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# SEISMIC BEHAVIOUR OF ISOLATED RC BRIDGES SUBJECTED TO ASYNCHRONOUS SEISMIC INPUT

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**Abstract.** *The seismic actions used to design long structures, as bridges, should be attentively evaluated, since, due to seismic wave propagation through soil, at distant foundation points signals are different. Signal frequency content varies from point to point for at least two reasons: soil-wave interaction; wave traveling time from one point to the other. Asynchronous seismic waves produce distortions at the bridge foundations which are usually not considered in design practice. In this paper, the responses of two RC bridges, one with deck supported by traditional bearing and one by Lead Rubber Bearings (isolators), subjected to asynchronous or synchronous signals were studied. These signals were generated at the surface starting from the EW components of the main shock recorded at two recording stations (AQA, AQV) near L'Aquila city (Italy) on 4-06-2009. The soil distortions which produce maximum stresses on deck or on piers were evaluated for the two bridges (non-isolated and isolated) in case of synchronous and non-synchronous excitations. The first results are discussed to understand the effects of asynchronous excitation on the responses of the two bridges.*

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## 1 INTRODUCTION

The seismic actions at distant foundation points of long structures are not evaluated properly in many international structural design codes and synchronous actions are usually considered during the design practice. However, the seismic waves, recorded at different points during the propagation of the seismic signal through soil, show differences which may be great in case of long structures. These differences are due to the change of the signal frequencies content for effect of soil-wave interaction (reflection, filtering, amplification, etc.). There is also a different arrival time of the wave at each point as wave propagation has a finite velocity.

Designers of long structures should take in account these differences to define with attention the asynchronous design actions which can be more detrimental than the synchronous ones [1-12].

In a few design codes, soil distortions are introduced to be applied at the foundation points of long structure to consider the effects of non-synchronism [13-14]. The resulting responses of the structure after the application of these distortions are combined with the inertial response of the structure. The inertial response can be obtained for example by means of the response spectrum method or by time history analysis. However, the definition of the soil distortions able to catch the more detrimental effects of non-synchronous actions on structures is still an open issue and further research efforts are necessary to improve this design approach.

The present study want to investigate: (i) when the effects of the asynchronous actions are detrimental for the seismic response of a structure; (ii) determine the soil distortions which should be applied on a structure to consider properly the asynchronous action effects during the structural design.

Case studies were taken according to ANAS (Italian agency for roads) as typical recent design for a two-span bridge. The selected bridge results an critical element in a network of structures and infrastructures after an earthquake [15-17] and was designed considering the modern design code philosophy [13, 14, 18-21] with deck placed on rubber isolators. Two bridge models based on the selected bridge were considered in this study: (i) bridge deck supported by traditional bearings (non-isolated bridge) and (ii) bridge deck supported by Lead Rubber Bearings (isolated bridge).

Two distinct numerical models were built using the software SAP 2000 [22] to perform Fast Linear and Nonlinear Analyses applying vertical loads on the bridge deck and asynchronous or synchronous displacement histories at the bridge foundation points.

These displacement histories were obtained elaborating the accelerograms generated at surface starting from the EW accelerometric components of the main shock recorded at two recording stations (AQA, AQV) near L’Aquila city (Italy) on 4-06-2009. The generation procedure [6, 7, 23-37] used to obtain the input displacement histories at the bridge foundation points was discussed in Lavorato et al. [11]. This procedure was implemented in MATLAB [38] as a framework of functions named GAS 2.0 - Generation of Asynchronous Signals -.

The seismic wave propagates along the direction x between the stations AQA and AQV and the generated displacement histories move the foundation points in the direction y perpendicular to the bridge deck (Figure 1). The three foundation points of each bridge (non-isolated and isolated) were distant 50 m each other and were placed in three different positions along the wave propagation direction x: (i) the position 123 near the station AQA; (ii) the position 789 near the station AQV; (iii) the position 456 near the middle point between the two stations (Figure 1).

Different arrays of asynchronous seismic signals were generated considering the three bridge locations starting from the same inputs. Each generation uses a different random extraction to considered statistical variability of the generated signals [11].

First considerations about the effects of non-synchronous actions on bridges deck deformations are given comparing the results of asynchronous analyses with the ones of synchronous analyses. Finally, the asynchronous soil distortions, which produce maximum stresses on deck or piers, were evaluated to give indications about the proper sets of soil distortions for asynchronous bridge design.

