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STEPGRAD
СТЕПГРАД

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ADVANCED ASSESSMENT OF SSI EFFECTS ON THE SEISMIC RESPONSE OF MULTI-SPAN RC GIRDER BRIDGES

Abstract:

The effects of soil-structure interaction (SSI) are usually neglected in the current practice of seismic analysis and design of bridges. The objective of this research study is to assess the significance of SSI for the seismic response of multi-span reinforced concrete girder bridges. The focus is on the behaviour of the integrated global bridge structural system. The study is based on the representation of a soil-bridge system. It has been found that SSI greatly affects the dynamic behaviour of bridge piers, leading to more flexible systems and larger total displacements. The soil medium has been analysed by applying different soil densities in order to consider the soil stiffness. The study has focused on soil-structure interaction effects, and the results are analysed accordingly. The soil medium has been taken into consideration as a four-layered infill, as a dense and loose medium. The bridge structure is taken to be an RC structure. The boundaries of the soil medium are considered as infinite elements in order to absorb the radiating waves. 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 the soil model in which the wave reflections are softened. The case study chosen in this work considers different strengths of soil models on which the bridge structural response is analysed in detail.

Keywords: soil-structure interaction, frame structure, seismic evaluation, numerical modelling, Eurocode 8.

УНАПРИЈЕЂЕНИ ПОСТУПАК ПРОЦЈЕНЕ УТИЦАЈА ИНТЕРАКЦИЈЕ ТЛА И КОНСТРУКЦИЈЕ НА СЕИЗМИЧКИ ОДГОВОР ВИШЕРАСПОНСКИХ АРМИРАНОБЕТОНСКИХ ГРЕДНИХ МОСТОВА

Сажетак:

Утицаји интеракције тла и конструкције (ИТК) се у тренутној пракси сеизмичке анализе и пројектовања мостова обично занемарују. Циљ овог истраживања јесте процјена значаја интеракције тла и конструкције на сеизмички одговор разматраних мостова, с нагласком на понашању интегрисаног глобалног конструктивног система мостова, а истраживање се заснива на моделирању система тло–мост. Утврђено је да интеракција тла и конструкције у великој мјери утиче на динамичко понашање стубова моста, доводећи до флексибилнијих система и већих укупних помијерања. Тло је анализирано примјеном различитих запреминских маса са циљем дефинисања крутости. У раду је посебна пажња посвећена утицајима интеракције тла и конструкције, а резултати су у складу с тим анализирани. Тло је узето у обзир као четверослојни насип, у збијеном и растреситом стању. Конструкција моста третирана је као армиранобетонска конструкција, при чему су границе тла моделиране као бесконачни елементи у циљу апсорпције рефлектујућих таласа. Извршена су поређења са референтним и експерименталним резултатима, при чему су постигнути задовољавајући резултати. Новопредложена методологија ефикасно моделира истовремено интеракцију тла и конструкције моста те далеко поље модела тла у коме су рефлексије таласа пригушене. Студија случаја, одабрана у овом раду, разматра различите чврстоће модела тла на којима је детаљно анализиран одговор конструкције моста.

Кључне ријечи: интеракција тла и конструкције, рамовска конструкција, сеизмичка евалуација, нумеричко моделирање, Еврокод 8.

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 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.

A number of studies investigated the influence of SSI on the earthquake response of conventionally designed bridges in recent years. Spyrakos [2-3] have showed that SSI greatly affects the seismic response of bridges leading toward more flexible systems and increased damping. Some studies show that SSI effects consistently decreased the ductility demands of the piers when compared to the system without SSI effects [4]. On the other hand, some other studies say that SSI can have both beneficial and detrimental effects on the response of the structure depending on the characteristics of the ground motion [5-6]. There are only a couple of publications available in the literature on how SSI influences the response of seismically isolated bridge structures. Tongaonkar and Jangid [7] looked at assessing the effects of SSI on three-span continuous deck bridges isolated with elastomeric bearings. They assumed linear elastic behaviour for the isolation system and the piers of the bridge and carried out a time–history analysis using the complex modal analysis method to account correctly for the large damping contributed to the system by the seismic isolators. They concluded that consideration of the SSI in the analysis will result in enhancement of safety and reduction in design costs. They also reported that under certain circumstances, isolation bearing displacements at abutment locations only might be underestimated if SSI is not accounted for in the analysis.

