On a Novel Seismic Design Approach for Integral Abutment Bridges Based on Nonlinear Static Analysis

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Abstract. This paper focuses on the seismic performance and design of a single-span integral abutment bridge (IAB), as a structural system characterised by a monolithic connection between deck and abutments. Although this is becoming a popular design solution due to its low maintenance requirements, there is still the need of developing robust design criteria for such structures under seismic conditions, mainly because of the complex soil-abutment-deck interaction. This study proposes an application of a novel design method for IABs to a reference case study inspired by a real integral bridge recently built in Italy. In the proposed method, the seismic capacity of the bridge is obtained through a nonlinear static analysis of the entire soil-structure system, in which the soil domain is perturbed by a distribution of equivalent forces aimed at reproducing the effects associated with the significant modes of the bridge. This approach is validated against the results of several dynamic analyses carried out on an advanced, full soil-structure model of the reference bridge implemented in OpenSees. Several seismic scenarios are taken into account, as well as the possibility to use an average response spectrum prescribed by technical provisions. This study demonstrates that the proposed design approach is able to reproduce quite satisfactorily the performance of the structure, in terms of maximum internal forces and displacements, with a very low computational demand.

**Keywords:** Integral abutment bridges · Seismic design · Nonlinear static analysis · OpenSees

1 Introduction

Integral abutment bridges (IABs) are structural systems characterised by an integral connection between deck and abutments (full transmission of forces and moments). This solution reduces to a minimum the maintenance of the bridge and the relative costs but can induce relevant internal stresses in the deck-abutment-embankment system, mainly due to thermal variations in the deck. A strategy aimed to minimise these internal stresses is to use abutment schemes characterised by a large deformability in the horizontal direction, for instance using a single row of piles as a foundation. Although numerous studies have been conducted on the static and dynamic behaviour of IABs, there is the

lack of standardized design guidelines around the world. In this regard, the present study is part of a wider research project on the dynamic response of integral abutment bridges aimed at devising simplified procedures readily applicable in seismic design. This paper illustrates a method based on the nonlinear static analysis of the entire soil-structure system, whose ability to predict the seismic performance of IABs is validated against the results of more demanding, nonlinear dynamic soil-structure analyses.

2 Reference Case Study

The reference case study is inspired by an integral single-span overpass recently built in Italy, along the A14 Adriatic highway, shown schematically in Fig. 1.a: the bridge deck is 50 m long and its cross section consists of a steel–concrete composite structure. The reinforced concrete abutments front wall presents a height of 8.0 m and width 2.2 m, and is supported by seven reinforced concrete piles, placed in a single row, with length and diameter of 20.0 m and 1.2 m, respectively.
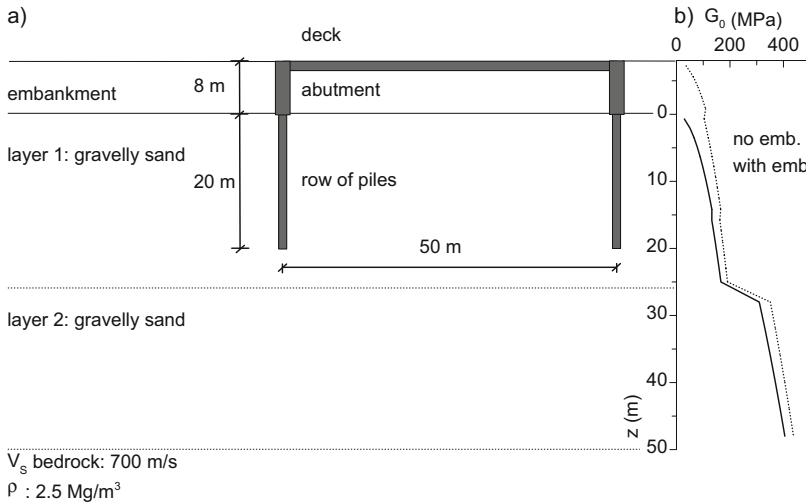

Fig. 1. (a) schematic longitudinal section of the case study; (b) profile of the small strain shear modulus G_0 with depth.

