Marija Vitanova
PhD, Assistant Professor
Ss. Cyril and Methodius University
Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Skopje
marijaj@iziis.ukim.edu.mk

Kemal Edip
PhD, Associate Professor
Ss. Cyril and Methodius University
Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Skopje
kemal@iziis.ukim.edu.mk

Viktor Hristovski
PhD, Full Professor
Ss. Cyril and Methodius University
Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Skopje
viktor@iziis.ukim.edu.mk

Radmila Salic
PhD, Assistant Professor
Ss. Cyril and Methodius University
Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Skopje
r_salic@iziis.ukim.edu.mk

SEISMIC RESPONSE OF ISOLATED BRIDGES INCLUDING SOIL-STRUCTURE INTERACTION (SSI) EFFECTS

Current practice usually neglects the effects of soil-structure interaction (SSI) in the seismic analysis and design of bridges. This work attempts to assess the significance of SSI on the seismic response of isolated multi span bridges.

The soil medium has been analyzed by applying different soil densities in order to consider the soil stiffness. The accent of the study has been given to the soil structure interaction effects and the results are analyzed accordingly. The soil medium has been taken into consideration as a four layered infill as dense and loose medium. The bridge structure is taken to be an RC structure. The boundaries in the soil medium are considered as infinite elements in order to absorb the radiating waves.

The formulation of infinite elements is the same as for the finite elements in addition to the mapping of the domain. Based on the iso-parametric concept, the infinite element in global coordinate is mapped onto an element in local coordinate system. In the formulation of the infinite element, only the positive direction extends to infinity thus allowing the waves to propagate outside of the soil medium.

Related comparisons are done with references and experimental results in which considerably acceptable results are obtained. The newly proposed methodology efficiently models both the interaction of soil and bridge structures and simultaneously the far field of soil model in which the wave reflections are softened. The case study chosen in this work considers different strength of soil models on which the bridge structural response is analyzed in detail.

Keywords: bridge structure, infinite elements, numerical analysis, SSI

1. INTRODUCTION

Bridges are very important elements of the infrastructure in modern societies. Due to their importance, loss of functionality after a seismic event is not an acceptable performance criterion for most of those structures. In the past few decades, extensive research has been conducted regarding the effects of soil–structure interaction (SSI) on the seismic response of civil engineering structures. Until recently, the general concession between engineers and researchers was that SSI effects are beneficial to the response of civil engineering structures.

The response of a structure under earthquake loading could be conservatively evaluated without taking the SSI effects into consideration (NEHRP specifications, 1997, [1]). That is because SSI provides additional flexibility and damping to the structural systems, or said differently, naturally isolates them from the shaking ground. These two effects, the period lengthening and the increase of damping, are also the fundamental premises behind the seismic isolation concept.

This paper investigates the effects of SSI on the seismic response of three span girder seismically isolated bridge, representing a typical stiff freeway overcrossing, which are founded on soft and medium dense soil. Using a nonlinear hysteretic model, which could account for the behavior of the isolation system, and assuming the upper structure will behave linearly, the inertial interaction between the foundation–soil system and the superstructure is studied for real seismic excitation with two intensities 0.2g and 0.4g.

2. SOIL-STRUCTURE INTERACTION

The seismic SSI problem involves two major components: the response of the soil as seismic waves travel through the soil deposit and the coupled foundation–superstructure response, which is usually assumed to be a superposition of the response of the pile foundation itself to the excitation in the absence of the superstructure (kinematic response) and the effect of the additional flexibility caused by the foundation to the response of the superstructure (inertial response) [2].

The soil response analysis is one of the most important aspects of earthquake engineering, as it will determine the ground motion that will be experienced at the top of soil without the presence of a structure or the so-called free field response. The analysis involves estimation of the seismologic characteristics of the region, and determination and modeling of the soil profile and its dynamic characteristics. Further, it accounts for the multiple reflections and refractions that will occur at the soil layer interfaces as the seismic waves propagate though the soil deposits. Although special purpose computer programs exist for this purpose, the validity of the results depend greatly on how accurate dynamic soil properties are estimated, which in spite the improvements in the in-situ testing, is still a challenging task. In the present study, no soil amplification analysis was performed, rather, the considered accelerograms were used directly to excite the structure and the springs, which were used to model the foundation.

