# Effect of Soil-structure Interaction on the Long-term Response of RC Structures

BEZIH Kamel, OUNIS HADJ Mohamed, LAOUCHE Mohamed and DJANENE Mohamed

***Abstract*—The evaluation of the performance of reinforced concrete structures during their service life is of major interest. The performance depends on both the action of the superstructure and the response of the soil. To insure the stability of reinforced concrete structures, a new model of finite element analysis that takes into account soil-structure interaction is developed. This model examines the nonlinear temporal behaviour of the soil in order to calculate the consolidation settlement and the bending moment of the beams of real reinforced concrete structures. The parametric study shows a significant impact of the soil-structure interaction on the design rules of reinforced concrete structures, especially when the compressibility parameters and the temporal nonlinearity of the soil are considered.**

***Keywords*— Soil-structure interaction, soil compressibility, mechanical analysis, reinforced concrete structure**

## I. INTRODUCTION

Knowledge of the stress state in contact with soil-structure overtime is necessary for a realistic design of the structure and needs 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. A relatively large attention to take into account the mechanical behaviour and the heterogeneity of soft soils in the design of reinforced concrete structures over time is necessary. This is mainly important to achieve more reliable and more economical dimensioning (Fontan et al. 2011 and Bezih et al. 2015). In this paper, to assess the stability of reinforced concrete (RC) structures, a finite element model of soil-structure interaction has been used (Bezih et al.,2020). This model takes into account the effect of long-term soil deformations on the stability of reinforced concrete structures. This model takes into account the effect of long-term soil deformations on the stability of reinforced concrete structures. This model is applied to a reinforced concrete bridge, where the soil-structure interaction is taken into account over time. The time-nonlinear behavior of the soil is the Soft Soil Creep Model (SSCM) developed in the work of (Vermeer & Neher, 1997and1999) has to be considered. The finite element method is used in this model to address the nonlinear time behavior of the soil and to calculate the consolidation settlement and the bending moment of the beams of reinforced concrete structures. Numerical simulation tests with different types of loading at the serviceability limit state (SLS) are carried out on silty sand soil. This is done in the case of a homogeneous and heterogeneous soil.

## II. MECHANICAL ANALYSIS OF THE EFFECT OF SOIL-STRUCTURE INTERACTION

The mechanical modelling of the soil-structure system is implemented using a one-dimensional model composed of a spring element to simulate the real case of continuous reinforced concrete beams in contact with the soil. In this work, the finite element model of soil-structure interaction is taken into account by a logarithmic relationship with the soil under the structure footings, as follows:

$$\sigma = \sigma_{p0}\exp\left(\frac{u}{Bz}\right)+\sigma'_{0}\exp\left(\frac{\frac{u}{z}-C\ln\left(\frac{\tau_{c}+t'}{\tau_{c}}\right)}{A}\right) \quad (1)$$

In the above equation, u is the vertical displacement of the footing and z is the depth of the influenced zone caused by the stress under the footing, which is taken as 1.5 times the footing width B, σ'0 represents the initial effective pressure before loading and σ' is the final effective loading pressure. The values σp0 and σpc represent the preconsolidation pressure, corresponding to before loading and end-of-consolidation states respectively; C and τc are the model parameters, and t' is the actual time. If the soil is normally consolidated (e.g., over consolidation ratio, OCR=1), with σ'0 =σp0 and where τc=1 day, the overall applied vertical stress, which can be expressed by the following relationship:

$$\sigma = \sigma'_{0}\left(\exp\left(\frac{u}{Bz}\right)+\exp\left(\frac{\frac{u}{z}-C\ln(t'+1)}{A}\right)\right) \quad (2)$$

## III. PRESENTATION OF CASE STUDY

This study will be divided into two parts; the first part deals, on the one hand, with numerical modeling of the soil-structure interaction using the finite element model of BEZIH et al., (2020) using MATLAB software for the design of an RC structure at SLS. This model, taking into account the soil-structure interaction and the long-term soil deformations of the soil. On the other hand, the influence of different soil compressibility parameters on the behavior of the structure in

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terms of stress and deformation. To calculate the soil total settlement and the maximum bending moment in the cross section of the bridge girders, it is necessary to define the mechanical model of the bridge as shown in figure 1. This model covers most of the effects of car and truck traffic. The structural analysis is carried out by considering the combination of the (SLS).

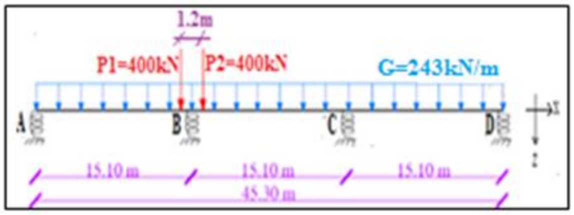

Fig. 1: Mechanical model of RC bridge with three identical spans

## IV. NUMERICAL RESULTS

In order to understand the effect of nonlinear behavior and to assess the impact of the soil heterogeneity on the deformation capacity of RC girders, the numerical model of soil-structure interaction (BEZIH et al., 2020) was used to calculate the bending moment and the displacement of the supports of an RC beam. In this section, the results of the numerical simulation model of the mechanical model of soil-structure interaction are shown in figures 2, 4 and 5.

