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EFFECT OF SOIL-STRUCTURE INTERACTION ON THE DYNAMIC IDENTIFICATION OF A PRESTRESSED CONCRETE BRIDGE

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Abstract

In recent years, safety assessment of existing bridges is becoming an urgent and critical issue in light of the increased number of collapses observed worldwide, most of which related to the high vulnerability of the structure itself due to material (concrete or steel) degradation over the years. In seismically-active areas, vulnerability of existing bridges might combine to the high seismic hazard of the site. The fatal consequence is that after a strong earthquake, total or partial interruption of the road infrastructure could occur with the bridge behaving as the weakest component of the chain. In order to shed light on the seismic response of existing r.c. bridges, the paper illustrates the numerical procedure developed by the authors to investigate the dynamic response of a pre-stressed reinforced concrete bridge placed in the highly seismic area of Benevento (IT). The paper investigates the effect of soil-structure interaction on the dynamic behavior of the bridge. A detailed 3D model representing the structure and the soil deposit was developed and solved through the finite element method with the software MIDAS FEA NX. The use of a 3D continuum approach also for the subsoil was motivated by the huge stratigraphic and topographical variability characterizing the soil deposit. After the calibration of the soil model, the bridge was added. At this stage of the work, the structure was modelled through solid elements and a perfect contact was imposed between the piers and the soil. A modal analysis was conducted on the complete model made of both soil and bridge to get the natural oscillation frequencies and mode shapes of the coupled system. These results were later compared to those provided by the analyses in which the superstructure was modelled with a fixed base or a compliant base with springs.

Keywords: Soil Structure Interaction, Finite element analysis, Modal Analysis, Pre-stressed concrete bridge.

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1 INTRODUCTION

In the last few years, there have been a high number of bridges collapsed both in Italy and abroad. This is due to the lack of inspections and maintenance of the road infrastructure, which has led to widespread deterioration of materials, especially for reinforced concrete bridges. Therefore, there is an increasingly urgent need for an assessment of the health condition of bridges [1], particularly in Italy. This urgency is enhanced by the fact that bridges and viaducts constitute infrastructure networks of strategic importance for the management of seismic and post-seismic emergencies in consideration of the high seismicity of large part of the Italian territory. As well as providing an escape route for the local population, they are also part of the main arteries for the arrival of emergency vehicles.

The dynamic identification of bridges has become an increasingly widespread technique, supported by numerous studies and research [4], to implement accurate and reliable models to perform later more complex analyses. Indeed, a common practice is to perform Ambient Vibration Testing (AVT) to assess the dynamic properties of existing structures within the elastic domain, simply using natural vibrations (e.g., micro-vibrations, wind, and anthropogenic activity). The obtained experimental dynamic properties in terms of vibration frequencies, damping and modal shapes are then used for the calibration of numerical models, which will be useful for design purposes. It is common practice to update the numerical model by changing the material properties in order to match the experimental dynamic response to that provided by the numerical model. This is usually assumed to be fixed based [5].

Reinforced concrete bridges are generally characterized by a strong development in length (hundreds of meters up to kilometers). Therefore, the analysis of the structure alone, even schematized with fixed constraints at its base, could not always correctly and exhaustively represent the real dynamic response of the structure. In fact, the dynamic response of the superstructure may significantly be modified if soil-structure-interaction (SSI) phenomena between the superstructure, the underlying foundation and the lateral soil take place. For long span bridges and viaducts, SSI effects may combine to ground motion asynchrony due to soil heterogeneity at the pier foundations [7].

Several studies accounting for soil-structure interaction in case of bridges can be found in literature [10]. Most studies use the simplified sub-structure approach, in which ground response, kinematic interaction (for defining input motion, FIM) and inertial interaction are analyzed separately. Complete three-dimensional models [18] are not yet widespread due to the complexity of modelling real morphological and soil layering setting (valleys, slopes, high stratigraphic variability) and the difficulty in solving complex numerical models with the available commercial softwares [21].

Developing numerical models including SSI is challenging, especially for existing bridges. It is well known that SSI could lead to a reduction of the fundamental frequency of the coupled system and, hence, to a modification of the seismic action at the base of the piers [22].

