Generation of Non-Synchronous Accelerograms to Evaluate the Seismic Bridge Response, including Local Site Amplification

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SUMMARY:
Non-synchronous seismic actions particularly affect the behaviour of infrastructures with significant longitudinal extension, as bridges, interacting with the soil at surface or below ground level. Some authors state that non synchronism may increase by a large amount the structural response. Several acceleration records relative to different points of the ground with different soil profiles at distances meaningful for bridge analyses, are not available in data banks. The objective of this work is the generation of arrays of asynchronous signals at different points in space, starting from natural accelerograms related to a given seismic event, to increase the number of the available data. The computer code GAS has been modified to use natural accelerograms. The procedure has been applied to a real case, L'Aquila main-shock, for which records in different points of the free field are known.

Keywords: non-synchronism, bridge, site amplification

1. INTRODUCTION

Asynchronous actions induce stress states on structures with significant longitudinal extension, such as dams and bridges, different respect to synchronous ones commonly considered for design. Models able to define the spatial variability of earthquakes have been developed in the last years, on the base of experimental data of simultaneous recordings of earthquakes (Abrahamson et al., 1991, Oliveira et al., 1991). Starting with the classical studies of Luco and Wong (Luco and Wong, 1986), different statistical models have been proposed (Santa-Cruz et al. 2000, Vanmarcke and Fenton, 1991).

The propagation of an earthquake through the soil depends by the different types of foundation soils and the heterogeneity of stratigraphic profiles, which cause a variation of the amplitudes and frequencies of the signals at different points in space.

In this study array of non-synchronous accelerograms are generated considering time lag and coherence between the signals. A program (GAS) implemented in MATLAB by some of the authors has already been successfully used in the case of acceleration response spectra according to Eurocode 8 given as inputs for the generation of arrays of asynchronous signals in different points in space.
The covariance matrix used to generate the stochastic field, is built by means of a modified Kanai Tajimi (KTM) function for the power spectra, calibrated properly to match the numerical power spectra of the inputs, and a classical correlation function of literature (Luco et al., 1986).

The program has been upgraded for considering also natural accelerograms as inputs using the numeric power spectrum of these signals without approximation by KTM power spectrum. In fact the KTM function has a bell shape difficult to calibrate that approximates incorrectly the power spectrum for natural accelerograms. A further modification, still in progress, is the definition and calibration of a suitable correlation function. The calibration of the main functions (i.e. coherence function) used in the process of generation is difficult because of there are a few available acceleration records of different stations distant in space for the same seismic event.

A procedure for extending artificially an array of records on the base of a few available records is proposed.

In particular bedrock signals are obtained by deconvolution of the available surface records and these signals are propagated along the bedrock by means of GAS. Finally these bedrock signals are amplified with EERA (J.P. Bardet, et al., 2000) considering locally the characteristics of the soil profile increasing the number of superficial signals.

The propagation of signals at the bedrock is simpler because only one type of soil is considered with characteristics simpler to define. The amplification procedure with EERA [J.P. Bardet, et al., 2000] is also well verified in many studies.

Several comparisons between the signals generated by GAS and the acceleration records given as input at the bedrock and at the surface have been performed to test GAS in terms of Fourier amplitudes spectra and acceleration response spectra.

The acceleration records at two stations (AQA and AQV) of the Valle Aterno relative to L'Aquila main shock (06-04-2009) are used as input for generating arrays of asynchronous accelerograms on the surface. Similarly, signals resulting by deconvolution process of the records of AQA and AQV for the same seismic event are used as input in GAS to create arrays of asynchronous signals at the bedrock. In particular five arrays of signals, each consisting of four surface accelerograms relative to four points in space which include the location of the stations AQA and AQV have been generated.
Other five arrays of signals have been generated at the bedrock consisting of four accelerograms at four points in space at the bedrock, including the bedrock stations AQA-B and AQB-B (stations along the vertical AQA and AQB).