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 behaviour 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) [8].

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, determination and modelling 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.

The soil medium has been analysed 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 analysed 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.

3. BRIDGE MODEL

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.

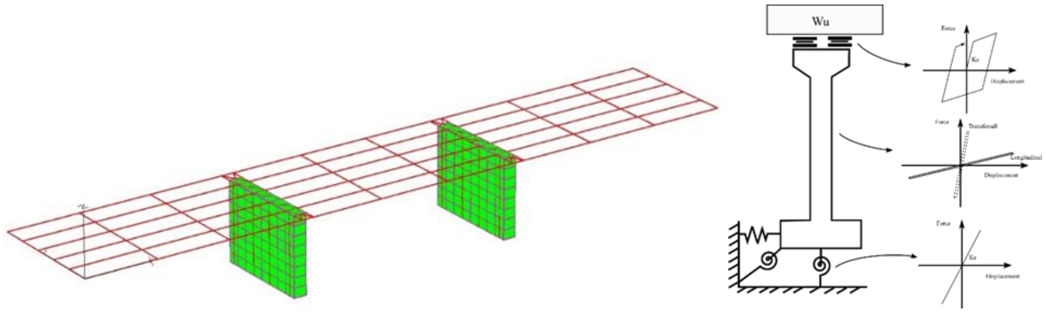


Figure 1. Three-dimensional mathematical FELISA/3M model composed of 3D finite girder and solid elements [9].

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 analysed by use of the verified FELISA/3M computer program [10]. A detailed description of the analytical model is given in Vitanova, 2015 [9]. 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. The seismic isolation system is considered to behave as a bilinear hysteretic spring with smooth elastic to post yielding behaviour. Although this behaviour 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 friction pendulum system isolators.

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

Table 1. Geometric and Mechanical Properties of Bridge Systems

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	528.0/429.4	2722.8/2229.5

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.

4. INFINITE ELEMENTS

The boundary conditions which represent important step in simulation of soil medium has to be considered carefully. The formulation of infinite elements follows the same fundamental principles as conventional finite elements, with the additional requirement of an appropriate mapping that allows the computational domain to extend to infinity. Infinite elements are first developed by Zienkiewicz et al. [11] and since then have been developed in frequency and time domain. In this work the development of infinite element has followed the techniques considering the time domain in which the infinite element is obtained from a six nodded finite element as shown in Fig 2.

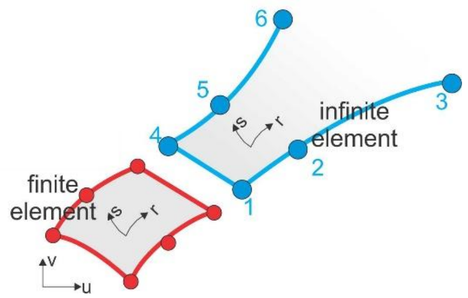


Figure 2. Nodes coupling of finite and infinite elements

The element displacement in u and v direction is interpolated with the usual shape functions N^1, N^2, $N^4$and N^5:

$$u = [N_1 \quad N_2 \quad 0 \quad N_4 \quad N_5 \quad 0]\mathbf{u}$$
$$v = [N_1 \quad N_2 \quad 0 \quad N_4 \quad N_5 \quad 0]\mathbf{v} \tag{1}$$

In expression (1), **u** and **v** are vectors with nodal point displacements in global coordinates. The shape functions are given in expression (2) as:

$$N_1 = -(1-s)r(1-r)/4$$
$$N_2 = (1-s)(1-r^2)/2$$
$$N_4 = -(1+s)r(1-r)/4$$
$$N_5 = (1+s)(1-r^2)/2 \tag{2}$$

Based on the isoparametric concept, the infinite element in global coordinate is mapped onto an element in local coordinate system using the expression in (3). In the formulation of the infinite element, only the positive r direction extends to infinity.

$$r = [M_1 \quad M_2 \quad 0 \quad M_4 \quad M_5 \quad 0]\mathbf{r}$$
$$s = [N_1 \quad N_2 \quad 0 \quad N_4 \quad M_5 \quad 0]\mathbf{s} \tag{3}$$

The number and location of the nodal arrangement at the finite-infinite element interface must be identical to ensure displacement continuity.