The aim of this work is to quantify the role of SSI on the dynamic behavior of a prestressed concrete bridge, strategic for the city of Benevento. The bridge is characterized by piers also working as abutments (pier-abutment). For this reason, a detailed three-dimensional model of the overall superstructure (deck and piers), with the foundations and the subsoil interacting with the bridge has been developed. Finally, the modal shapes and natural frequencies of the bridge were computed numerically and compared with those obtained experimentally during the investigation works detailed in [27].

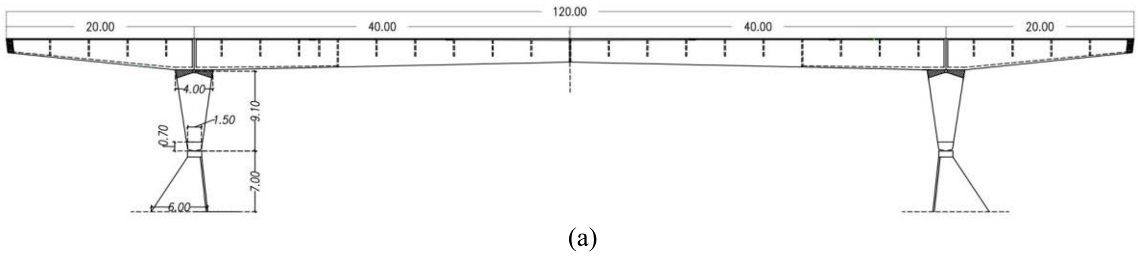
2 SAN NICOLA BRIDGE

The San Nicola bridge, located in the city of Benevento (Italy), connects the Capodimonte area with the upper part of the city, known as Cretarossa district (Figure 1). The structure was designed in between 1952 and 1955 by the engineer Riccardo Morandi, who also designed the much more famous bridge over the Polcevera River in Genoa, collapsed in 2018. A detailed analysis of the San Nicola bridge can be found in the previous studies [27], the most important data of which are recalled hereinafter.

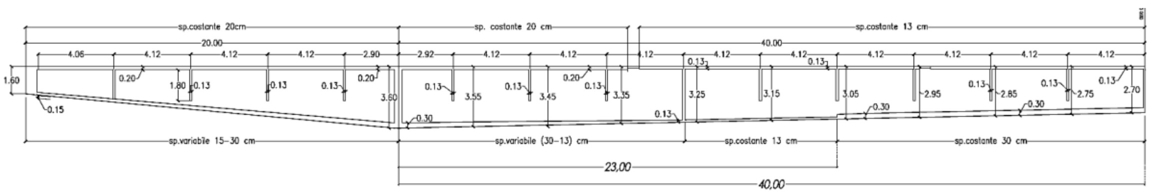
(a) (b)

Figure 1 : Side view (a) and detail of the abutment (b) of the San Nicola Bridge

The bridge deck is made of pre-stressed concrete, cast in situ, while the piers and foundations are made of reinforced concrete. As shown in Figure 2, the deck consists of 80 m-long main span and two 20 m-long side cantilevers. The deck has a variable depth across the spans (beam with curved intrados), providing for a beneficial arch effect. It consists of four pre-stressed box girders whose thickness varies from a minimum of 13cm in the center to a maximum of 30cm at the supports. A lower slab, forming a multi-cell box section with 8 cells, completes the section in the negative moment zone. The total width of the bridge is 9 m with a deck of 7 m.



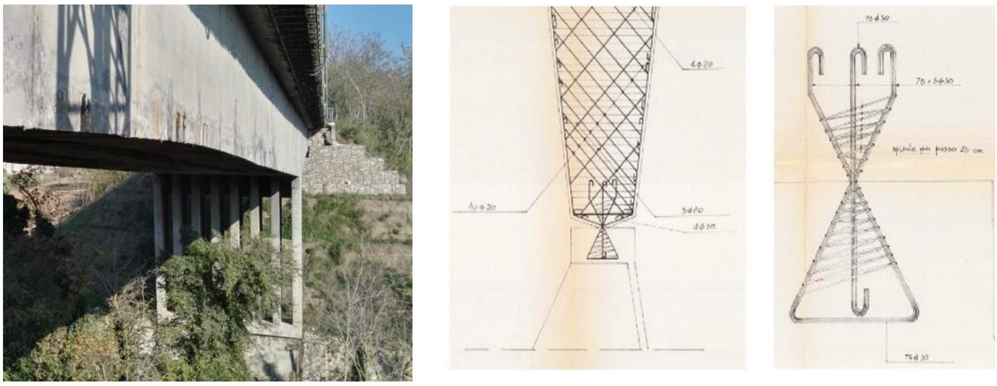
(a)