## 2 CASES OF STUDY: NON-ISOLATED AND ISOLATED BRIDGES

A case of study was taken according to ANAS (Italian agency for roads) typical recent design for a two-span bridge to evaluate the effects of asynchronous seismic motions on bridge. This bridge was designed in compliance with the Italian structural design code [14] and has a continuous bridge deck built by means of a mixed steel-concrete system with a very modest curved form. The deck metal structure is made up of three welded beams with varying height (from 1.7 m to 2.2 m) distant 3.5 m one from the other (Figure 2). These beams are connected to each other by steel crosspieces spaced 6.25 m.

The concrete slab of the deck has a thickness of 25 cm and a width varying from 12.00 m and 12.55 m. The metal structure is connected to the concrete slab by means of steel connectors. There is one pier only with height of 13.0 m and rectangular cross section with dimensions 6 x 1.43 m (Figure 2). The materials used to design the bridge were: concrete C32/40 for the deck slab, steel S355 for the deck beams and concrete C28/35 for the pier. Elastic frame elements were used to model the pier and the deck of each bridge (§4) and so the steel reinforcements of the pier and deck are not described here.

The bridge deck is supported by linear rubber isolators placed at the abutments and on the top of the pier. However, two alternative bridge deck support systems were considered in this study: (i) a deck supports system realized by traditional bearings without isolation properties; (ii) a deck supports system realized by Lead Rubber Bearings (LRB). The LRBs have stiffness 1.69 kN/mm, yield strength 225 kN, post yield ratio 0.06 and maximum displacement of 350 mm.

The bridge deck was loaded with the weight of the structural elements and the one of the non-structural elements ($G_2$ = 46 kN/m) which were distributed over the entire length of the bridge (Figure 2).

## 3 ASYNCHRONOUS AND SYNCHRONOUS ACTIONS ON THE BRIDGES

The displacement histories, calculated by means of the software Seismosignal [39] starting from the accelerograms generated in [11], were selected to represent the seismic actions applied on the two selected bridges (non-isolated and isolated) to perform asynchronous and synchronous analyses (§4). These signals were obtained starting from the EW accelerometric components of the main shock recorded at two recording stations (AQA, AQV) near L'Aquila city (Italy) on 4-06-2009 [11]. The soil motion below each foundation is along the direction y in Figure 1; this direction is perpendicular to the bridge deck and so the bridge behavior was studied in this direction only (§4).

The two bridges were placed in three different positions along the wave propagation direction (x, Figure 1): (i) the position 123 near the station AQA; (ii) the position 789 near the station AQV; (iii) the position 456 near the middle point between the two stations (Figure 1). In each position, the displacement histories change as the seismic wave propagates and changes its characteristics [6, 7,11, 23-37]. These positions were chosen to consider accelerometric signals at the bridge foundations which have differences due to: (i) the distance among the generation points and (ii) the local site effects due to the soil characteristics below each generation point.

The position 456 was selected to discuss the first results of the numerical synchronous and asynchronous analyses presented in this paper (§4). The two bridges (non-isolated and isolated) placed in this position have the foundation point 4 on the soil U-AQA and the foundation points 5 and 6 on the soil U-AQV; the two soils were characterized by two different power spectra as inputs for the generation procedure [11]. The signal generated at the point 4 is characterized mainly by the power spectrum of the input signal at AQA whereas the signals generated at points 5 and 6 are also characterized by the power spectrum of the input signal at AQV. The two input power spectra are different and so there are greater relative displacements among the generation points respect to the other bridge positions [11].

The selected sets of displacement histories at the foundations of the two bridges at position 456 (Figure 1) are: (i) three arrays of three non-synchronous displacement time history (one set for analysis) generated at points 4, 5 and 6 (at pier and at abutments foundations, Figure 1); (ii) three arrays of three synchronous displacement time histories (one set for analysis). Each synchronous set is composed starting from the asynchronous sets assuming the displacement history of the pier foundation at point 5 also in correspondence of the bridge abutments (points 4 and 6, Figure 1).

