



# Seismic Isolation of Bridges: Practice-Oriented Considerations

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**Abstract.** Seismic isolation is an effective method to control seismic forces, seismic displacements and to govern modal shapes on a structure or a part of it. Seismic isolation devices are widely used in the design of new bridges and retrofit of existing structures due to their effectiveness in the reduction of seismic forces and the relatively simple methods of installation. This work aims to provide practical considerations to be included when dealing with the design of new bridges equipped with seismic isolator devices and in particular the paper focuses on the study of seismic isolator stiffness variation and inclusion of soil-structure interaction. The purposes of the paper are a) to set a fast design procedure for the design of seismically isolated bridges b) to investigate how the stiffness of an equivalent system composed of foundations, piers and bearings can be affected by varying the stiffness of the individual components. Both these objectives will be described following a sort of flow chart containing the different main steps to be included for the design of seismically isolated bridges. This study can provide practical oriented considerations to the designers dealing with seismic design of isolated bridges and can help to understand how stiffness variations of the single components might affect the global behavior of the structure and thus the sizing of the structural elements.

**Keywords:** Seismic isolation · Bridges · Fast design procedure · SSI

## 1 Basic Concept of Seismic Isolation of Bridges

### 1.1 Introduction

Seismic isolation techniques have increased their usage during the last years, especially in high intensity earthquake prone zones.

Bridges are, in most cases strategic structures which need to be protected from damages ensuring functionality after a seismic event and seismic isolation could be used to concentrate damages in few elements, easy to check and replace.

The main reason to prefer seismic isolation over other seismic design choices is to take advantage of the period elongation, by means of a decrease in stiffness, in order to reach convenient values in terms of acceleration (i.e., forces) demand for the structure

or a part of it [1]. With this approach, it is possible to protecting a part of the structure, assuring an elastic response.

Since bridges are usually simple structures regarding the expected global behavior and most of the mass is concentrated at the deck level, seismic isolation could be particularly convenient to apply corrections to the global response by means of the modification of stiffness distribution.

A bridge could be irregular from the point of view of the longitudinal distribution of mass (e.g. in case of a variation of the deck width along the longitudinal axis) or stiffness (e.g. for the presence of piers with different transversal sections or different heights), hence the main goal of the above mentioned modification is to have an isolated system with optimized motion capacity in order to avoid torsion and with respect to isolation devices and expansion joints displacement capabilities.

In addition, seismic isolation is also effective to increase the energy dissipation capacity of the system or to regularize the seismic behavior of the structure.

At the same time, within the design process of an isolated structure such a bridge, Soil-Structure Interaction (SSI) is an important issue to be considered and it may have greater or lesser extent in sizing phase of the structural elements.

This work aims to show the effect of the variation of substructures (i.e., piers and foundation piles) stiffness on an isolated bridge, in order to understand its influence on the global behavior.

## 2 Simplified Preliminary Design of Seismic Isolation System

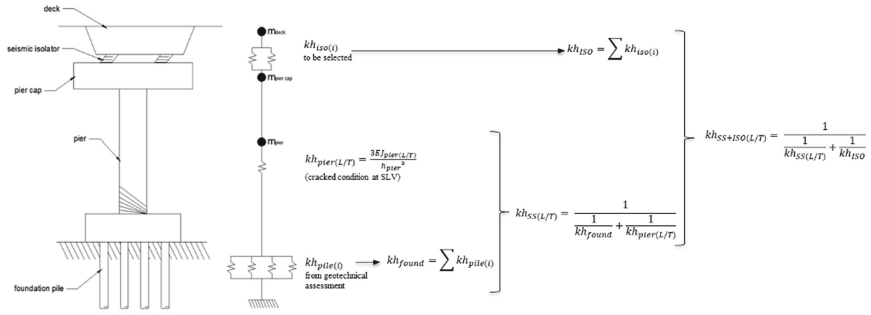
The present research work aims at providing a simplified preliminary design procedure for a fast initial design of the isolation system of a bridge, according to the most usual typologies of devices adopted in common practice for these structures. Similar procedures have been already developed and are available in literature, especially for buildings and other civil structures [2].

The procedure here presented is based on a simplified schematization of the bridge in sub-components as represented in Fig. 1: each support of the bridge is treated as a system of springs (characterized by their values of stiffness) and masses. The approach followed is that of the “sub-component method” presented in Priestley et al., 1996 [3].