(b)

Figure 2: (a) Longitudinal scheme of the bridge and (b) detail of the deck

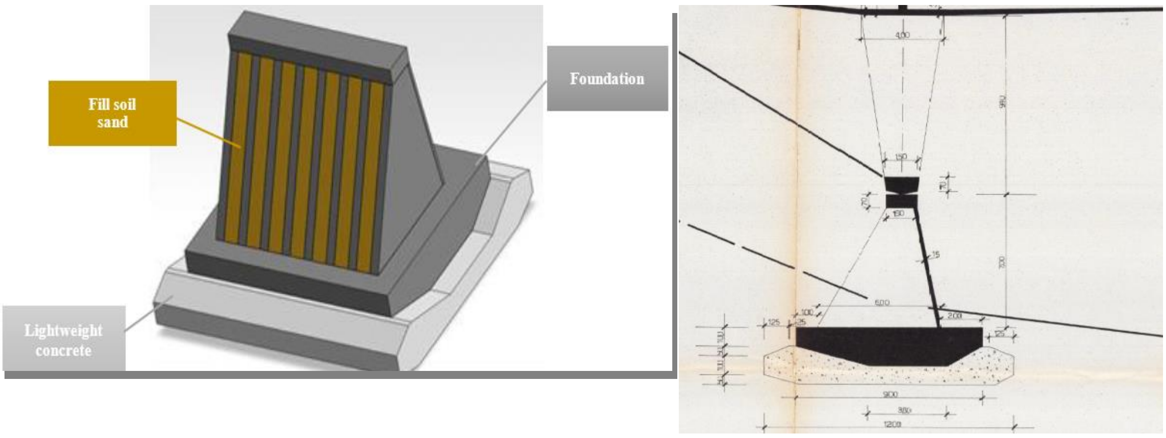
The two 9.40 m-high piers are connected to the foundations by steel hinges (see Figure 3b). The piers consist of eight rectangular columns, 40.0 cm-thick and variable in width from 1.50 m at the base to 4.00 m at the top. They are connected at the base and top by a transverse beam (see Figure 3a).



(a) (a)

Figure 3: Transversal view of the pier (a) and original detail of the hinges (b).

The structure is very complex and innovative for its time, also in terms of foundation geometry (Figure 4). Furthermore, the San Nicola Bridge is a rare case of a bridge with a pier-abutment, unlike other cases where the main structural elements of the bridge (deck, pier, and abutment) are clearly identified. The foundation is very similar to the structure of the pier itself, with eight columns, each one 40 cm thick, connected at the top by a rigid transverse element. As an outcome of several tests carried out on the foundation structure in 2020, it was discovered that the laminae are filled with sandy soils.



(a) (a)

Figure 4: 3D detail (a) and the original scheme (b) of the foundation – abutment.

3 GEOPHYSICAL AND GEOTECHNICAL SITE DATA

For the geotechnical characterization of the site in correspondence of the bridge piers, two different experimental campaigns were performed, the former carried out in 2015 for the stabilization of the right slope and the latter in 2020. Three boreholes with Standard Penetration Test (SPT) were carried out together with laboratory tests (oedometer test and triaxial tests) on the fine-grained materials. The characterization of the soil shear wave velocity in correspondence of the right pier was achieved through a downhole test (DH) and a Multichannel Analysis of Surface Waves (MASW) test while for identifying the fundamental frequencies of the subsoil close to the pier base Horizontal-to-Vertical Spectral Ratio (HVSR) analyses were carried out. The location of above-mentioned tests is schematically shown in Figure 5.

