



Effect of Long-Term Soil Deformations on RC Structures Including Soil-Structure Interaction

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Abstract

Lifetime service of Reinforced Concrete (RC) structures is of major interest. It depends on the action of the superstructure and the response of soil contact at the same time. Therefore, it is necessary to consider the soil-structure interaction in the safety analysis of the RC structures to ensure reliable and economical design. In this paper, a finite element model of soil-structure interaction is developed. This model addresses the effect of long-term soil deformations on the structural safety of RC structures. It is also applied to real RC structures where soil-structure interaction is considered in the function of time. The modeling of the mechanical analysis of the soil-structure system is implemented as a one-dimensional model of a spring element to simulate a real case of RC continuous beams. The finite element method is used in this model to address the nonlinear time behavior of the soil and to calculate the consolidation settlement at the support-sections and the bending moment of RC structures girders. Numerical simulation tests with different loading services were performed on three types of soft soils with several compressibility parameters. This is done for homogeneous and heterogeneous soils. The finite element model of soil-structure interaction provides a practical approach to show and to quantify; (1) the importance of the variability of the compressibility parameters, and (2) the heterogeneity soil behavior in the safety RC structures assessment. It also shows a significant impact of soil-structure interaction, especially with nonlinear soil behavior versus the time on the design rules of redundant RC structures.

Keywords: Soil-Structure Interaction; Soil Compressibility; Mechanical Analysis; RC Structures.

1. Introduction

The process of monitoring RC structures in service that includes inspections, specific measurements damages and evaluations of existing structures, is targeting the safety of the structure while begin in use. To achieve this objective, the designer must ensure the integrity of these structures throughout their lifetime. However, the performance of these structures depends in most cases on the interaction between the soil and the structure. The interaction depends on the load applied to ensure the overall stability of these structures. Various researches have been conducted on the effect of soil-structure interaction highlighting its overall importance in the prediction of the response of the coupled system [1, 2]. To simplify the actions of the structure in the analysis of soil-structure interaction, it is common to model the structure of a beam element characterized by rigidity (EI) and modelling the soil as a homogeneous and isotropic elastic medium [3]. The need to vary the contact force versus displacement has been treated with a non-linear model

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analysis by Frank and Thepot (2005) and Viladkar et al. (2006) [4, 5]. These studies have underlined that the nonlinear effects can alter the stiffness of the soil under the foundation. They showed the importance of using nonlinear material models in the analysis of soil-structure interaction. Fontan et al. (2011) and Bezih et al. (2015, 2017) [6-8] have studied the soil-structure interaction of RC bridges under static loading. The study presented by Fontan et al. (2011) [6] has shown the complexity of the soil-structure interaction and the need for considering the specific properties of soil and structural stiffness. In this regard, the work conducted by Bezih et al. (2015, 2017) [7, 8] show the significant effect of soil-structure interaction on the reliability of RC bridges. Jahangir et al. (2012) [9] developed analytical model to investigate the effects of the shrinkage of clayey soils on buildings through soil-structure interaction analysis. Recently, Masaeli and Panali (2018) [10] presented a numerical model for analyzing the nonlinear soil-structure interaction. The Winkler soil-foundation interaction model has been used for modelling the nonlinear behaviour between the structure and the soil. Their numerical results showed that the nonlinear soil-structure interaction has a significant effect on the efficiency of the tuned mass damper, especially when the nonlinear behaviour of soft soils is considered. Subsequently, a new analytical model of soil-structure interaction for creep soil was presented by Montero et al. (2020) [11]. This model can be used to calculate the load evolution on an anchored structure over time and the associated creep strains. The results demonstrate the relevance of having specific creep tests for at least a minimum duration. This will help not only in making an adequate estimation of the used parameters but also to obtain an accurate prediction.

Knowledge of the stress state in contact with soil-structure overtime is necessary for a realistic design of the structure and needed to be established. This implies that for a given stress state, a relationship that expresses the evolution of the deformation of the soil over time is needed. This constraint on contact plays a more important role in the study of soil-structure interaction, especially in soft soils behavior. This is caused by the existence of hydro-mechanical phenomena which is causing many geotechnical disorders (e.g., differential settlement, primary and secondary consolidation). In addition, because of their low permeability, the shear strength of soft soils differs significantly from the granular soils. Disorders can cause the reduction of life and even premature failure of elements of these structures. For these reasons, the structural analysis of RC structures is essential in studying these structures in Serviceability Limit States (SLS), when the high heterogeneity of the soil is involved in the mechanical behavior of the superstructure.

In the present work, a new finite element model for soil-structure interaction is developed to calculate the consolidation settlement, and the bending moment in the foundation of an RC structure. This model is considering the influence of the long-term soil deformations of soft soils. The finite element model is applied to a real RC structure where soil-structure interaction is considered with time. Before considering the interaction effects, it is necessary to specify the soil behaviour model. This model will be introduced in the mechanical analysis of the soil-structure system. In the present section, the nonlinear behaviour of the soil versus time is based on the Soft Soil Creep Model (SSCM) developed by Vermeer and Neher (1999) [12]. The modelling mechanical system soil-structure interaction is implemented in a one-dimensional model of a spring element in a real case of RC continuous beams. This study evaluates, not only, the sensitivity and identifies the roles of the different compressibility parameters and heterogeneity of the soil, but also the effect of long-term soil deformations, as well as the nonlinear behaviour versus time and assessment of the safety RC structures. The methodology adopted in this work is shown in Figure 1.

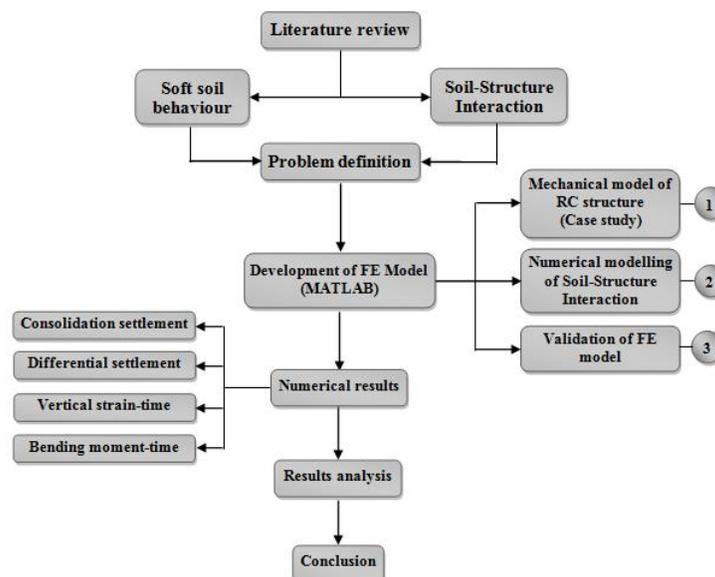


Figure 1. Flowchart of research methodology

2. Literature Review on Soft Soil Behaviour

When RC structures are built on soft soils, they transfer through the foundation loads to the soil. When the saturated soil is compressed due to imposed constraints, it causes an increase in the hydrostatic pressure in the pores of the soil. Initially, the compression has led to increasing the density of soil, which leads to an immediate settlement of the foundation. However, with time, the pore pressure dissipated is generated by applying loads to the soil. This last continue to deform under a constant effective stress, which is known by secondary consolidation or the creep phenomenon, this phenomenon generally occurs after an instantaneous deformation, which is characterized by the coefficient of secondary consolidation which characterize the skeleton viscosity by Buisman (1936) [13]:

$$C_{\alpha e} = \frac{\Delta e}{\Delta \log t} \quad (1)$$

Mesri and Godlewski (1977) and Mesri and Castro (1987) [14, 15] have shown, however, that $C_{\alpha e}$ correlated to the index of compression of the soil C_c by the simple relation:

$$\frac{C_{\alpha e}}{C_c} \approx 0.04 \quad (2)$$

This report indicates that the process of change in volume of soil is depending on the effective stress and the skeleton structure modifications (e.g., internal arrangement of grains) over time have the same nature. The behaviour of soft soils has been the subject of much research. The experimental investigations from previous literature made in the laboratory and in situ on natural soft clays show that the deformations are not instantaneous, which leads also to model viscous phenomena (time effect and strain-rate), which can be approached by viscoelastic laws (e.g., when deformations are completely reversible) or elasto-viscoplastic (e.g., when deformations are partly irreversible).

The first theory of soil consolidation was presented by Terzaghi in 1925. Subsequently, analytical solutions based on dimensional consolidation of Terzaghi, it was extended in two and three dimensions [16]. Both theories of Biot and Terzaghi suppose that the behavior of linear elastic soil. Also, we can retain the works of Casagrande (1936) and Taylor (1942) [17, 18]. These works were later recaptured by Bjerrum (1967) [19], who introduced a term to describe the delayed consolidation, which can undergo secondary consolidation of the natural deposits under the effective stress constant or slightly variable. The research of Bjerrum (1967) [19] has been demonstrated that the void ratio of the clay soil decreases with time under a constant confining stress, a secondary effect of the consolidation of the soil. This decrease in void ratio leads to an increase in the apparent pre-consolidation pressure. Since the work of Bjerrum (1967) [19], which studied the creep behaviour of soft soils, considering the deformation of the soil for the short time has been developed with different models by many researchers [20-24]. Most of these researchers are turning to numerical methods. They suggested models for nonlinear soil behaviour and implemented these models in a finite element program, which allows considering the time effect when the secondary consolidation is developed. Some general three models (3D) creep models were directly generalized from the 1D differential formulation by some authors [12, 20, 25, 26]. The relationship stress-strain-time behaviour of soils also plays an important role in the study of the deformation behaviour of geotechnical materials in the long term. Several authors have introduced the effect of soil creep in their studies. In this regard, we can mention the work of Yun and Leroueil (2001) [27]. He proposed a nonlinear viscoplastic model considering the effects of strain rate on the viscoplastic consolidation of natural clay. It has been verified that, this nonlinear viscoplastic model can be used in the calculation of the consolidation behaviour of natural clay. Leong and Chu (2002) [28] have studied experimentally the effect of creep on the instability of loose sand behaviour. They showed that from a basis of experimental data, we can determine a limit specifies the condition in which the instability of loose sand undrained can be induced by creep.