Finally two type of comparisons 1 and 2 have been performed by means of Fourier amplitude spectra and acceleration response spectra to verify the procedure for increasing the number of accelerations data: the comparison 1 at surface is between the arrays of asynchronous signals generated with GAS and the arrays of signals obtained by amplifying with EERA the arrays of asynchronous signals generated at the bedrock with GAS whereas the comparison 2 at the bedrock is between the arrays of signals obtained with GAS and the arrays of signals calculated by deconvolution of the signals generated by GAS at the surface.

2. RESEARCH OBJECTIVES

The research objectives are the calibrating of the functions of the program GAS for the generation of arrays of asynchronous accelerograms at different points in space on the base of natural acceleration records considered as input.

A large number of experimental data related to a seismic event recorded in different points in space are necessary for a correct calibration of the coherence function but a few data are available.
Here is proposed a procedure to increase the number of surface signals "artificially" starting by a few surface records.

The procedure is simple: a deconvolution process produces the bedrock signals corresponding to the surface records; these signals are inputs in GAS to generate arrays of asynchronous signals at the bedrock which are amplified by EERA, known the mechanical characteristics of the soil profile above these points. The surface signals obtained are the artificial signals that increase the number of the surface records.The April 6 2009 L'Aquila earthquake (Mw 6.3) is the case of study examined.
In the first part of the study some comparisons between recordings and signals generated by GAS are presented considering five array of signals generated at surface and at bedrock respectively and their mean values.

In the second part of the study two types of surface signals have been compared (comparison 1) to verify the procedure for the data extension: a) array of signals at different points obtained propagating with GAS the surface recordings; b) array of signals at different points resulting by amplifying with EERA the signals propagated with GAS at the bedrock.

Finally two types of bedrock signals have been compared (comparison 2) to control the deconvolution procedures: c) array of signals resulting by the propagation with GAS using as inputs the signals obtained by deconvolution of the surface registrations; d) array of signals resulting by deconvolution of the signals obtained with the propagation by GAS on the surface on the base of the surface records. The comparisons are in term of Fourier amplitudes spectra and acceleration response spectra.

3. ACCELERATION RECORDS AND SITE GEOLOGICAL CHARACTERISTICS

The April 6 2009 L'Aquila earthquake (Mw 6.3) main shock has been selected for this study because of it was recorded by more than 50 strong motion stations (RAN) distributed along the Apennines, mostly NW and SE of the source area. The event took place along a normal fault trending NW-SE (strike 147°) with dip SW < 50°. Four of the RAN stations (AQG, AQA, AQV and AQM) are located on the hanging wall side of the fault and form an array transversal to the upper Aterno valley. Records are collected in the Italian Accelerometric Archive ITACA (http://itaca.mi.ingv.it/ItacaNet/)). Spectral acceleration and PGA values for the records of the AQA and AQV stations which present site effects, are generally higher that those recorded at AQG station placed on an outcropping rock. Table 1 shows PGA and magnitude for the main shock and for other two relevant seismic events related near L' Aquila.

Table 1 Date, magnitude and PGA recorded by stations AQA and AQV at Valle Aterno, L'Aquila.

Date	Magnitude (Ml)	Code station AQA	PGA [g]	Code station AQV	PGA [g]
14/10/1997	5,6	1B1_AQA	0,0116	1B2_AQV	0,0167
06/04/2009	6,3	1A1_AQA	0,444	1A2_AQV	0,6557
09/04/2009	5,4	1G1_AQA	0,058	1G2_AQV	0,1555

Figure 1 shows for the stations AQA and AQV (on B soils according to EC8), the profiles of the shear waves recorded by tests for the two soil columns below the stations and the curves for the shear modulus G and the damping D normalized respect to the initial values (Chiarini et al.,2011). The AQV and AQA are on the recent alluvial deposits of the Aterno River.