5. RESULTS COMPARISON

Three span isolated girder bridge system with the soil-structure interaction is analysed 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 (transverse) 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.

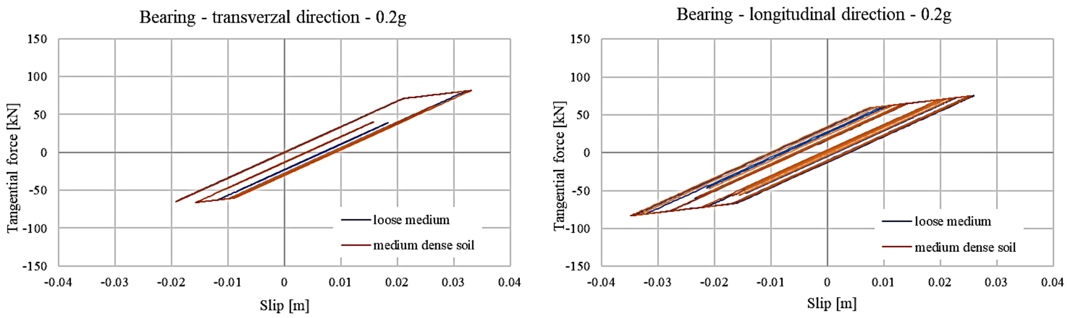


Figure 3. Stress-strain curves for bearing in horizontal directions, El Centro earthquake, 0.2g

Fig. 3 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. 4 shows the behaviour of the same bearing, but the bridge structure subjected to 0.4g intensity. All these diagrams show that the behaviour of the bearing in both horizontal directions does not change concerning the soil type.

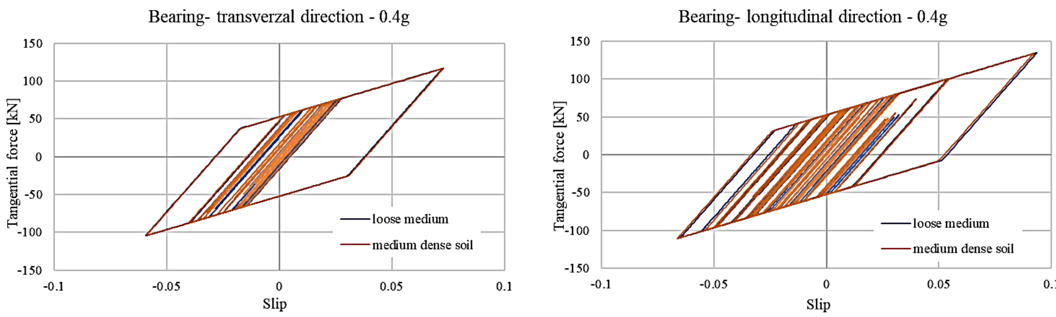
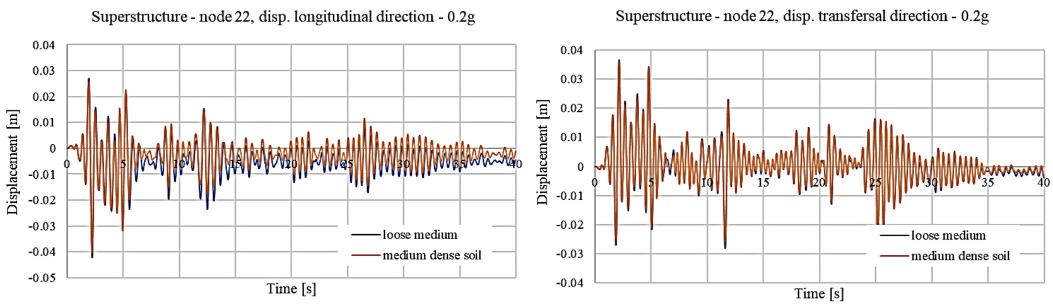


Figure 4. Stress-strain curves for bearing in horizontal directions, El Centro earthquake, 0.4g.