The springs accounted in this approach, placed in series, from the bottom to the top of the support, are the following:

- Resultant spring of the foundation piles (the foundation piles are seen as springs in parallel), calculated from geotechnical assessment of pile-soil interaction.
- Spring of the pier (stiffness calculated from the Young Modulus  $E$ , the Moment of Inertia  $J_{\text{pier}}$  of the cross section and the height of the pier  $h_{\text{pier}}$ ), considering both longitudinal and transversal inertia.
- Resultant spring of the isolation system (the isolation devices are seen as springs in parallel).

A preliminary knowledge of deck geometries, position of piers and abutments, expected mass of the deck in the seismic condition, mass and inertia of deck, piers



**Fig. 1.** Simplified spring-mass system (foundation piles, pier and isolation devices).

and pier caps is necessary to set up the procedure. In parallel, it is important to know the foundation layout, hence a preliminary evaluation of the soil springs due to SSI.

Since abutments are assumed extremely rigid with respect to the piers, masses and inertia of the abutments and foundation plinth is neglected.

Figure 2 shows a flow chart of the simplified procedure here presented.

A first evaluation of the period of piers, taken as single elements (i.e., without isolation system and SSI), is performed with the purpose to assess the influence of concrete cracking in the positioning of the first mode of the piers in the pseudo-acceleration response spectrum. In this step it is also possible to determine the position of the center of mass of the bridge, CoM.

The second step is to repeat the same evaluation, considering the SSI effect (i.e., springs of the foundation system) to assess its influence in the determination of the substructures natural periods, and subsequently on the seismic action these can receive due to their own mass and stiffness. Dynamic stiffness of pile group can be calculated with analytic procedure available in literature, e.g., the one proposed by Novak et al. [4].

Finally, the stiffness of the isolation devices is chosen with the aim to meet several requirements:

- the period of the structure must be close to 2 s uncoupling of the motion between the deck and the substructures;
- the center of stiffness of the bridge, CoS, must be as close as possible to its center of mass, CoM, to avoid torsional modes of the deck, reducing the displacements of the deck and to make them compatible with commercial expansion joints and isolation devices [6].

It is worth to note that the simplified procedure here described can be more easily applied to Elastomeric Damping Rubber Bearings [5], since the assumption of linear-elastic behavior of the force-displacement curve is more applicable than for Friction Pendulum [7].

Additionally, design equivalent viscous damping of the isolation devices does not represent a key parameter in the selection of the types of isolation devices and plan layout.

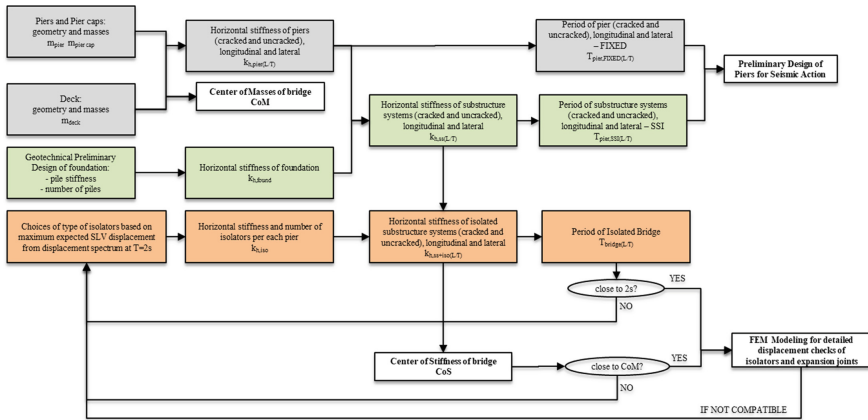


Fig. 2. Flow chart of the procedure.

On the other hand, damping represents a very important parameter to limit actions and displacement on substructures and foundations.

### 3 Sensitivity Analysis on the Effect of Geometry Variations and Soil-Structure Interaction on the Seismic Response of Isolated Bridges

This chapter reports the sensitivity analyses carried out with the purpose of providing practical considerations potentially useful in the design of the isolated bridges, especially when the design flow requires quick assumptions necessary to go in parallel with the design phases.