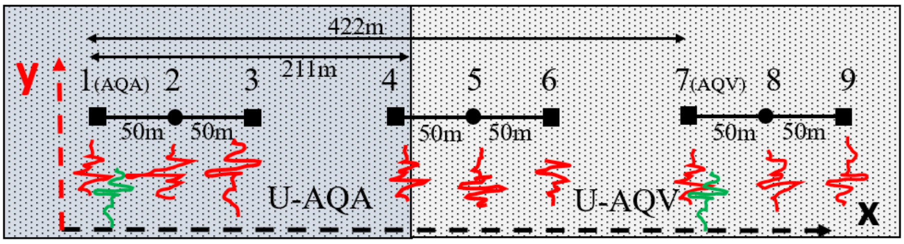


Figure 1 Three alternative positions (123, 456 and 789) of each bridge (no isolated and isolated) along the seismic wave propagation direction (x); U-AQA and U-AQV are the two different soils crossed by the seismic wave [11]; The generated displacement histories are indicated by red lines whereas the generation input signals recorded at point 1 and 7 (recording stations AQA and AQV) are indicated by green lines

## 4 NUMERICAL ANALYSES

The two bridges (non-isolated and isolated) described in §2 were modelled in SAP 2000 [22] to perform asynchronous and synchronous analyses applying the vertical load and the displacement histories described in §2 and §3. During the bridge modelling phase, some simplifying hypotheses, considered insignificant for the purposes of the study, were assumed: the viaduct was considered straight, the beam-slab system was modelled by an equivalent section, the abutments were modelled as simple supports (with isolators in the case of the isolated bridge), the soil-structure interaction at the bridge foundations was neglected.

The model of the deck section was made using the SAP 2000 integrated section designer (Figure 2), which enables the construction of an equivalent section with concrete slab and steel beams. Four sections were defined to consider the variability of the deck sections (§2).

The bridge deck was divided into 16 segments of the same length (6.25 m) and the pier into 10 segments of 1.15 m. The pier cap was modelled by a frame element and rigid links simulate the connection between the barycenter of the equivalent deck sections and the pier cap (Figure 2). The non-structural elements vertical loads described in §2 and the self-weight of the bridge elements, calculated automatically by SAP2000 starting from the material properties and the section geometries, were applied on the bridge deck of the two bridge models.

The bridge masses were calculated by SAP 2000 starting from the self-weight of the bridge elements and were distributed among different structural nodes. A damping value equal to 2% was assumed for the non-isolated bridge model. The same damping value and the damping due to the Lead Rubber Bearings were assumed for the isolated bridge model.

Elastic frame elements were used to model the pier and the deck of each bridge (§4) whereas the Lead Rubber Bearings of the isolated bridge were modelled as nonlinear links with the nonlinear properties defines in §2. The non-isolated bridge model was elastic whereas the isolated bridge model had local nonlinearity due to the nonlinear link behavior.

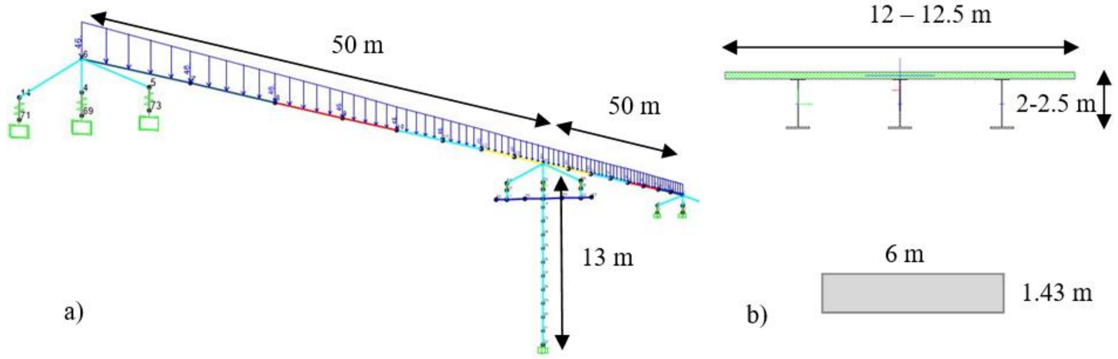


Figure 2 Isolated Bridge numerical model in SAP2000 [22]: a) lateral view of the bridge stick model; b) deck and pier sections; The no-isolated bridge model is without the nonlinear link on the top pier and on the abutments

The first results of asynchronous and synchronous analyses for the two bridges (non-isolated and isolated) at position 456 (Figure 1) are given in term of soil distortion and corresponding bridge deck configuration. The results presented here were evaluated at specific time instants, namely: (i) t1 when the soil distortion maximizes the distance of one foundation point from the line drawn between the other two foundation points; (ii) t2 when the pier drift is maximum.