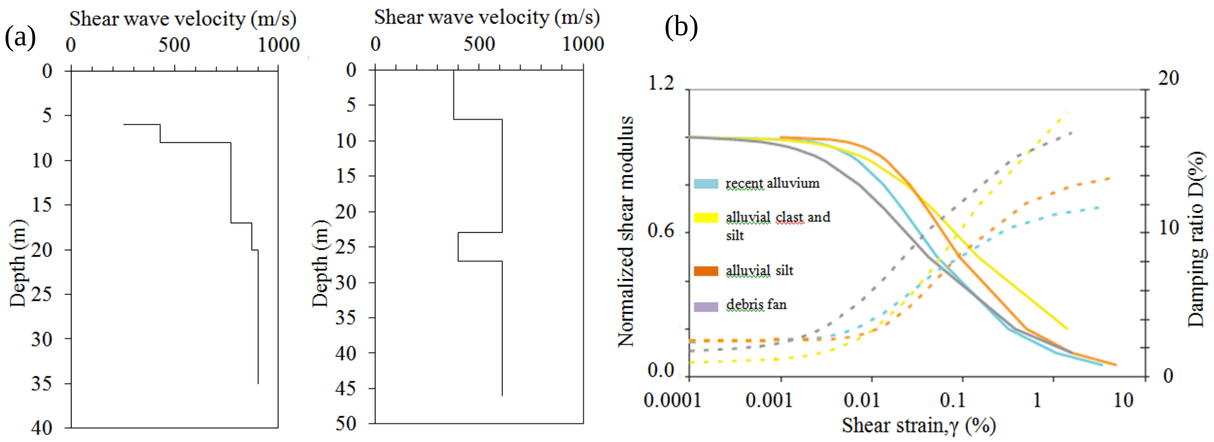

Figure 1. (a) shear wave profiles for the stations AQA and AQV;
(b) normalized shear modulus and damping curves for the type of soils below AQA and AQV stations.

4. UPGRADE OF GAS CODE

In this study the computer code GAS (Nuti and Vanzi, 2005) has been upgraded. The original GAS code generated earthquake samples of a random field matching given response spectra according to Eurocode 8. At the base of the generation a Fourier expansion represents an earthquake acceleration recording at point P in space (Vanmarcke and Fenton, 1991):

$$A_P(t) = \sum_k \left[B_{PK} \cdot \cos(\omega_K \cdot t) + C_{PK} \cdot \sin(\omega_K \cdot t) \right] \tag{1}$$

In equation (1), A_p is the measured acceleration in point P at time t, k is an index varying from 1 to the number of circular frequencies ω_k considered, B_{Pk} and C_{Pk} are the amplitudes of the k-th cosine and sine functions. In the hypothesis that acceleration $A_P(t)$ is produced by a wave moving with velocity V towards a different point Q in space placed at distance X_{PQ} from P, the acceleration at the point Q at time t is given by:

$$A_Q(t) = \sum_k \left[B_{QK} \cdot \cos(\omega_K \cdot (t - \tau_{PQ})) + C_{QK} \cdot \sin(\omega_K \cdot (t - \tau_{PQ})) \right];$$
$$\tau_{PQ} = \frac{X_{PQ}}{V} = X_{PQ} \cdot \left(\frac{\cos(\psi)}{v_{app}} \right) \tag{2}$$

In equation (2) ψ is the angle between the vector of surface wave propagation and the vector that goes from *P* to *Q*, τ_{PQ} is the time delay of the signal and v_{app} is the surface wave velocity. The amplitudes B_{Qk} and C_{Qk} would be respectively equal to B_{Pk} and C_{Pk} if the medium through which the waves travel did not distort them. In a real medium, B_{Pk} is correlated with B_{Qk} and C_{Pk} is correlated with C_{Qk} and the *B*'s and *C*'s are independent. The amplitudes B_{PK} and C_{QK} are statistically independent, for any points *P* and *Q*, and any circular frequency ω_K, with the only exception of B_{PK} and B_{QK} i.e. same circular frequency but different points in space. The same holds for C_{PK} and C_{QK}. The amplitudes are assumed normally distributed with zero mean and this assumption is experimentally verified. In order to quantify the acceleration time histories in different points in space, equations (1) and (2), all is needed is definition of the correlation between amplitudes and of their dispersion, as measured by the variance or, equivalently, of the covariance matrix of the amplitudes.