Mesri and Vardhanabhuti (2005) [29] indicate that the creep deformation of soil is higher in organic soils and increases with the water content and the type of organic soil material. The very organic soils are normally subject to considerable secondary consolidation. In Leoni et al. (2008) [26] study, a new anisotropic model for the time-dependent behavior of soft soils was developed. The authors also show that, this model is capable of capturing key features of viscous soft soil behaviour; they found that due to the simple formulation of the model proposed, it is easy in applications such as engineering. In Linchang et al. (2008) [30] study, an analytical solution to calculate settlement-time relationship of a foundation built on a dual compressible layer has been proposed. A parametric study has been carried out, demonstrates the effect of loading time on the degree of consolidation of the double-layered soil. They concluded that the stiffness of the double layer soil profile above the foundation plays an important role in the calculation of the consolidation. Bodas Freitas et al. (2012) [31] presented a numerical study on the effect of creep characteristics of a fine soil, including soft clay (e.g., amplitude and the type of law creep) and the rate of loading applied to the calculation of the bearing capacity of shallow foundations preloaded in the short term. The soil is modelled using an elastic-viscoplastic model. They showed that the onset of creep over time represents a significant increase bearing capacity of shallow foundation. Recently, Wang et al. (2016) and Zhu and Bing (2018) [32, 33] have developed a model that can well reproduce temperature-dependent creep behavior of soft intact clay under the one-

dimensional loading condition. For their part, Qi et al. (2017) [34] proposed a model which can well reproduce the time-dependent behaviour with creep degradation for natural soft clays under one-dimensional condition. The secondary compression coefficient is by far the most useful and commonly used parameter for describing secondary compression [35]. The importance of this parameter stems from the fact that for some soils, the parameter indicates a nearly constant value for a given load increment [36]. This was the main reason, why numerous studies have been carried out by different researchers in order to compensate for the long-term behavior of the soil on civil engineering structures [29-37].

The overall result of the literature was to analyze the effects of time (e.g., phenomena of secondary consolidation) on the behaviour of soft soils and their inclusion in the structure calculation. Indeed, the phenomena of secondary consolidation are nature complex viscous that occurs over time, can have serious consequences on the structure decades after its completion. The effect of long-term soil deformations on the structural safety calculation of RC structures deserves to be studied with precision, considering the factors influencing this phenomenon. It is not yet fully understood, with a rigorous and structural safety study of soil-structure interaction.

3. Development of Finite Element Model

3.1 Model for Simulating Soft Soils Behaviour

The main objective of this numerically study is to analyse the effects of soft soils behaviour. The soil model that all incorporate creep effects is the SSCM. This model is focusing on their capabilities to capture the time-dependent soil behaviour as well as the influence of anisotropy and structures of the creep effect.

The constitutive description presented in this section is the one-dimensional version of that presented by Vermeer et al. (1997) [23]. The SSCM is an extension of the original soft soils model to take the time dependency of soft soils strains into account. The fundamental one-dimensional creep model for the SSCM is constructed based on the work of [13, 19, 38]. According to them, the total strains are composed of two parts; the elastic part and the inelastic part (e.g., viscoplastic or creep) strains, where the inelastic part is not only occurring under constant effective stresses but also is incorporated into the consolidation phase. Moreover, the pre-consolidation pressure is closely linked to the creep strain accumulated during the time [19].

Buisman (1936) [13] proposed the following equation to describe creep behaviour under constant effective stress.

$$\varepsilon = \varepsilon_c - C_B \log\left(\frac{t}{t_c}\right) \quad (3)$$

Where ε_c is the strain up to the end of consolidation, t the time measured from the beginning of loading, t_c the time to the end of primary consolidation and C_B is a material constant. For further consideration, it is convenient to rewrite this equation as:

$$\varepsilon = \varepsilon_c - C_B \log \frac{t_c + t'}{t_c}, \quad \text{for } t' > 0 \quad (4)$$

With $t' = t - t_c$ being the effective creep time. For small strains, it is possible to show that (Vermeer et al. [23] and Vermeer et al. [12]):

$$C = \frac{C_\alpha}{(1+e_0)\ln 10} = \frac{C_B}{\ln 10} = \frac{C_B}{2.3} \quad (5)$$

With e_0 being the initial void ratio and C_α is a secondary consolidation index. This shows that the logarithmic strain is approximately equal to the engineering strain. By taking into consideration classical literature, it is possible to describe the end of consolidation strain ε_c , by the Equation 6:

$$\varepsilon_c = \varepsilon_c^e + \varepsilon_c^c = A \ln \frac{\sigma'}{\sigma_0} + B \ln \frac{\sigma_{pc}}{\sigma_{p0}} \quad (6)$$

In the above Equation 6, ε the logarithmic strain, σ_0 represents the initial effective pressure before loading and σ' is the final effective loading pressure. The value σ_{p0} and σ_{pc} representing the preconsolidation pressure, corresponding to before loading and end-of-consolidation states respectively. Consequently, an expression of total strains is formulated in Equation 7 and illustrated in Figure 1.

$$\varepsilon_c = \varepsilon_c^e + \varepsilon_c^c = A \ln \frac{\sigma'}{\sigma_0} + B \ln \frac{\sigma_{pc}}{\sigma_{p0}} + C \ln \frac{\tau_c + t'}{\tau_c} \quad (7)$$

Where C and τ_c are the model parameters, and t' is the actual time. The material parameters A , and B , may be expressed in terms of the swelling index C_r and compression index C_c as:

$$A = \frac{C_r}{(1 + e_0) \ln 10} \tag{8}$$

$$B = \frac{(C_c - C_r)}{(1 + e_0) \ln 10} \tag{9}$$

The first part of the Equation 7 is the elastic strains due to an increase of effective stresses in the total given period of time t . The second part considers the creep strains during the consolidation phase, described by the increase of preconsolidation pressure during t_c . The final part stands for a pure creep strain under constant effective stresses, started from the end of the consolidation, t' .

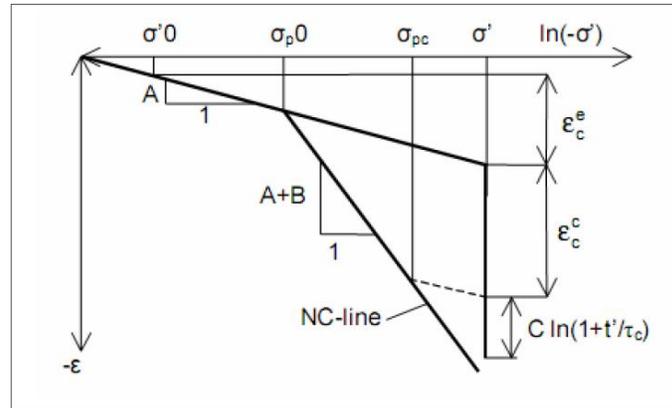


Figure 2. Idealized stress-strain curve with different strain increment [12]

The previous equations confirm the relationship between creep and accumulated time for a given constant effective stress. To solve the problems of transient or continuous loading, it is necessary to formulate a constitutive law in differential form (e.g., more details can be seen in Vermeer et al. [12]). The main disadvantage of the SSCM is the problem of modelling the deviatoric creep behaviour, lacking the possibility of modelling the real deviatoric creep behaviour of the over-consolidated soil.

3.2. Finite Element Model of Soil-Structure Interaction

The finite element model of soil-structure interaction developed in this work was used to calculate the settlement at the support-sections and the bending moment of RC structure. For this model and in order to obtain an analytical expression for the applied vertical stress in the soil, a basic idea connected to Bjerrum's and Janbu's approaches has been adopted [19-39]; here the total strain is supposed to be the sum of a time independent elastic part and a time dependent creep (viscoplastic) part. Therefore, if the effective stress σ' will be applied to the soil sample, the total strain ϵ_c is calculated as:

$$\epsilon_c = \epsilon_c^e + \epsilon_c^c = A \ln \frac{\sigma'}{\sigma'_0} + C \ln \frac{\tau_c + t'}{\tau_c} \tag{10}$$

For the same strain, it is possible to write the following equation:

$$\epsilon_c = \epsilon_c^e + \epsilon_c^c = A \ln \frac{\sigma'}{\sigma'_0} + B \ln \frac{\sigma_{pc}}{\sigma_{p0}} \tag{11}$$

The elastic deformation part can be written in the form of the consolidation pressure according to the relationship:

$$\sigma_{pc} = \sigma_{p0} \exp \left(\frac{u}{Bz} \right) \tag{12}$$

Where u is the vertical displacement of the footing and z is depth of the influenced zone caused by the stress under the footing, which is taken as 1.5 times the footing width.

The time dependency of the preconsolidation pressure may be found by combining Equations 10 and 11:

$$B \ln \frac{\sigma_{pc}}{\sigma_{p_0}} = C \ln \frac{\tau_c + t'}{\tau_c} \quad (13)$$

So, the deformation in the part of time-dependent creep can be written in the form of the final effective loading pressure as follows:

$$\sigma' = \sigma'_0 \exp \left(\frac{\frac{u}{z} - C \ln \left(\frac{\tau_c + t'}{\tau_c} \right)}{A} \right) \quad \text{for: } t' > 0 \quad (14)$$

In this work, the soil-structure interaction is taken into account by a logarithmic relationship for the soil under the structure footings, as following:

$$\sigma = \sigma_{p_0} \exp \left(\frac{u}{Bz} \right) + \sigma'_0 \exp \left(\frac{\frac{u}{z} - C \ln \left(\frac{\tau_c + t'}{\tau_c} \right)}{A} \right) \quad \text{for: } t' > 0 \quad (15)$$

Where σ is the applied vertical effective stress. If the soil is normally consolidated (over consolidation ratio, OCR= 1), with $\sigma'_0 = \sigma_{p_0}$ and where τ_c is precisely one day, the overall applied vertical stress, which can be expressed by the following relationship:

$$\sigma = \sigma'_0 \left(\exp \left(\frac{u}{Bz} \right) + \exp \left(\frac{\frac{u}{z} - C \ln (t' + 1)}{A} \right) \right) \quad \text{for: } t' > 0 \quad (16)$$

Considering the above equations, it becomes possible to consider the effect of compressibility parameters (e.g., including the nonlinearities and heterogeneity of the soil versus time) in order to estimate the long-term soil deformations. The compressibility can affect an RC structure considering the soil-structure interaction at SLS.

3.3. Numerical Modelling

In order to carry a numerical simulation of the model developed in the above sections, a finite element program in MATLAB environment has been developed. The RC structure is modelled by usual beam finite elements and the soil behaviour is modeled by nonlinear spring elements under the footings. The interface elements between the soil and the structure's foundations are modelled by a spring model, which constitutes an independent unidirectional support. The characteristic vertical displacement of the foundation is therefore defined by the use of identical, independent, and nonlinearly elastic springs because of the non-linearity of the constitutive law of the soil used (e.g., SSCM by Vermeer).

