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Asynchronous earthquake strong motion and RC bridges response

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HIGHLIGHTS

- A new procedure to generate asynchronous seismic signals is presented.
- Real signal characteristics permit to consider soil-wave interaction phenomena.
- The worse excitations are studied for a real bridge also with seismic isolators.
- Bridges responses are discussed for synchronous and asynchronous actions.

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ABSTRACT

The dynamic response of long structures (e.g., bridges) is sensitive to the spatial variability of strong ground motion (asynchronous motion). Ground motion differences increase from point to point with increasing foundation distance. This latter is due to two physical phenomena: soil-wave interaction, that causes the loss of coherence and local amplification; wave traveling with finite velocity, that causes signals time lag. This ground motion variability produces a different structural demand compared to the synchronous one, which is the only one considered by designers in the majority of cases. A few codes consider this type of actions, therefore further research efforts are necessary. In this study, asynchronous ground motions are generated by means of a new generation procedure implemented in the software GAS 2.0 using as input the simultaneous strong motion records from the April 6th, 2009, L'Aquila (Italy) at the seismic stations AQA and AQV, located in the Aterno River valley. These records are used to calibrate the generation model and to produce sets of asynchronous earthquake sampling. The asynchronous earthquake sets are applied on a typical highway reinforced concrete bridge to study its dynamic response considering two different configurations: non-isolated with traditional supports and isolated bridge with lead rubber bearings. The bridge is placed in two positions along the wave propagation direction: a position near one recording station and a position between the two stations to consider local soil effects. The response parameters investigated are the maximum relative displacements of soil and deck. The results show that there is an

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important variation of relative displacement along the direction of wave propagation due to asynchronous motion with effects that designer should consider for the structural details design of isolated and non-isolated bridges.

1. Introduction

Asynchronous seismic motions can lead to high demand for structures such as bridges and large dams. Seismic waves, recorded at different points along the propagation path of the seismic signal through the soil, can present large differences due to many factors, such as the change in frequency content and the effects of interactions between soil and waves. These interactions include reflection, filtering and amplification, which are complex soil-wave phenomena that are traditionally taken into account via a loss of coherence (Der Kiureghian, 1996; Oliveira et al., 1991; Santa-Cruz et al., 2000). Moreover, given the wave propagation velocity, there is also a different wave arrival time at each point of the surface. The differences among signals increase with the distance between the recording points, therefore larger effects are observed for extended structures. The issue of the effects of asynchronous motion on bridges was addressed by many authors, which highlighted the fact that the traditional seismic bridge design, which does not consider the spatial variability of the strong ground motion, can bring to an unsafe design (Burdette and Elnashai, 2008; Carnevale et al., 2010, 2012b; Lupoi et al., 2005; Monti et al., 1994, 1996; Nuti et al., 2004; Sextos et al., 2003; Shinozuka et al., 2000; Tzanetos et al., 2000).

The majority of seismic codes and design guidelines only take into account the effects of asynchronous motion indirectly. Some design codes introduced simplified methods (soil static differential displacements) to consider the problem of spatial variability of strong ground motion (Eurocode 8, 1998; Ministero Infrastrutture, 2008) as highlighted in some previous work made by Nuti and Vanzi (2005) and Sexto and Kappos (2009). In these methods, the static response is then combined with the dynamic structural response. However, further research effort is necessary both for the static analysis and for its combination with dynamic effects.

The specific case of the effects of asynchronous motion on isolated bridges was addressed by some authors: Zanardo et al. (2002) and Bi et al. (2011) carried out a parametrical study to investigate the effects of pounding. Ates et al. (2006) studied the response of bridge isolated with friction pendulum systems, taking into account the incoherence, wave-passage and site-response effects. Lupoi (2009) followed a similar approach, adopting a statistical approach in order to consider the uncertainties in the variability of ground motion and on the bridge configuration.

The present work has two main goals: (i) the generation of asynchronous ground motions sets making different assumptions and the comparison of the results obtained; (ii) the evaluation of the effects of the generated ground motions on the seismic response of a simple bridge structure.

In the first part of the work, a procedure which allows to generate asynchronous seismic signals at the ground surface is presented. The method considers both the signal frequencies content variation and the time lag. For the sake of comparison, also the synchronous motion signals are used.

In the second part of the paper, the generated signals (asynchronous and synchronous) are used as the input to evaluate the response of a bridge in two different cases (isolated and non-isolated), and for two different positions of the selected bridge depending on the characteristics of the soil underlying the structure.

The numerical asynchronous signals propagation procedure described in Nuti and Vanzi (2004, 2005) and Carnevale et al. (2012a, c) was improved (Lavorato et al., 2017a, b) and implemented in Matlab (MATLAB, 2018). The computer program has been named GAS 2.0 - generation of asynchronous signals.

The signal frequency content at each point is calculated assuming a normal distribution of the signal amplitudes. Mean and variance of normal distributions are obtained from point to point taking into account amplitude distribution conditional to the sampling at previous points. The frequency content of the input signals and the coherence function that describes how the signals frequency content changes from point to point considering local site effects and frequency content variation (Harichandran and Vanmarcke, 1986; Vanmarcke et al., 1993).