The behaviour 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.5. 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 they 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 both earthquake intensities. The difference is more distinct for the transversal direction. This indicates that soil-structure interaction effects are more pronounced at the foundation-pier interface than at the superstructure level.



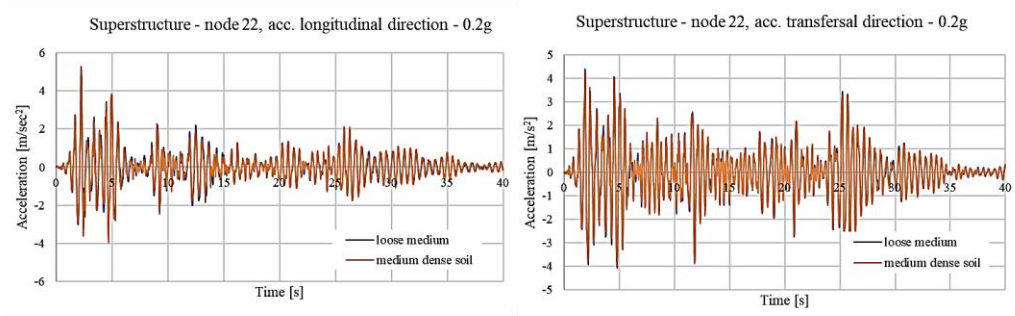


Figure 5. Time history of displacement (up) and acceleration (down) for superstructure in horizontal directions, El Centro, 1940, 0.2g.

These results show that the behaviour of the upper part of the bridge structure is not dependent on the soil type of foundation. The behaviour of the substructure is directly dependent on 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. The isolation bearings successfully shield the bridge deck from foundation flexibility effects, maintaining consistent response characteristics regardless of underlying soil conditions. In stark contrast, the substructure response is strongly dependent on soil properties, as the piers are directly connected to the foundation system without any isolation interface. For both directions and both intensities, pier displacements increase substantially when founded on loose medium versus medium dense soil—typically by 30-45% in the longitudinal direction and up to 50% in the transversal direction. These findings underscore the importance of accurate soil modelling in predicting pier demands and designing appropriate foundation systems.

In Fig. 6, time-history diagrams of displacement are presented for acceleration levels of 0.2g (top) and 0.4g (bottom), for the superstructure in the horizontal directions, in the context of the 1940 El Centro earthquake. The diagrams show that, in the transverse direction, the displacements are significantly smaller for the bridge analyzed on medium dense soil, whereas in the longitudinal direction there are no substantial differences. Furthermore, the intensity of the acceleration does not significantly influence these observed differences in structural behavior.