#### 3.1 Description of the Case Studies

The bridge of the case study here presented is composed by a steel-concrete composite deck with a main bridge and two access ramps. The bridge is in a very high seismic area and presents a total length of 330 m with typical span between 35 and 50 m. The main deck is supported by 7 reinforced concrete piers and 2 abutments, 1 pier and 2 additional abutments support the deck of the access ramps. The deck is a continuous structure with transversal expansion joints at the abutments only. All the substructures are founded on foundation piles.

Figure 3 shows a longitudinal and a plan view of the bridge.

Starting from the layout of the bridge shown above, four different cases have been analyzed with the purpose of analyzing the effect of SSI and bridge geometries on the design of the isolation system and its effect on the substructures and foundation.

The cases showed in Fig. 4 have been examined:

- Case A: Rock and squat piers (pier height between 6.5 m and 9.5 m).
- Case B: Non-competent soil and squat piers (pier height between 6.5 m and 9.5 m).

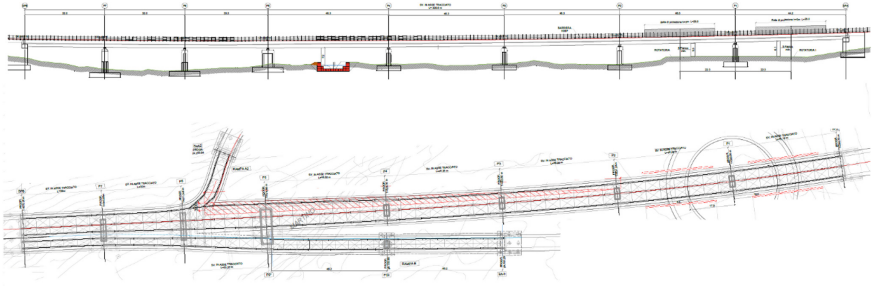


Fig. 3. Case study bridge longitudinal and plan view.

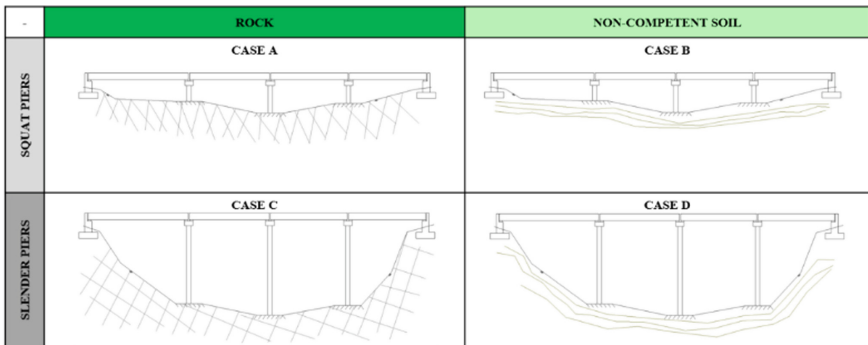


Fig. 4. Simplified and qualitative sketches of the four cases assessed in the sensitivity analysis.

- Case C: Rock and slender piers (pier height between 16 m and 24 m).
- Case D: Non-competent soil and slender piers (pier height between 16 m and 24 m).

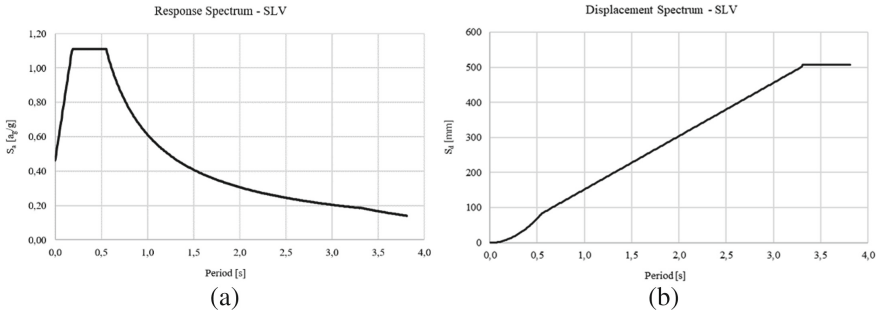
For each of these cases, the simplified procedure previously described has been applied.