The soil distortion at time t1 is one of the most detrimental for the bridge deck deformation. However further investigations are needed to draw simplified conclusions.

The pier drift was evaluated as the difference between the displacement of the node placed in correspondence of the center of gravity of the cap beam on the pier top and the displacement of the base node of the pier.

The displacements of soil and deck points were evaluated respect to the soil and deck position before the arrival of the seismic excitation (not deformed bridge, continuous thick black line in Figures 3-6). The seismic excitation is perpendicular to the bridge deck longitudinal axis

The soil distortions (soil456) and the bridge deck configurations (p456) for the non-isolated bridge at the location 456 at time t1 and at time t2 are given in Figure 3 and Figure 4 respectively considering the three asynchronous (-ns) and the three synchronous (-s) arrays (-g1, -g2 and -g3) of displacement histories generated in [11].

The soil distortions (soil456) and the bridge deck configurations (p456) for the isolated bridge at the location 456 at time t1 and at time t2 are given in Figure 5 and Figure 6 respectively considering the three asynchronous (-ns) and the three synchronous (-s) arrays (-g1, -g2 and -g3) of displacement histories generated in [11].

These first results were compared and discussed in the conclusions (§5).

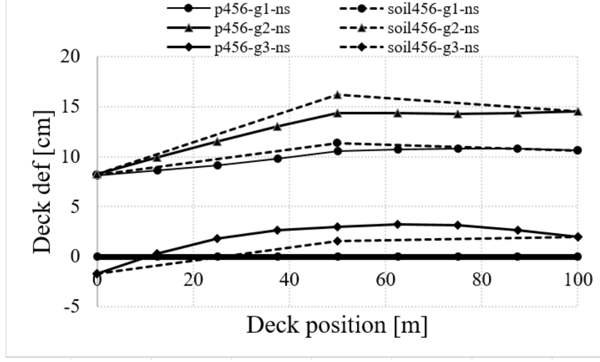
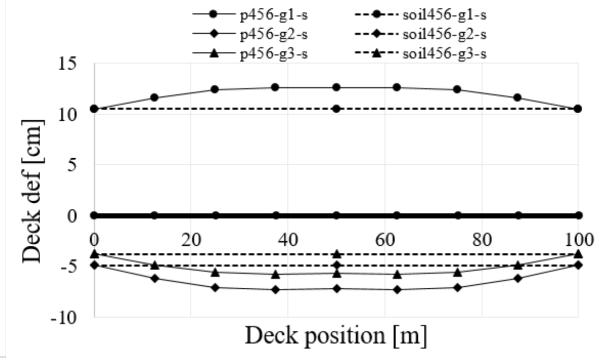
| Non-isolated asynchronous excitation | Non-isolated synchronous excitation |
|---|---|
|  |  |

Figure 3 Non-isolated bridge: soil distortion (soil456, dashed line) when the distance of one foundation point respect to the line drawn between the other two foundation points is maximum and corresponding bridge deck configuration (p456, continuous line) for three asynchronous sets (soil456-g1-ns, soil456-g2-ns and soil456-g3-ns; p456-g1-ns, p456-g2-ns and p456-g3-ns) and three synchronous sets (soil456-g1-s, soil456-g2-s and soil456-g3-s; p456-g1-s, p456-g2-s and p456-g3-s) of displacement histories at the foundations for the bridge position 456; "deck position" is the position of a node of the bridge deck; "deck def." is the transversal deck displacement

| Non-isolated asynchronous excitation | Non-isolated synchronous excitation |
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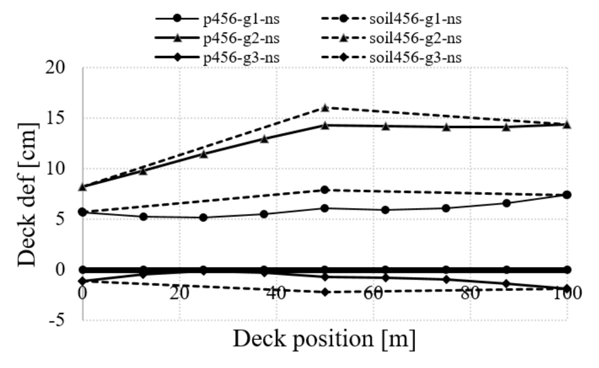
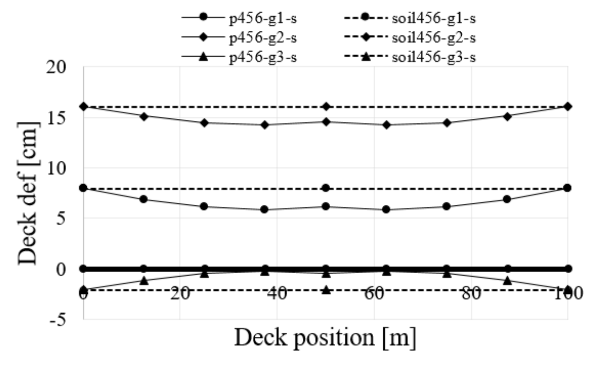
|  |  |