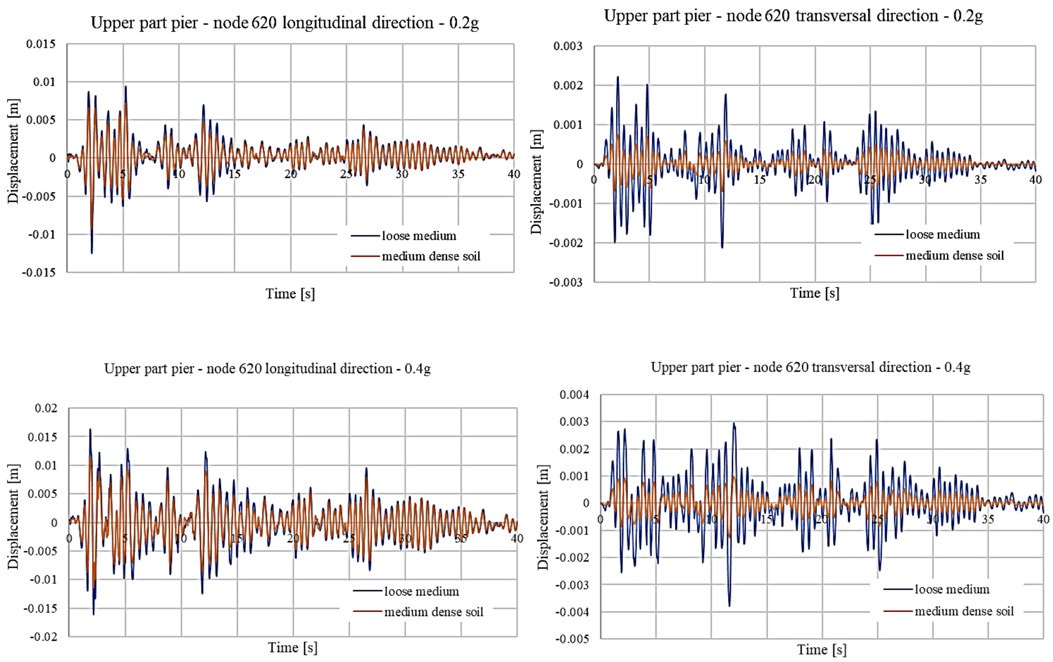


Figure 6. Time history of displacement for 0.2g (up) and 0.4g (down) for superstructure in horizontal directions, El Centro, 1940.

Fig. 7 presents the P–Δ relationships for the bearing for both soil types and earthquake intensities. It can be observed that the difference between loose and medium dense soil is not significant.

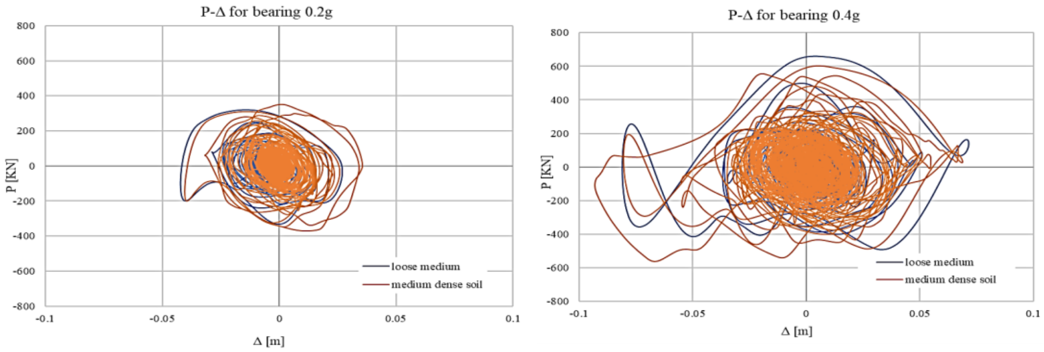


Figure 7. P-Δ diagram for the bearing, El Centro, 1940, 0.2g and 0.4g

Although noticeable differences in pier displacements were observed between loose and medium dense soil conditions (Figures 5 and 6), the bearing force-displacement behaviour shows minimal variation. This indicates that the isolation system's hysteretic characteristics—including its effective stiffness and damping properties—are not significantly influenced by foundation soil type. The primary factor affecting bearing response is earthquake intensity, with the 0.4g excitation producing approximately twice the displacement and force demands compared to the 0.2g case

6. CONCLUSIONS

The isolated bridge system with two soil-structure interaction conditions is analysed. 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.

- The behavior of the substructure is strongly dependent on the soil conditions, confirming that soil–structure interaction plays a significant role in the overall seismic response of the bridge.
- The type of foundation soil does not significantly influence the behavior of the bridge superstructure. The differences in displacement and acceleration at the superstructure, for earthquakes of the same intensity and under the same conditions, are negligible.
- There is no significant difference between nonlinear behaviour of the bearing elements when the bridge is analysed 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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