First, the isolation system has been selected to design an isolated bridge having a longitudinal and transversal period of about 2.0 s and the center of stiffness as close to center of masses as possible. For all the cases, the cracked stiffness for the piers has been considered with a reduction of the gross inertia equal to 50%, considering a SLV event.

### 3.2 Seismicity of the Site

The bridge is located in a high seismic area in Italy. The Acceleration Response Spectrum at the site is showed in Fig. 5 (a) for the SLV event. Peak ground acceleration is 0.46 g, and the range of periods of the plateau is included within 0.19 s and 0.55 s. The Displacement Spectrum represented in Fig. 5 (b) shows the expected displacement at the site for the SLV event.

Due to high seismicity of the site, the expected displacement of the deck at natural period of 2 s is around 300 mm. This parameter shall be considered as a first reference to select appropriate isolation devices.



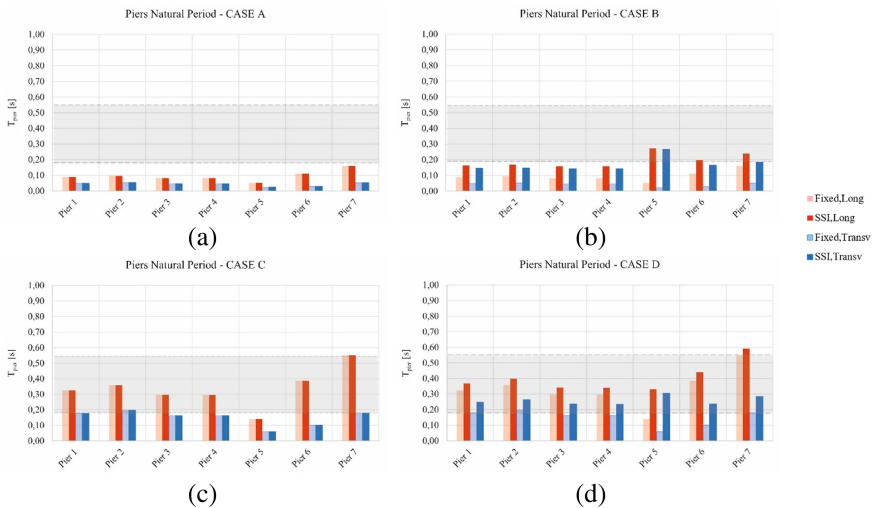
**Fig. 5.** Response spectrum (a) and displacement spectrum (b) at the site for SLV event.

For comparison purposes only, the same response spectra are adopted in the study for all the four cases.

### 3.3 Substructures Dynamic Properties

Per each of the 7 piers of the bridge, Fig. 6 shows the longitudinal and transversal first natural periods, considering the fixed base hypothesis and the soil-structure interaction effects.

Light red and red columns represent the longitudinal natural periods in fixed based and SSI condition respectively. Light blue and blue columns represent the transversal natural periods in fixed based and SSI condition respectively. The grey strip represents the periods of the plateau of the SLV seismic spectrum at the site previously showed in Fig. 5.



**Fig. 6.** Longitudinal and transversal natural period of piers – Fixed based vs. SSI effects: (a) Case A; (b) Case B; (c) Case C; (d) Case D.

For both the cases of squat and slender piers in good soil condition (cases A and C respectively), the effect of SSI in modifying substructures stiffness and natural period can be neglected. On the contrary, in case of non-competent soil (cases B and D), SSI cannot be ignored since this effect can provide very different values of natural periods of the piers, especially when dealing with squat piers or in the transversal direction of the bridge (typically more rigid than longitudinal for higher inertia of the pier). This is in general agreement with the indications found in literature (see for example Priestley et al. 1996 [1], Priestley et al. 2007 [3]).

In addition, the same figure shows that for all the 4 cases, both longitudinal and transversal natural periods of the substructures are far from the estimated natural periods foreseen for the isolated deck (around 2.0 s). The more the substructures are stiff, the more the uncoupling degrees between deck and substructure is expected.

### 3.4 Isolation System

As previously described in Chapter 2, the selection of the isolators (types of devices and layout) is one of the main goals of the proposed procedure. For this reason, different isolators, and relevant plan positioning can be expected for each of the four cases. In general, for all the 4 cases, Elastomeric Damping Rubber Bearings have been foreseen.