The idealised soil domain is constituted by two dry layers of gravelly sand with increasing stiffness and by a coarse-grained embankment. Figure 1.b shows the profile of the small-strain shear modulus with depth where the dashed line in the figure considers the increase in effective stresses produced by the embankment.

With the aim of investigating the dynamic response of the system, a numerical model was developed by Gallese [1] using the analysis framework OpenSees [2], while the mesh generation and the visualization of the results was performed through the pre/post-processor software GID. The focus is on the longitudinal response as the one significantly

affected by dynamic soil-structure interaction [3, 4], and therefore only half of the soil-bridge system was modelled, as shown in Fig. 2.a, taking advantage of the symmetry about the vertical plane. The entire soil domain was discretized by using SSPbrick eight-noded hexahedral elements [5], with mechanical behaviour described by the Pressure Dependent Multi-Yield model developed by Yang et al. [6]. The abutment wall and the deck were modelled as assemblies of elastic beams with properties proportional to their respective influence areas. A linearly elastic behaviour was assigned to the piles, abutment walls and deck while the soil-pile and the soil-abutment contact are modelled by means of rigid links and thin layers of solid elements with reduced strength respect to the surrounding soil.
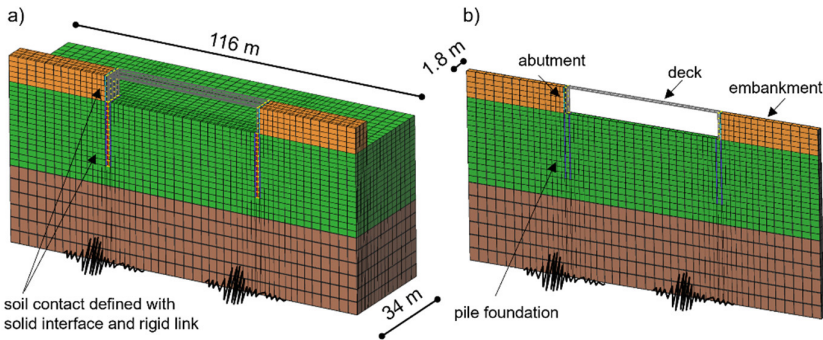
Fig. 2. (a) half of the 3D soil-bridge model used in the analysis and (b) equivalent 2D model developed in OpenSees.

An additional two-dimensional model was developed, as depicted in Fig. 2.b, where appropriate boundary conditions are employed to reproduce a plane strain deformation for the soil; plane stress conditions are instead considered for the structural elements. This 2D model considers a length of 1.8 m in the transverse, corresponding to the pile spacing, and incorporates a single pile, the abutments and the deck.

Particular attention was devoted to simulate the construction stages of the bridge. The procedure used herein, omitted for sake of brevity, follows the construction of the prototype, that was aimed at minimising the internal forces in the deck and particularly in the foundation piles under static conditions. The end of construction represents the starting point for the subsequent dynamic analyses as well as for the non-linear static analysis described in Sect. 5. The OpenSees parallel computing, performed by using the application OpenSeesSP [7], was employed to get reasonable computation times. Part of the analyses were carried out through the DesignSafe facility [8].

3   Seismic Input

The seismic hazard on stiff outcrop for the site of the bridge (Gatteo, Italy) is defined by elastic response spectra referring to soil type A, evaluated in accordance with Italian technical provisions (Italian Building Code 2018). In the present study, two seismic

scenarios were investigated: Damage Limit State (DLS), with a probability of exceedance PR = 63%, and No-Collapse Earthquake (NCE), with PR = 5%.