The procedure has been applied using real strong motion records from recent earthquakes. More precisely, the EW components of the mainshock of the 2009 L'Aquila (Italy) earthquake recorded at two seismic stations were considered as generation inputs. The generated signals were compared with the characteristics of the input recordings (power spectra, acceleration response spectra, displacement response spectra). Finally, the displacement histories of the generated signals were obtained using Seismosignal software (Seismosoft, 2016) to evaluate the soil relative displacements.

The signals thus obtained were applied to a model of a real bridge for two configurations: isolated and non-isolated. The bridge was designed based on a database of the Italian Authority for Roads Management (Anas). A bridge geometry representative of a widespread bridge typology was first chosen, and it was redesigned with a seismically isolated deck, considering modern design code philosophy (Fiore et al., 2012, 2013; Fiore and Marano, 2018; Trentadue et al., 2014; Vanzi et al., 2015; Quaranta et al., 2014). A second redesign was then made, using traditional bearings (i.e., non-isolated bridge).

Therefore, two configurations based on the selected structure were considered in this study: (i) one with traditional deck supports (non-isolated bridge) and (ii) one with deck supported by lead rubber bearings (isolated bridge). For both cases, the numerical model was built using a commercial software (SAP, 2000 Computers and Structures, 2017).

Ongoing work regards the evaluation of the seismic response of existing bridges repaired and retrofitted after strong seismic damage (Albanesi et al., 2008, 2009; Lavorato and Nuti, 2010, 2011, 2015; Lavorato et al., 2010, 2015, 2017d; Imperatore et al., 2012a, 2012b, 2013; Zhou et al., 2014, 2015a, 2015b). The seismic behavior of bridges subjected to asynchronous excitation will be defined also considering near fault earthquakes (Ma et al., 2017a, b) and evaluating the seismic input by means of a seismic hazard assessment (Fiorentino et al., 2015). These analyses will be performed considering different bridge geometries and earthquake inputs, with a focus on innovative bridges (Huang et al., 2014). Further analyses will be performed including incremental dynamic pushover analyses for bridges (Bergami et al., 2015; Bergami and Nuti, 2013a, 2013b, 2015).

2. Generation of asynchronous signals

2.1. *Description of the model*

The earthquakes happened in Italy in the last years have highlighted the vulnerability of the Italian building stock. Recently, the seismic events of August and October 2016 caused many victims and heavy damage to structures (Di Ludovico et al., 2017; Fiorentino et al., 2017). It is well known that bridges are critical elements in a network of structures and infrastructures after an earthquake (Nuti et al., 2004, 2010; Rasulo et al., 2004) and therefore deserve special design consideration.

Asynchronous signals have been sampled for the area in the Aterno River valley, near L'Aquila (Italy). Two seismic stations of the Italian Accelerometric Network located in the valley were chosen: AQA and AQV (Luzi et al., 2016), lying on two different soil profiles U-AQA and U-AQV (Fig. 1), respectively. Bridge positions (123, 456 and 789) along the seismic wave propagation direction (x); U-AQA and U-AQV are the two different soils crossed by the seismic wave; the generated signals are indicated by red lines whereas the generation input signals recorded at points 1 and 7 (locations of the recording stations AQA and AQV) are indicated by green lines; section (top) and plan (center); example of generation of asynchronous signals in terms of displacements (bottom). The soil units U-AQA and U-AQV have been classified as soil B according to EC8 classification based on the value of the shear wave velocity $V_{S,30}$. In fact, the value of $V_{S,30}$ for AQA and AQV is 549 and 474 m/s, respectively. The complete shear wave velocity profile was reported in previous literature. Even if the soil profiles of U-AQA and U-AQV are composed by different materials, the global nonlinear behavior of soil can be modeled with a 1D equivalent analysis (Lavorato et al., 2017c).

Earthquake samples have been derived with reference to the geometrical configuration of the bridge presented in the next

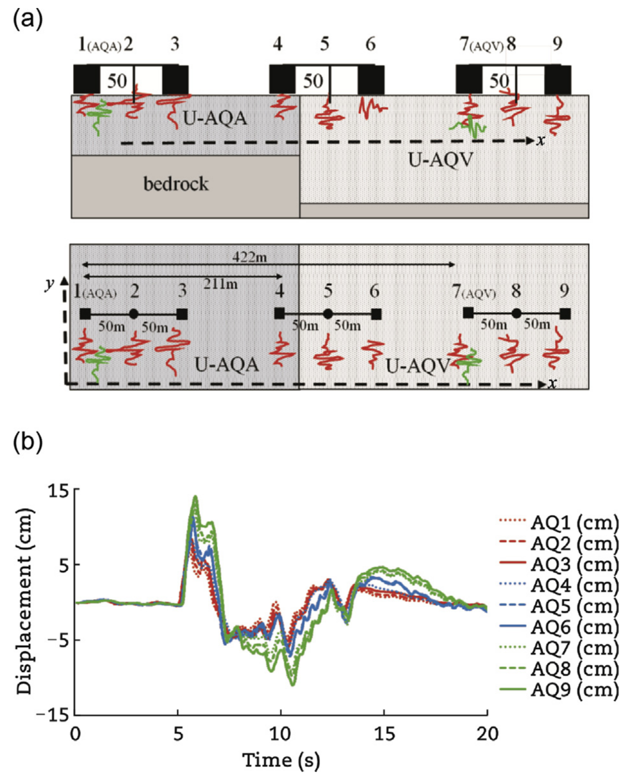

Fig. 1 – Samples in Aterno River Valley. (a) Two seismic stations. (b) Asynchronous signals-generation g1.

sections. The three foundation points of the bridge have a mutual distance of 50 m. For the sake of comparison, they were assumed being placed in three different positions along the line that connects AQA and AQV. The three positions are: (i) 123 near the station AQA (all foundation points on soil U-AQA); (ii) 456 near the middle point between AQA and AQV (one foundation point on soil U-AQA and two on soil U-AQV); (iii) 789 near the station AQV (all foundation points on soil U-AQV).