Figure 4 Non-isolated bridge: soil distortion (soil456, dashed line) when the pier drift is maximum and corresponding bridge deck configuration (p456, continuous line) for three asynchronous sets (soil456-g1-ns, soil456-g2-ns and soil456-g3-ns; p456-g1-ns, p456-g2-ns and p456-g3-ns) and three synchronous sets (soil456-g1-s, soil456-g2-s and soil456-g3-s; p456-g1-s, p456-g2-s and p456-g3-s) of displacement histories at the foundations for the bridge position 456; "deck position" is the position of a node of the bridge deck; "deck def." is the transversal deck displacement

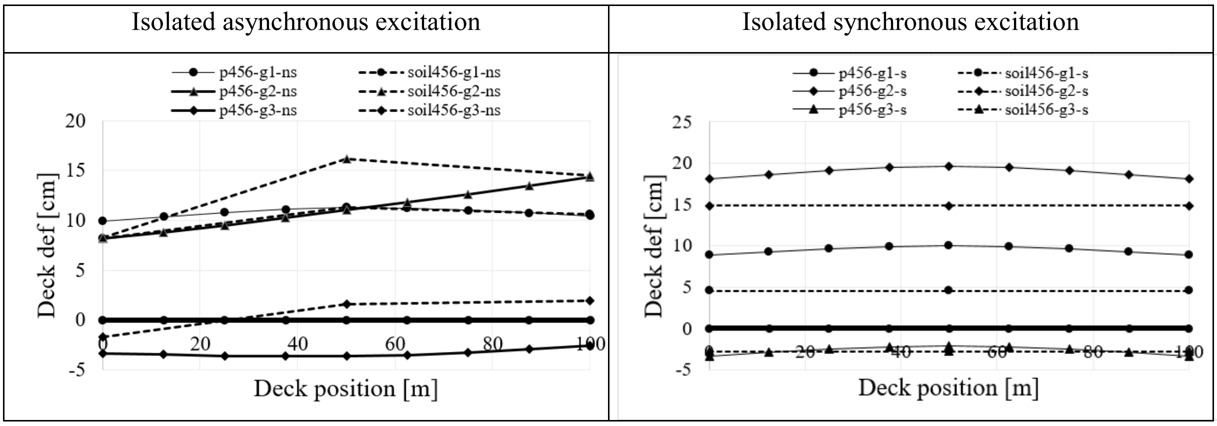


Figure 5 Isolated bridge: soil distortion (soil456, dashed line) when the distance of one foundation point respect to the line drawn between the other two foundation points is maximum and corresponding bridge deck configuration (p456, continuous line) for three asynchronous sets (soil456-g1-ns, soil456-g2-ns and soil456-g3-ns; p456-g1-ns, p456-g2-ns and p456-g3-ns) and three synchronous sets (soil456-g1-s, soil456-g2-s and soil456-g3-s; p456-g1-s, p456-g2-s and p456-g3-s) of displacement histories at the foundations for the bridge position 456; "deck position" is the position of a node of the bridge deck; "deck def." is the transversal deck displacement

