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SURFACE GENERATION OF ASYNCHRONOUS SEISMIC SIGNALS FOR THE SEISMIC RESPONSE ANALYSIS OF BRIDGES

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Abstract. *The seismic signals, recorded at different surface points during the propagation of the seismic waves through soil, show differences due to the soil-wave interaction. The seismic design actions should be evaluated properly in case of distant foundation points as these differences can be great. In this paper, asynchronous seismic signals are generated at surface starting from a few well-known recordings for the same seismic event. The EW accelerometric components of the main shock recorded at two recording stations (AQA, AQV) near L'Aquila city (Italy) on 4-06-2009 are the generation inputs. The seismic wave propagates along the direction between AQA and AQV. These signals are representative of a possible asynchronous excitation applied on a bridge. Five arrays of asynchronous accelerograms are generated at the foundations of the bridge to perform statistical elaboration of the results. Different bridge positions are supposed along the propagation direction of the wave to evaluate the spatial variability of the generated signals. The generated signals at AQA and AQV stations are compared with the available recordings at the same points (generation inputs) in term of power spectra, acceleration and displacement response spectra. Finally, the most detrimental soil distortions for the bridge deck are calculated for some bridge positions.*

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1 INTRODUCTION

The seismic actions used to design long structures, as bridges, should be attentively evaluated as the signals, recorded at distant foundation points in occasion of the same seismic event, can be much 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.

However, synchronous actions are usually considered during the design and this practice can be unsafe in case of long structures [1-12]. There are a few international design codes [13-14] which consider the effect of asynchronous seismic actions applying relative displacements among the foundation points. However, comprehensive analyses are needed to their calibration and further research efforts are necessary.

The asynchronous signal transformation from point to point can be performed by means of different models [15-29]. In this paper, a new procedure is presented to generate asynchronous seismic signals (accelerograms) at the ground surface starting from a few well-known accelerometric recordings for the same seismic event at different surface points. This procedure considers the signal frequencies content variation and the different arrival time of the wave from point to point. The numerical asynchronous signals generation procedure described in [6, 7] was improved [28, 29] and implemented in MATLAB [30] as a framework of functions named GAS 2.0 -Generation of Asynchronous Signals -.The signal frequency content at each point is calculated by assuming a normal distribution of the signal amplitudes. The mean and variance of this normal distribution are obtained from point to point considering the amplitudes of the signals generated at previous points by means of the joint conditioned probability theory and the covariance matrix of the propagation problem. The frequency content of the input signals and the coherence function that describes how the signals frequency content changes from point to point include local site effects and frequency content variation in the generation procedure [19]. The EW accelerometric components of the main-shock recorded at two stations (AQA and AQV in [31]) near L'Aquila city (Italy) on 04-06-2009 were the generation inputs. A bridge located in a highly seismic area was chosen as case study. This bridge was designed considering the modern design code philosophy [13, 14, 36-39].

The three foundation points of this bridge were located at three positions along the wave propagation direction to study the spatial variability of asynchronous motion. Five arrays of asynchronous accelerograms, each composed by nine signals (three foundation points for three bridge positions, Figure 1), were generated starting from the same inputs. This number of generations permitted a statistical elaboration of the results. The generated signals at AQA and AQV stations were compared with the recordings at the same points (generation inputs) in term of power spectra, acceleration response spectra and displacement response spectra.

Finally, the displacement histories of the generated accelerometric signals were obtained by SEISMOSIGNAL software [32]. The elaboration of these displacement histories permitted to find the soil distortions which are the most detrimental for the bridge deck.

2 CASE OF STUDY

A bridge, that results a critical element in a network of structures and infrastructures after an earthquake [32-35], represents a valid case of study to evaluate the effects of asynchronous actions on bridges. It is supposed that this bridge is placed in Aterno valley near L'Aquila city (Italy) where there are two recording stations AQA and AQV (station code in ITACA [31]) placed on two different soils U-AQA and U-AQV (Figure 1) with characteristics described in [28, 29]. The three foundation points of the bridge, which have a mutual distance of 50 m, were placed in three different positions along the line that connect the two stations AQA and AQV (direction x, Figure 1): (i) the position 123 near the station AQA (each foundation point on soil

U-AQA); (ii) the position 456 near the middle point between AQA and AQV (foundation points on soil U-AQA or on soil U-AQV); (iii) the position 789 near the station AQV (each foundation point on soil U-AQV). 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.