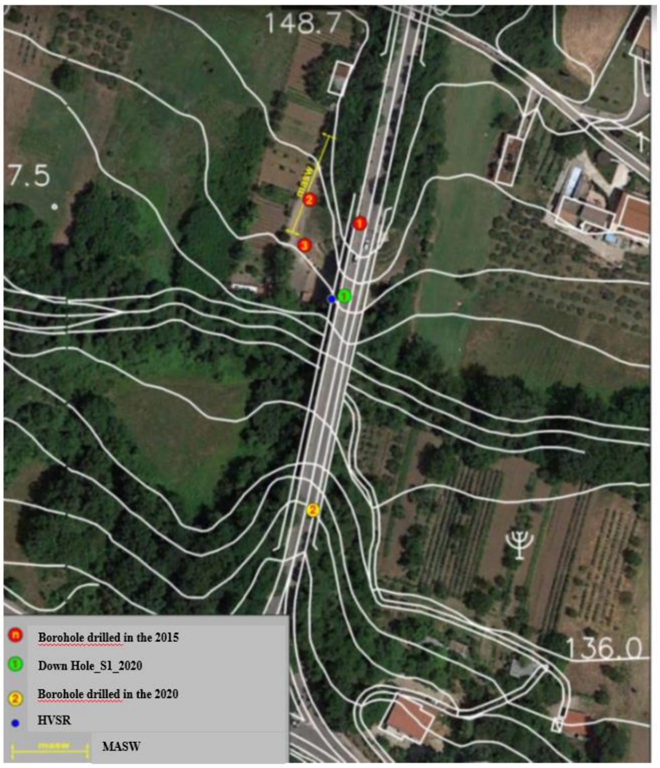


Figure 5: Overview of the bridge valley with location of the geotechnical investigations carried out in 2015 and 2020.

The performed investigations lead to the 2D geotechnical model shown in Figure 6. In the same figure the schematic location of the boreholes and the bridge have been overlapped.

The following soil layers have been identified: an artificial fill (AF), alluvial deposits consisting of sand and gravel (YS), fluvial colluvial deposits (FC), alluvial deposits consisting of sandy silt to clayey places (LS), and blue-grey clayey silt (BGC). The rigid bedrock formation, represented by the bottom blue-grey clay layer, was detected at a depth of 65 m from the ground level in correspondence of the east pier (borehole S1-2020). The main physical and mechanical parameters for each soil layer are reported in Table 1.

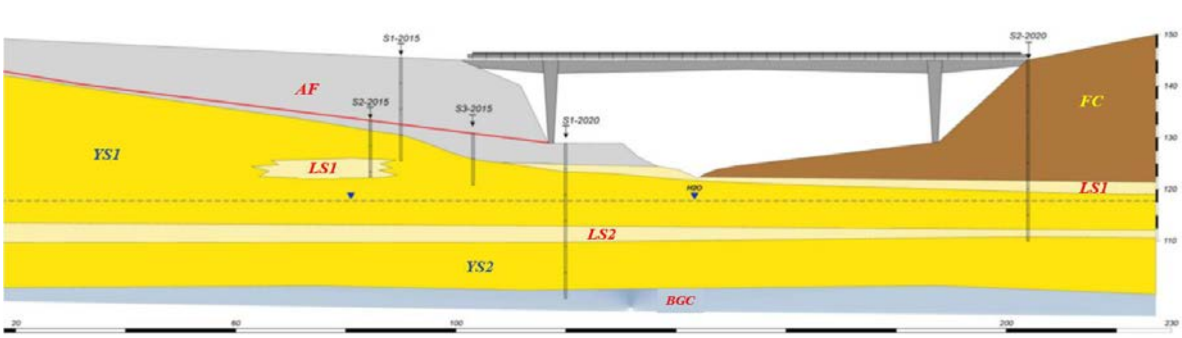


Figure 6: Longitudinal section of the valley with a superimposed sketch of the bridge

Layer	γ [kN/m^3]	V_s [m/s]	G_0 [MPa]	D_0 [%]
AF	18	370	256	2
FC	18	185 - 225	63 - 94	2
LS 1	18	320	198	2
YS 1	21	300 - 640	192 - 903	2
LS 2	18	660	822	2
YS 2	21	680	1004	2
BGC	19	650	815	2
Bedrock	19	800	1200	2

Table 1: Physical and mechanical parameters assigned to the soil layers

4 NUMERICAL MODELS

For the dynamic characterization of the bridge, a 3D finite element model was developed with the software MIDAS FEA NX [29]. As stated above, two numerical models were built: a fixed base model (FB) with the superstructure only and a complete model (SSI) with the bridge structure, the foundations and the soil. The FB model is the reference one for evaluating the soil contribution to the overall dynamic response of the structure.