The main characteristics of the isolation devices adopted in the four cases are summarized in Table 1. For all the cases, isolators with displacement capacity of 350 mm have been selected in order to satisfy the expected displacement demand at the design period of 2.0 s. An important aspect to highlight is that the definition of the isolator stiffness in the different locations is driven by the necessity to accomplish the two goals: the uncoupling criteria and the reduction of the eccentricity between CoM.

**Table 1.** Elastomeric damping rubber bearings adopted in the four case studies

	Type A	Type B	Type C
Nominal horizontal stiffness $kh_{ISO}$ (kN/mm)	3.20	1.90	4.20
Displacement capacity (mm)	350	350	350
Equivalent viscous damping coefficient $\xi$ (%)	15	15	15
Dynamic Shear Modulus $G$ for $\gamma = 1$ (MPa)	1.4	1.4	1.4
Maximum ULS vertical load (kN)	6900	7400	12000

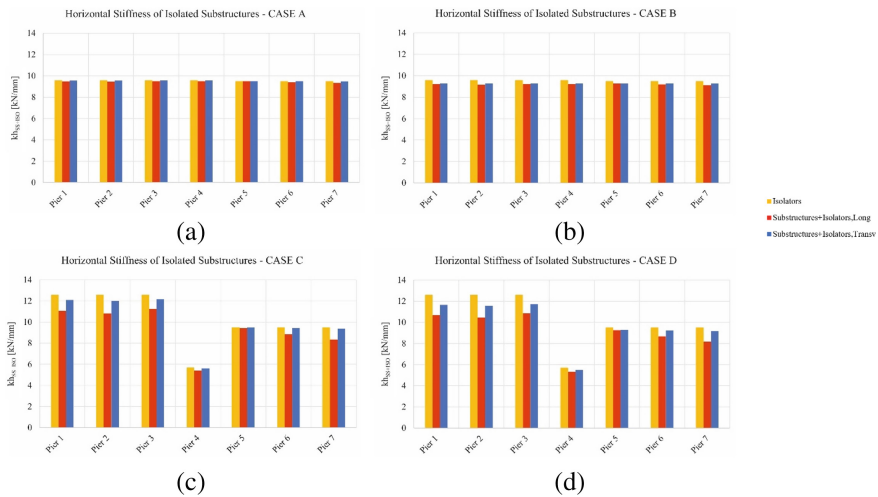
### 3.5 Uncoupling Degree

Table 2 summarizes the main properties of the isolated deck in the four cases analyzed. In detail the table reports the first longitudinal and transversal natural period of the isolated deck in the four cases, as well as the longitudinal and transversal distances between center of masses and center of stiffnesses of the bridge.

**Table 2.** Natural periods of isolated deck and CoM – CoS distances for the analyzed cases

	Case A	Case B	Case C	Case D
Longitudinal Period $T_L$ (s)	1.80	1.82	2.06	2.08
Transversal Period $T_T$ (s)	1.79	1.81	1.98	2.01
CoM – CoS Longitudinal distance (m)	-0.4	-0.4	-1.0	-1.0
CoM – CoS Transversal distance (m)	-5.1	-5.0	0.6	0.8

Per each of the 7 piers of the bridge, Fig. 7 shows the effect of uncoupling deck and substructures with seismic isolation systems. The yellow columns represent the horizontal stiffness of isolators only, placed on top of each pier. Red and blue columns represent the longitudinal and transversal horizontal stiffness of the substructure in the isolated configuration considering isolation, flexural inertia of the piers and SSI effect.



**Fig. 7.** Horizontal Stiffness of Substructures vs. Horizontal Stiffness of Isolators: (a) Case A; (b) Case B; (c) Case C; (d) Case D.

For the analyzed scenarios, independently of the soil type, the isolator type and layout are mainly governed by the stiffness of the piers, and it can be argued that SSI does not represent a key factor to define the most appropriate isolation system. Indeed, despite very different soil conditions, Cases A and B present the same isolator layout and the same natural period of the isolated deck in both longitudinal and transversal direction. The same situation occurs for cases C and D, which present same isolators configuration and very similar natural period for both longitudinal and transversal directions. This result shows an important beneficial effect of the bridge isolation: given the uncoupling between deck and substructure, the seismic behavior of seismically isolated bridges is not greatly influenced by SSI effect.

