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GENERATION OF ASYNCHRONOUS SEISMIC SIGNALS CONSIDERING DIFFERENT KNOWLEDGE LEVELS FOR SEISMIC INPUT AND SOIL

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Abstract

The seismic waves show a variation of the signal characteristics at different points during the motion through soils. This difference is not only due to the time lag among the signals but also to the change of the signal frequencies content for effects of physical phenomena associated to the wave propagation (reflection, filtering, etc.). Long structures as a bridge, have foundations on different distant points; the correct evaluation of the variation of the signals at each foundation point is much important to define correctly the design actions. However, the structural design codes do not consider satisfactorily this complex type of action and the time lag difference is often the only effect of the non-synchronism considered to define the design actions. In this paper, a more complete evaluation of the asynchronous action considering time lag and signal frequencies content variation is presented. In particular, the results of two generation procedures of non-synchronous signals at different surface points are discussed. The first procedure (PR1) generates directly signals at surface starting from the soil characteristics defined by Eurocode 8 and the recorded signals at two surface points for the same seismic event. The second procedure (PR2) produces surface signals by amplifying the bedrock signals obtained by a bedrock propagation. The bedrock propagation is performed starting from the signals obtained by means of a deconvolution process starting from the recorded surface signals used as inputs for the PR1 procedure. The soil characteristics are known well (shear wave velocity profiles and layer material shear moduli and damping curves) and deconvolution and amplification are performed by SHAKE91 [1]. The propagation of the signal at surface or at bedrock was performed by a procedure proposed by the authors and implemented in a computer code MATLAB (Gas) [8], [9]. The EW component of the main shock of the earthquake at L'Aquila (4-06-2009) in Italy was studied. The results of the comparisons between the different procedures are discussed in term of effect on the structure responses (acceleration response spectra) and characteristics of the generated signal (Fourier amplitude, coherences). The critical overview of these results helps to draw important considerations about reliability and safety level useful to the designer that has to define the correct actions for long structures.

Keywords: generation, asynchronous, local amplification, deconvolution, seismic signals

1. Introduction

The seismic waves recorded at different surface points for the same seismic event, are different. This difference is due to the time lag among the seismic signals at different points (time in which the wave moves through different soil points) and to the variation of the earthquake signal frequencies content for effect of physical phenomena associated to the wave propagation and to the soil-wave interactions (reflection, refraction, filtering, local amplification and attenuation, etc.). This signal transformation varies greatly from soil to soil and in case of long structures and the soil geometries and properties (density, shear modulus, damping, etc) can change a lot along the structure. However, the non-synchronism of the seismic signal from point to point is not evaluated properly in seismic design codes yet. In this paper, the generation of surface seismic asynchronous signals at the base of a bridge with eight piers (Fig. 1), that is placed in Aterno valley near L'Aquila city (Italy), is discussed to evaluate asynchronous signals along a long structure on the base of different levels of knowledge about the input signals and about the foundation soil properties. This Valley was selected as different recordings are available for the same seismic event at points, which are distant each other as in case of bridge foundations. The components EW recorded at the AQA and AQV stations ("AQA" and "AQV" are station code labels in ITACA database) in occasion of the Main shock (2009-04-06) at L'Aquila city (Italy) were considered as inputs for the generation procedures. The generation of surface seismic asynchronous signals was performed by two different numerical procedures: Procedure 1 (PR1) that consists in the generation of signals directly at surface starting from two surface input signals recorded at AQA and AQV; Procedure 2 (PR2) that consists in the amplification of the signals obtained by a generation at bedrock starting from the input signals obtained by the deconvolution of the signals recorded at AQA and AQV. The amplification of the signals during procedure PR2 introduces a high level of knowledge obtained by in situ test, about the soil local effect on surface signal definition. For that reason, the signals obtained by PR2 are considered with a high level of knowledge about the soil. At the contrary PR1 considers a low level of knowledge about the soil as the shear wave (Vs) is defined by Eurocode 8 indication only. However, it is matter of fact that the PR1 generation procedure starting from the surface recorded signals includes in the input signals the soil local effects. The comparison among the results of the two procedures at AQA and AQV the same points where are also available the recordings, permits to evaluate the reliability of the generated signals.

2. Asynchronous signal generation model

The transformation of the seismic wave from point to point due to the wave-soil interaction (NS1) and to the signal time translation, as the seismic wave gets to a different point after a given time (time lag) (NS2), can be considered separately in a RF (Random Field) generation procedure. In the last years, several RF models able to define the spatial variability of earthquakes were presented. These models were developed on the base of experimental data for simultaneous recordings of the same earthquake (Abrahamson et al. 1991[13]; Oliveira et al. 1991[12]) or on different statistical models (Luco and Wong 1986 [14] ; Santa-Cruz et al. 2000; Van Marcke 1991 [2]). In this paper, the RF generation procedure proposed by the authors [8]-[9] was updated to generate asynchronous signals at different space points for a given seismic event starting from earthquake recordings at surface and soils properties. This generation procedure considers the NS1 effects by means of a few earthquakes recordings at different points and by a coherence function properly calibrated to model the frequencies content variation of the signals with the distance crossed by the seismic wave. Finally, a time translation is applied to the generated signals to consider the NS2 effects. The amplitudes of the generated asynchronous signals at different points are assumed normally distributed with zero mean and are computed at each new generation point by a conditioned joint probability procedure. This procedure considers the amplitudes of the signals generated at the previous generation points by the elaboration of the problem covariance matrix. The covariance matrix is assembled at each frequency starting from the power spectral density functions of the input signals and by a correlation coefficient (ρ) defined by the coherency model (1) [2]:

$$\rho = e^{\wedge}(-\omega X /(2 \pi V_s s)) \qquad (1)$$

where ω is a circular frequency, X the distance between two generation points, V_s the wave shear velocity and s a coherence parameter. The mean value of s was calibrated on the base of the coherences values for each frequency calculated by MATLAB function starting from two input signals (Fig. 2, Fig. 3). In fact, the equation 1 permits the definition of s starting from X, V_s and the coherences values. Finally, the scaling of the generated signals is done guaranteeing the same Arias coefficient between input and generated signals. The Arias coefficient measures in a time windows the strength of a ground motion and results a very effective scaling factor to reproduce reliable generated signals. The proposed RF model was implemented in MATLAB by a functions framework named GAS (Generation of Asynchronous Signals) that generates asynchronous signals at n points in case of ns soil unities starting from a given number of recorded accelerometric signals for the same seismic event.

3. Generation of surface asynchronous signals at the base of a bridge at L'AQUILA

The case of study deals with the problem of the generation of surface asynchronous accelerometric earthquake seismic signals at different points of the Aterno valley near L'Aquila city (Italy). This place was selected in this study as different recording stations are placed in this valley and so different earthquake recording for the same seismic event are available in the earthquake database ITACA [6]. In particular, the main part (20s) of the components EW recorded at the AQA and AQV stations (Fig. 1) during L'Aquila Main-shock event (2009-04-06, Magnitude 6.3) was considered as generation inputs. These recording stations (AQA and AQV) are distant 422 m and the line across the station is placed with an angle of about 27° with respect to the EW line. This angle is important as the generation point distances crossed by the EW components are considered along the EW line during the generation. The signals were generated in correspondence of eight pier foundations (AQA, AQ2, AQV, AQ4, AQ5 - AQ8, Fig. 1) of a bridge with longitudinal axis along the lines between AQA and AQV stations (Fig. 1). This bridge has two piers (AQA, AQ2) on soil unit U-AQA and six piers (AQV, AQ4 - AQ8) on soil unit U-AQV. These two soil units have the layer geometries and the soil material properties given in Fig. 4. The generation of asynchronous signals at surface was performed considering two different procedures (PR1, PR2, Fig. 1):

- PR1: propagation by GAS directly at surface starting from earthquake recording at AQA and AQV and by using the coherence parameters s obtained from elaboration of input signals. The V_s for the coherence model was assumed for U-AQA and U-AQV according to Eurocode 8 soil type indication [11]. The soil level of knowledge is low.

- PR2: deconvolution of the recorded signals at AQA and AQV (the same used as input in PR1); propagation by GAS at bedrock starting from the deconvoluted signals below AQA and AQV and coherence s parameters tuned by the elaboration of these deconvoluted signals. Finally, an amplification of the generated bedrock signals considering the local soil characteristics of U-AQA and U-AQV units produces the surface signals. The soil characteristics were obtained by in situ test. The soil level of knowledge is high.

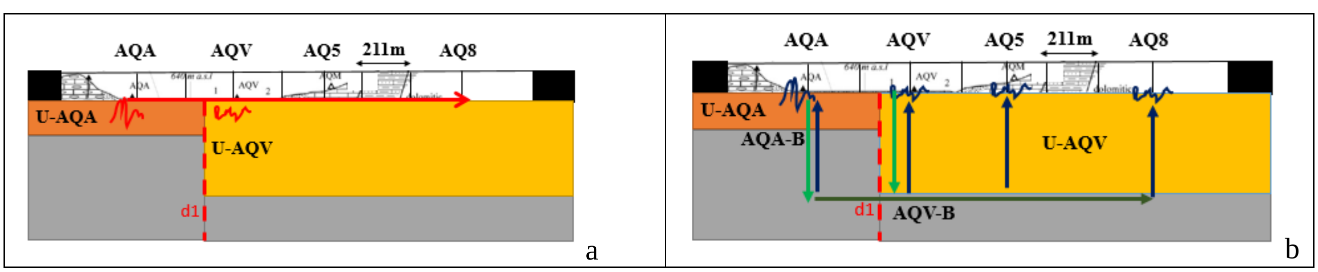

Fig. 1 Generation procedures of asynchronous earthquake signals at surface in correspondence of eight bridge pier foundations: a) PR1 generation starting from recording accelerograms at AQA and AQV stations; b) PR2 bedrock generation starting from signals obtained from deconvolution of the signals recorded at AQA and AQV and next surface amplification by SHAKE91 software [1].