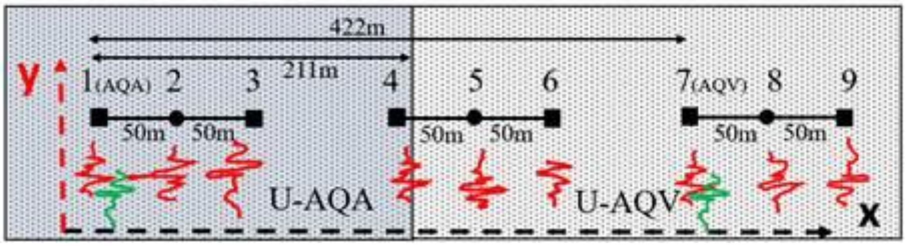

Figure 1 Three alternative positions (123, 456 and 789) of a bridge along the seismic wave propagation direction (x); U-AQA and U-AQV are the two different soils crossed by the seismic wave; The generated accelerograms are indicated by red lines whereas the generation input signals recorded at point 1 and 7 (locations of the recording stations AQA and AQV) are indicated by green lines

The software GAS 2.0 -Generation of Asynchronous Signals- was used to obtain the asynchronous accelerometric signals at surface on the base of the generation procedure described in [6, 7, 28, 29]. The EW accelerometric components of the main shock recorded at the recording stations AQA and AQV (station code in ITACA [31]) on June 4 2009 were the generation inputs for this procedure. The generation was performed assuming (Figure 1): (i) the EW accelerometric component of the main shock that moves the soil in the y direction (Figure 1) while it propagates along the direction x (Figure 1); (ii) the recording stations AQA and AQV placed on the direction x (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, Figure 1) placed on the soil U-AQA or on the soil U-AQV; (iv) the characteristics of the input signal (power spectrum) recorded at AQA to include the local site effect (wave-soil interaction) in U-AQA for the generation points 1-4; (vi) the characteristics of the signal (power spectrum) recorded at AQV to include the local site effect (wave-soil interaction) in U-AQV for the generation points 5-9.

The local site effects lead to the amplification of the original bedrock signal at the ground surface. These signal transformations depend on the peculiar characteristics of the soil crossed by the seismic wave. The amplifications of the bedrock signal in the soils U-AQA and in the soil U-AQV are different; it is evident from the comparison between the power spectra of the EW components recorded at AQA and AQV stations placed on U-AQA and U-AQV soil respectively (Figure 2).

The frequency content variation from point to point was modelled by the Van Markel et al. model [19, 20]. The parameters of this model were calibrated [28, 29] using the recordings at AQA and at AQV assuming the shear wave velocity V_S equal to 580 m/s according to the NTC2008 [14] indications in case of soil B.

The different arrival times of the wave front at the different generation points were calculated assuming that the seismic wave propagates along the x direction from 1 to 9 moving with a speed V_{app} equal to 2000 m/s.

Five arrays composed by nine asynchronous accelerometric signals (generation points from 1 to 9, Figure 1) were generated. Each array describes a different numerical evaluation of the signals which can be recorded at the generation points during the propagations of the selected seismic event along the direction x.

3 RESULTS OF THE GENERATION OF ASYNCHRONOUS SEISMIC SIGNALS

The five arrays of accelerometric signals generated in §2 permitted a statistical analysis of the results evaluating the mean, the mean plus and the mean minus standard deviation curves of: (i) the power spectra (§3.1); (ii) the acceleration response spectra (§3.2); (iii) the displacement response spectra (§3.3).

Firstly, the characteristics of the generated signals at the points 1 and 7, where are placed the stations AQA and AQV, were compared with the available recording at the same points (input of the generation procedure) to check the reliability of the generation procedure.

Subsequently, the displacement histories at each generation point were calculated by SEISMOSIGNAL [32] starting from the generated accelerometric signals. These displacement histories will be used in [11] to evaluate the bridge response in case of asynchronous excitation.