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3. GOVERNING EQUATIONS OF MOTION

The equations of motion of the isolated bridge model with SSI effects (Fig. 1) under two horizontal components of earthquake ground motion is expressed in the following matrix form:

$$[M]\{\ddot{z}\} + [C]\{\dot{z}\} + [K]\{z\} = -[M][r]\{\ddot{z}_g\} \quad (1)$$

$$\{z\} = \{x_1, x_2, x_3, \dots \dots ., x_n, y_1, y_2, y_3, \dots \dots, y_n\}^T \quad (2)$$

$$\{\ddot{z}_g\} = \begin{Bmatrix} \ddot{x}_g \\ \ddot{y}_g \end{Bmatrix} \quad (3)$$

where [M], [K] and [C] represents the mass, stiffness and damping matrix, respectively, of the foundation–bridge structure system; {€z}; {z} and {z} represent structural acceleration, structural velocity and structural displacement vectors; [r] is the influence coefficient matrix; $\{\ddot{z}_g\}$ is the earthquake ground acceleration vector; $\ddot{x}_g$ and $\ddot{y}_g$represents the earthquake ground acceleration in longitudinal and transverse directions, respectively; and xi and yi are the displacements of the i-th node of the bridge in longitudinal and transverse directions, respectively.

4. DESCRIPTION OF THE BRIDGE

Three-span reinforced concrete (RC) bridge structure typical for Republic of N. Macedonian region [9] is selected. The bridge models under consideration consist of two piers supporting the superstructure. The central piers in this type of bridges most frequently had been designed as reinforced-concrete walls.

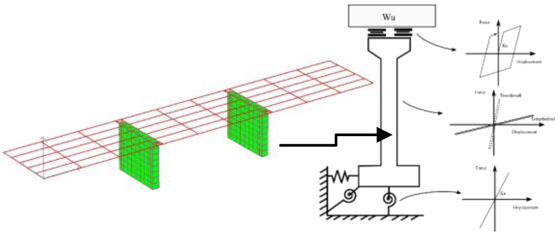

Figure 1. Three-dimensional mathematical FELISA/3M model composed of 3D finite girder and solid elements [3]

They are founded on strip foundation. The superstructure consists of 6 T shaped concrete girders resting on the substructure through elastomeric bearings and supporting the continuous reinforced-concrete slab. For the representative bridge, 3D finite element analytical model has been defined and analyzed by use of the verified FELISA/3M computer program [4]. A detailed description of the analytical model is given in Vitanova, 2015 [3]. Fig. 1 presents a typical isolated bridge structure and its corresponding model used in this study. The main and transverse girders have been defined as frame elements. The central piers have been modeled with solid elements. The support of the main girders at the ends has been modeled by link elements that represent the bearings. As for the surrounding soil, four layered infill as dense and loose medium assumption is adopted. The boundaries in the soil medium are considered as infinite elements in order to absorb the radiating waves. The effect of foundation flexibility is incorporated into the mechanical model via lateral, rocking, and cross-lateral-rocking springs.

Table 1. Geometric and mechanical properties of the models

System properties	Loose medium	Medium dense soil
Pier height [m]	5.0	
Width of the superstructure [m]	8.0	
Middle pier cross sections [m]	0.8/7.2	
Bearing stiffness-vertical/horizontal [kN/m]	1000000.0/ 3380.0	
SSI stiffness - vertical/horizontal [kN/m]	17606.4/ 14499.8	95963.8/ 79029.7
Damping – vertical/horizontal [kN/m]	528.0/ 429.4	2722.8/ 2229.5

The seismic isolation system is considered to behave as a bilinear hysteretic spring with smooth elastic to post yielding behavior. Although this behavior is typical to lead rubber bearings, the results presented in this study could be applicable for isolation systems consisting of sliding bearings with metallic yielding devices, or sliding bearings with restoring force capabilities, such as the friction pendulum system isolators.

The geometric and mechanical properties of the models are listed in Table 1.