The generation of signals at surface and at bedrock during procedure PR1 and PR2 was performed by GAS using the update proposed generation model. In particular, fifteen accelerometric signals were generated in correspondence of each bridge foundation to perform some statistical considerations by means of the estimations of the mean and the deviation standard of the elaborated generated signals characteristics. The amplification and deconvolution of the accelerometric signals were performed by SHAKE91 [1] that considers a 1D soil equivalent elastic model. The V_s profile for each soil unit assumed for the local deconvolution and amplification procedures are shown in Fig. 4 [10]. The selected seismic event with great magnitude (M = 6.3) produced a great nonlinear response of the soil. This soil behavior can be reproduced properly by selecting for the equivalent soil analysis the shear moduli and damping curves proposed by Rollins for the gravel layers ([10], Fig. 4). It is important to underline that the selected event is a near source seismic event and so the 1D equivalent model for the soil amplification and deconvolution can be not proper for the correct signals definition. Furthermore, the station AQA is near the edge of the Aterno valley and so the 2D local effects are inevitable. For that reason, the 1D model results should be considered with attention. However, the obtained signals resulted complete for the analysis and discussion proposed here by an engineer's point of view.

3.1 Generation of asynchronous signals at surface by procedure 1

The PR1 generation procedure was performed directly at surface. The input PSDs (power density function) are calculated by MATLAB built-in function staring from the earthquake signals recorded at AQA and AQV stations (Fig. 2). The generation is performed in correspondence of each bridge foundation point (Fig. 1). The mean value of the s parameter of the coherence model used in the generation procedure is equal to 9.06. This value was obtained by means of the calculation of the coherence between the two surface recorded signals (Fig. 2) by the built-in function of MATLAB. In particular, the mean value of s was evaluated in the frequencies range fr [0.25, 5 Hz] (Fig. 2). This range corresponds to the frequencies of long structures on which non synchronism effects are more important. The shear velocity V_s was assumed equal to 580 m/s, the mean value in the V_s range [360, 800 m/s] as it is defined for type B soil by Eurocode 8 [11].

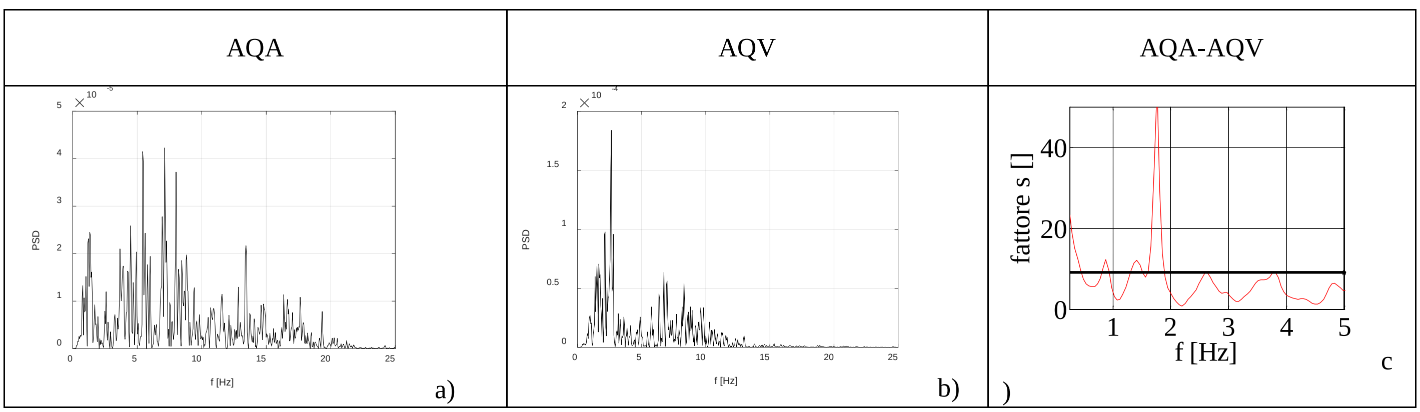

Fig. 2 Procedure 1: generation at surface of asynchronous signals, PSD functions at a) AQA-B and b) AQV-B stations (Fig. 1) and c) calibration of the factor s for the numerical coherence model [2] assumed in generation procedure. The PSD are scaled by acceleration of gravity (g) and number of Fourier (number of points of the accelerogram generated, nfft)

3.2 Generation of asynchronous signals at surface by procedure 2

The PR2 procedure produces asynchronous signals at surface amplifying the signals generated at bedrock by GAS by means of an Equivalent-linear Earthquake Site Response Analysis (Bardet 2000, Shake91). The generation at bedrock had as input the earthquake signals obtained by a deconvolution process applied on the recorded signals at AQA and AQV (the inputs for procedure PR1). The deconvolution of the surface recordings was performed by computer code Shake 91 and produces deconvoluted signals at hypothetical bedrock stations AQA-B and AQV-B below the surface stations AQA and AQV respectively (Fig. 1). The earthquake signals were generated by GAS at bedrock below each bridge foundation point. The mean value of the s parameter used to calibrate the coherence model of the generation in the interest frequencies range (fr) is equal to 4.68. This value was obtained elaborating (how it was described for PR1) the coherences calculated by MATLAB between the two deconvoluted input signals at AQA-B and AQV-B (**Fig. 3**). The shear velocity V_s was assumed in the coherence model equal to 1125 m/s. This is the mean value of the experimental bedrock shear wave velocities (V_s) measured by in situ tests [10] below AQA and AQV stations. Finally, the signals obtained by the generation at bedrock were amplified using SHAKE91 [1] considering the same material properties, soil layers' geometries, V_s profiles and nonlinear soil behaviors used for the deconvolution procedure of AQA and AQV recording. The surface signals obtained are the results of PR2 surface propagation.