Several seismic records were selected through the web-based PEER ground motion database (https://ngawest2.berkeley.edu/) as compatible seismic actions with the seismic demand discussed above. Figure 3.a shows the lower and upper envelopes and the average elastic response spectra of the selected records, relative to the longitudinal direction of the bridge, for the DLS and the NCE, for which 9 and 7 records were considered, respectively. Figure 3.b refers instead to the ground motion at the top of the embankment, evaluated separately through a free field site response analysis on a soil column including the embankment.
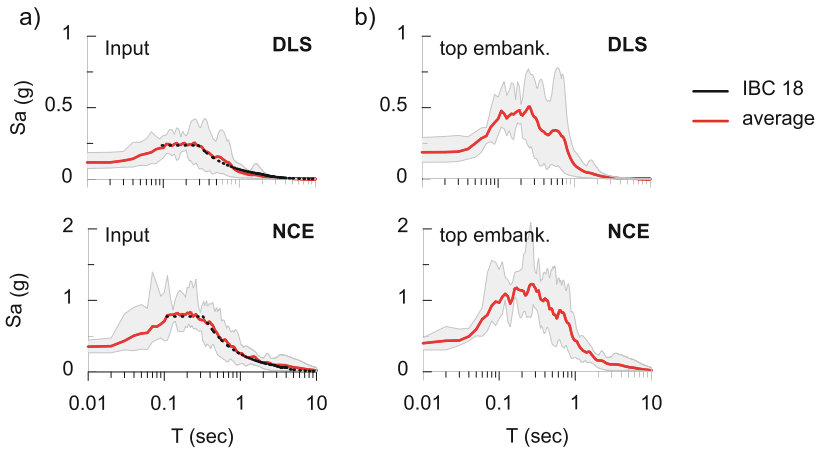
Fig. 3. Lower and upper envelopes (shadowed area) and average trend of the 5%-damped elastic spectra of the longitudinal components of the selected seismic records for the limit states DLS and NCE; (a) relative to the input motion (outcrop); (b) relative to the motion computed at the top of the embankment

4   Nonlinear Dynamic Analysis

After the construction stages, the reference soil-bridge models (Fig. 2) were subjected to the longitudinal component of the selected records. The seismic input was applied as a velocity time-history to the base of the soil domain through the interposition of viscous dampers to simulate a compliant bedrock, the latter reflecting the properties reported in Fig. 1. Periodic constraints were applied along the lateral boundaries, forcing the soil nodes placed on opposite sides at the same elevation to undergo the same displacements. Figure 4.a represents, for a selected seismic scenario belonging to the NCE, the time histories of the bending moment (for a unit deck width) in the deck-abutment node and pile head. As the 2D model was seen to provide similar results as the 3D model, it was taken as the reference for carrying out all the analyses discussed in the following, by virtue of its much higher computational efficiency.
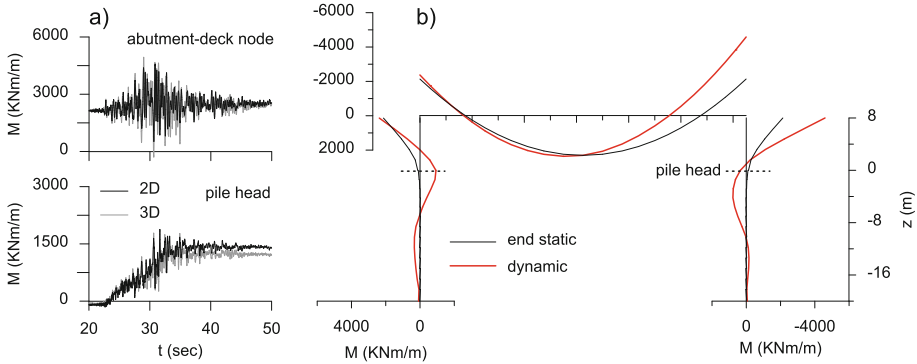
Fig. 4. (a) time histories of the bending moment at the right deck-abutment contact and right pile relative to a selected ground motion for the NCE; (b) bending moment in the structure at the end of static stage and in the instant when the maximum bending moment is reached on the right abutment.

Figure 4.b shows, for a selected ground motion belonging to the NCE, the bending moment in the structure in the instant when the maximum bending moment at the right deck-abutment contact is reached. The bending moment at the deck-abutment node elongates the top fibers of the deck and the internal fibers of the abutment. Conversely, at the top of the piles the bending moment elongates the external fibers (away from the embankment). With respect to the static conditions (black lines), increases of the bending moment are obtained at the deck-abutment contact and at the pile head, which constitute therefore the critical locations to consider for a direct assessment of the seismic performance.