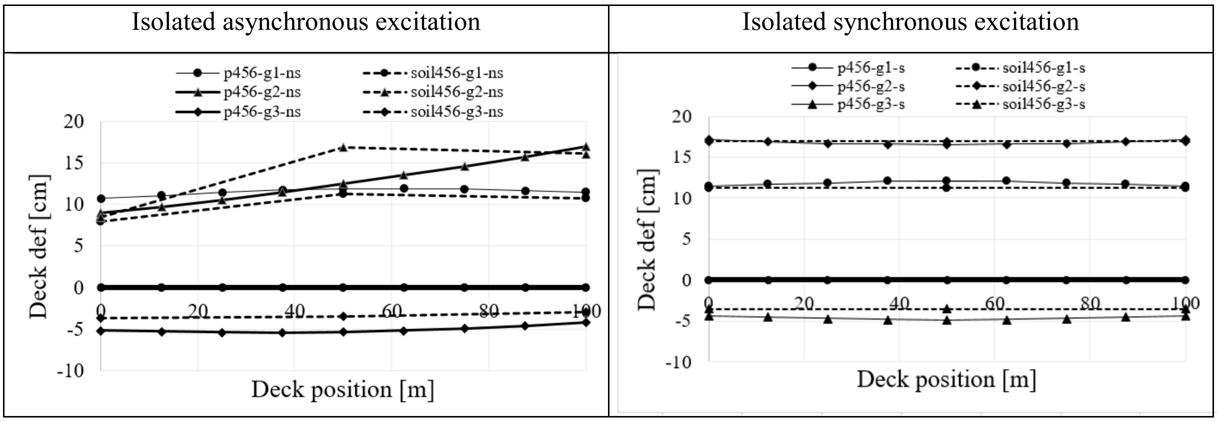


Figure 6 Isolated bridge: soil distortion (soil456, dashed line) when the pier drift is maximum and corresponding bridge deck configuration (p456, continuous line) for three asynchronous sets (soil456-g1-ns, soil456-g2-ns and soil456-g3-ns; p456-g1-ns, p456-g2-ns and p456-g3-ns) and three synchronous sets (soil456-g1-s, soil456-g2-s and soil456-g3-s; p456-g1-s, p456-g2-s and p456-g3-s) of displacement histories at the foundations for the bridge position 456; "deck position" is the position of a node of the bridge deck; "deck def." is the transversal deck displacement

## 5 CONCLUSIONS

The responses of a non-isolated and an isolated RC bridge were studied applying asynchronous or synchronous displacement histories at the bridge foundation points. Case studies were taken according to ANAS (Italian agency for roads) typical recent design for a two-span bridge. Two bridge configurations have been considered: (i) bridge deck supported by traditional bearings (non-isolated bridge) and (ii) bridge deck supported by Lead Rubber Bearings (isolated bridge).

The asynchronous excitations were obtained by the generation procedure proposed by some of the authors in [11, 36, 37] starting from the recordings measured at the two stations AQA and AQV during the main shock at Aterno Valley near L'Aquila City (Italy) on 6-9-2009.

First results of asynchronous and synchronous analyses for the two bridges (non-isolated and isolated) at position 456 (Figure 1) are given in term of soil distortion and corresponding bridge deck deformation.

The results presented here were evaluated at specific time instants, namely: (i) t1 when the soil distortion maximizes the distance of one foundation point from the line drawn between the other two foundation points; (ii) t2 when the pier drift is maximum. The soil distortion at time t1 is a reasonable proxy for the most detrimental bridge deck configuration.

The following preliminary conclusions can be drawn:

- The deck deformations of the isolated bridge are smaller than the ones of the non-isolated bridge for each analysis. This is an expected result, since imposed deformations at the foundation points are concentrated at the isolators. The bridge deck has modest deformations.
- The bridge deck of the isolated bridge showed large "rigid rotation" (the deck has modest deformations) in case of asynchronous excitation for effect of the different excitations at the foundation points. The design of the seismic joints should consider this rotation that is not observed in case of synchronous excitation on the same bridge.
- For the non-isolated bridge, the soil distortion at time t1 can produce, in the case of asynchronous actions, deck deformation larger than the ones obtained in case of synchronous actions for the deck points far from the abutments. The relative displacements between deck point in correspondence of the pier and the deck points in correspondence of the abutments are similar in case of synchronous and asynchronous excitations (Figure 3).
- For the isolated bridge, the soil distortion at time t1 produces, in case of asynchronous actions, deck deformation very similar to the ones obtained in case of synchronous analyses (Figure 5).
- The same considerations described in case of soil distortion at time t1 can be done in case of the soil distortion at time t2. The only difference is that when the maximum pier drift is realized there is a local deformation of the bridge deck portion near the pier that can be in the opposite direction respect to the ones on the other deck parts. This local deformation imposes different local state of stresses which should be evaluated during the bridge design

These analyses will be performed considering also different bridge geometries and earthquake inputs. The new selected cases of study will include also some existing bridges repaired and retrofitted after strong seismic damage by some new rapid techniques [40-55]. The seismic behavior of bridges subjected to asynchronous excitation will be defined also considering near fault earthquake [56, 57].

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