The software GAS 2.0 -generation of asynchronous signals- was used to obtain the asynchronous ground motion at the ground surface based on the generation procedure described in Nuti and Vanzi (2004, 2005). The inputs of the procedure are natural accelerograms recorded by seismic stations which are located at a certain distance in a given site and the soil characteristics of the soils underlying the seismic stations. The outputs are the asynchronous signals at points of a random field defined by the user (Lavorato et al., 2017c).

The EW accelerometric components of the mainshock recorded by the seismic stations AQA and AQV, extracted from the European strong motion database (Luzi et al., 2016) on June 4, 2009 were used as inputs for the procedure. Geometric assumptions for the generation are: (i) earthquakes propagate along the x direction; accelerations are in y direction; (ii) recording stations AQA and AQV are placed on the x direction (points 1 and 7 correspond to the positions of the stations AQA and AQV respectively); (iii) nine generation points 1–9 (three foundation points for three bridge positions) are placed on the soil U-AQA or on the soil U-AQV; (iv) signals recorded at points 1–4 include the local site effect (wave–soil interaction) of U-AQA; (vi)

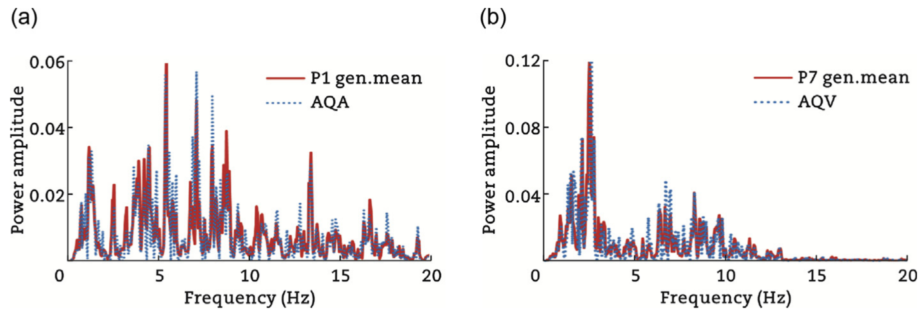

Fig. 2 – Characteristics of the generated signals at points 1 and 7. (a) Point 1. (b) Point 7.

signals recorded at points 5–9 include the local site effects (wave–soil interaction) of U-AQV.

Local site effects lead to surface amplification of the original bedrock signal. The degree of amplification depends on the soil parameters. The amplifications of the bedrock signal in the soils U-AQA and U-AQV are different: this is evident from the comparison between the power spectra of the EW components recorded at AQA and AQV stations, respectively on U-AQA and U-AQV soil respectively (Fig. 1). The frequency content variation from point to point is modelled with the Vanmarcke et al. model (Vanmarcke and Fenton, 1991; Vanmarcke et al., 1993). The model parameters are calibrated using the AQA and AQV recordings, assuming shear wave velocity $V_{S,30}$ = 580 m/s, according to the Italian code indications for soil B. The different arrival time of the wave front at the different generation points was calculated assuming that the seismic wave propagates along the x direction from 1 to 9 moving with an apparent speed, V_{app} = 2000 m/s. Five earthquake sets, each formed by nine asynchronous accelerometric signals (generation points from 1 to 9, Fig. 1), were generated. Each set is a sampling of the signals which can be recorded at the generation points during the propagations of the selected seismic event along the x direction. An example of asynchronous generated signals is given in Fig. 1(b).

2.2. Asynchronous signals analysis

It is possible to compare the generated signals in terms of: (i) power spectra; (ii) acceleration response spectra; (iii) displacement response spectra. As a first step, the characteristics of the generated signals at points 1 and 7 (stations AQA and AQV), were compared with the available records at the same points (input of the generation procedure) to check the reliability of the procedure. This is shown in Fig. 2. Power spectra from generation of asynchronous signals: comparison between the mean curve of the power spectra (P1 gen. mean and P7 gen. mean; red lines) obtained considering five generated accelerometric signals and the power spectrum curve of the recorded accelerogram (AQA and AQV; black dotted line) at points 1 (left) and 7 (right). The power spectra were evaluated using Seismosignal (Seismosoft, 2016) using Eq. (1).

$$\text{PowerAmplitude} = \text{FourierAmplitude}^2/(\text{Pi}^*\text{duration}^*R_{ms}\text{Acc}^2) \tag{1}$$

where the duration is the time length of the record and R_{ms}Acc is the root-mean-square of the acceleration.