The soil distortion at time t1, when the distance of one foundation point respect to the line drawn between the other two foundation points is maximum, was calculated for three generations considering the bridge position 123 and 456 (Figure 1). These soil distortions are reasonably the most detrimental for the bridge deck.

3.1 Power spectra comparison

In Figure 2 the power spectrum curves of the input signals (black dotted line, Figure 2) at point 1 and 7, where are placed the stations AQA and AQV (Figure 1), were compared with the mean curves of the power spectra obtained for the five generated signals at the same points (red line, Figure 2). The power spectra were evaluated using SEISMOSIGNAL [32] by the expression (1):

$$\text{PowerAmplitude} = \text{FourierAmplitude}^2/(\text{Pi}*\text{duration}*\text{Rms}_{\text{Acc}}^2) \qquad (1)$$

where the duration is the time length of the record and Rms_{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.

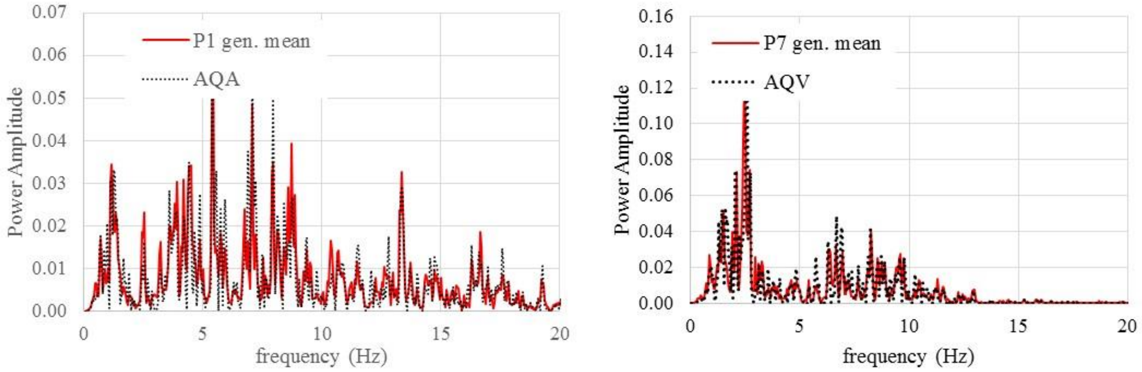

Figure 2 Generation of asynchronous signals: comparison between the mean curve of the power spectra (P1 gen. mean and P7 gen. mean; red lines) obtained considering five generated accelerometric signals and the power spectrum curve of the recorded accelerogram (AQA and AQV; black dotted line) at points 1 (left) and 7 (right)

3.2 Acceleration spectra comparison

In Figure **3** the acceleration response spectra of the input signals (black dotted lines, Figure 2) at point 1 and 7, where are placed the stations AQA and AQV (Figure 1), were compared with the mean, the mean plus and the mean minus standard deviation curves of the acceleration response spectra obtained for the five generated signals at the same points 1 and 7. The acceleration response spectra were obtained by SEISMOSIGNAL [32]. It is possible to observe that there is a general good agreement between generated and recorded signals.