4.1 Fixed base model (FB)

The geometry of the structure was determined according to the results of the geometric surveys and in-situ inspections, as detailed in [27]. The various components of the structure were modeled considering their real geometry with three-dimensional (solid) finite elements, obtaining the 3D model of the structure (deck+piers) shown in the Figure 7. This model was restrained at the base by means of hinges. The steel sidewalk, added after the construction of the bridge, was modelled by the insertion of a longitudinal beam (frame element) with transverse stiffness equivalent to the sidewalk-guard-rail-parapet system that runs along the entire deck. In particular, the bridge was modeled as a continuous homogeneous material using a tetrahedral mesh with a size of 0.3 m. At this stage of the work, a linear-elastic constitutive model was attributed to the bridge material, with the mechanical properties listed in Table 2. The assigned parameters were derived from a previously developed and tuned f.e. model [27].

Figure 7: Fixed-base model of the San Nicola Bridge in MIDAS FEA-NX

Element	f_{cm} [MPa]	E [MPa]
Deck	46.1	32965
Piers	33.8	2400

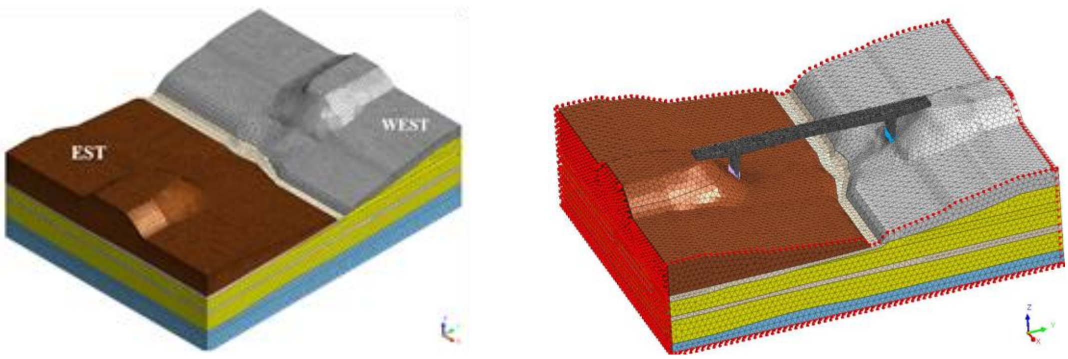
Table 2: Mechanical parameters for the bridge

The in-situ dynamic tests [27] showed that the lateral cantilevers of the San Nicola Bridge in its current state are constrained horizontally (due to the filling of the expansion joint with concrete) and vertically, due to retaining walls (gabions) built a few decades after the bridge construction. Consequently, in the structural model fixed horizontal constraints and vertical springs were inserted at the ends of the bridge cantilevers consistently with the previous study [27]. In summary, the constraint conditions adopted in the FB model of the bridge are as follows: fixed longitudinal hinge-type constraints; vertical and lateral elastic constraints at the ends of the two bridge cantilevers for representing the interaction with the road abutments and gabions, and hinges at the base of the piers.

4.2 Full model (SSI)

The full model was obtained by adding the foundation below each pier and the soil volume interacting with the bridge itself. One of the most complex aspects of the overall modelling procedure was to reproduce the real morphology of the valley. For this purpose, the photogrammetric survey of the Municipality of Benevento was used, and the 3D digital elevation model of the strait was generated.

The overall soil domain corresponds to a volume with a plan of 250m x 200m and a height of 67 m (Figure 8a). This soil domain, made of solid tetrahedral elements with the size respecting the Kuhlemeyer and Lysmer's (1973), contains the different soil layers described in section 3. All soil layers were assumed to have a linear elastic behavior, with the physical and mechanical properties listed in Table 1. To improve model accuracy, the f.e. mesh was made denser close to the bridge foundations. Solid elements with a tetrahedral mesh size of 0.3 m were also used for the abutments. In this first stage of the work, a perfect contact between the pier foundations and the surrounding soil was considered. The same constraints of the FB model at the boundaries between the soil and the bridge lateral cantilevers were adopted.