The bridge is subjected to a real ground motion records scaled to two intensity levels. One set of ground motion time histories is used in this study. It consists of pair of horizontal acceleration time histories from El Centro earthquake. The excitation is scaled to two levels of intensity 0.2g and 0.4g. The ground motion is used to analyze the bridge funded to loose medium and medium dense soil.

5. ANALYSES RESULTS

Three span isolated girder bridge system with the soil structure interaction is analyzed using seismic excitation scaled to two levels of intensity. Nonlinear time–history analyses are performed, and the system response variables considered are the displacement of the isolation system (isolation drift) and the shear force the pier. These two response variables are critical for the design of the bridge superstructure and the design of the bridge substructure accordingly.

Fig. 2 represents the compared stress-strain curves for the middle pier bearing for loose medium and medium dense soil subjected to El Centro earthquake with 0.2g intensity. Fig. 3 show the behavior of the same bearing, but the bridge structure subjected to 0.4g intensity. All these diagrams show that the behavior of the bearing in both horizontal directions does not change concerning the soil type.

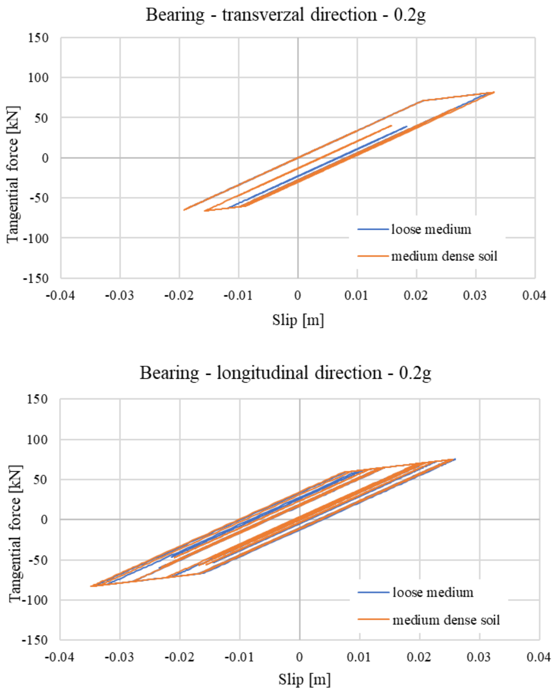

Figure 2. Stress-strain curves for bearing in horizontal directions, El Centro earthquake, 0.2g

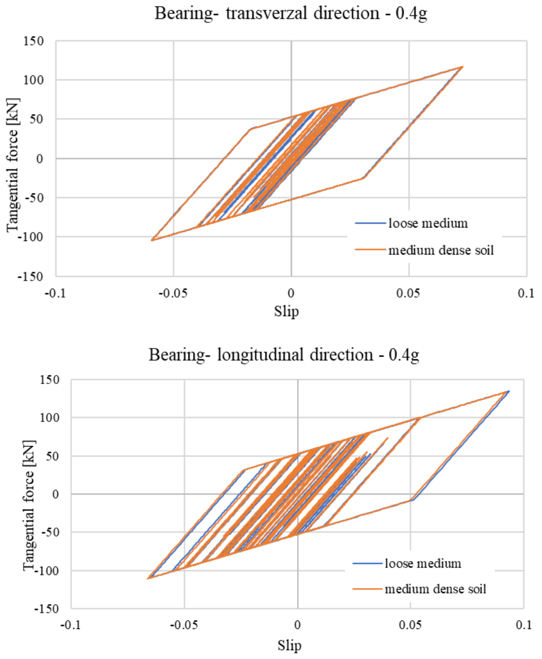

Figure 3. Stress-strain curves for bearing in horizontal directions, El Centro 1940, 0.4g

The behavior of the upper part of structure is almost the same for both soil types. The acceleration and displacement time histories for both types of soil conditions are shown on Fig.4. The little difference can be noticed in the displacement in longitudinal direction for 0.2g. The same results are obtained for the analyses of bridges exposed to earthquake intensity 0.4g but there are not presented in this paper. Regarding the displacement of the top point of the pier, i.e. bottom point of the bearing, the results are different. In this part of the structure, the difference is significant in both directions for the both earthquake intensity (Fig. 5). The difference is more distinct for the transversal direction.