5   Simplified method

As an efficient method readily applicable at the design stage, a simplified procedure is herein proposed, in which the Capacity Spectrum Method (CSM) [9] is used in conjunction with a nonlinear static analysis of the soil-bridge system to account for the nonlinear features of the mechanical behaviour. This method, commonly used for the seismic evaluation of structures, was recently extended to the case of geotechnical systems by Laguardia et al. [10]. To apply the method, two basic ingredients are needed, namely: the capacity curve of the system, and seismic demand, in the form of the acceleration-displacement elastic response spectrum (A-D response spectrum).

The capacity curve of the system is obtained by applying equivalent inertial forces to all nodes of the model. These forces are taken to be proportional to a seismic coefficient k_h, representing the ratio of the horizontal body forces to the unit weight of the soil. In the present work, the spatial distribution of k_h is aimed to reproduce the deformation patterns associated with the dominant vibration modes of the overall soil-bridge system that rule the dynamic response. To this end, a modal analysis was carried out on the 2D model referring to the small-strain elastic stiffness of the soil, that depends on the stress state. Figure 5.a shows the deformed shapes of the two dominant modes, the first and

the fourth, maximising the internal stresses in the reference structural points (abutment-deck connection and the pile head). In particular, the fourth mode involves mainly the participation of the embankment (relative participating mass, M_{emb}, reported in Fig. 5.a) which has a strong influence on the structural performance as also demonstrated in some recent works [3, 4, 11].
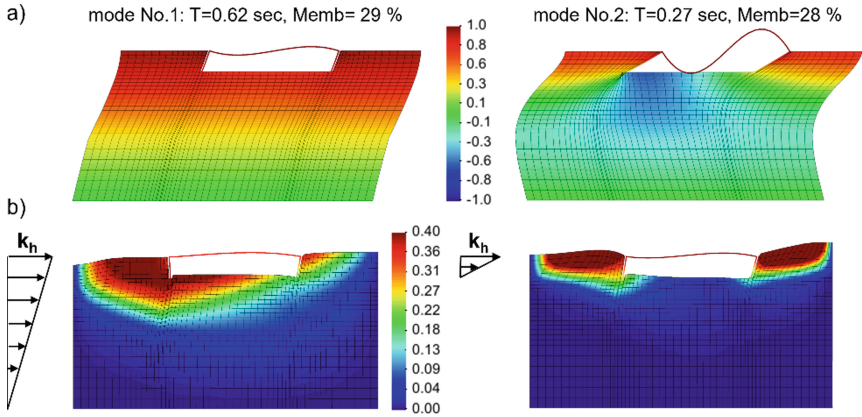
Fig. 5. (a) first and second modal shapes of the 2D model, with representation of the contours of the corresponding longitudinal displacements; (b) representation of the assumed profiles of the longitudinal seismic coefficient k_h and of the corresponding deformed shapes.

To reproduce the deformation patterns associated with these dominant modes, two linear profiles of k_h were assumed in the capacity analysis, as illustrated in Fig. 5.b: k_h varies linearly from the embankment top to a null value at the base of the soil domain and of the embankment, for the first and fourth mode, respectively. The resulting capacity curves of the soil-bridge system at hand are shown in Fig. 6.a, in which k_h and the horizontal displacement u refer to the top of the abutment.
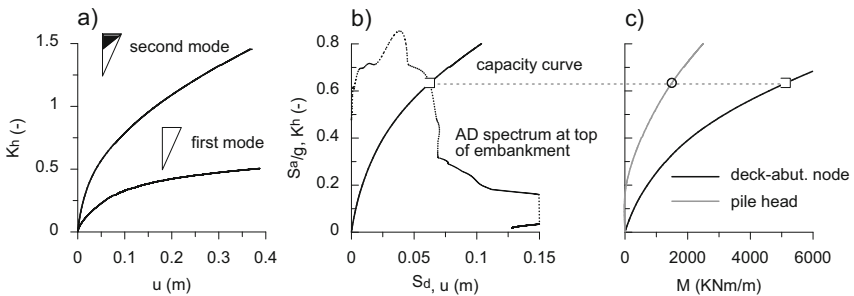

Fig. 6. (a) Capacity curves of the reference soil-structure system obtained in OpenSees; (b) evaluation of the performance point (intersection) with the proposed design method; (c) moment-seismic coefficient (k_h) curves and evaluation of the maximum forces in the structural elements.