It is possible to observe that there is a general good agreement between generated and recorded signals. In particular, for point 7 (Fig. 1) corresponding to station AQV there is a better agreement between power spectra while for point 1 (station AQA) there are some local peaks in the generated signal power spectrum which differ from the recorded one.

Fig. 3 shows the acceleration response spectra of the input signals (black lines) at points 1 and 7, (stations AQA and AQV), are compared with the mean, plus and minus one standard deviation, of the acceleration response spectra obtained for the five generated signals. Acceleration response spectra from generations of asynchronous signals: comparison among the mean, the mean plus and mean minus standard deviation (P1 gen. mean, P1 gen. mean + Std, P1 gen. mean-Std, P7 gen. mean, P7 gen. mean + Std, P7 gen. mean-Std) curves of the acceleration response spectra obtained

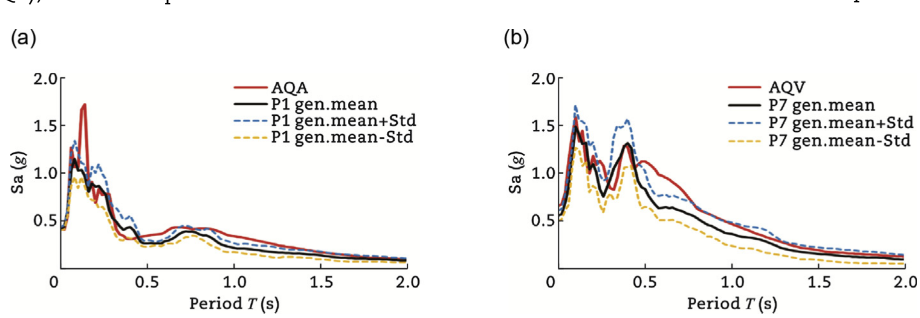

Fig. 3 – Acceleration response spectra of the input signals at poin1 and point 7. Sa: spectural acceleration. (a) Point 1. (b) Point 7.

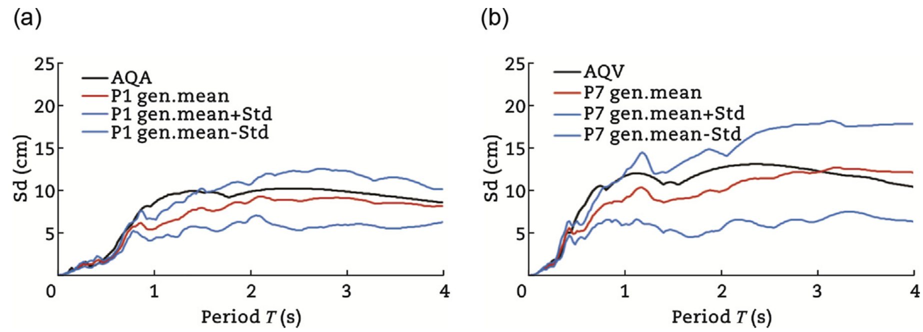

Fig. 4 – Displacement response spectra of the input signals at point 1 and point 7. Sd: spectural displacement. (a) Point 1. (b) Point 7.

considering five generated accelerometric signals and the acceleration response spectra curves of the recorded accelerogram (AQA and AQV, black lines) at points 1 (left) and 7 (right). Also in this case the agreement between the generated and recorded signals is good. It can be observed that the recorded signal at AQA shows a peak at $T = 0.15$ s, which is about 30% higher than the mean of generated spectra. This difference is due to the numerical procedure used in generating the asynchronous signals. However, the vibration period of the bridge is around 1 s, therefore there is no effect on the bridge behavior. It is possible to highlight a similar effect in the AQV.

Fig. 4 shows the displacement response spectra of the input signals (black dotted line) at points 1 and 7 (stations AQA and AQV) are similarly compared with the displacement response spectra obtained for the five generated signals at the same points. Displacement response spectra from generation of asynchronous signals: comparison among the mean, the mean plus and mean minus standard deviation (P1 gen. mean, P1 gen. mean + Std, P1 gen. mean-Std, P7 gen. mean, P7 gen. mean + Std, P7 gen. mean-Std; red lines) curves of the displacement response spectra obtained considering five generated accelerometric signals and the displacement response spectra curves of the recorded accelerogram (AQA and AQV, black dotted line) at points 1 (left) and 7 (right). Good agreement is observable also in this case. The displacement histories are used as input excitations on the bridge foundations to evaluate the bridges response for the case of asynchronous excitation.

3. Case study: non-isolated and isolated bridge

A continuous deck bridge, selected from the ANAS (Italian National Agency for Highways) database was chosen as the case study. The choice of this particular bridge was made because this is a widespread bridge typology for Italian and European highway bridges, thus the results obtained in this study can be extended to a large number of similar structures. The bridge has two 50 m spans, resulting in a total length of 100 m. It was redesigned in compliance with the Italian structural design code. The deck is a mixed steel-concrete system, and it is composed of three welded beams with different heights (from 1.7 m to 2.2 m), with 3.5 m spacing (Fig. 5). The beams are connected by steel crosspieces.