The input data for numerical simulation are; the geometry (e.g., span, section), the Young's modulus of the beam structure, the initial effective pressure, the preconsolidation pressure and the soil compressibility parameters. The calculation procedure of the used model is summarized as follows: First, the service charges are applied to the soil. Next, an iterative, incremental resolution process is necessary to guarantee the balance of internal and external forces at the nodes of the foundation at the end of each increment. The well-known Newton-Raphson [40] scheme allows us to solve the equilibrium equations and therefore to determine the load-displacement-time curve under various load cases [8]. For each new point in the iterative process, the settlement at the footings in the RC structures and the ultimate moments on the girder cross-sections are computed for the load cases at the SLS. This is achieved by using the numerical model developed under MATLAB, in which the soil-structure interaction is appropriately considered.

Figure 3 depicts the flowchart of the solution procedure of the numerical model. The result leads to the settlement at the support-sections as well as the ultimate moments of the considered cross-sections.

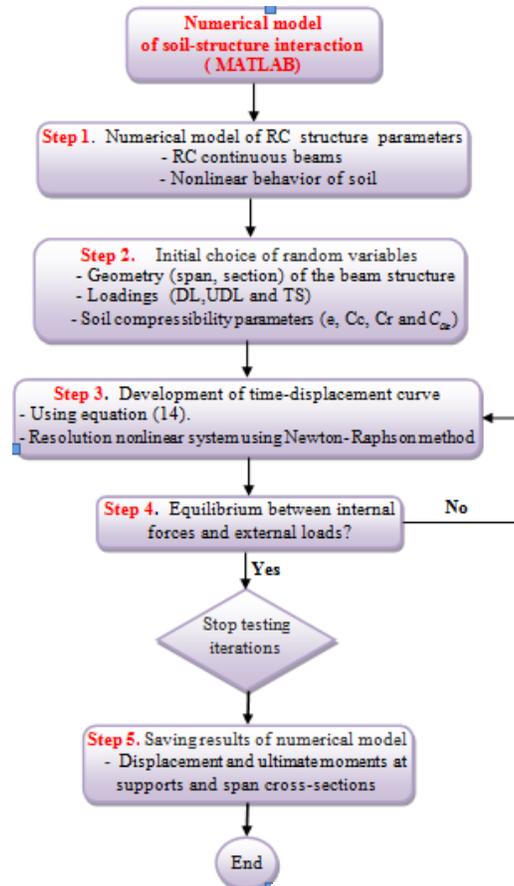


Figure 3. Flowchart of the algorithm procedure using numerical models

4. Presentation of Case Study

The numerical analysis procedures will be divided into two parts. The first part deals on: (a) the numerical modelling of the soil-structure interaction of RC structures at SLS, considering the long-term soil deformations, and (b), the influence of different soil compressibility parameters, in terms of stress and deformation for two types of soil (e.g., homogeneous and heterogeneous soils). In the second part, a numerical modelling has been conducted using three types of soft soils, by introducing the real data of RC structures. The objectives of this application is in one hand, to give a contribution to enhance the understanding of the influence of geotechnical and mechanical parameters of the soil and the structure, and on the other hand to assess the effects of long-term soil deformation including soil-structure interaction for RC structures.

4.1. Model Application on Existing RC Structures

4.1.1. RC Bridge of Total Length Equal to 45.30 m

The model developed in MATLAB environment is used in this study to calculate the bending moment and the displacement of the supports of an RC beam. The model uses the SSCM of the soil as mentioned above. This is done to best model the nonlinear time behavior of the soft soils before failure and modeling the creep behavior of the over-consolidated soil. In this section, the results of the numerical simulation model of the effect of long-term soil deformation on the structural safety of Oued Medila Bridge are presented. This bridge is located in the east of Algeria, precisely in Tebessa area. The bridge is joining the two cities of Fercane and El-Meita. The design phase was initiated in 2006; the bridge was open to the traffic in 2010.

4.1.2. Bridge Configuration

The considered bridge is 407 m long and 9 m wide. It is constituted of a series of three-span girders separated by expansion joints. Due to the repetitive aspect of the bridge, it is chosen only to consider the El-Meita side access for this study. This access side is constituted of three-span girders of total length equal to 45.30 m. Each one of the three spans has a length of 15.10 m, with a constant moment of inertia. The design of this bridge is checked according to

Eurocode1 and Eurocode2 [41, 42]. Table 1 illustrates the structural and geometric characteristics of the RC bridge studied.

Table 1. General characteristics of the studied RC bridge

Structural characteristics			Geometrical characteristics			Dimension of the cross section in "T"		
Number of beams	Number of spacers	Number of spans	Number of tracks	Bridge width (m)	Bridge length (m)	Height (m)	Lady width (m)	Table width (m)
6	3	3	2	8.80	45.30	1.15	0.35	1.50

The geotechnical information is used to study the interactions between soil and structural elements of RC bridge foundations. Bearing capacity of the soil used in the structural design is calculated from the pressuremeter test, showing an allowable soil stress of 260 kPa. It is anticipated that the proposed bridge piers and abutments will require shallow foundations to support the substructure loads due to the compressibility clay layer underlying the site.

5. Numerical Results

5.1. Configuration Test

The verification of the settlement is an integral part of the process of the design of a shallow foundation of RC bridges, because it is well known that the settlement criteria is more critical than the bearing capacity in the design of shallow foundations. Available methods for calculating RC structure settlement are the layer-wise summation method, empirical formulation method, and finite element method (FEM) and etc. Of these methods, FEM is a very powerful numerical tool for solving complicated 1D consolidation settlement problems. It can handle arbitrary boundary conditions, different loading schemes and it considers the coupling effects of loading and soil consolidation [35, 43, 44]. For modeling long-term settlements in this case study, FEM method has been used in MATLAB environment. Before applying the design procedures at SLS of RC bridges considering the creep behaviour of the over-consolidated soil, a test consists of simulating the contact between the soil and the foundation by elements of linear and nonlinear elastic support is done. This test concerns two types of soil (e.g., homogeneous and heterogeneous soil). Following the conventional approach, the soil total settlement is divided into three components; immediate, primary, and secondary. The immediate settlement of soft soils includes elastic settlement and consolidation settlement was validated using elasticity solution. The secondary settlement is validated using Buisman's Equation [13].

The evaluation of the settlement " S_i " of any infinitely rigid foundation (uniform settlement) or flexible (uniform stress) placed on isotropic, linear, elastic and semi-infinite mass is written in the general form with the direct formula (Elastic method) by:

$$S_i = q \frac{1-\nu^2}{E} BC_f \quad (17)$$

With, E and ν are Young's modulus and Poisson's ratio of the soil mass respectively. B is the width or diameter of the foundation. C_f is a coefficient depending on the shape of the foundation, its rigidity and the position of the point considered. q is stress applied to the foundation (uniform or medium).

For the evaluation of the secondary consolidation by Buisman's equation, the coefficient of secondary consolidation C_{ae} has been very often used. The coefficient C_{ae} can be defined from the variation of the void ratio e with time t for a given load increment,

$$C_{ae} = \frac{\Delta e}{\log t_2 - \log t_1} = \frac{\Delta e}{\log \left(\frac{t_2}{t_1} \right)} \quad (18)$$

Where Δe is change of void ratio and t_1 is the time for which secondary consolidation is calculated (in days), and t_2 is time for primary consolidation (>1 day). The magnitude of the secondary deformation can be calculated as,

$$S_s = C_\alpha H \cdot \log \left(\frac{t_1}{t_2} \right) \quad (19)$$

Where, the rate of secondary consolidation develops at a slow and continually decreasing rate and may be estimated as follows:

$$C_\alpha = \frac{C_{ae}}{1 + e_p} \quad (20)$$

Where e_p is void ratio at the end of primary consolidation and H is the total thickness of soil layer undergoing secondary settlement.

To calculate the soil total settlement and the bending moments in the cross section of the bridge girders, it is necessary to define the mechanical model of the bridge as shown in Figure 4. The traffic on the bridge is defined by the load model (LM1) in Eurocode1. This model covers most of the effects of car and truck traffic to calculate the soil total settlement of foundations and the bending moments in the bridge girders. The structural analysis is carried out by considering the combination of the (SLS).

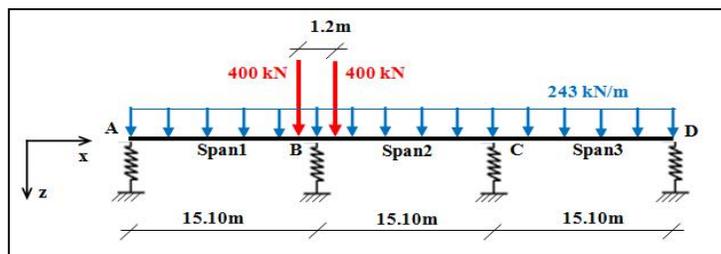


Figure 4. Mechanical model of RC bridge with three identical spans

Considering a maximum allowable displacement of 6 cm, the displacement of the foundation is determined for each iterative procedure and tends towards a constant value when the state of static equilibrium is reached in the soil. This value represents the displacement of the foundation due to an applied service load.

5.2. Results, Comparison and Validation

At this level of the study, it is imperative to validate the results obtained by the numerical model, with the direct formula (Elastic method) and Buisman's equation. The theoretical error *E* of the settlement is calculated with numerical model and the direct formula (Elastic method) and Buisman's equation as following:

$$E(\%) = \frac{s_f - s_0}{s_0} \times 100 \tag{21}$$

Where *s₀* is the settlement calculated with the direct formula (Elastic method) or with by Buisman's equation and *s_f* is the final settlement calculated with numerical model.

In the present study and for a configuration test, silty sand is considered. The constitutive model is used then to capture the one-dimensional stress-strain-time characteristics for which the physical and mechanical properties of soil are listed in Table 2, where the loading values are given for the SLS in the case of the homogeneous and heterogeneous soils.

Table 2. Physical and mechanical properties of soil in the soil-structure model in the case of the homogeneous and heterogeneous soils

Silty Sand	Cross Section	E (kPa)	v	q (kPa)	B (m)	C _f	e ₀	C _c	C _r	C _{ac}
Homogeneous soil	A	4400	0.33	99.40	1.50	1.50	0.80	0.05	0.005	0.002
	B	11500	0.33	159.70	3.00	1.50	0.80	0.05	0.005	0.002
	C	11500	0.33	135.15	3.00	1.50	0.80	0.05	0.005	0.002
	D	4400	0.33	98.00	1.50	1.50	0.80	0.05	0.005	0.002
Heterogeneous soil	A	4400	0.33	102.68	1.50	1.50	0.80	0.05	0.005	0.002
	B	11500	0.33	155.93	3.00	1.50	0.80	0.05	0.005	0.002
	C	23000	0.33	138.70	3.00	1.50	0.75	0.02	0.002	0.0008
	D	12000	0.33	95.21	1.50	1.50	0.75	0.02	0.002	0.0008

Based on an examination of the numerical data, the time corresponding to 100% primary consolidation is taken to be one day. We carried out numerical simulations by considering the consolidation time on a low compressible soil, which has the same compressibility characteristic. In this case, the creep effect was treated in a way that the soil subjected to permanent and constant loads for 1, 10, 100, 500, 1000, 3000, 6000, and 12000 days. This period is generally sufficient to reach the end of the primary consolidation and observe the start of creep [2]. The results of computation of total soil settlement under the bridge foundations are evaluated in Figures 5 and 6. The elastic method and Buisman's equation have been used for the evaluation of the immediate settlement and the secondary consolidation, respectively, as well as results from the linear and nonlinear elastic computation of the numerical model developed in this study.