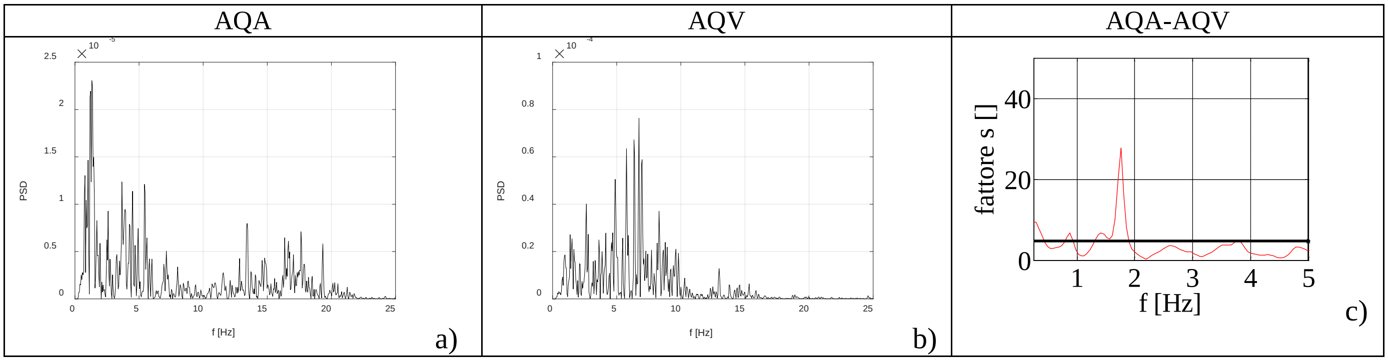

Fig. 3 Procedure 2: generation at bedrock of asynchronous signals, PSD functions at a) AQA-B and b) AQV-B stations (Fig. 1) and c) calibration of the factor s for the numerical coherence model [2] assumed in generation procedure. The PSD are scaled by acceleration of gravity (g) and number of Fourier (number of points of the accelerogram generated, nfft)

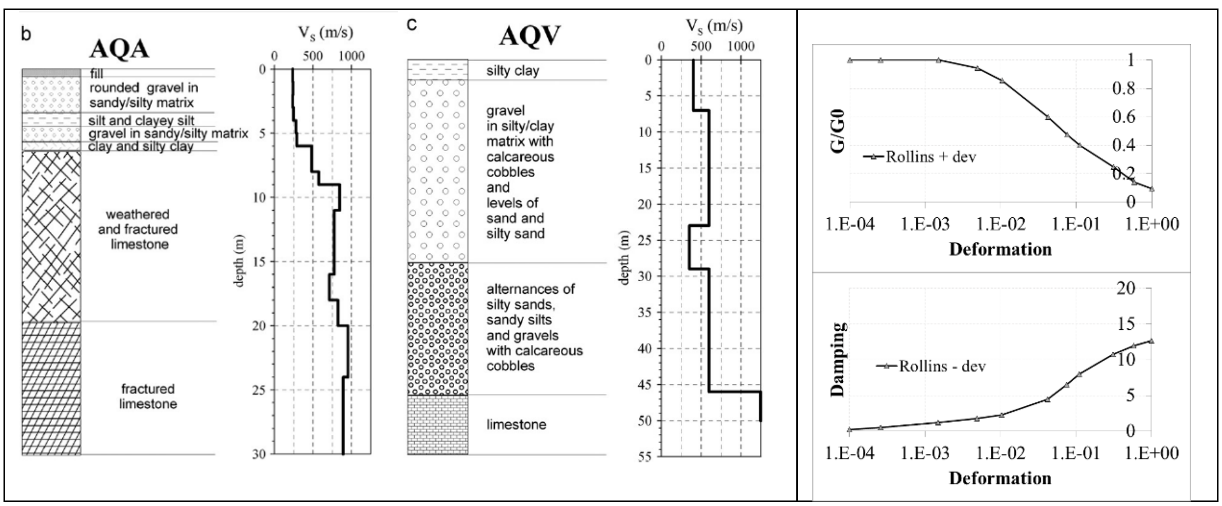

Fig. 4 Soil units U-AQA and U-AQV at AQA and AQV stations respectively: a) layers geometries, material types and shear wave (Vs) profiles; b) shear modulus and damping curves proposed by Rollins for gravel. In particular, gravel behavior was well defined by Rollins mean plus deviation curve for shear modulus and Rollins mean minus deviation curves for damping [10].