The deck thickness is 250 mm; width varies from 12.00 to 12.5 m. There is only a central pier with height of 13.0 m and a rectangular cross section with dimensions 6 m × 1.4 m (Fig. 5). The materials used to design the bridge are: concrete C32/40 ($f_{ck} = 32$ MPa) for the deck slab, steel S355 ($f_{yk} = 355$ MPa) for the deck beams and concrete C28/35 ($f_{ck} = 28$ MPa) for the pier, where f_{ck} and f_{yk} are the characteristic values of the

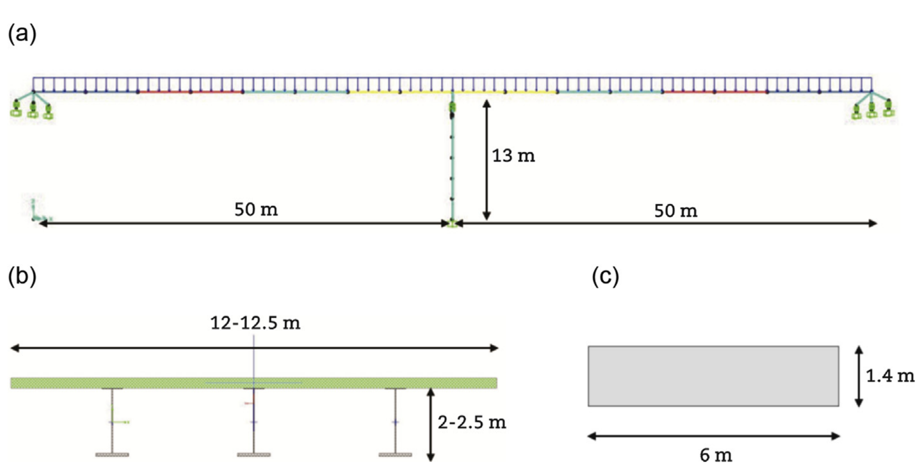

Fig. 5 – Bridge numerical model in SAP 2000. (a) Lateral view of the bridge stick model. (b) Deck. (c) Pier section.

cylindrical strength of concrete and the yield strength of steel, respectively. Elastic frame elements were used to model the pier and the deck of each bridge, therefore the steel reinforcements of the pier and deck are not described here.

In the paper at hand, two types of design have been considered: (i) deck supports system realized with traditional elastomeric bearings without isolation properties; (ii) deck supports system realized with lead rubber bearings (LRB). LRB's have stiffness of 1.69 kN/mm, yield strength 225 kN, post yield ratio 0.06 and maximum displacement of 350 mm. The bridge deck is loaded with the weight of the structural elements and of the non-structural elements (G2 = 46 kN/m), distributed over the entire length of the bridge.

4. Numerical analyses

The bridge (isolated and non-isolated) was first modelled in SAP 2000 (Computer and Structures, SAP, 2000, 2011) to perform asynchronous and synchronous analyses applying the static vertical loads (dead load plus non-structural permanent loads).

Then, the displacement histories defined in the previous sections were applied. In the modelling phase, simplifying assumptions were made: the viaduct was considered straight, the beam-slab system was modelled by an equivalent section, abutments were modelled as simple supports (with isolators in the case of the isolated bridge), soil-structure interaction at the bridge foundations was neglected.

The model of the deck section was made using the SAP 2000 integrated section designer, 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.

As depicted in Fig. 5, the bridge deck was divided into 16 segments with 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 to simulate the connection between the center of mass of the equivalent deck sections and the pier cap. The vertical loads of non-structural elements described in previous sections and the self-weight of the bridge elements, calculated automatically by SAP 2000 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 with SAP 2000 starting from the self-weight of the bridge elements and were distributed on the structural nodes. A damping value equal to 2% was assumed for the non-isolated bridge model, following common literature assumptions (Clough and Penzien, 1993). The same value plus the damping due to the lead rubber bearings was assumed for the isolated bridge model (Fiore et al., 2016; Liu et al. 2015).

Elastic frame elements were used to model the pier and the deck of each bridge. Lead rubber bearings of the isolated bridge were modelled as non-linear links on the top of piers and abutments. The non-isolated bridge model is elastic whereas the isolated bridge model had local nonlinearities due to the non-linear link behavior.

Results of asynchronous and synchronous analyses for the two configurations (non-isolated and isolated) considering the soil profile at positions 123 and 456 are given in term of soil displacements and corresponding bridge deck configuration. The results presented here are evaluated at specific time instants, namely: (i) t_1: time instant corresponding to the maximum distance of one foundation point from the line drawn between the other two foundation points; (ii) t_2: time instant corresponding to the maximum pier drift. Soil displacement at time t_1 is very demanding for the bridge deck stress. Seismic excitation is perpendicular to the bridge deck longitudinal axis.

Soil displacement and bridge deck configurations for the non-isolated case at instants t_1 and t_2 are given in Figs. 6–7 and Figs. 8–9 for positions 123 and 456, respectively, considering three asynchronous and three synchronous sets (-g1, -g2 and -g3) of displacement histories. Dg1, Dg2, Dg3 are deck displacements for three different signals generations g1, g2 and g3. Sg1, Sg2, Sg3 are soil displacements for three different signals generations g1, g2 and g3. Deck def is transversal deck displacement.

