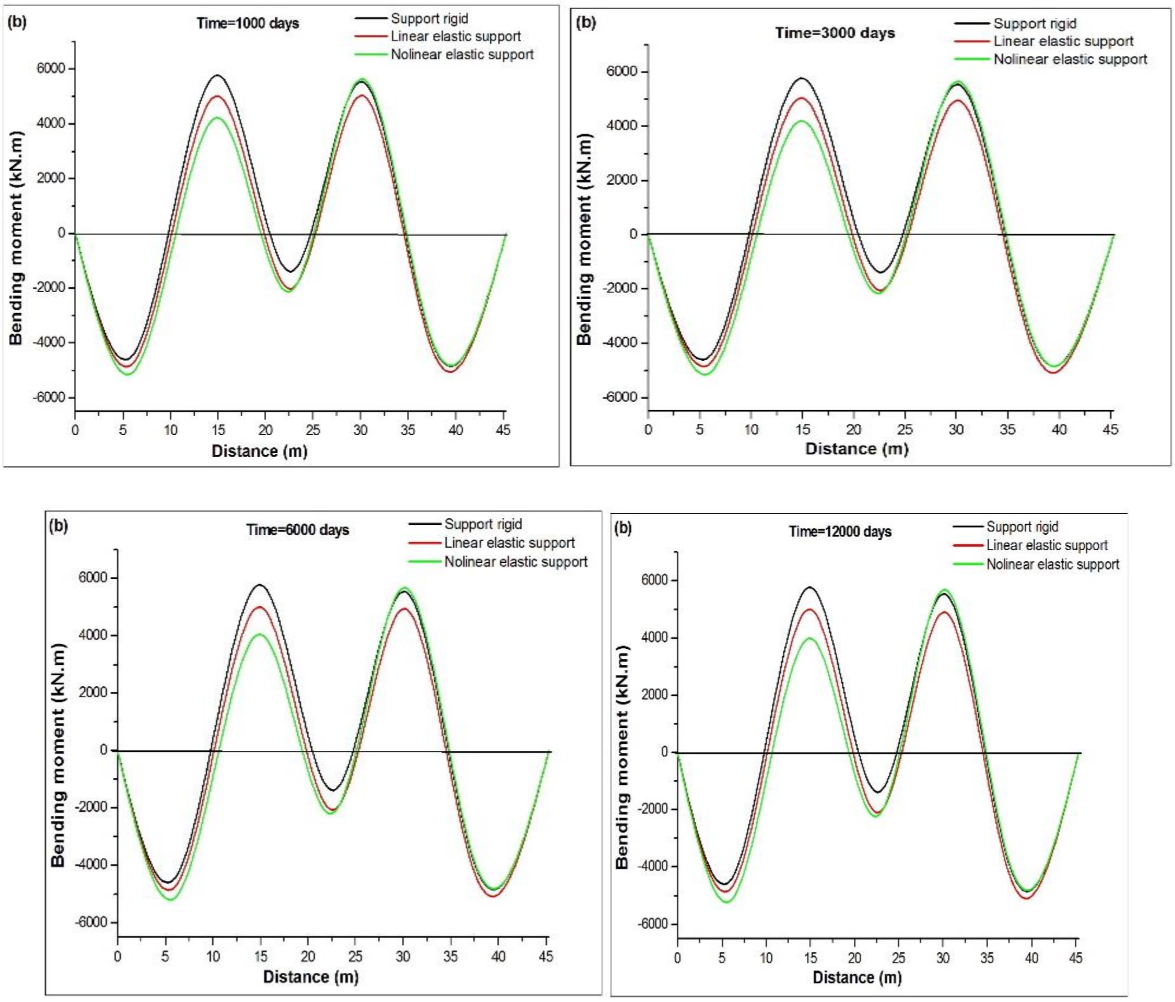


Figure 11 - Bending moment-time diagrams in beam girders with compressible soil under various soil conditions, (b) heterogeneous soil.

3.5. Bending Moment Diagrams with Nonlinear Soil Models

This research investigates how soil heterogeneity and nonlinear behavior affect the deformation capacity of reinforced concrete (RC) girders. We performed numerical simulations using a mechanical model of SSI to determine the convoy position and critical section. The analysis considers a duration of 12,000 days. We study soil heterogeneity and nonlinearities using bending moment distributions. The study takes into account the bending moment in beam girders on compressible soil under different soil conditions, both homogeneous and heterogeneous.