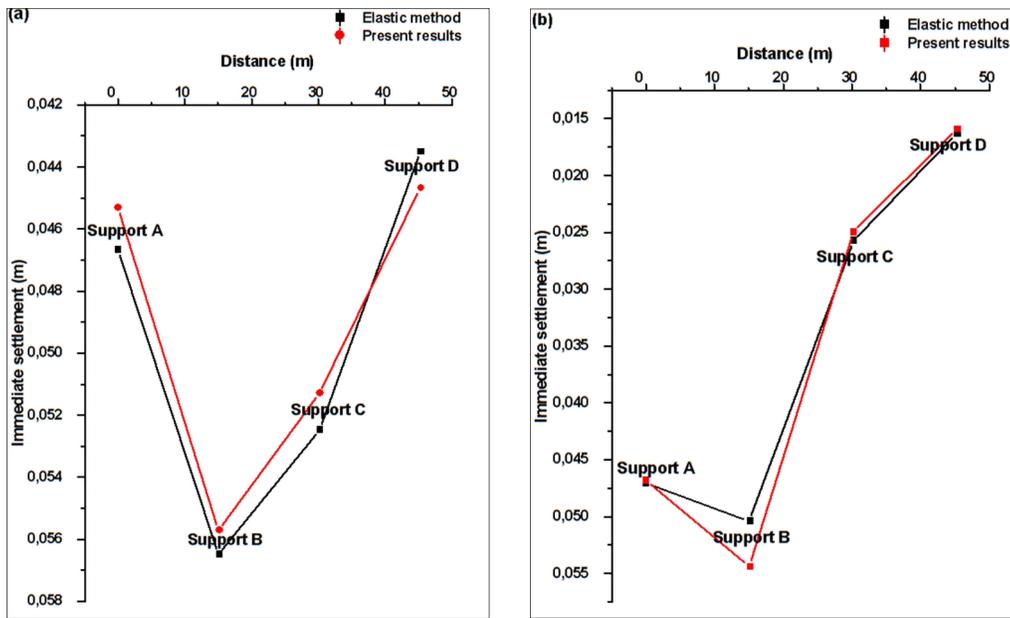


Figure 5. Comparison of the immediate settlement calculated with numerical model and the direct formula (Elastic method): (a) homogeneous soil and (b) heterogeneous soil

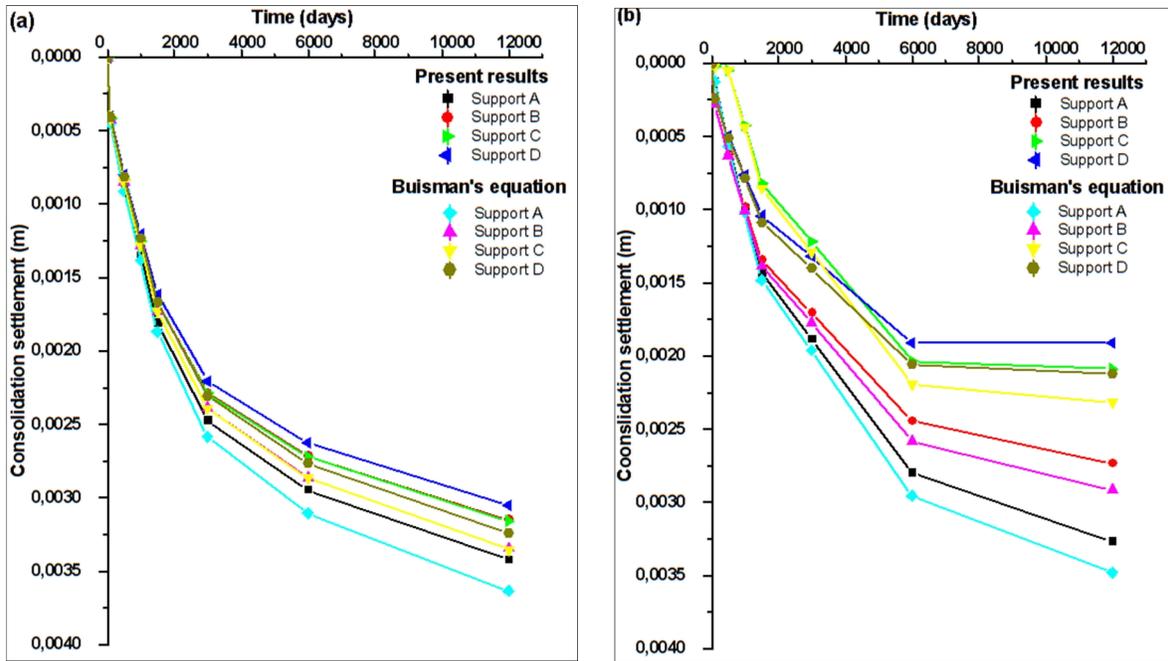


Figure 6. Comparison of the consolidation settlement calculated with numerical model and the Buisman's equation: (a) homogeneous soil and (b) heterogeneous soil

According to the compaction estimation results on the supports A, B, C and D are shown in the Figures 5 and 6. In the case of a homogeneous soil and for different values of the loads applied by the work on the soil foundation, we notice very little significant difference in the values of settlements and which are less than 3% and 6% in the case of supports A, B, C and D, respectively. Consider the case of two intermediate supports B and C placed in a soil with different elastic properties. Here, we are interested in the variation of soil total settlement as a function of variations or the heterogeneity of soil properties. We also note that there is not a very significant difference in the values of settlements of our model compared to the two other methods, which they are less than 8% in the case of the support B and 3% in the case of the supports A, C and D compared to results from the direct formula (Elastic method). This difference is equal to 7% in the case of the supports A and B, and 9% in the case of the supports C and D compared to the Buisman's equation. This result is explained by the fact that the error in the calculation of settlement of supports A, B, C and D rest still relatively low (<10%).

All the results of the settlement in supports A, B, C and D given by the numerical model are generally satisfactory and agree well with the calculation results given by the direct formula (Elastic method) and the Buisman's equation. Therefore, the numerical model of soil-structure interaction developed in this study is able to predict the behaviour of such soft soils, including a time effect.

6. Parametric Studies of Effect Soil-Structure Interaction

6.1. Influence of the Compressibility Parameters of the Soil

In order to well assess the effect of the compressibility parameters of the soil on the structural safety, three types of soil have been considered; silty sand which is a low compressible soil, Dozulé clay which is a medium compressible soil, and Romainville clay which is highly compressible soil. At this step of the study, it is important to note that, the calculated consolidation settlements, differential settlement, vertical strain and bending moments are time dependent curves conditioned by the real compressibility characteristic values of these three types of the soft soils. Subsequently, all the consolidation parameters values of the different soils in the parametric studies of soil-structure interaction effect (e.g., over consolidation ratio, $OCR=1$) are listed in Table 3, where the loading values are given for SLS.

During the numerical simulations, these soils are subjected to initial effective pressure σ'_0 equal to 45kPa for all soft soils. Subsequently, parametric studies including the different stress-strain states, and different durations of times and loading are conducted using the numerical model of soil-structure interaction for the three types of the soft soils.

Table 3. Consolidation parameters and loading values of different soft soils in the model of soil-structure interaction of RC bridge girder at the SLS

Soil	Cross section	Homogeneous soil					Heterogeneous soil				
		q (kPa)	e_0	C_c	C_r	C_{ac}	q (kPa)	e_0	C_c	C_r	C_{ac}
Silty Sand	A	99.40	0.80	0.05	0.005	0.0020	102.68	0.80	0.05	0.005	0.0020
	B	159.70	0.80	0.05	0.005	0.0020	155.93	0.80	0.05	0.005	0.0020
	C	135.15	0.80	0.05	0.005	0.0020	138.70	0.75	0.02	0.002	0.0008
	D	98.00	0.80	0.05	0.005	0.0020	95.21	0.75	0.02	0.002	0.0008
Dozulé Clay	A	55.13	0.51	0.11	0.011	0.0044	52.56	0.51	0.11	0.011	0.0044
	B	78.91	0.51	0.11	0.011	0.0044	76.58	0.51	0.11	0.011	0.0044
	C	67.19	0.51	0.11	0.011	0.0044	69.84	0.79	0.18	0.018	0.0072
	D	55.15	0.51	0.11	0.011	0.0044	48.16	0.79	0.18	0.018	0.0072
Romainville Clay	A	52.56	0.79	0.18	0.018	0.0072	50.59	0.79	0.18	0.018	0.0072
	B	76.58	0.79	0.18	0.018	0.0072	79.46	0.79	0.18	0.018	0.0072
	C	69.84	0.79	0.18	0.018	0.0072	67.00	0.51	0.11	0.011	0.0044
	D	48.16	0.79	0.18	0.018	0.0072	50.00	0.51	0.11	0.011	0.0044

6.1.1. Consolidation Settlement

The consolidation settlement of RC bridges on soft soils is traditionally an important geotechnical engineering problem and has been extensively studied by a large number of researchers [45-47]; they found that the excessive consolidation settlement can render the highways unserviceable, increase the cost of maintenance, and even be detrimental to the stability of embankments. Therefore, the aim of this part is to study more precisely the effect of time on the one-dimensional behavior of three types of the soft soils (silty sand, Dozulé and Romainville clay). We carried out numerical simulations by considering the consolidation time on a low, medium and a highly compressible soil, which have the same compressibility characteristics. The total predicted period is 32 years [2].

Figures 7(a) show the evolution of settlement over time on a logarithmic scale of all the values of the settlement considered in the case of homogeneous soil, while Figures 7(b) show the same curves in the case of heterogeneous soils.