The covariance matrix Σ of the amplitudes B and C is assembled via independent definition, at each circular frequency ω, of its diagonal terms, the variances in each space point and frequency, and of the correlation coefficients. The diagonal terms Σ_{PP} are quantified via a power spectrum.

The correlation coefficient between the amplitudes is expressed via the coherency function: the form originally proposed by Uscinski (1977) on theoretical grounds and Luco (1987) is retained:

$$\rho = \exp\left(-\omega^2 \cdot X^2 \cdot \left(\frac{\alpha}{\nu} \right)^2 \right) \tag{3}$$

The correlation decreases with increasing distance X and circular frequency ω and increases with increasing soil mechanical and geometric properties as measured by ν/α. α is the incoherence parameter, ν the shear wave velocity. The incoherence parameter ν is the most difficult aspect in the coherency function assessment. However, values in a range as wide as 0.02-0.5 are reported in past experimental studies.

A modified version of GAS considers natural accelerograms as inputs. The upgrade permits to overcome some numerical problems which limited the number of points in which to generate the signals, adds the possibility to introduce directly the recorded accelerograms and consents the use of the numerical power spectra to build the covariance matrix. In particular the previous version of GAS used the Kanai-Tajimi modified function (KTM) for the power spectrum that worked very well in case of spectra according the codes. The KTM curve cannot approximate very well the numeric power spectrum in case of natural accelerograms because of the bell form of this curve does not fit the irregular profile of this power spectrum with many relative peaks of acceleration. Furthermore the code has been tested, extended and refined on the base of the flexible functions already implemented for considering more soils along the wave propagation divided by discontinuities.

5. COMPARISON BETWEEN GAS SIGNAL GENERATION AT SURFACE AND AT BEDROCK

Some comparisons have been performed considering surface and bedrock signals generated by GAS.
In particular the accelerograms recorded at the AQA and AQV stations for the 06-04-2009 main-shock at L' Aquila, are the inputs in GAS for the generation of the surface signals whereas the bedrock signals obtained by means of a deconvolution process of the records AQA and AQV by EERA [J.P. Bardet, et al., 2000], are the inputs for the arrays of signals at the bedrock.

The records of the AQA and AQV stations used are the NS and EW components provided by the database ITACA, filtered with baseline corrected. These recordings have been projected and composed along the line that connects the two stations, arranged at an angle of 69.7° with respect to the azimuth.
The recordings have been temporally corrected by means of a signal time translation using absolute time references (trigger) because of the records have a different trigger.

At the surface the arrays of asynchronous signals are constituted by accelerograms generated in four points (P1-S, P2-S, P3-S, P4-S) 215m equidistant and arranged along the straight line joining the two stations AQA and AQV (Figure 2). Similarly four points (P1-B, P2-B, P3-B, P4-B) 215m equidistant, arranged along the line that connects the two hypothetical stations at the bedrock AQA-B and AQV-B (Figure 2) on the vertical for AQA and AQV respectively, are considered for the generations at the bedrock. The station AQA is located in the point P1-S, the station AQV at the point P3-S whereas the stations AQA-B and AQV-B are located at the bedrock points P1-B and P3-B.

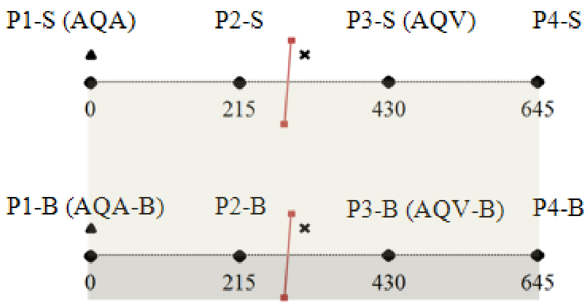

Figure 2. Points P1-S, P2-S, P3-S, P4-S at surfaces
and points P1-B, P2-B, P3-B, P4-B at bedrock for GAS generations; the red line is a soil discontinuity.