4. Comparison of the generated signals by procedure PR1 and PR2 at surface

The generated signals at surface by PR1 and PR2 procedures were compared in term of signals characteristics (Fast Fourier Transformation amplitude spectra and coherence among signals at different generation points) and structural response (acceleration response spectra). In particular, the signals obtained at surface in correspondence of the bridge foundations AQA, AQV, AQ5 and AQ8 were considered. The comparison was performed in term of signal difference at different generation points along the bridge due to non-synchronism NS1 that measures the signals transformation for effect of the complex soil-wave interaction. For that reason, the signals were not corrected to consider also the time lag effect due to non-synchronism NS2.

4.1 Comparison among FFT amplitude spectra

The Fast Fourier Transformation amplitude spectrum (FFT AMP) was calculated by MATLAB built in function for the generated signals by means of PR1 and PR2 procedures. Furthermore, the FFT AMP mean curve and the mean plus standard deviation and mean less standard deviation curves considering the 15 generated signals at the points AQA, AQV, AQ5 and AQ8 by procedure PR1 or PR2 are shown in fig 5. The FFT AMP are shown in the range of frequencies (f) [0, 10Hz] as it includes the more interesting frequencies range for civil structures [0.25, 5Hz] and gives also information on some higher frequencies. The green lines represent the FFT AMP of the recorded surface signals at AQA and AQV. The comparison among the results of the two procedure shows that each procedure can simulate very well the surface signals. In fact, the FFT AMP mean curves are in very good agreement with the ones of the recorded signals at AQA and AQV in term of amplitude frequencies contents and so also in term of power of signals. For that reason, these generation procedures are able to produce reliable earthquake signals.

4.2 Comparison among the coherences of the signals at different surface points

The coherence for each frequency was calculated by MATLAB built in function considering the generated signals at the couple of points AQA-AQV, AQA-AQ5 and AQA-AQ8 with procedure PR1 or PR2. The mean curve and the mean plus standard deviation and mean less standard deviation curves considering 15 generated signals by procedure PR1 or PR2 are shown in fig 6. The results of the coherence model assumed for the generation of the signals is shown in black lines (fig 6). The coherences are shown in the range of frequencies (f) [0, 5Hz] as it is the more interesting frequencies range for civil structures and it is the range in which the s factor of the coherence model was calibrated. The generated signals are in very good accordance with the coherence model assumed for the generation (black line) in case of both the generation procedures (PR1 and PR2). The proposed generation procedures are able to generate signals at different points reliable in term of coherence among the signals. This is important as the coherence measures the variation of the signals characteristics during the propagations. This difference among the signals produces relative displacements among the different foundation points. The effects of these relative displacements are very important in the design of long structures (i.e. actions on bridge deck). However, these actions are in many cases not considered or considered not properly in international codes and so the design can result not safe.