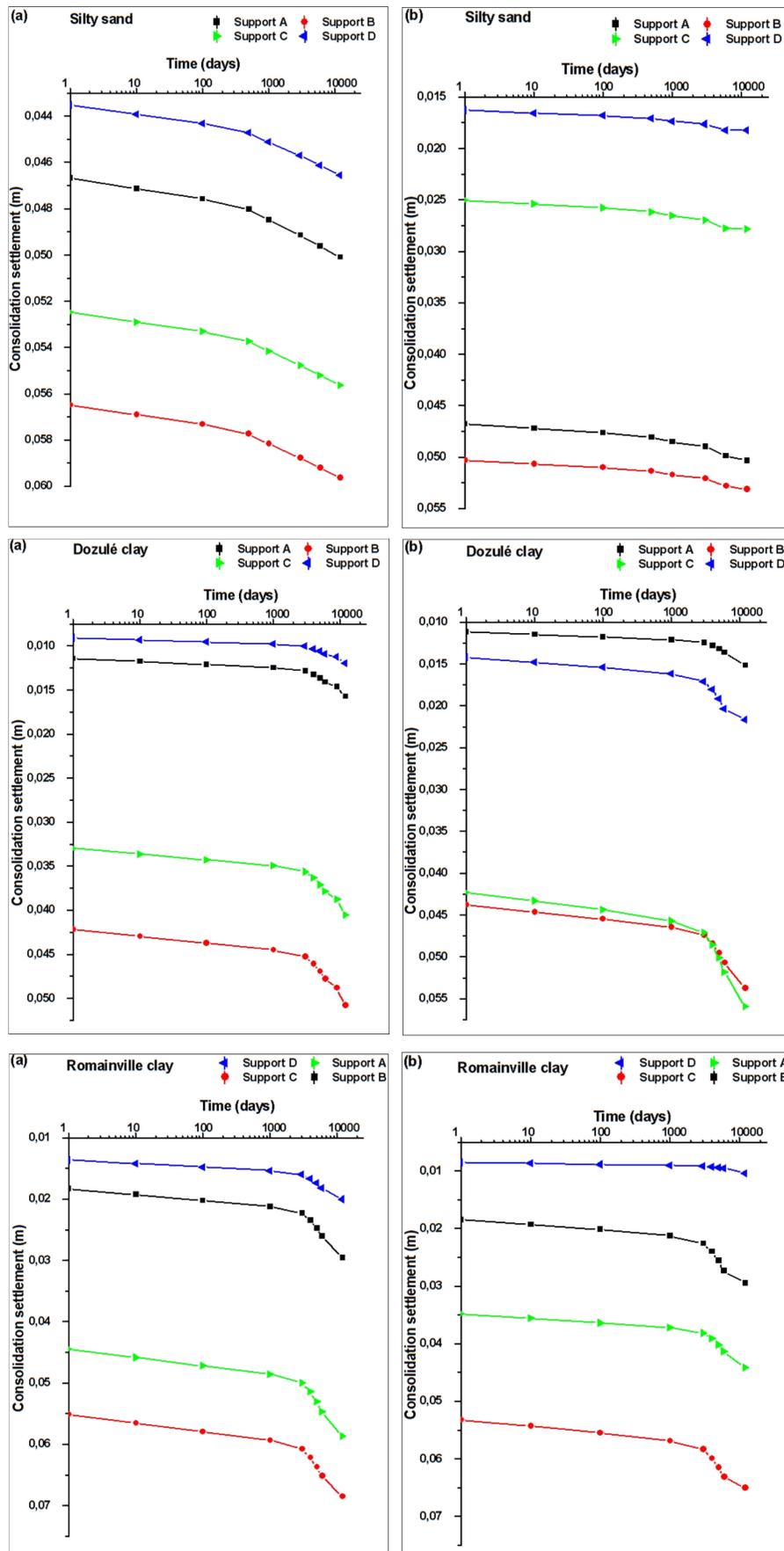


Figure 7. Settlement diagrams in the bridge girder with three types of the soft soils: (a) homogeneous soil (b) heterogeneous soils

In the result analysis, the goal is to focus on the comparison of the time settlement curve in the case of a homogeneous and heterogeneous soil with the three types of soft soils. In Figure 7, the results are illustrated as the vertical settlements calculated versus time under the footings A, B, C and D of the bridge. From the numerical results shown in Figure 7, it can be seen that in most cases for the load corresponding to the pseudo-elastic phase, the representative curves are straight lines and it is valid for the three types of soft soils. Similar results in terms of immediate settlement of soft soils under different surcharge loads with two different bridges are reported in [47]. The analysis of the consolidation time can be usefully enhanced by the study of the variation of delayed settlement obtained between times t_1 and t_2 after the application of the corresponding load. By way of an example, t_1 and t_2 were taken respectively equal to 100 days and for the 12000 days after the application of the corresponding load.

Figures 7(a and b) suggest that the time settlement curve could be divided into immediate, primary, and secondary creep in the case of Dozulé and Romainville clay. However, on the strain rate graph (Figure 7.a and b), it appears that there is no secondary creep in the case of silty sand; it seems like this secondary creep do not appears on the time settlement curve only because of the scale of graphical representation. It can be observed that the compressibility parameters of the soft soils also play a significant effect on the safety of RC cross-sections. As the increase of consolidation time, the numerical model predicted that the difference between the total settlement in the case of silty sand and Romainville clay are about 27% and 6% for the cross-section at support B and about 28% and 49% for the cross-sections at support C in the case of a homogeneous and heterogeneous soil respectively. It is also found that one obtains very low settlement difference at the support A and D whatever the type of the soil. This discrepancy is low, considering the effect soil-structure-interaction in the model. This will point out the fact that small settlement at the end footing C and D leads to high increase of consolidation time at the cross-section B, which reveals that the compressibility parameters of the soft soils also has a significant effect on the consolidation settlement, especially when the soil is heterogeneous. Contrary to what one expected, the soil settlement is almost not uniform; this can only be explained by the strong soil-structure interaction. Compare to the related works from the literature [44], the total settlement at the surface after 46 years, in the FE analysis, is equal to 1.151 m, and the measured settlement in the field is 1.102 m. In the current study, the values of consolidation settlements are in good agreement with those calculated by Feng et al. [44] at 4.5 m depth. However, the slight differences are mainly explained by the applied loading, applied duration and some parameters as those chosen in the soil layer studied. This confirms that the consolidation settlements represent not negligible part of the total settlements in very soft soils. The comparison of the values thus obtained for the different soft soils with the same numerical model reveals the relative propensity of these soils to creep and thus, the numerical model developed in this work turns out to be relevant to predict the long-term settlements of this RC bridge.

6.1.2. Differential Settlement

The differential settlement estimation is influenced principally by soil properties, layering, stress history, and the actual stress profile under the applied load [48]. For the analysis and design of RC structures, considering the heterogeneity of the geotechnical properties of soft soils can be achieved using a model that includes the soil-structure interaction. Although, it is important to consider the total settlement of a footings on cohesive soils in a design of a RC structures. However, construction costs to repair the disturbances caused by differential settlement can be quite substantial and productivity losses to an owner may occur if the structure must be taken out of service [49]. The differential settlement between two adjacent foundations is often a parameter of interest. Tolerance criteria for foundation deformation should be established consistently with the function and type of structure, anticipated service life, and the consequences of unacceptable movements on structure performance, as outlined by Eurocode.

The differential settlement (δ) between any two supports elements within an RC structure is given by:

$$\delta_{12} = |u_1 - u_2| \quad (22)$$

Where u_1 and u_2 are the total displacement for each support element, respectively. The criteria adopted by Eurocode considering the angular distortion (δ/l) between adjacent footings for continuous-span bridge is:

$$\frac{\delta}{l} \leq 0.002 \text{ to } 0.004 \quad (23)$$

Where l is center-center spacing between adjacent footings.

In order to understanding the effect of the differential consolidation settlement of the types of the soft soils (low, medium and highly compressible soil) on the bridge, a numerical analysis is performed for the service loads. These loads are applied to the footings and the vertical displacements at the footings centers (u_1 and u_2) are then calculated. The differential settlement is calculated as the absolute difference between u_1 and u_2 . Figures 8 plot the differential consolidation settlement in function of time with the three types of the soft soils in the case of homogeneous and heterogeneous soil.

With different types of the soft soils, it should be noted that the results of this study also show that the differential settlements progress in a nearly linear manner up to 1000 days when plotted against log time. Before the 1000 days, both in the case of the homogeneous and heterogeneous soils, the results of the differential settlement for the silty sand are almost uniform and constant; this is not the case for Dozulé and Remainville clay. The effect of soil compressibility parameters of the soft soils is still significant, although the heterogeneity soil is considered. The same results were conducted by Karim et al. (2004) [45], which have analyzed the final settlement of a bridge embankment on soft soils using a simple linear approach. Thus, this method is proposed to overcome uncertainties in settlement predictions arising mainly from the presence of soft soil layers. The differential settlement must be reasonably taken into consideration during the consolidation as it is not negligible.

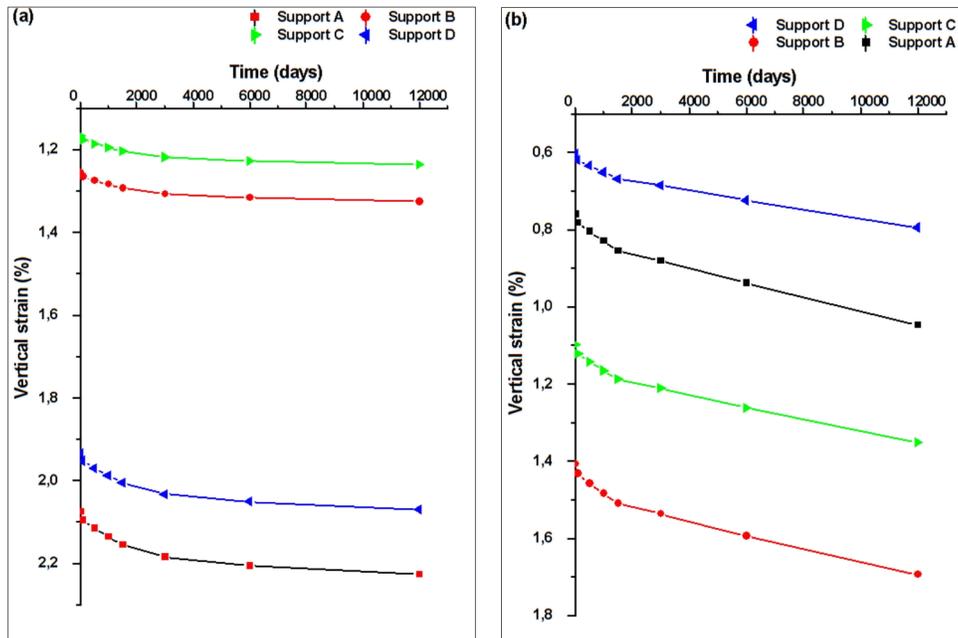
The effect of the compressibility parameters of the soft soils is much more significant between any two supports elements B and C, than for the other two supports elements; this is concordant well with the analysis performed in section 6.1.1. It can be noticed that despite the large settlements expected after 12000 days (e.g., 32 years) due to the ground consolidation (e.g., small differential settlement is around 0.04m), the differential settlement is not negligible when the time increases. Thus, the differential settlement of the soil between any two adjacent supports elements AB, BC or CD is almost not uniform and is very sensitive to the variability of compressibility parameters of the soft soils. The interaction effect increases by nearly six time between any two adjacent supports elements BC, and even more for the cross-section in adjacent support elements AB or CD for Dozulé and Remainville clay in the case of the heterogeneous soil.