GAS generates arrays of asynchronous signals also for the propagation of an earthquake through different soils category (EC8). A discontinuity separates soils of different types and for each type of soil an accelerogram, the PGA of the record, the duration of the event, the speed of the waves on the surface, the incoherency parameter (α) and the speed of the shear wave (ν) are given as inputs.
The two stations AQA and AQV recorded different accelerograms but they are located on the same soil category.

However a soil discontinuity is considered for assigning the two different accelerograms. In particular a discontinuity between P2-S and P3-S on the surface is considered for assigning the power spectrum of AQA to the points P1-S and P2-S and the one of AQV at the points P3-S and P4-S whereas a discontinuity at the bedrock between the points P2-B and P3-B is introduced for assigning the spectrum of AQA-B to the points P1-B and P2-B and the spectrum of AQV-B at the points P3-B and P4-B. The other input data are the same for the two soils divided by the discontinuity: a speed of

surface waves of 2000m/s, a shear wave velocity ν =580m/s and the parameter α = 0.5 have been assigned for the surface soils of type B whereas a speed of surface waves of 3000m/s, a shear wave velocity ν = 800m/s and the parameter α = 0.5 have been considered for the bedrock type A soil.
A first series of analysis has the purpose to evaluate the characteristics of the signals generated by Gas. Five arrays of signals at the points P1-S, P2-S, P3-S and P4-S on the surface and five arrays of signals at the four points P1-B, P2-B, P3-B and P4-B on the bedrock have been considered.

In Figure 3 the Fourier amplitude spectra for the signals generated on the surface at the points P1-S and P3-S relative to five different generations (P1-S-1, P1-S-2, ..; P3-S -1, P3-S-2, ...), the average spectrum of the five generations (Mean-P1-S, Mean-P3-S) and the Fourier amplitude spectra of the input records on the surface (AQA, AQV) are shown. From the comparison between the average spectrum and the one of the AQA record at the point P1-S, it is observed that the average spectrum presents amplitudes generally higher than ones of AQA, smaller differences for frequencies below 7Hz and greater differences for the other frequencies. Similar considerations can be made for the signals in P3-S even if a greater difference between the average spectrum and the spectrum of the record AQV is also observed in the frequency range between 3.3 and 4.3Hz.