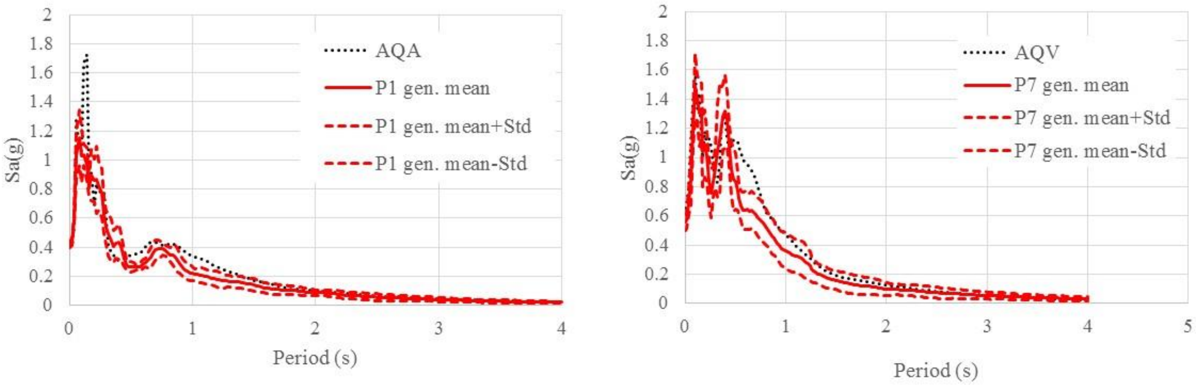

Figure 3 Generation of asynchronous signals: comparison among the mean, the mean plus and mean minus standard deviation (P1 gen. mean, P1 gen. mean+Std, P1 gen. mean-Std, P7 gen. mean, P7 gen. mean+Std, P7 gen. mean-Std; red lines) curves of the acceleration response spectra obtained considering five generated accelerometric signals and the acceleration response spectra curves of the recorded accelerogram (AQA and AQV, black dotted line) at points 1 (left) and 7 (right)

3.3 Displacement spectra comparison

In Figure 4 the displacement response spectra of the input signals (black dotted line in Figure 2) at point 1 and 7, where are placed the stations AQA and AQV (Figure 1), were compared with the mean, the mean plus and the mean minus standard deviation curves of the displacement response spectra obtained for the five generated signals at the same points. The displacement response spectra curves were obtained by SEISMOSIGNAL [32]. It is possible to observe that there is a general good agreement between generated and recorded signals.

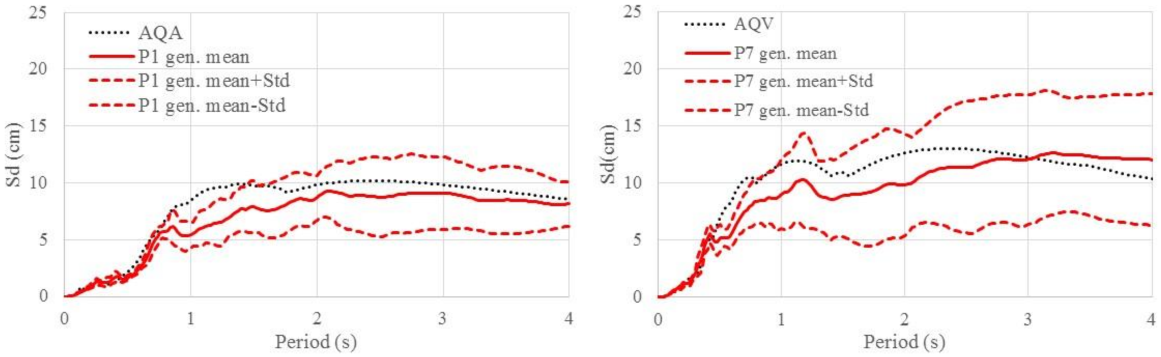

Figure 4 Generation of asynchronous signals: comparison among the mean, the mean plus and mean minus standard deviation (P1 gen. mean, P1 gen. mean+Std, P1 gen. mean-Std, P7 gen. mean, P7 gen. mean+Std, P7 gen. mean-Std; red lines) curves of the displacement response spectra obtained considering five 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)

3.4 Soil distortions at the bridge foundations

The displacement histories were calculated by means of the software SEISMOSIGNAL [32] starting from the generated accelerometric signals. These displacement histories are used as input excitations on the bridge foundations in [11] to evaluate bridge response in case of asynchronous excitation.

The relative displacements among the different generation points (soil distortion) were also evaluated elaborating these displacement histories. The soil distortion at the time t1 (Δd_{max}), when the distance of one foundation point respect to the line drawn between the other two foundation points is maximum, is the much interesting one. In fact, this distortion is reasonably the most detrimental one for the bridge deck.

The distortions Δd_{max} obtained elaborating three arrays of signals generated at the bridge positions 123 (soil123-g1-ns, soil123-g2-ns and soil123-g3-ns) and three arrays generated at the bridge position 456 (soil456-g1-ns, soil456-g2-ns and soil456-g3-ns) are shown in Figure 5. The soil distortions at 123 present smaller relative displacements among the foundation points respect to the ones calculated for the bride position 456 (Figure 5). This is due to the positions of the generation points on the two soil U-AQA and U-AQV (Figure 1).

The signals generated at the bridge location 123 present smaller differences as the generation points 1, 2 and 3 are placed on the same soil U-AQA (Figure 1) and the distances among the points are modest. The generated signals are characterized mainly by the power spectrum of the input signal at AQA and so there are smaller relative displacements among the generation points.