(a) (b)

Figure 8: Ground domain (a) and full model (b) in MIDAS FEA-NX

5 RESULTS

To investigate the influence of soil compliance on the dynamic response of the bridge in the linear field, only modal analyses were performed on the two numerical models described above, FB and SSI. The calibration of the numerical model on the experimental data is the first step to perform later on more complex analyses, such as the seismic analysis of the bridge. For this reason, the numerical results (num) obtained by modal analysis were compared to the experimental results (exp) obtained from the in-situ test [27], in terms of frequency discrepancy, D_f, through eq. (1) and modal assurance criterion MAC [30], defined in eq. (2).

$$D_f = \frac{\left(f_{num} - f_{exp}\right)}{f_{exp}} \tag{1}$$

$$MAC = \frac{\left(\{\varphi_{num}^T\}\cdot\{\varphi_{exp}\}\right)^2}{\left(\{\varphi_{num}^T\}\cdot\{\varphi_{exp}\}\right)\cdot\left(\{\varphi_{num}^T\}\cdot\{\varphi_{exp}\}\right)} \tag{2}$$

5.1 Modal Analysis for the FB model

The results of the modal analysis on the FB model in terms of fundamental frequencies and modal shapes are summarized in Figure 10 and Table 3. It is worth to note that a good match between the experimental and the numerical modal shapes (see the MAC values in Table 3) was obtained, especially for the first two vibration modes of the bridge. Higher frequency discrepancies of 40% and 14% were respectively obtained for the transverse bending mode (first mode) and the vertical torsional mode (third mode) while the value is acceptable for the vertical bending mode (second mode).

1st Mode 2nd Mode 3rd Mode

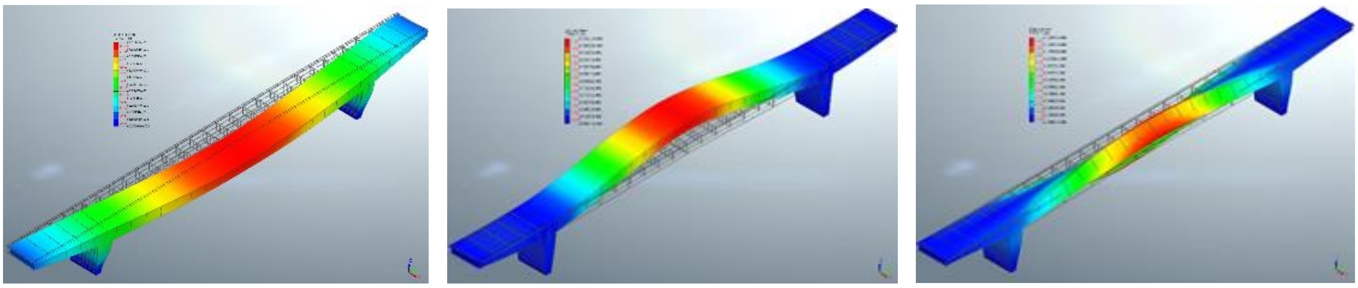
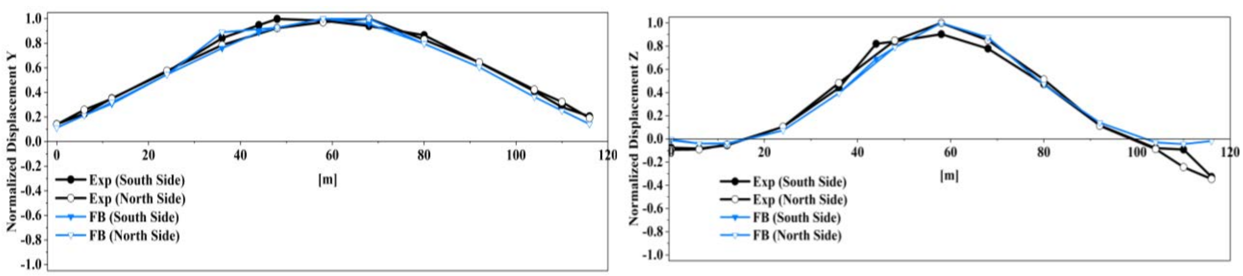