The current study further demonstrates that the differential settlements between two footings can have great repercussions on the redistribution of forces in the RC structure. This is even truer in the case of heterogeneous soils, for which the phenomenon of differential settlement is increased. These results show clearly that the differential settlement increases largely when the compressibility parameters of the soft soils are considered, especially, in the case of the highly compressible soils. This effect is strongly amplified in the case of the heterogeneous soils. The compressibility of the soil plays an important role in the variation of the soil strength with time and we must be careful considered in the design of RC structures.

6.2. Influence of the Applied Loading

6.2.1. Vertical Strain-Time Curve

In order to well assess the effect of the soil deformation characteristics with time on the structural safety of the RC structures, it has been chosen to consider the three types of the soft soils (silty sand, Dozulé and Romainville clay), for which the properties of the applied loading and compressibility parameters are given in section 6.1. Figures 9 show the influence of the applied loading on the vertical strain at the four critical cross-sections in case of homogeneous soil. The aim of this section is to investigate the effect of the applied loading on the deformation capacity of RC girders.



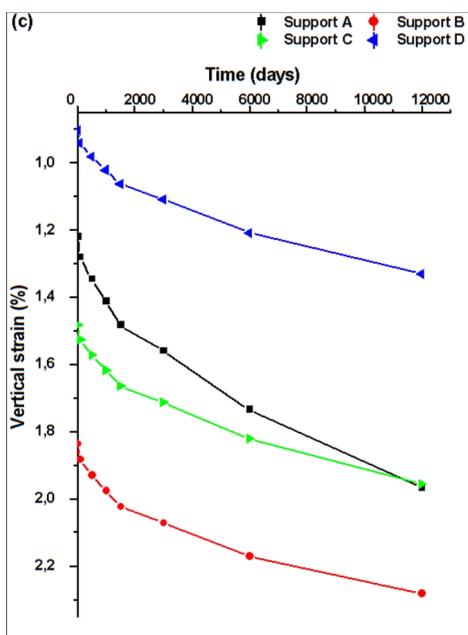


Figure 9. Vertical strain diagrams in the bridge girder with three types of the soils: (a) Silty sand, (b) Dozulé clay and (c) Romainville clay

For comparison, under different staged loadings, it is very clear from the graphs that the vertical strain rate depends on the applied vertical stress and on the soft soils layer models in terms of creep speed. The same observations were made by Qi et al. [34], and Hu and Ping [37]. When analysing the results (see Figure 9), we can see that the development of axial strain during creep is closely related to the applied load. When this load is large enough, the axial strain rate will continuously increase, and this will accelerate the failure of soil. After one day of the application of the corresponding load in the mechanical model of soil-structure analysis, it can be seen that, at the supports (A, B, C and D) the creep speeds are (2.07%, 1.25%, 1.16% and 1.93%), (0.75%, 1.40%, 1.43% and 0.60%) and (1.21%, 1.83%, 1.48% and 0.90%) for the silty sand soil, Dozulé and Romainville clay, respectively. These values increase to (2.23%, 1.32%, 1.23% and 2.08%), (1%, 1.69%, 1.9% and 0.79%) and (1.96%, 2.88%, 1.95% and 1.32%) after the 12000-th day in the case of a homogeneous soil for silty sand, Dozulé and Romainville clay, respectively. The cross-sections at the supports are very sensitive to the vertical strain rates on the bridge. Under different applied loadings, the same trend is observed in the cross-sections at supports A, C and D, but with higher rate increase in the cross-sections at support B, for the three types of the soil. These results show clearly that the applied vertical stress largely increases when the compressibility parameters are considered for a homogeneous soil, this effect is even strongly amplified. The mechanical model of soil-structure predicts that the vertical strain rate increases with time in the case of the low, medium and highly compressible soil. In this example, the impact of the applied loading is influenced by the variations of soil properties and increases the deformation capacity at the internal supports cross-sections of RC girders. These results show clearly that the response of soil-structure interaction model was found to be very sensitive to; (1) the uneven intensity of charges from one support to another, (2) rigidity of supports (e.g., dimensions) and (3) variations of soil properties.

6.2.2. Bending Moment-Time Curve

In order to understand the effect of nonlinear behaviour and to assess the impact of the soil heterogeneity on the deformation capacity of RC girders, the numerical simulations results of the mechanical model of soil-structure interaction are shown in Figures 4. This is done by calculating the critical section as well as the position of the convoy, which gives the maximum reaction on the supports and the spans of the beam of the bridge. It has been chosen to keep only two durations in this analysis: 10 and 12000 days. The bending moment distributions that have been calculated are also of interest to investigate the nonlinearities and heterogeneity of the soil. The structural analysis is carried out by considering the most unfavorable combination of the SLS. The bending moment-time curve obtained in the bridge girders are shown in Figures 10 to 12 for three types of contact conditions: rigid supports (e.g., without soil deformation), linear and nonlinear elastic soil behavior (e.g., with soil behavior described by Equation 15). We carried out numerical simulations by considering the bending moment of RC girders with three types of soils: silty sand, Dozulé and Romainville clay. This time, the deformation of RC girders effect was taken in a way that the soil subjected to permanent and variable loads in both cases of a homogeneous and heterogeneous soil.

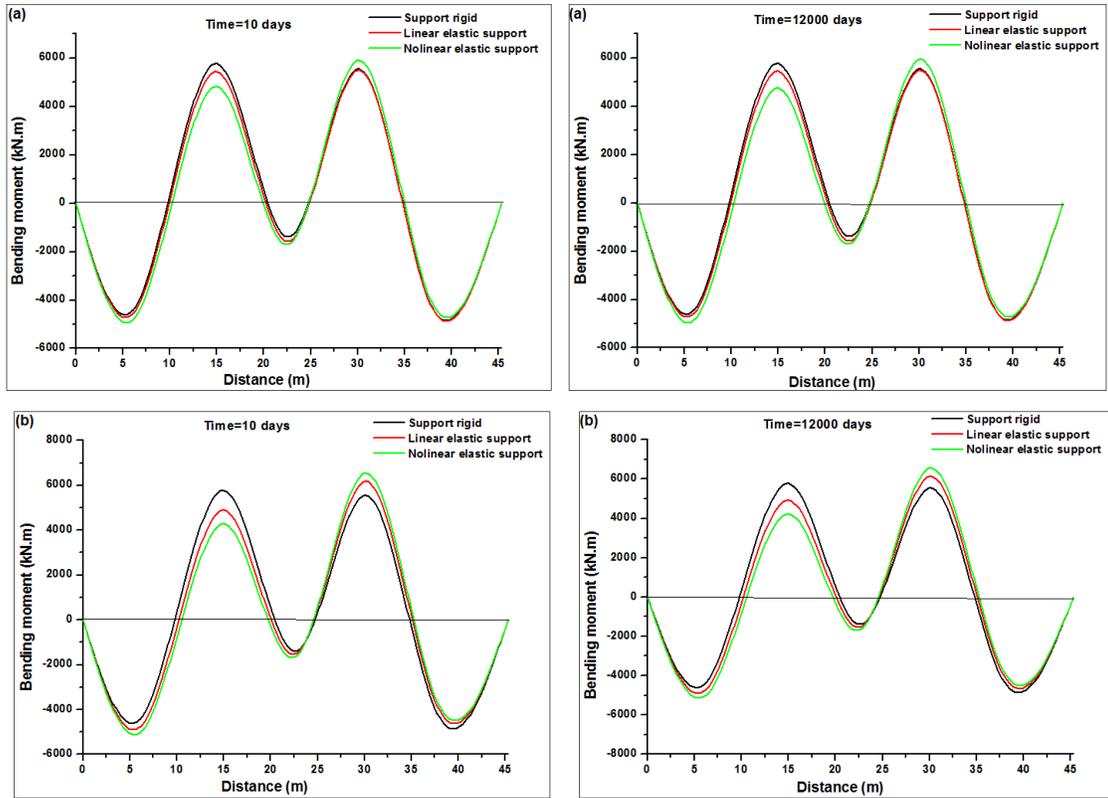


Figure 10. Bending moment-times diagrams in the bridge girder with silty sand soil (a) homogeneous soil, (b) heterogeneous soil

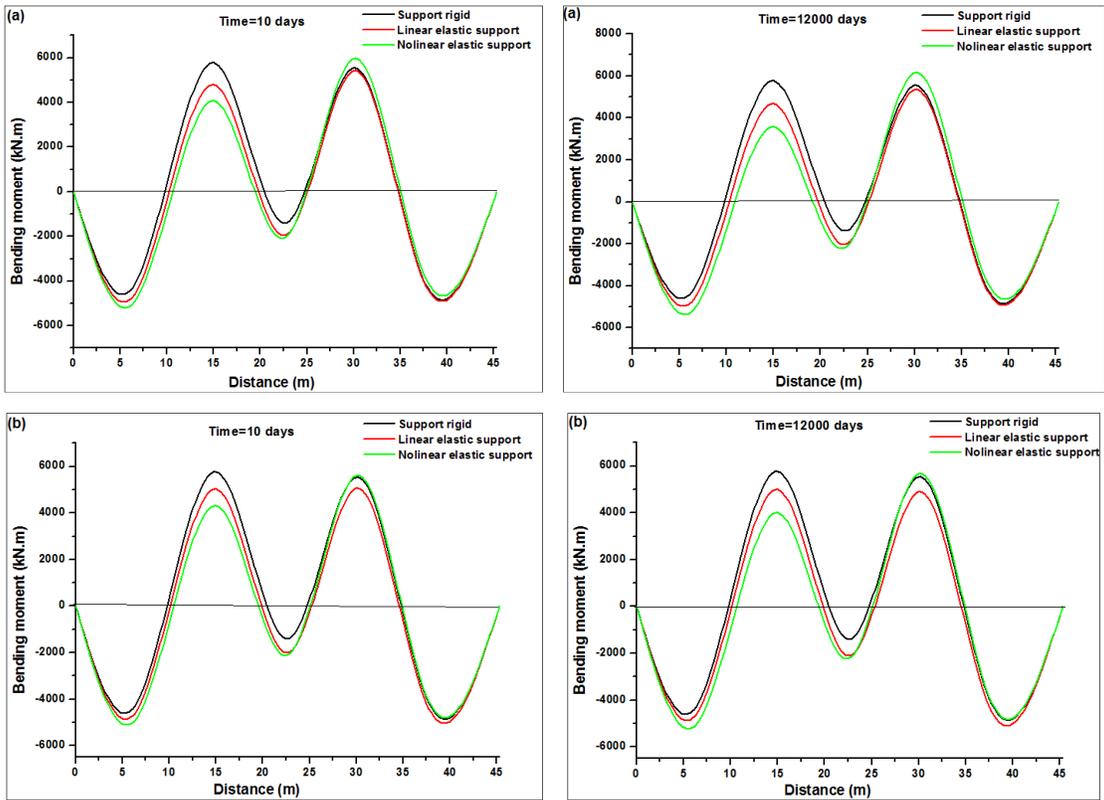


Figure 11. Bending moment-times diagrams in the bridge girder with Dozulé clay: (a) homogeneous soil, (b) heterogeneous soil