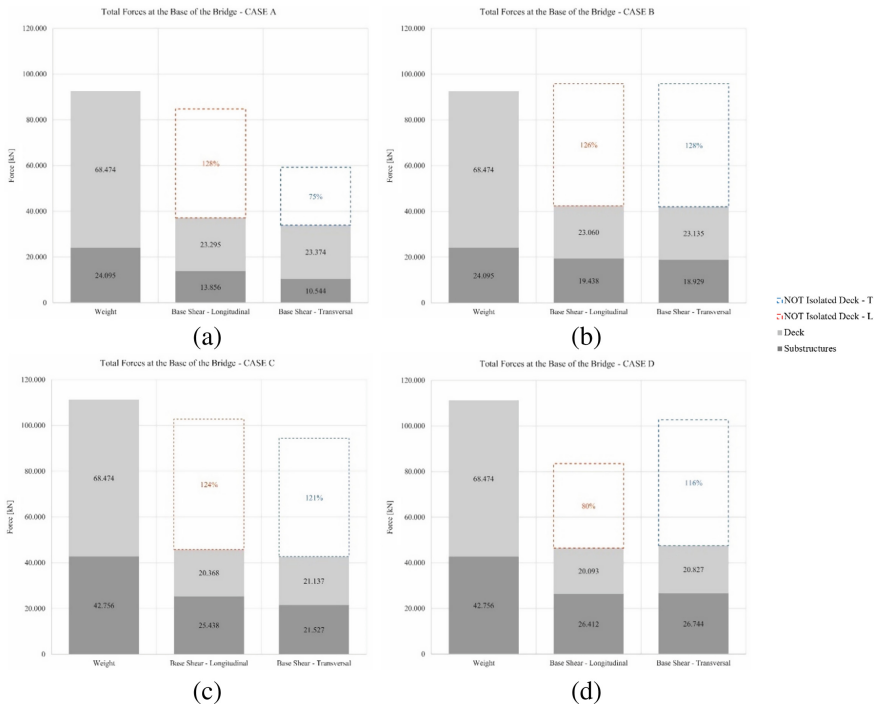


In addition, Fig. 7 suggests another important consideration. Uncoupling is almost complete when dealing with squat piers for both rock and non-competent soil (in cases A and B the red and blue columns are almost overlapped with yellow ones). On the other hand, uncoupling tends to reduce when dealing with slender piers: in cases C and D the overall horizontal stiffness of each substructure starts to decrease, especially in longitudinal direction, where piers are more flexible (red columns show the tendency to low from the yellow ones).

### 3.6 Actions on Bridge Foundations

This section has the goal of showing the seismic actions transferred from the deck and the substructures to the foundations. Figure 8 reports the total forces transferred from the substructure to foundations for both longitudinal and transverse direction.

Masses due to foundation plinths and abutments are not included. The first column represents the weight transferred to ground, composed by two terms: the light grey is the deck component, while the dark grey is the substructure component. The second and the third columns of each diagram represent the total longitudinal and transversal base shear due to seismic SLV event respectively.



**Fig. 8.** Total forces at the base of the bridge – Deck and Substructures contributes: (a) Case A; (b) Case B; (c) Case C; (d) Case D.

The red and the blue dashed lines show the values of the longitudinal and transversal base shear in case of non-isolated deck.

From this figure it is worth to highlight some significant considerations.

The effect of isolation system is always beneficial for the 4 cases analyzed also when uncoupling is not total (cases C and D): indeed, the reduction of the base shear with respect to the non-isolated condition is significant.

As second consideration, the contribution of SSI is relevant when dealing with non-competent soil to avoid underestimation of base shear. Indeed, in both cases of squat and slender piers, the base shear due to the deck part is approximatively the same, while the SSI provide an increment of the portion of base shear due to substructures.

### 3.7 Validation of the Simplified Procedure

The methodology here described has been tested for several bridges with different geometries and number of piers showing a very good agreement with the results of the more refined Finite Element Analyses.

As an example, the FE model here presented includes all the elements of the bridge (i.e., deck, isolators, pier caps, piers, foundation plinths and foundation piles) used in the design of the Case B. The main deck has been modeled with beam elements, considering the effective mass, weight, and inertia of beams, diaphragms and slab. The isolators have been modeled as elastic link placed on top of each pier cap. The piers have been modeled as beam elements. Finally, foundation plinths have been modeled as shells, connected to the foundation piles, modeled as springs.