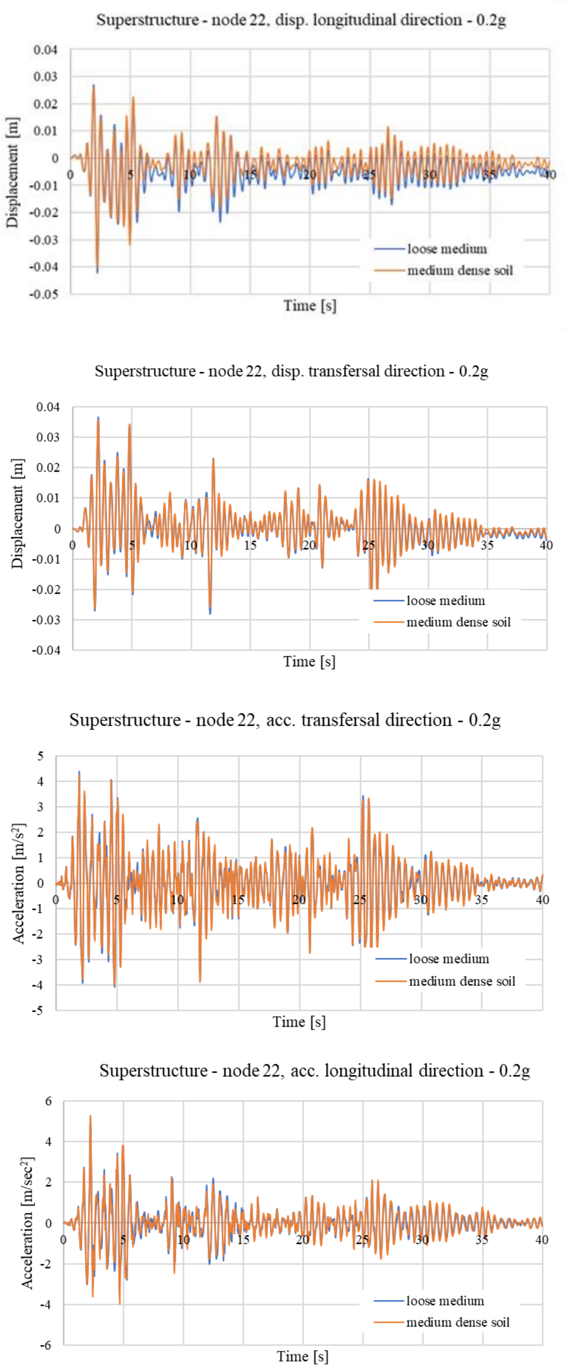

Figure 4. Time history of displacement (up) and acceleration (down) for superstructure in horizontal directions, El Centro, 1940, 0.2g

These results show that the behavior of the upper part of the bridge structure is not adjective to the soil type of the foundation. The behavior of the substructure is directly subjected from the soil conditions. For both directions and for both intensities the displacements are larger when the structure is founded to the loose medium unlike medium dense soil.