The signals generated at the bridge location 456 present greater differences as the generation point 4 is placed on the soil U-AQA whereas the generation points 5 and 6 are placed on a different soil, the soil U-AQV (Figure 1). 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.

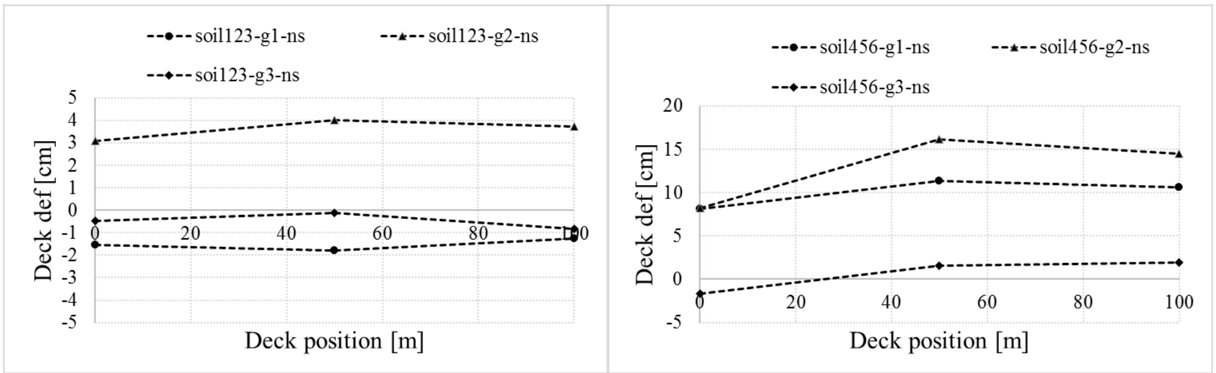

Figure 5 Generation of asynchronous signals: soil distortions when the distance of one foundation point respect to the line drawn between the other two foundation points is maximum at bridge position 123 (soil123-g1-ns, soil123-g2-ns and soil123-g3-ns) and at the position 456 (soil456-g1-ns, soil456-g2-ns and soil456-g3-ns) along the wave propagation direction between AQA and AQV stations

4 CONCLUSIONS

The EW accelerometric components, recorded at AQA and AQV strong motion stations during the main-shock of L'Aquila seismic event happened on 04-06-2009, were used as inputs to generate arrays of asynchronous earthquake signals at the ground surface in correspondence of three points in a line with a span of 50 meters, possible foundation points of a bridge, through the software GAS 2.0 [6, 7, 9, 10, 26-29].

Three bridge positions were considered along the direction between AQA and AQV stations: (i) position 123 near the station AQA, (ii) position 789 near the station AQV or (iii) position 456 near the middle point between the two stations (Figure 1).

Five arrays of signals were generated for each bridge position, in the three surface points (bridge foundations) starting from the same input recordings. Preliminary results show that the signals generated at AQA and AQV are very similar to the strong motion records (i.e. input for the generation procedure) in terms of signals characteristics (power spectra, acceleration response spectra and displacement response spectra), as a confirm of the meaningfulness of the generation procedure.

The relative displacements among the different foundation points in case of asynchronous excitation were also evaluated. The soil distortions, which are reasonably the most detrimental for the bridge deck, were calculated for three arrays of generated signals at the positions 123 and 456. By observing these results, it is evident as the effects of asynchronous actions in term of soil distortion applied at the bridge foundations, can show an important variation along the seismic wave propagation direction. These soil distortions are in many cases not considered during the design of long structures and this practice can be unsafe.

These relative displacements are one of the essential input for simplified nonsynchronous analyses of structures, and are now tentatively included in some codes, for example Eurocode 8 [13]. Comprehensive analyses are needed to their calibration and we are moving in that direction.

The asynchronous earthquake signals, generated by the proposed generation procedure, were used to study the response of existing bridge in [11]. Further analyses are in progress to evaluate the seismic response of existing bridges repaired and retrofitted after strong seismic damage [41-56]. The seismic behavior of bridges subjected to asynchronous excitation will be defined also considering near fault earthquake [57, 58].

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