### A. *Vertical strain time*

In order to well assess the effect of the soil on structural safety, it has been chosen to consider the silty sand soil, which is a low compressible, and the properties of the compressibility parameters of this soil are: initial void ratio, e0 = 0.80, compression index, Cc = 0.05. It is important to note that, in this case, the calculated vertical strain is conditioned by the real compressibility characteristic values of the soil. During the numerical simulation, this soil is subjected to the initial effective pressure and isotropic preconsolidation pressure σpo of 45kPa and 85 kPa respectively. For one day, the loads of 100kPa, 160kPa, 135kPa and 98kPa was applied on the supports A, B, C and D respectively in the bridge girder and the soil is subject to creep under this constraint. 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 was subjected to permanent and constant loads for 10, 3000, and 12000 days. This period is generally sufficient to reach the end of the primary consolidation and observe the start of creep (AI-Shamrani et al, 2002).

Figure 2 shows the influence of the compressibility parameters on the vertical strain at the four critical cross-sections. The aim of this section is to investigate the effect of the compressibility characteristic (i.e., void ratio and compression index) of the soil on the deformation capacity of RC girders.

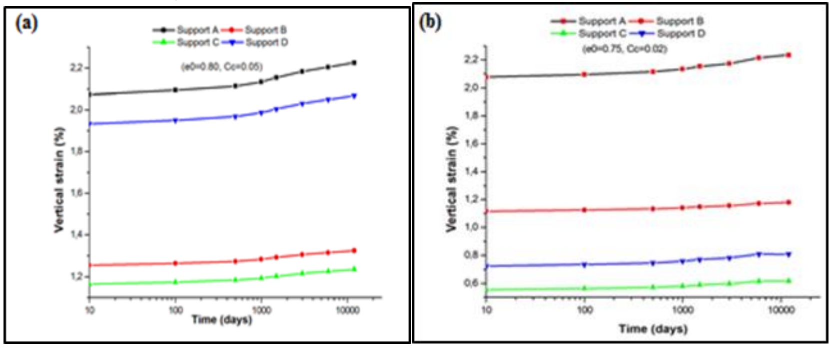

Fig. 2: Vertical strain diagrams in the bridge girder with two type of the soil:
(a) homogeneous soil and (b) heterogeneous soil.

It is clearly observed that the vertical strain depends on the applied vertical stress, compared to the silty sand layer models, in terms of creep speed, in the support B and D the creep speed is (1.32%) and (1.23%) in the case of a homogeneous soil with (e0 = 0.80, Cc = 0.05). These values are taken as reference to assessing the role of soil heterogeneity. These values decrease to (1.17%) and (0.61%) in the case of a heterogeneous soil with (e0 = 0.75, Cc = 0.02). The same trend is observed in the cross-sections at support A and D, but with the highest increase rate. The heterogeneity of the system response was found to be very sensitive to the heterogeneity of the soil compressibility parameters. In this application, the impact of heterogeneity of the soil decreases by nearly a factor of two the deformation capacity at the internal support cross-sections of RC girders. As already known from structural analysis, the cross-sections in supports are very sensitive to the heterogeneity of the soil.

### B. *Bending moments diagram*

In order to understand the effect of nonlinear behavior and to assess the impact of the soil heterogeneity on the deformation capacity of RC girders, the numerical simulation results of the mechanical model of soil-structure interaction are shown in figure 3. This figure shows the mechanical model of the bridge to calculate the bending moments in the bridge girders. As the length of the beam spans of the continuous bridge is identical, the different load cases to be considered for the beam are shown in the following figures (3.a and 3.b). Each of these load cases is combined with the different positions of rolling loads.

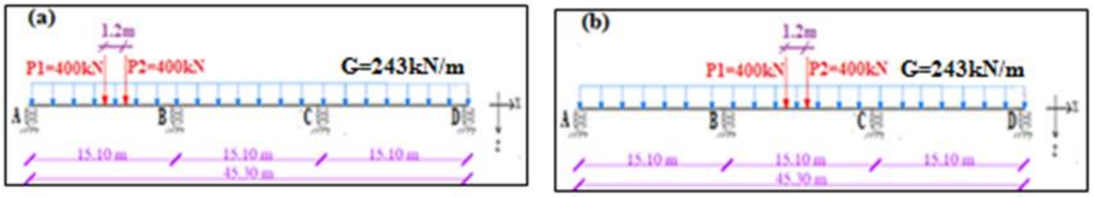

Fig. 3: Finite element model of RC Bridge with three spans identical:
(a) $1^{st}$ loading case and (b) $2^{nd}$ loading case (homogeneous soil and heterogeneous soil).