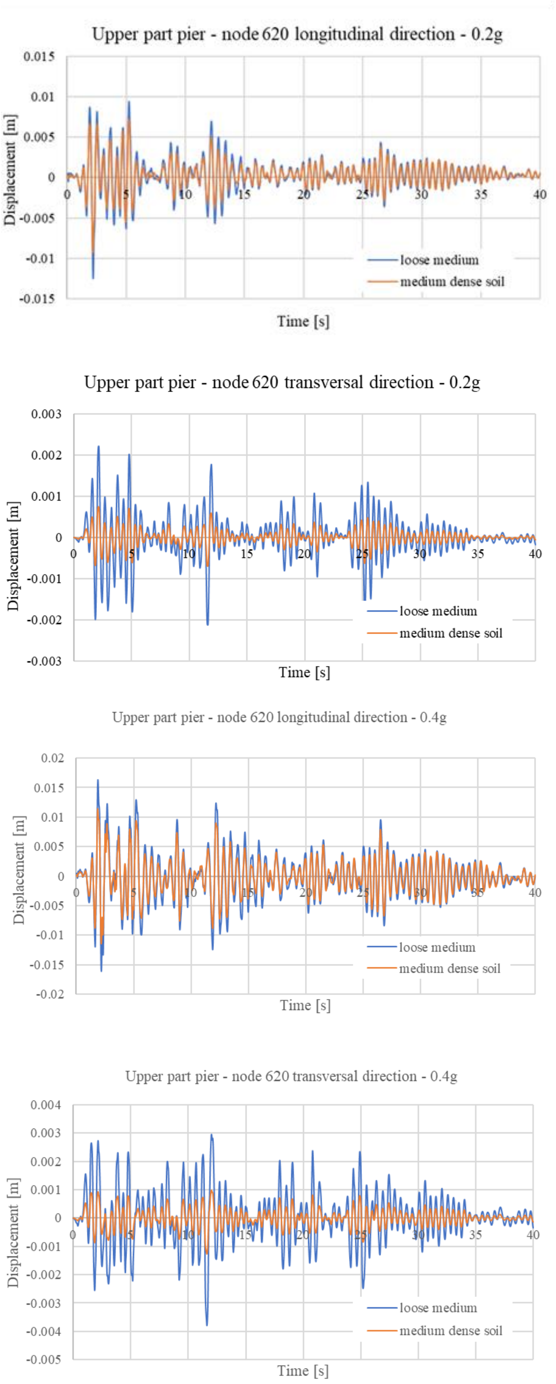

Figure 5. Time history of displacement (up) and acceleration (down) for superstructure in horizontal directions, El Centro, 1940, 0.2g, 0.4g

Fig. 6 shows the P-Δ analyses for the bearing for both soil types and earthquake intensities. The difference between loose and medium dense soil is not so obvious.

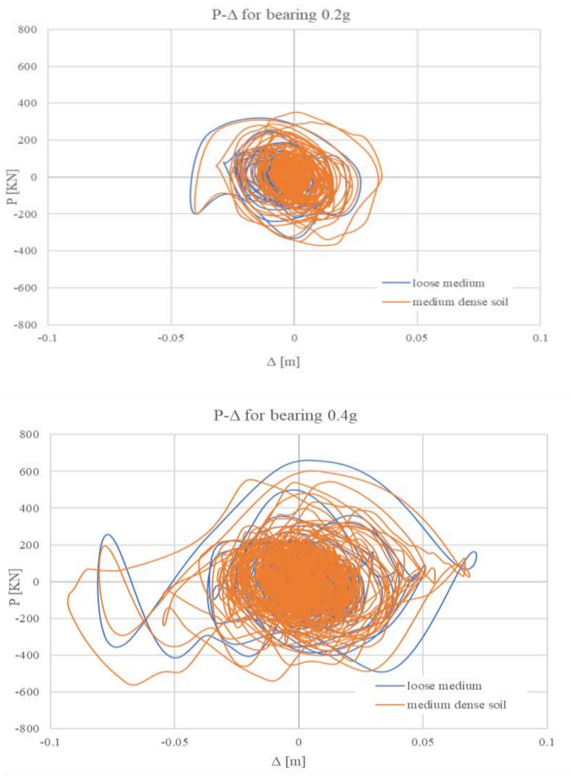

Figure 6. P-Δ diagram for the bearing, El Centro, 1940, 0.2g and 0.4g

6. CONCLUSIONS

The isolated bridge system with two soil structure interaction conditions is analyzed. The soil mediums are modelled by frequency independent coefficients of soil stiffness and damping. Loose medium and medium dense soil are used for the analyses. Non-linear time history analyses are preformed using real time history earthquake motion scaled to two intensities 0.2g and 0.4g. This analysis is used to account for the nonlinear hysteretic nature of the seismic isolation system on the bridge structure. The system response variables considered are displacement of the substructure and superstructure of the bridge and the shear force in the pier. These two response variables are critical for the design of the bridge superstructure and the design of the bridge substructure accordingly. From all the analyses results, the following concluding remarks can be made:

- The type of foundation soil does not have influence on the behavior of the superstructure of the bridge. The difference of the displacement and acceleration in upper structure node due to earthquake with the same intensity and same is negligible.

- There is no significant difference between nonlinear behavior of the bearing elements when the bridge is analyzed on the loose medium and medium dense soil.

- The variation in the damping in the bearings does not have noticeable effects on the response of isolated bridges with SSI effects.

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