The second ingredient of the method is the seismic demand defined by the A-D spectrum. In the proposed simplified method, a decoupled approach is employed in which the seismic demand derives from a one-dimensional site response analysis including the presence of the embankment. As in the original CSM, the equivalent damping ratio ξ of the A-D spectrum is found by an iterative procedure, i.e., by evaluating the damping ratio spectrum (using the Masing unloading–reloading rule) at the intersection of the capacity curve with the A-D, called *performance point*, and re-plotting the spectrum accordingly with the calculated damping. Once convergence on the value of ξ is attained, the actual performance point is located, as shown in Fig. 6.b−c: this provides the maximum acceleration, and the displacement of the abutment top. In turn, using the relationship between the relative bending moment and k_h obtained by the nonlinear static analysis (Fig. 6.c), the ordinate of the performance point can be used to determine the maximum internal forces in the structural elements of interest. To explore the validity of the method also when the seismic demand is provided by a technical-code spectrum, the same procedure was be applied using directly the average spectra of Fig. 3. In this case, the iteration on the damping ratio required a recalculation of the elastic response for all the ground motions, to evaluate the updated average spectrum.

6   Results and Concluding Remarks

The proposed design method is here applied to predict the seismic performance of the reference bridge of Fig. 1. To this end, Fig. 7 shows a systematic comparison between the results obtained with the proposed method (non-linear static analysis, NLSA) and with the full dynamic analysis (DYN) for the two limit states considered. Since the proposed method returns an estimate of the maximum effects induced by the seismic action, the results of the dynamic analyses refer only to the variations computed with respect to the static condition.
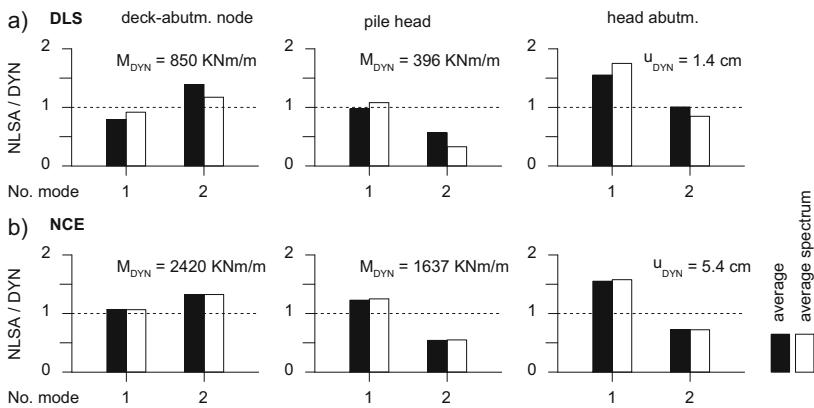
Fig. 7. Results of the proposed design method for the DLS (a) and NCE (b): ratios of the maximum bending moment at the deck-abutment node, pile head, and of the maximum displacement of the deck.

Three output quantities are considered: the maximum bending moments at deck-abutment node, and at the pile head, and the maximum deck displacement. For each output quantity the average value obtained with the dynamic analyses is reported above each plot. The application of the procedure considering the average spectrum (Fig. 3) is defined by the term "average spectrum", while the average of the results of the procedure applied to the individual ground motions is indicated as "average". It is evident that the two different ways to characterise the seismic demand do not influence significantly the average results yielded by the proposed method. Considering the simplicity and rapidity of the NLSA, the comparison with the results of the dynamic analyses is quite satisfactory. It appears that the internal forces at the deck-abutment node may be calculated using the capacity curve associated with the second mode, while the curve associated to the first mode may be used to evaluate the internal forces in the pile foundation. The first mode provides systematically greater displacements of the deck, while a limited underestimation is provided by the second mode solution.

These results demonstrate that the proposed design method may be efficiently used for a direct assessment of the seismic performance of single-span integral bridges. This requires the sole application of nonlinear static analysis methodologies, as a robust framework that, if properly validated, generalized and systematized, may be also extended for the seismic design of similar soil-structure systems.

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