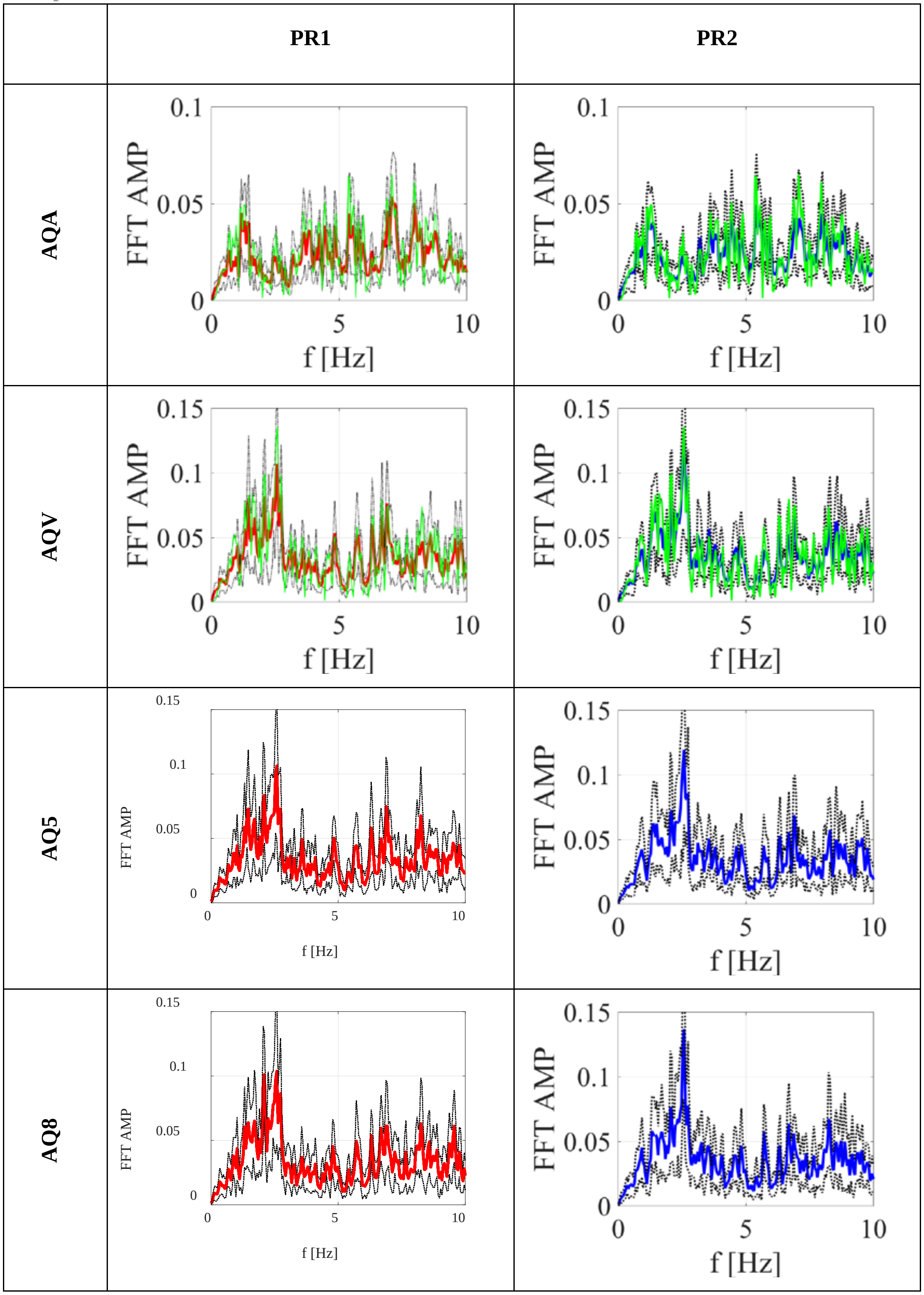

Fig. 5 Comparison between procedure 1 and 2 (PR1, PR2): FFT amplitude spectra (FFT AMP) at AQA, AQV, AQ5 and AQ8; mean of the FFT AMP considering 15 generations (red line for PR1, blue line for PR2) and mean plus or minus standard deviation considering 15 generations (dot black line); The green lines are the FFT amplitude spectra of the recorded signals at AQA and AQV.