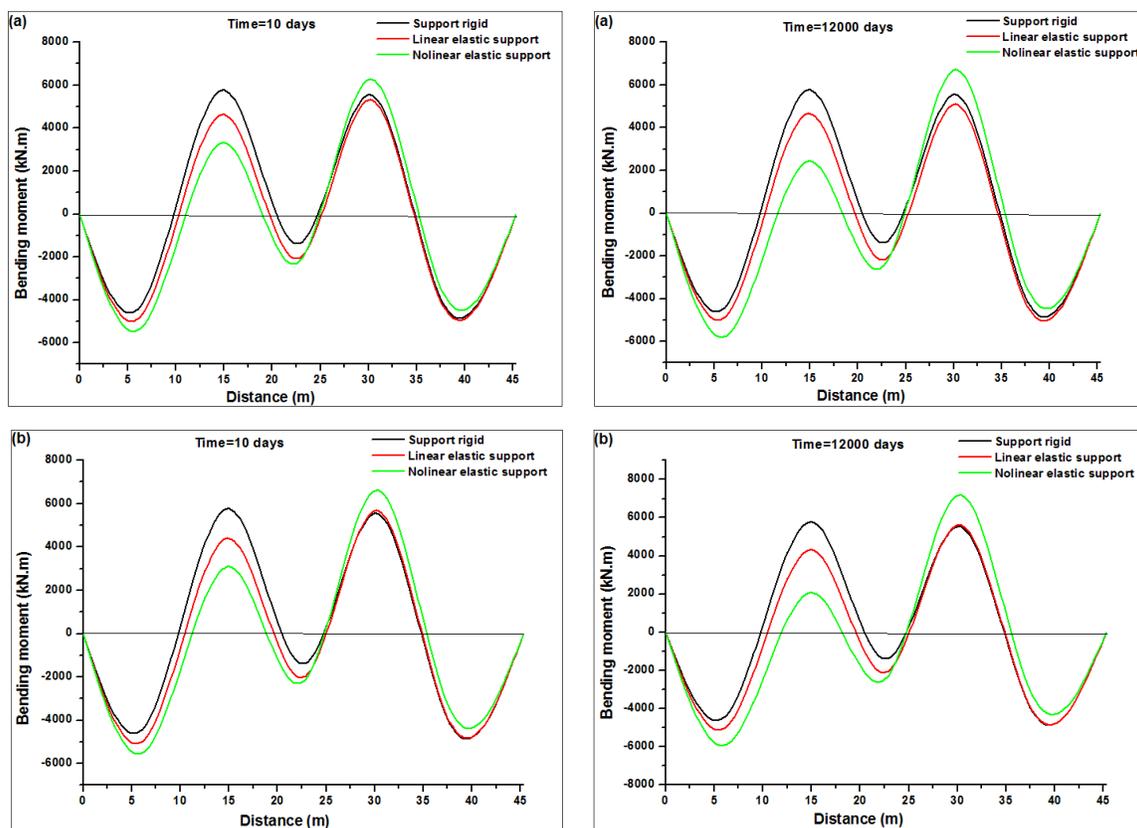


Figure 12. Bending moment-times diagrams in the bridge girder with Romainville clay: (a) homogeneous soil and (b) heterogeneous soil

The analysis of the bending moment-time curve can be practically supplemented by the study of the variation of bending moment obtained between 10 and 12000 days after the application of the corresponding load. The case of a fully rigid supports under SLS loading, between 10 and 12000 days, is compared to the case of nonlinear elastic behaviour of the three soft soils. The first observation that can be made from the analysis of the results, is that they are also notable differences in the distribution of moment at the internal supports and at span cross-sections considering soil-structure interaction. In the case of homogeneous soils, calculation results show a reduction in negative moment equal to (18%, 39% and 58%) at the support B with a decrease of about (12%, 32% and 44%) of the positive moment in the second span. We observe also a decrease of about (9%, 17% and 24%) of the positive moment in the first span with a decrease of about (6%, 11% and 18%) of the negative moment at the support C and this for silty sand, Dozulé and Romainville clay, respectively. However, in the case of the silty sand, a negligible effect of soil-structure interaction in the first span and at the support C is highlighted. In the case of heterogeneous soils, calculation results show also a reduction of the negative moment equal to (27%, 31% and 65%) at the support B with, in the same moment, a decrease of about (16%, 3% and 23%) at the support C. We observe also a decrease in the interaction effect for the cross-section in the second span equal to (18%, 37% and 43%) and even more for the cross-section in the first span equal to (13%, 14% and 25%), this for silty sand, Dozulé and Romainville clay, respectively. The increase of bending moment is extremely large for the cross-section at support B and in the first span, and is more than the double for the cross-section in the second span with the three types of the soft soils.

In summary, considering the effect of soil-structure interaction by parameters such as the nature of supports or soils behavior impact strongly on the global behaviour of the structure. Indeed, the observation of the relative percentages to soil-structure interaction effects shows also that the soil heterogeneity plays an important role in the redistribution of the moments within the bridge girder. There is a noticeable difference between rigid supports (e.g., without soil deformation), and nonlinear elastic supports taken as a boundary conditions at the foundation level; this is significant compared to the effects of dead and live loads. Also, in both cross-sections of the bridge girder, the influence of these boundary conditions on bending moment is high. These results clearly show that considering the heterogeneity of the soils notably reduces bending moments by the effect of soil-structure interaction. In particular, when assuming rigid support conditions, one observes that the maximum bending moment in the time is underestimated.

Figures 13 and 14 compare the nonlinear soil models, in terms of time on the bending moments at the critical cross-sections of the RC girders of silty sand, Dozulé and Romainville clay, respectively, in the case of both homogeneous and heterogeneous soils.