The relative displacements (soil 456) and bridge deck configurations (position 456) for the isolated case at instants t_1 and t_2 are given in Figs. 10–11 and Figs. 12–13 for positions 123 and 456, respectively, considering the three asynchronous (-ns) and the three synchronous (-s) arrays (-g1, -g2 and -g3) of displacement histories generated.

The first observation can be done on soil relative displacements both for the isolated and non-isolated cases, within the synchronous case, by definition, displacements are

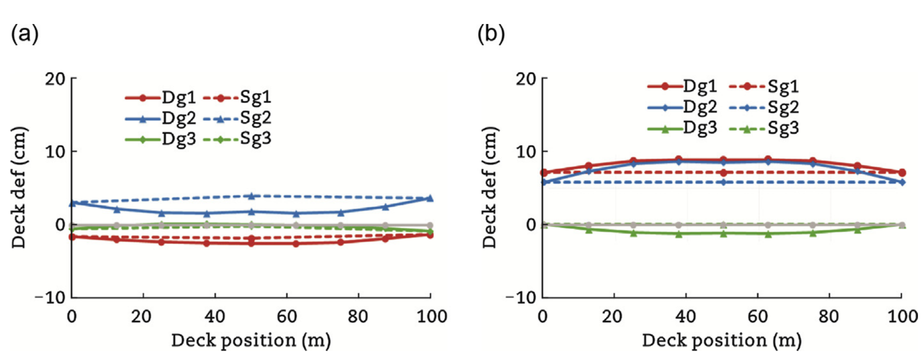

Fig. 6 – Non-isolated bridge, position 123. Soil (dashed lines) and deck relative displacements (solid lines) at time instant t_1. (a) Asychronous motion. (b) Synchronous motion.

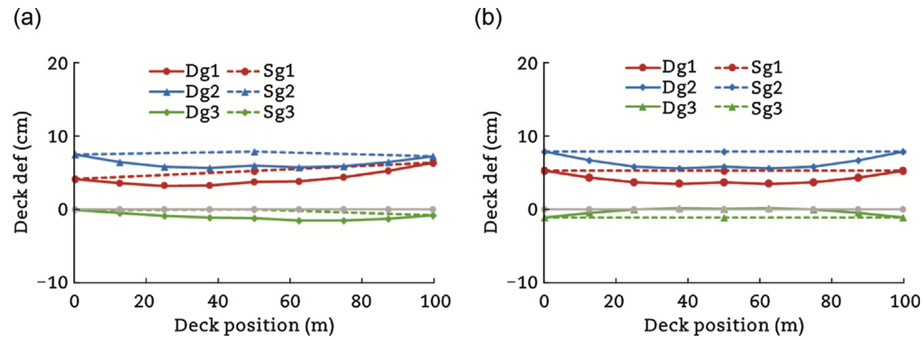

Fig. 7 – Non-isolated bridge, position 123. Soil (dashed lines) and deck relative displacements (solid lines) at time instant t_2. (a) Asychronous motion. (b) Synchronous motion.

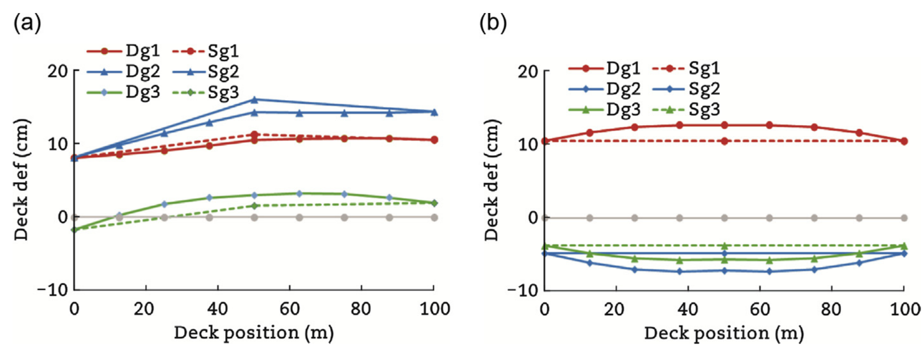

Fig. 8 – Non-isolated bridge, position 456. Soil (dashed lines) and deck relative displacements (solid lines) at time instant t_1. (a) Asychronous motion. (b) Synchronous motion.

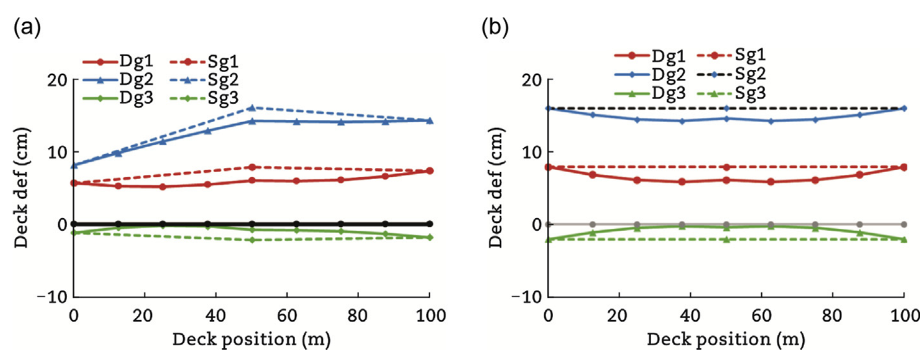

Fig. 9 – Non-isolated bridge, position 456. Soil (dashed lines) and deck relative displacements (solid lines) at time instant t_2. (a) Asychronous motion. (b) Synchronous motion.

the same at each foundation point, thus resulting in a rigid translation of the bridge deck. Conversely, in the case of asynchronous motion the soil show relative displacements which can be very different from one generation to another.