The structural analysis is carried out by considering the most unfavorable combination of the service limit state (SLS), for three types of contact conditions: rigid supports (i.e. without soil deformation), linear and nonlinear elastic soil behavior (with soil behavior described by equation 2) and the case of a homogeneous and heterogeneous soil. The maximum bending moment diagram obtained from the bridge girders is shown in Figure 4 and 5.

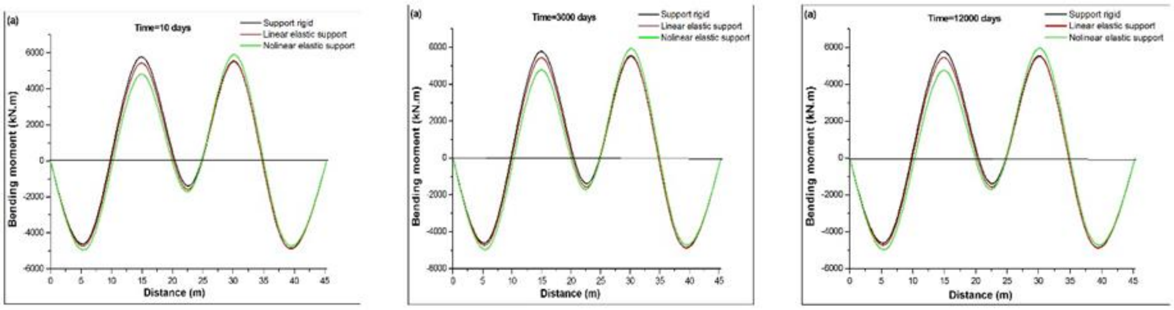

Fig. 4: Bending moment diagrams in the bridge girder with $1^{st}$ loading case :
(a) homogeneous soil and (b) heterogeneous soil.

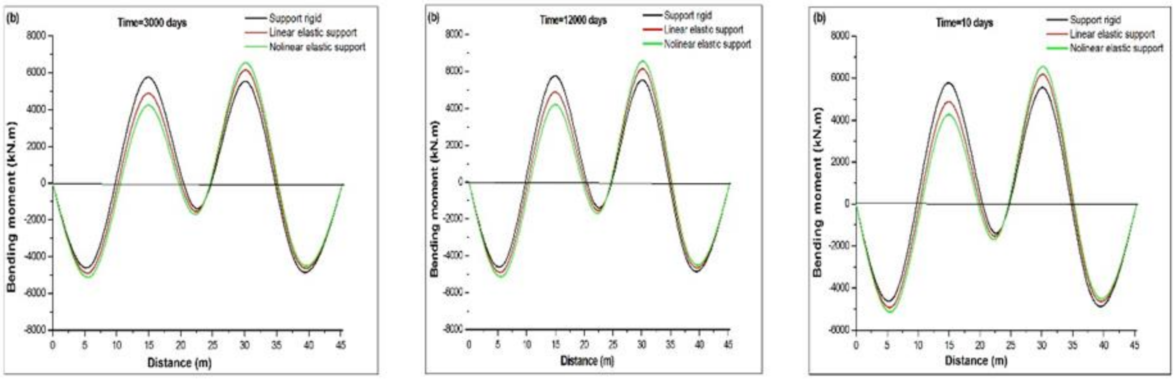

Fig. 5: Bending moment diagrams in the bridge girder with $2^{nd}$ loading case :
(a) homogeneous soil and (b) heterogeneous soil.

The analysis of the bending moment-time curve can be practically supplemented by the study of the variation of bending moment obtained between 10, 3000 and 12000 days after the application of the corresponding load. The case of a fully rigid support under SLS loading, between 10 and 12000 days, is compared to the case of nonlinear elastic behavior of the silty sand. The first observation that can be made from the analysis of the results, is that there 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% at support B, with a decrease of about 12% form the positive moment in the second span. We also observe a decrease of about 9% of the positive moment in the first span with a decrease of about 6% of the negative moment at the support C and this for silty sand. We also observe a decrease in the interaction effect for the cross-section in the second span equal to 18%, and even more for the cross-section in the first span, equal to 13%. The increase in bending moment is extremely large for the cross-section support B and in the first span, and is more than double for the cross-section in the second span with the soft soil. These results explain clearly the effect of soil-structure interaction on the behavior of the structure and demonstrate that the maximum bending moments are underestimated when assuming rigid support conditions.

## V. CONCLUSION

The objective of this work is to show and quantify the importance of the characteristics of soil compressibility in the redistribution of internal forces in the evaluation of the performance of reinforced concrete structures. This analysis can have a significant impact on the design rules for reinforced concrete structures. Finally, a parametric study showed that when a large variation is considered for the soil compressibility parameters, the results are very different in the case of structures with rigid supports. Therefore, the soil-structure interaction and the soil heterogeneity are important in the evaluation of the performance of reinforced concrete structures, which is greatly amplified by the nonlinearity of soil behaviour. Therefore, the soil-structure interaction and soil heterogeneity is important for RC structures, safety assessment, which is strongly amplified by nonlinearities.

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