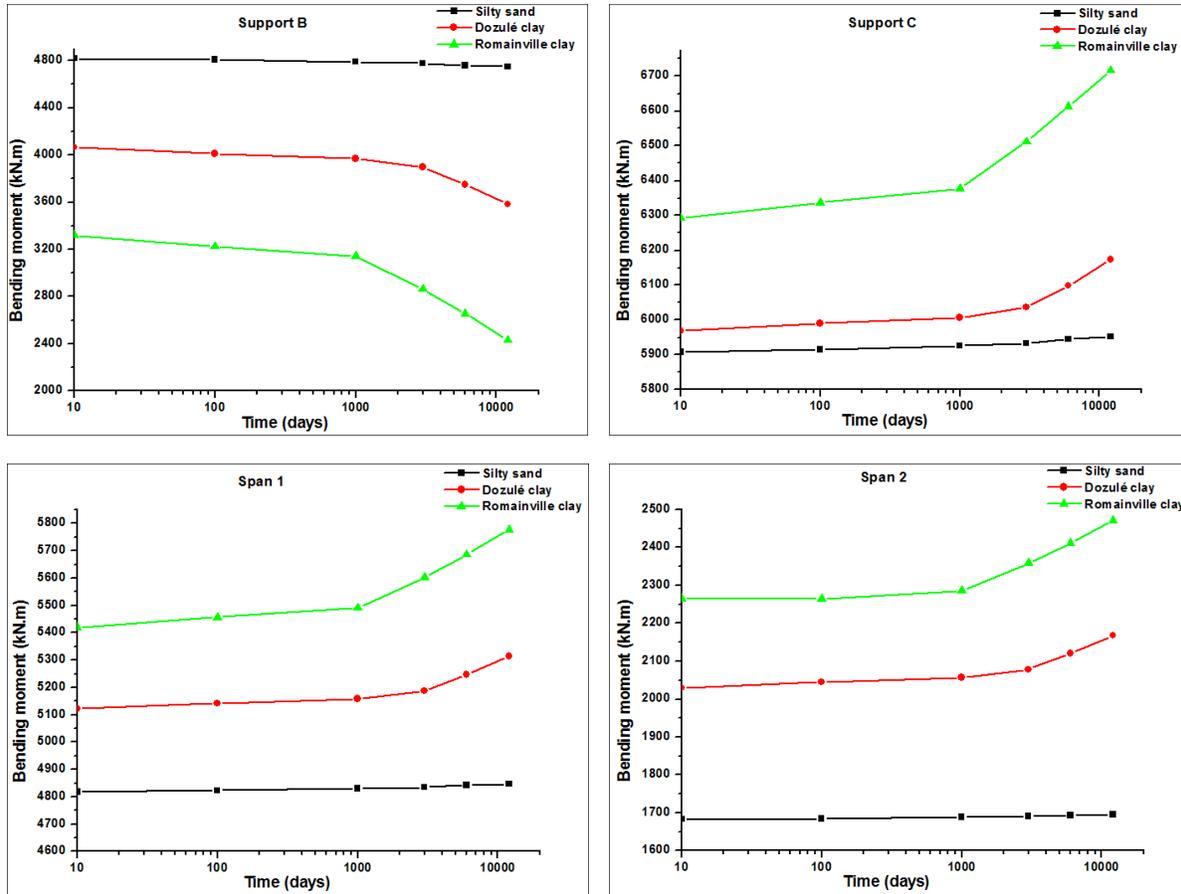
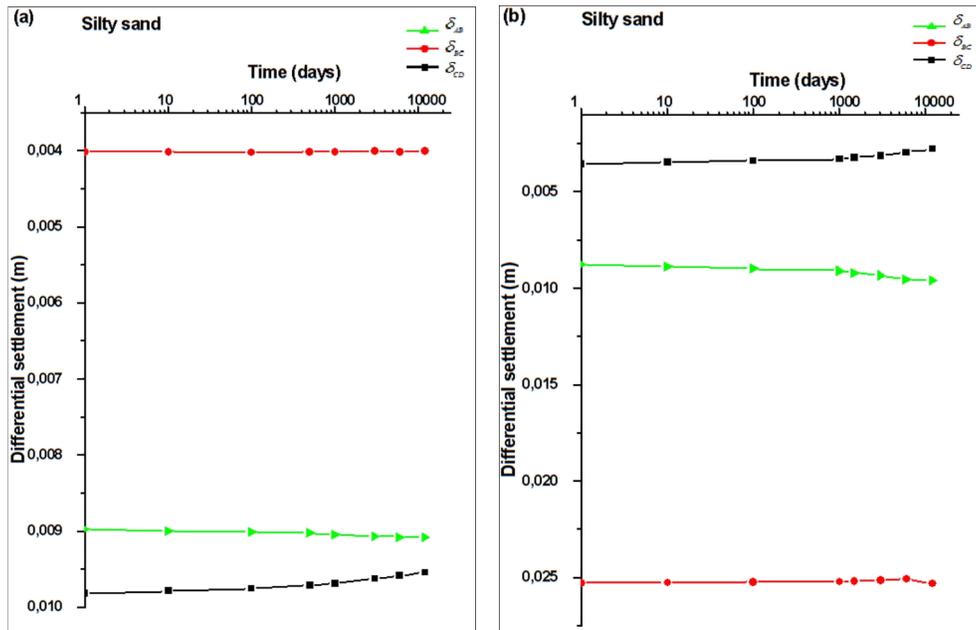
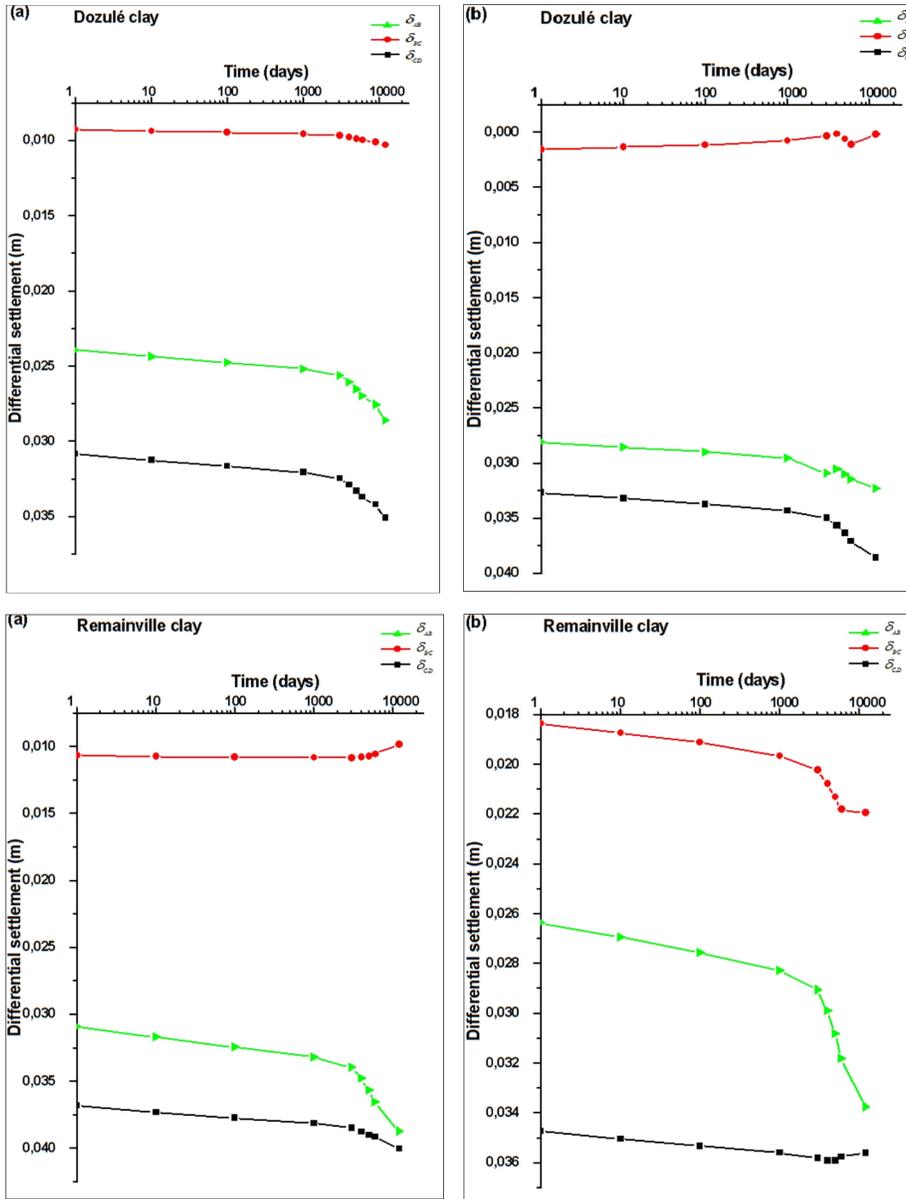
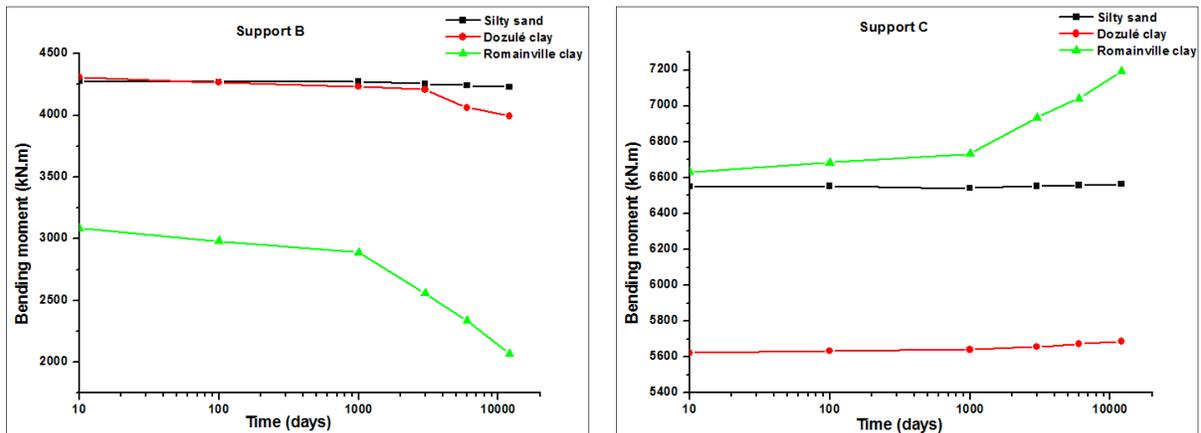


Figure 13. Bending moment diagrams with nonlinear soil models with the three types of soft soils in the bridge girder: case of homogeneous soil





Figures 8. Differential settlement diagrams in the bridge girder with three types of the soil: (a) homogeneous soil and (b) heterogeneous soil



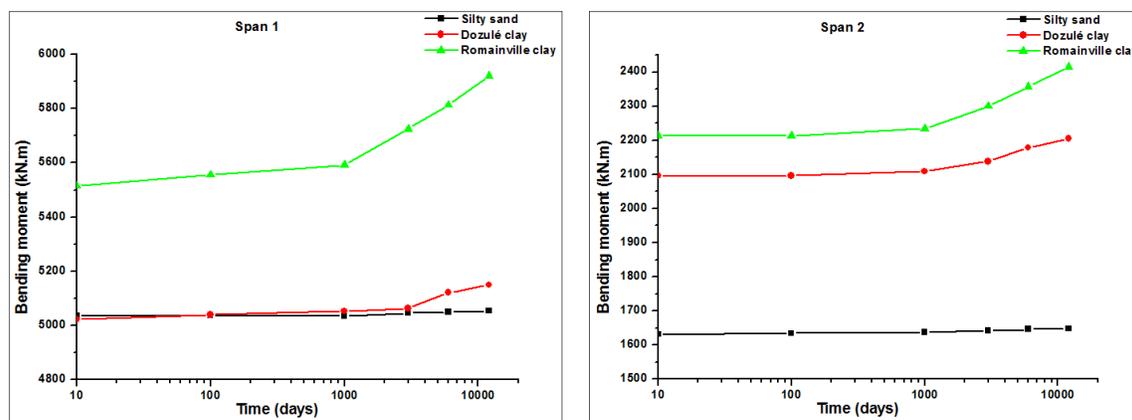


Figure 14. Bending moment diagrams with nonlinear soil models with the three types of soft soils in the bridge girder: case of heterogeneous soil

At the support B, it is shown that for nonlinear soil models, in the case of homogeneous soil, the bending moments decrease from (4817.36, 4063.90 and 3319.79 kN.m) after 10 days to (4747.19, 3581.25, and 2431.28 kN.m) after 12000 days for silty sand, Dozulé and Romainville clay, respectively. When the soil is considered as heterogeneous, the bending moments increase from (4278.16, 4309.55 and 3083.11 kN.m) after 10 days to (4228.93, 3993.71 and 2069.88 kN.m) after 12000 days for silty sand, Dozulé and Romainville clay, respectively. The same trend is observed in the cross-sections at support C and span 2, but with a lower increase rate in span 1. The results shown in this section are just for a qualitative assessment of the factors influencing the distribution of bending moments in the internal supports and span cross-sections as well as their respective deformations. These comparisons show that the bending moment time curve, with a non-linear soil models, produces notable differences in the distribution of forces in the cross-section of the RC girders and in the foundations. In contrary with the observations made on the same bending moment time-curve without soil-structure interaction.

Similar to the results obtained in section 6.2.2, the variability of the system response model of soil-structure interaction was found to be very sensitive to the variability of the compressibility parameters and the heterogeneity of the soil. Finally, this result indicates that if we consider large values to the compressibility parameters of the soil, the results are very different from the calculated with the rigid supports of the structure. The consideration of the soil-structure interaction in the design of RC bridges is strongly influenced by the heterogeneity and the actual behaviour of the soil.

7. Conclusion

In this paper, one proposes a novel finite element model of soil-structure interaction to assess the structural safety of RC structures. This is achieved by considering the applied loading, the soil compressibility parameters and its heterogeneity coupled with its nonlinear time behavior. The obtained results from this study indicate the quantification of soil heterogeneity effect. Also, one observes the importance of soil-structure interaction on the redistribution of bending moments in RC structure as well as its effect on the safety assessment of such structures. This study can have significant impact on the deformation capacity and the design rules of redundant RC structures, especially when the soil compressibility characteristic and time-nonlinearity are considered. Finally, the parametric study showed that when large variation is considered for the compressibility parameters of the soil, the results are very different from the case of rigid bearing structures. Indeed, a significant increase of compressibility parameters of soils leads to a reduction of soil stiffness and consequently to greater displacements and higher bending moments in the structure caused by important differential settlements. As conclusion, the soil-structure interaction and soils heterogeneity are important for RC bridges and consequently the safety assessment. This behaviour is strongly amplified by nonlinear time behaviour imposed by the choice of supports boundary conditions.

8. Conflicts of Interest

The authors declare no conflict of interest.

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