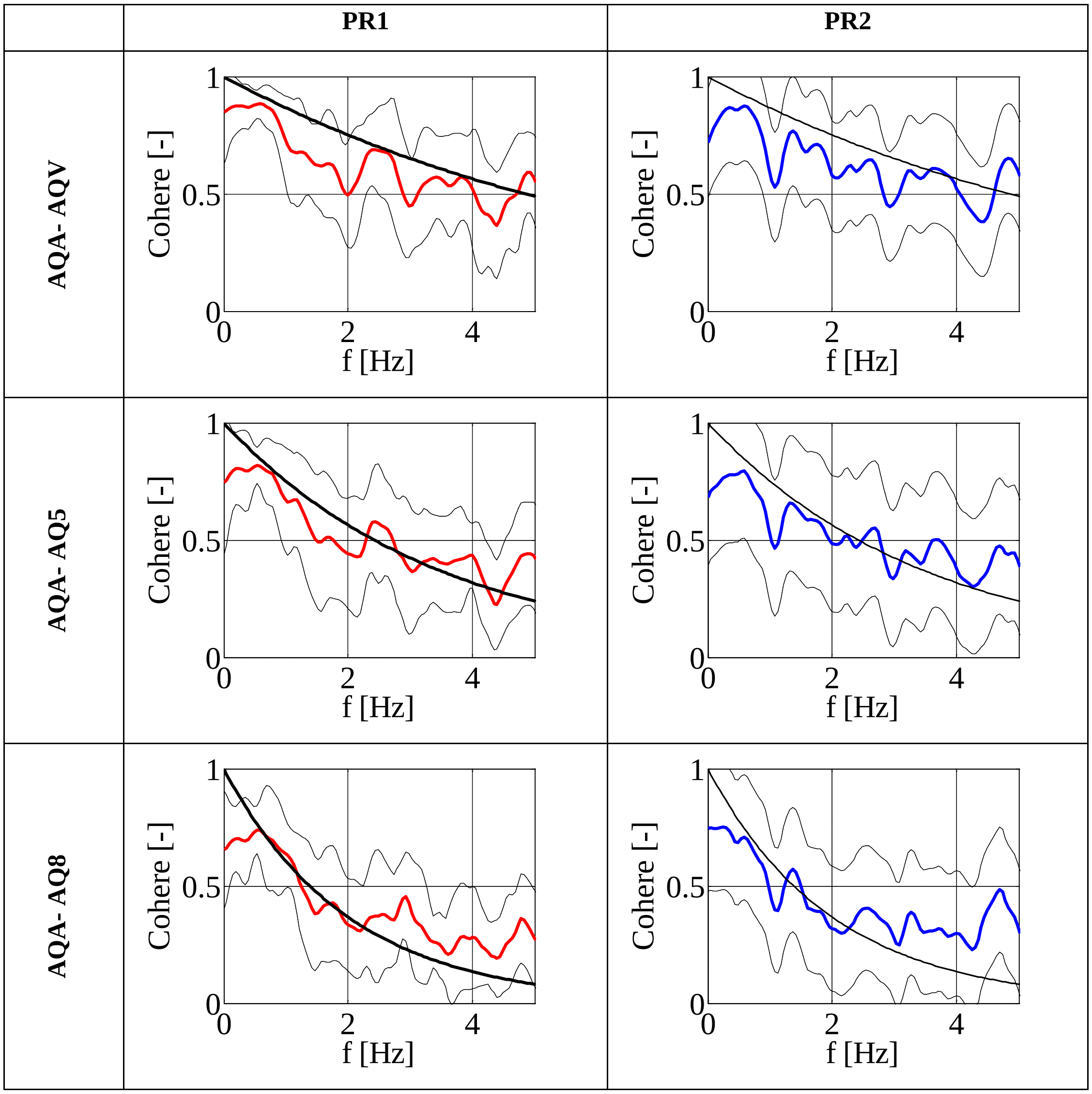

Fig. 6 Comparison between the procedure 1 and 2 (PR1, PR2): coherence between the pier foundations AQA-AQV, AQA-AQ5 and AQA-AQ8 (Fig. 1); mean curve of the coherence considering the 15 generations (red line for PR1, blue line for PR2) and mean plus or minus standard deviation curves considering the 15 generations (dot black lines). The black line is the coherence estimated by the numerical coherence model assumed in the generation procedure (GAS.)

4.3 Comparison among the acceleration response spectra Sa

The acceleration response spectrum (Sa) was calculated for each generated signal by a user defined MATLAB function. Furthermore, the Sa mean curves and the mean plus standard deviation and mean less standard deviation curves (fig 7) were calculated considering the fifteen generated signals at pier foundation points AQA, AQV, AQ5 and AQ8 (Fig. 1) by procedure PR1 or PR2 (fig 7). The green lines in fig 7 represent the Sa of the recorded signals at AQA and AQV. The Sa are shown in the range of periods [0, 2.5s] as it is the more interesting range for the civil structures. It is evident by the comparison between the mean Sa curves of the generated signals and the ones of the recorded signals (fig 7) that both procedure PR1 and PR2 are able to generate surface signals with very good agreement with the recorded ones at AQA and AQV. This is important as the Sa measures the effects of the generated earthquake signals on structures. These reliable generated signals can be used to a proper structural long structure design and the proposed procedures represent a valid generation tool for a designer.