Figure 9: Numerical modal shapes of the FB model

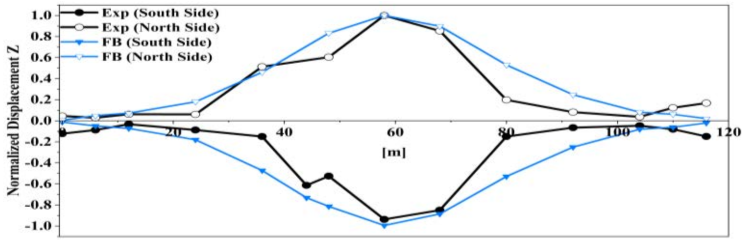
Mode N.	Mode Type	f_{exp} [Hz]	f_{num} [Hz]	D_f [%]	MAC [-]
1	Transverse bending mode	1.19	1.97	40	95
2	Vertical bending mode	2.12	2.22	5	94
3	Vertical torsional mode	5.64	6.61	14	88

Table 3: Comparison between experimental and numerical results for the FB model

Figure 10 shows the almost perfect overlapping between the numerical and experimental mode shapes along the two lanes of the bridge.



(a) Transverse bending mode (b) Vertical bending mode



(c) Vertical torsional mode

Figure 10: Comparison of the experimental and the numerical modal shapes: (a) transverse bending mode; (b) vertical bending mode; (c) vertical torsional mode

5.2 Modal Analysis for the SSI model

To identify the dynamic response of the compliant base model (SSI), a preliminary model containing only the soil below the bridge valley was firstly validated [31]. In short, the modal analysis procedure, typically used in the structural field, was also extended to the soil in order to identify the fundamental frequencies of the soil deposit and the corresponding modal shapes. For the soil, a more complex frequency response was predicted as more exhaustively described in [31].

Once the soil model was validated, the modal analysis was then carried out on the full model encompassing the bridge and the soil. For such an aim, fixed constraints along the base and free-field elements along the lateral boundaries of the soil domain were adopted.

Figures 11 and Table 4 show the results of the modal analysis on the SSI model in terms of fundamental frequencies and modal shapes. In Figure 12 the comparison between the experimental and the numerical results is also provided. Due to soil contribution, the SSI model gives lower eigenfrequencies (more flexible) than the fixed-base model. From Table 4, a closer agreement between the numerical and experimental data may be observed. Compared to the fixed base model, the SSI contribution appears stronger on the third mode of vibration.

1st Mode 2nd Mode 3rd Mode

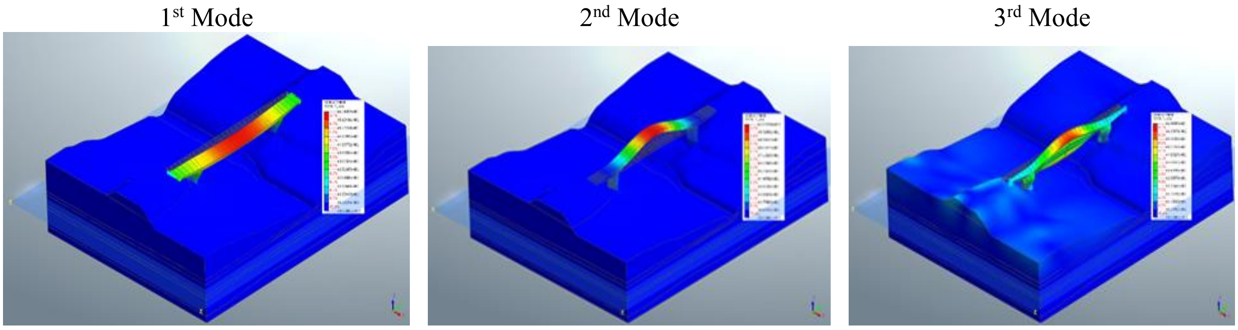


Figure 11: Numerical modal shapes for the SSI model

Mode Type	f_{exp}	Fixed-Based model (FB)			Full Model (SSI)		
	[Hz]	f_{num} [Hz]	D_f [%]	MAC [-]	f_{num} [Hz]	D_f [%]	MAC [-]
Transversal bending mode	1.18	1.97	40	95	1.56	24	99
Vertical bending mode	2.12	2.22	5	94	2.08	-2	96
Vertical torsional mode	5.69	6.61	14	88	6.02	5	92