By comparing the relative displacements obtained for positions 123 and 456 in the isolated and non-isolated for asynchronous motion, it is worth noting that for position 123 the relative displacements obtained are smaller than those obtained for position 456. This difference is due to the fact that in position 123 configurations all the piers lie on the same ground and thus the asynchronous motion mainly depends on the power spectrum of the recorded signal in AQA (Lavorato et al., 2017c), while in position 456 two piers lie on a different soil with respect to the third one, therefore the generated motion at the different piers is influenced both by the power spectra of both AQA and AQV, thus resulting in a higher variability of motion.

Regarding the deformations of the bridge deck, for all the analyses the deformations obtained for the isolated bridge are smaller than those of the non-isolated bridge. This is an expected result, since imposed deformations at the foundation points are concentrated at the isolators. Moreover, it can be pointed out that the deck of the isolated bridge has modest deformations.

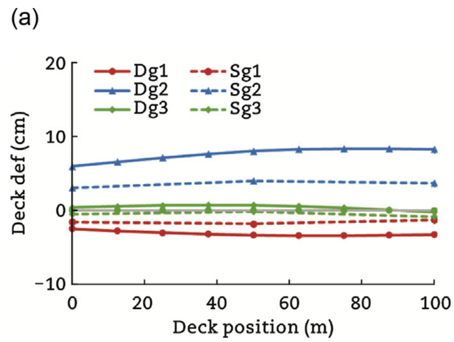

Fig. 10 – Isolated bridge, position 123. Soil (dashed lines) and deck relative displacements (solid lines) at time instant t_1. (a) Asychronous motion. (b) Synchronous motion.

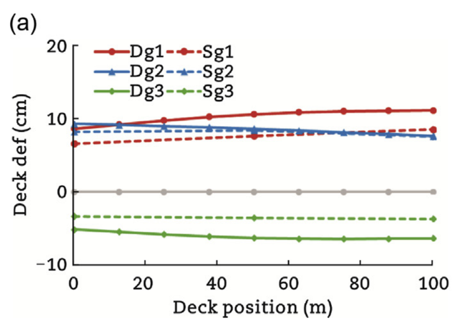

Fig. 11 – Isolated bridge, position 123. Soil (dashed lines) and deck relative displacements (solid lines) at time instant t_2. (a) Asychronous motion. (b) Synchronous motion.

Large "rigid rotation" is observed in the deck of the isolated bridge in case of asynchronous excitation as a result 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.

In the case of non-isolated bridge, the relative displacement at time t_1 can produce, in the case of asynchronous motion, deck deformations larger than the ones obtained in case of synchronous actions for the central node of the bridge (i.e., far from the abutments). It can be also highlighted that the relative displacements between the central node and the abutments are similar both for asynchronous and synchronous motion (Fig. 6).

In the case of the isolated bridge, the relative displacement at time t_1 produces, in case of asynchronous motion, deck deformations which are very similar to the ones obtained in case of synchronous motions (Fig. 8).

The same considerations described for the case of relative displacement at time t_1 can be done in the case of the relative displacement at time t_2 (Figs. 7 and 9). The only difference is that when the maximum pier drift occurs there is a local deformation of the portion of the bridge deck which is close to the pier. This local deformation can occur in the opposite direction of the deformations at the abutments. This local deformation imposes different local state of stresses which should be evaluated during the bridge design.

It is worth noting that the soil displacements in the isolated and non-isolated cases are different, and this is due to the fact that the larger relative displacements of the structure happen at different time instants for the two different configurations.

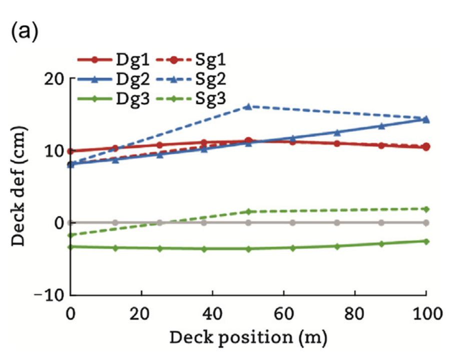

Fig. 12 – Isolated bridge, position 456. Soil (dashed lines) and deck relative displacements (solid lines) at time instant t_1. (a) Asychronous motion. (b) Synchronous motion.