Figure 12 presents a comparison of nonlinear soil models over time, specifically focusing on bending moments at critical cross-sections of RC girders situated on compressible soil.

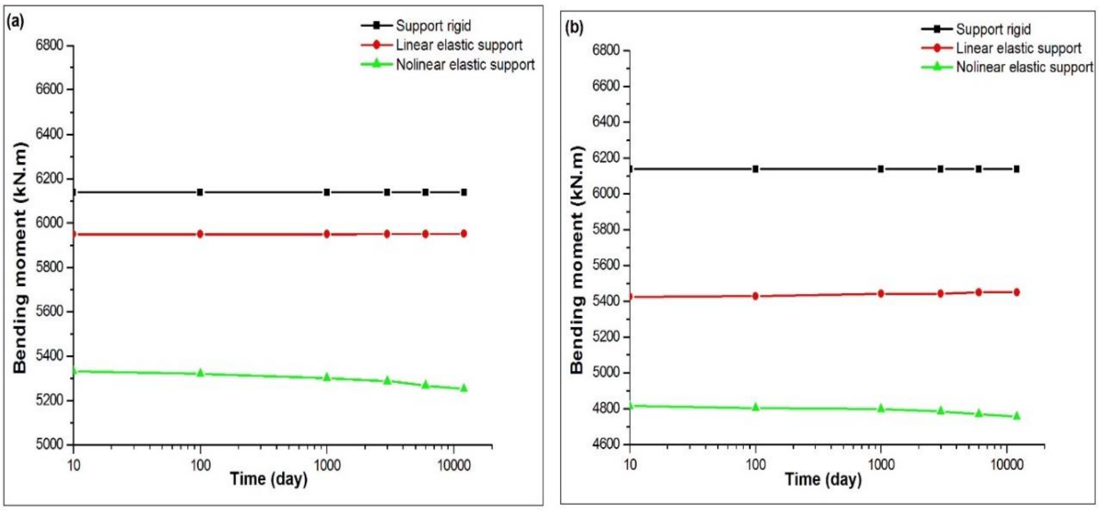


Figure 12 - Bending moment diagram using nonlinear soil models for: (a) uniform soil, and (b) varied soil conditions.

The study's findings show that nonlinear soil models can significantly influence the distribution of bending moments in RC girders and foundations built on compressible soil. It is evident that bending moment behavior varies significantly across different soil compositions. In particular, bending moments tend to increase in diverse soil conditions, whereas they decrease in homogenous soil settings. This observation implies that the inherent heterogeneity and compressibility parameters of the soil intricately link to the complexities of SSI. As a result, the variability observed in the SSI system's response emphasizes the model's sensitivity to these soil characteristics. These results highlight the critical role played by soil heterogeneity and the realistic behavior of soil in the design process of RC beams. Understanding these nuances is imperative for engineers and designers aiming to ensure the structural integrity and performance of RC beam structures in varying soil conditions.

4. Conclusion

The primary objectives of this study are the identification and measurement of how soil compressibility characteristics affect the internal force redistribution within reinforced concrete (RC) structures, and the evaluation of how these characteristics impact the safety assessment of these structures. The analysis has significant implications for the design standards aimed at controlling redundant RC structures.

The results show how important it is to take soil heterogeneity into account. They show that the interaction between soil and structure has a big effect on the ability of RC structures to deform, especially when soil nonlinearity and compressibility are taken into account. This study demonstrated that significant variations in the parameters governing soil's compressibility led to significant variations in its behavior compared to rigid foundation structures. Changes in the soil's compressibility led to significant differences in the parametric study. This shows how important it is to think about how the soil interacts with structures and how different types of soil affect the safety of RC structures. Soil nonlinearities reinforce the critical need to include these factors in safety analyses.

Also, research is being done to create an integrated mechanical-reliability analysis method that takes into account how uncertainties in the behavior of the soil itself and the interaction between the soil and the structure can spread. This approach will enhance the prediction and management of risks associated with variations in soil characteristics, thereby improving the reliability and safety of reinforced concrete structures.

In conclusion, this study emphasizes the critical importance of accounting for soil compressibility characteristics and heterogeneity in the design and assessment of RC structures. The findings and future research efforts will contribute to the development of more robust design standards and more accurate safety assessment methods, ensuring greater infrastructure durability and safety.

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