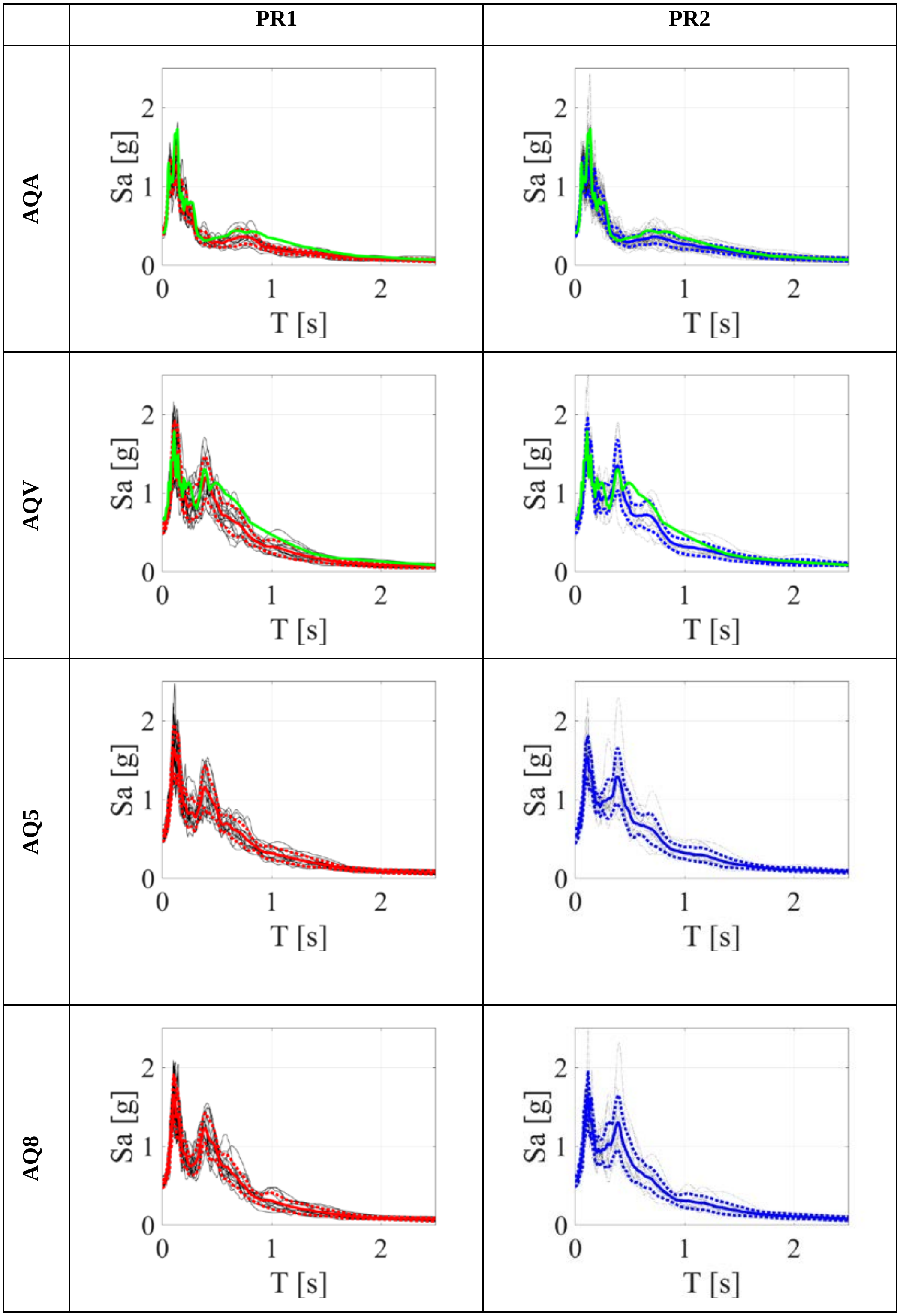

Fig. 7 Comparison between procedure 1 and 2 (PR1, PR2): Acceleration response spectra (Sa) at pier foundations AQA, AQV, AQ5 and AQ8 of each generated accelerograms (black lines), mean of the Sa considering 15 generations (red line for PR1, blue line for PR2) and mean plus or minus standard deviation considering 15 generations (red dot line for PR1, blue dot line for PR2). The Sa of the input accelerograms at AQA and AQV are given in green lines.

5. Conclusion

Two generation procedures (PR1 and PR2) were performed to obtain asynchronous earthquake signals at different surface soil points in correspondence of the foundations of a long bridge. These procedures consider a low or a high level of knowledge about the soil. The bridge is placed in Aterno Valley where seismic recordings at different recording stations (i. e. AQA and AQV) for the same seismic event are available. The EW components of the L'AQUILA main-shock (2009-04-06) recorded by two stations (AQA and AQV) were used as input earthquake signals for both the procedures. Two bridge pier foundations were placed in correspondence of AQA and AQV stations to evaluate the agreement among recorded and generated earthquake signals. The first procedure PR1 performed an asynchronous earthquake signals generation directly at surface in correspondence of eight bridge pier foundations which were distant each other 211 m, starting from the recorded signals at two stations AQA and AQV of the Aterno Valley. This procedure considers a low level of knowledge about the soil characteristic. In fact, the soil shear velocity Vs is assumed according to the indication of the Eurocode 8 for a soil type B and it is the only soil characteristic used during this generation procedure. The second procedure PR2 started from an asynchronous earthquake signals generation at bedrock using as input two bedrock earthquake signals below the station AQA and AQV. These input signals were obtained by means of a deconvolution process. The signals generated at bedrock below each bridge foundation, were amplified considering the local site response to obtain the surface signals in correspondence of each bridge pier foundations. The local soil effects are much important for the definition of the surface signals and the level of knowledge about the soil characteristics can be essential to define properly the surface signals. An equivalent elastic soil model (it was implemented in code Shake91 [1]) was used to perform the signals amplification. This model was calibrated on the base of detailed information about the nonlinear soil behavior obtained by in situ tests [10]. This approach includes a high knowledge level about soil characteristics in the generation procedure but it results more expensive in term of computational efforts. For that reason, the generation procedure PR1 starting from recorded surface signals, which include implicitly the local soil behavior effects, can result reliable and simpler than procedure PR2. Fifteen earthquake signals were generated in correspondence of each bridge foundation to perform a statistical comparison between the results of the two procedures by evaluating mean and standard deviation curves for each elaborated result. In particular, the comparison among the signal generated by the two procedures was performed in term of signals characteristics (FFT amplitude spectra, coherence among signals at distant points) and structural response (acceleration response spectra, Sa). The result of this comparison showed that both the procedure can generate reliable earthquake signals. In fact, the generated signals at AQA and AQV stations by the two procedures were in very good agreement with the recorded input signals at the same points in term of mean Sa and FFT amplitude spectra. The coherences among generated signals at distant points along the bridge were in very good agreement with the numerical model assumed in the generation procedure in case of both the procedure. The proposed calibration of the coherence numerical model on the base of the input signals can reproduce well the real coherence among the input signals in the range of frequencies of interest for the civil structures. This is important as the coherence measures the variation of the signals characteristics during the propagations. This difference among the signals produces relative displacements among the different foundation points. The effects of these relative displacements are very important in the design of long structures (i.e. actions on bridge deck). However, these actions are in many cases not considered or considered not properly in international codes and so the design can result not safe. The procedure PR2 that uses a high level of knowledge about the soil produces results very similar to the ones produces by the PR1 procedure that uses a low level of knowledge about the soil. For that reason, the PR1 procedure performed directly at surface starting from the recordings at some surface points without detailed soil characterization by test in situ results reliable and simpler. Finally, this procedure can be a valid solution for a designer to determine asynchronous seismic actions on long structures.

6. Acknowledgements

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