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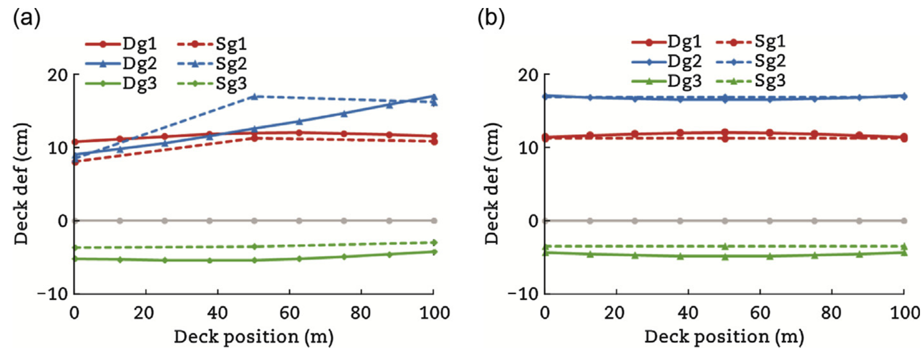

Fig. 13 – Isolated bridge, position 456. Soil (dashed lines) and deck relative displacements (solid lines) at time instant t_2. (a) Asychronous motion. (b) Synchronous motion.

5. Conclusions

This paper deals with the response of isolated and non-isolated continuous bridges subjected to asynchronous ground motions. A generation model that describes the signal variation from point to point by a coherence function calibrated on the base of the input data, the input signals power density function (to include the local site effects) and a time translation of the signal (to consider the wave velocity) is described. The strong motion signals recorded at AQA and AQV seismic stations during the mainshock of L'Aquila earthquake happened on 04-06-2009 were used as inputs to generate five sets of asynchronous earthquake signals at the ground surface by a MATLAB software (GAS 2.0) that implements the generation procedure. A continuous RC bridge, which represents a wide-spread bridge typology, is selected as case of study considering the bridge deck supported by traditional bearings or isolators. The sets of generated signals are applied on the two bridge configurations considering two possible bridge positions: position 123 which is close to the first input recording point (AQA); position (456) between the two recording points (AQA and AQV).

The results obtained for the two bridge configurations (isolated, non-isolated) and the two positions (123, 456) are in terms of: (1) deck deformation corresponding to the maximum relative soil displacement; (2) soil relative displacement corresponding to maximum pier drift. These two conditions are usually considered more detrimental for the bridge response.

The first conditions results showed that:

- As expected, the synchronous motion does not produce significant relative displacements at the bottom of piers and abutments. It is worth noting that in the asynchronous case, for position 456 the relative displacements can have significant values (the maximum pier displacement can be the double of the abutment displacement).
- For position 456 in case of synchronous motion, in the isolated case the relative displacements between pier and abutments can reach 10%, while for the non-isolated case they can reach 20%.
- The asynchronous motions for the isolated case at position 456 produce soil relative displacement of the pier which is double in comparison with the abutment, while for position 123 the pier-abutment relative displacement is only 20%. This is due to the fact that while in 123 all the piers lie on the same soil profile, in position 456 the piers lie on different soil profiles thus increasing the variability of motion. In fact, due to its location, the generated signals at position 123 are affected strongly by the recorded signal at AQA and by soil U-AQA, while the signals at position 456 are both affected by AQA and AQV and their soil conditions U-AQA and U-AQV. Soil local effects can produce relevant effects and thus they are important to define relative soil displacement and corresponding bridge deformations.
- Regarding the deformations of the bridge deck, it can be observed that for all the analyses the deformations obtained for the isolated case are smaller than those of the non-isolated case, because in the first case the deformations are concentrated in the isolators. For the isolated bridge in the case of asynchronous motion a large rotation is obtained (differently from the synchronous case) which must be considered in the design of seismic joints and isolators.
- In the non-isolated bridge, for the asynchronous motion the curvature of the bridge deck remains constant, while for the asynchronous motion there are local peaks of curvature, which can bring to local failures. According to these results, particular care must be devoted to the design of the construction details of the bridge deck section where the maximum local curvature of deck is attained; seismic joints and bearings considering the appropriate constraint condition (e.g. if a significant rotation is observed at the abutments, the bearings should allow rotations).
- In the isolated bridge, the asynchronous displacements are absorbed by the isolators and there is not a local peak of curvature of the bridge deck. However, there is still the need to consider properly the effects of the deck rotations to better understand how to design the seismic joints and the seismic isolators.

The second conditions results showed that:

- The soil relative displacements for the non-isolated case are very similar to the ones obtained for the isolated case.
- The difference of the displacement of the deck point at the pier location with respect to the pier foundation point calculated for each generation are very similar in the non-

isolated case but a great difference can arise for the isolated case (it is 3 times the one observed for the no isolated bridge for the G1 generation). For that reason, attention should be given to the design of isolator and pier in isolated case.

- The bridge deck deformation in correspondence of the pier in the non-isolated case shows local abrupt changing of the tangent to the bridge deck deformed shape and so attention should be given in the design detail for this part of deck. This is not evident in case of soil relative displacement that produces the maximum soil deformation.

Different soil relative displacement should be investigated to maximize the bridge deformation and so stresses in case of no synchronous action for isolated or not isolated case.

Conflicts of interest

The authors do not have any conflict of interest with other entities or researchers.

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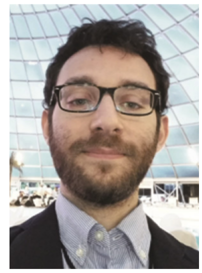

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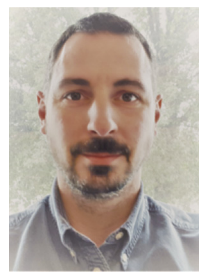

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