Table 4 Comparison between experimental and numerical results for the FB and SSI models

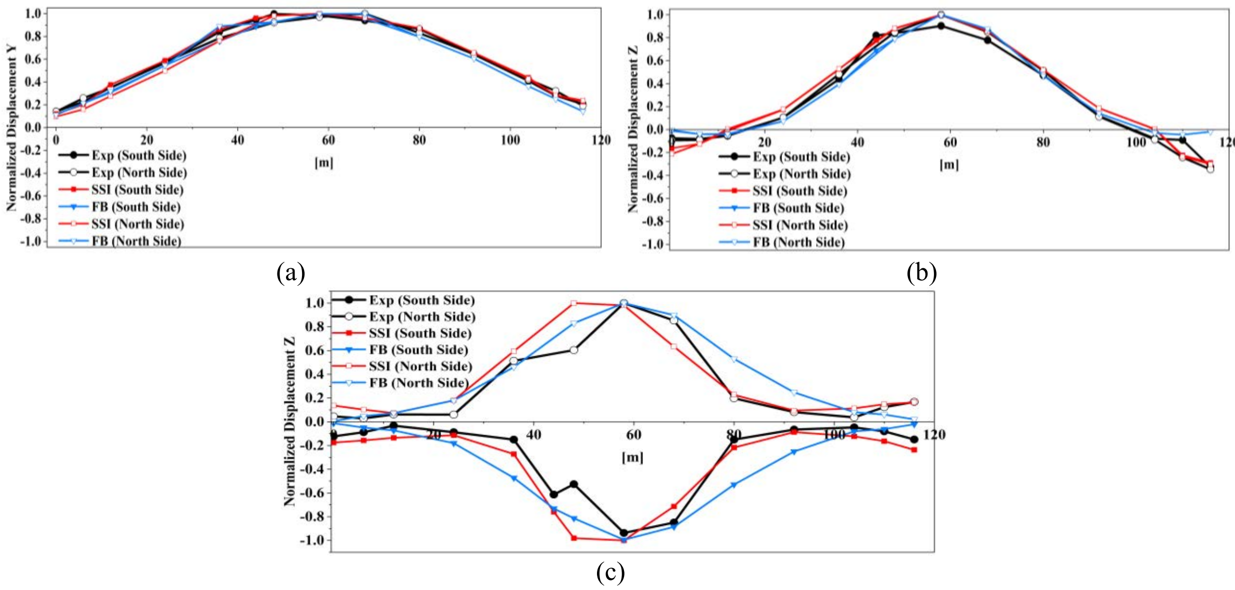


Figure 12: Comparison between experimental and numerical modal shapes for the SSI model: (a) transverse bending mode; (b) vertical bending mode; (c) vertical torsional mode

6 CONCLUDING REMARKS

This paper describes the first results of a more comprehensive numerical study aimed at evaluating the effect of soil-structure interaction on the dynamic behavior of a pre-stressed reinforced concrete bridge built in the 1950s. The objective of the study is the definition of an accurate model including the structure and the soil, which is propaedeutic to investigate the seismic performance of the bridge through advanced analyses. Based on the results of these preliminary analyses, the following main conclusions may be drawn:

- The fixed base model of the bridge allows modal shapes to be properly reproduced but the corresponding frequencies are significantly different from those obtained experimentally with values of frequency discrepancy (D_f) factor up to 40% .
- The contribution of soil compliance in the numerical model allows the best-fitting of both experimental frequencies and modal shapes of the bridge. The frequency discrepancy (D_f) is significantly reduced, especially for the last two modes. The values of the MAC also improved, especially for the higher-order torsional mode.

The outcomes of the performed study highlight the limits of the common practice of updating the fixed-base numerical model of a bridge to match the experimental results of environmental vibration tests by modifying only the mechanical properties of the construction materials. Accurate numerical models, which include also soil contribution, may turn to be essential to perform also advanced seismic analyses, to properly reproduce ground motion asynchronism in correspondence of the bridge piers and abutments.

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