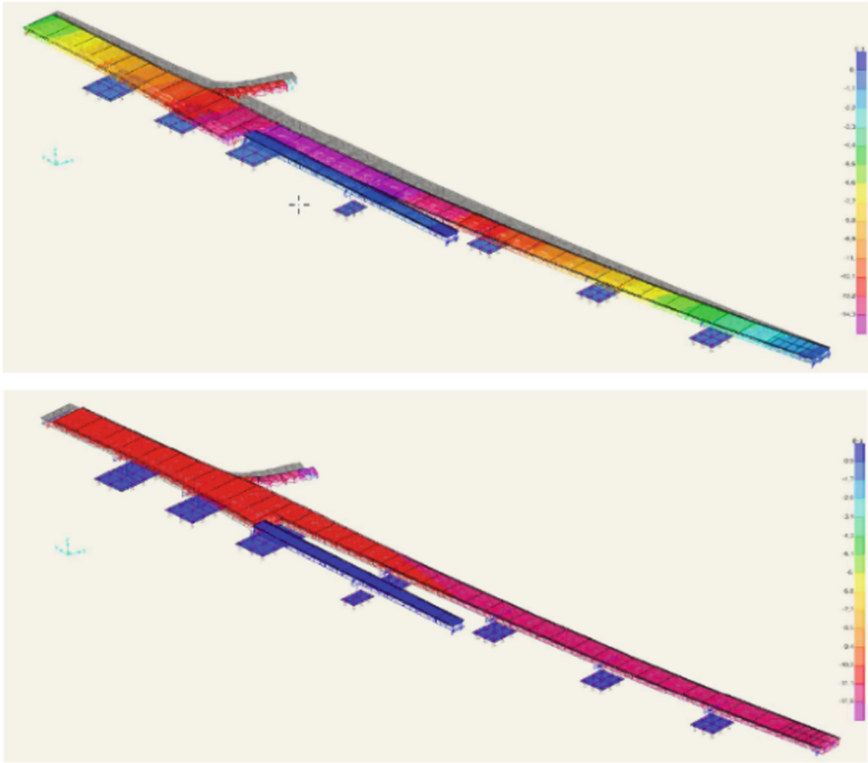
**Table 3.** Comparison of Natural Period - FE model vs. simplified procedure

	FE model	Simplified procedure (Case B)
Longitudinal period $T_L$ (s)	1.89	1.82
Transversal period $T_T$ (s)	2.00	1.81

The model has been subjected to several sanity checks and the same has been used to perform the verification of all the element of the bridges, under different static and seismic load conditions. The figures here reported (Fig. 9) shows the first natural modes of the deck resulting from modal analysis.

Table 3 show compares the values of natural period of the simplified procedure with those resultants from the FE analysis.

Considering the different levels of complexity of the two models, a good match is shown with differences between 4% and 10%.



**Fig. 9.** First modal shapes from FE model: (a) Long  $T_L = 1.89$  s; (b) Transv  $T_T = 2.00$  s.

## 4 Conclusions and Practice Oriented Considerations

Within the design process of an isolated bridge, it is important to be aware of the following aspects, in order to correctly steer the design approach:

1. The simplified procedure allows to define the choice of the isolation layout (i.e. the distribution of the isolator's stiffness on the different locations) also in very complex systems prior to set a FE analysis. This can be a quite important time-saving operation in terms of modelling and can be a useful simplified check of the FEM results at the same time.
2. Increasing the stiffness of the piers, the SSI effect increases its importance: the neglect of the SSI effect can lead to an underestimation of the seismic action acting on the foundations.
3. The SSI, however, does not affect the choice of the isolation devices, nor the global fundamental period of the isolated structure. The choice of the devices is indeed greatly influenced by deck's geometry and mass and pier's layout.
4. SSI does not affect the type of devices, but it is important to include SSI in seismic design of bridges, especially for soft soil and stiff structures, because the contribution to the base shear can be significant. Indeed, higher modes effect might be much

affected by SSI with the results that the base shear due to the sub structure can varies significantly considering SSI.

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