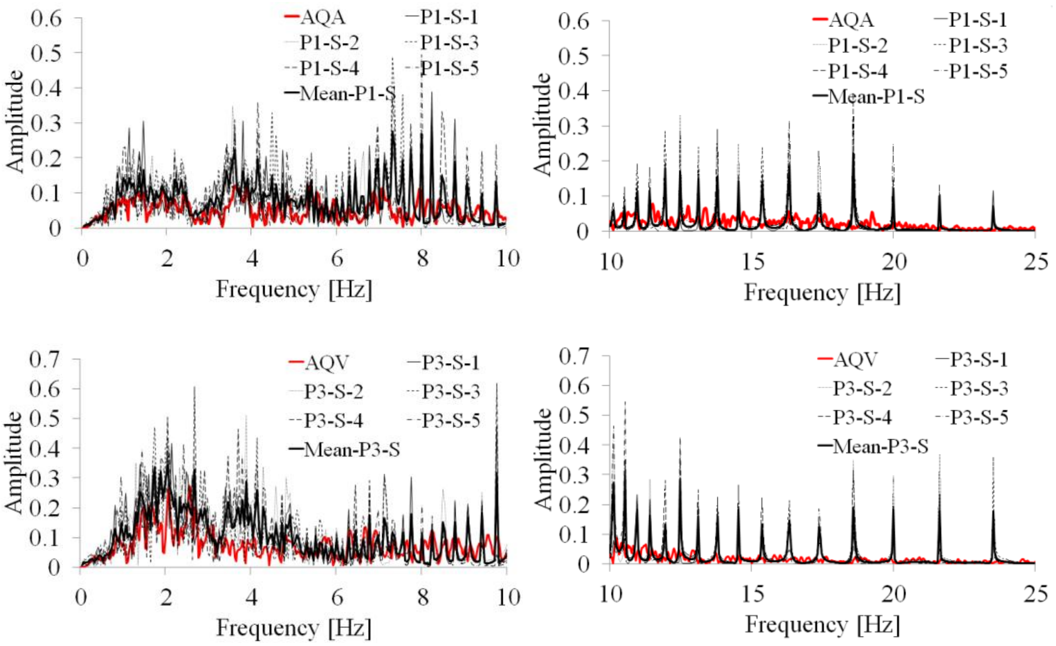

Figure 3. Comparison between Fourier amplitude spectra of accelerograms at points P1-S (P1-S-1, P1-S-2, P1-S-3, P1-S-4, P1-S-5) and P3-S (P3-S-1, P3-S-2, P3-S-3, P3-S-4, P3-S-5) for five array of surface signals generated by GAS, average curves of the five Fourier amplitude spectra in P1-S and P3-S (Mean-P1-S, Mean-P3-S) and Fourier amplitude spectra of the accelerograms recorded at P1-S and P3-S (AQA, AQV).

In Figure 4 the acceleration spectra of the signals generated by GAS at the surface, the average spectra of the generated accelerograms, and the acceleration spectra of the input records are presented. The average spectrum is in good agreement with the spectrum of recording at P3-S while greater differences are observed at P1-S where the average spectrum is lower than one of the records for almost all periods.

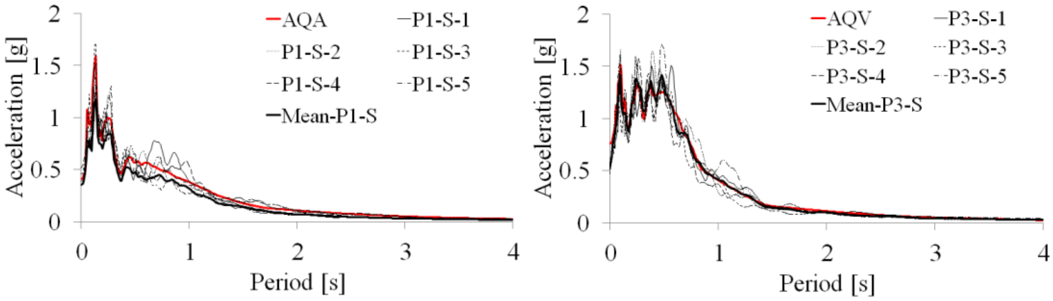

Figure 4. Comparison between acceleration spectra of accelerograms at points P1-S (P1-S-1, P1-S-2, P1-S-3, P1-S-4, P1-S-5) and P3-S (P3-S-1, P3-S-2, P3-S-3, P3-S-4, P3-S-5), mean curves of the five spectra in P1-S and P3-S (Mean-P1-S, Mean-P3-S) of five array of surface signals generated by GAS and acceleration spectra of accelerograms recorded at P1-S and P3-S (AQA, AQV).

In Figure 5 the Fourier amplitudes spectra for the signals generated at the bedrock in P1-B and P3-B relative to five different generations (P1-B-1, P1-B-2, ..; P3-B-1, P3-B-2, ...), the average spectra of the five generations at the bedrock (Mean-P1-B, Mean-P3-B) and the Fourier amplitudes spectra of the input records at the bedrock (AQA -B, AQV-B) are given. It is noted that at the bedrock in terms of amplitudes at the point P1-B, there are greater differences between the average spectrum (Mean-P1-B) and the spectrum AQA-B for frequencies above 7Hz but also for a range of frequencies between 1 and 1.8 Hz. In P3-B the agreement is very good for frequencies below 7 Hz and after this frequency there are differences similar to those found for the signals at P1-B.

In Figure 6 the acceleration spectra of the signals generated by GAS at the surface, the average spectra of the generated accelerograms, and the acceleration spectra of the input records are shown. The average spectrum is in good agreement with the spectrum of AQV-B at P3-B while greater differences are observed in P1-B between the periods between 0.5 and 1.1s.

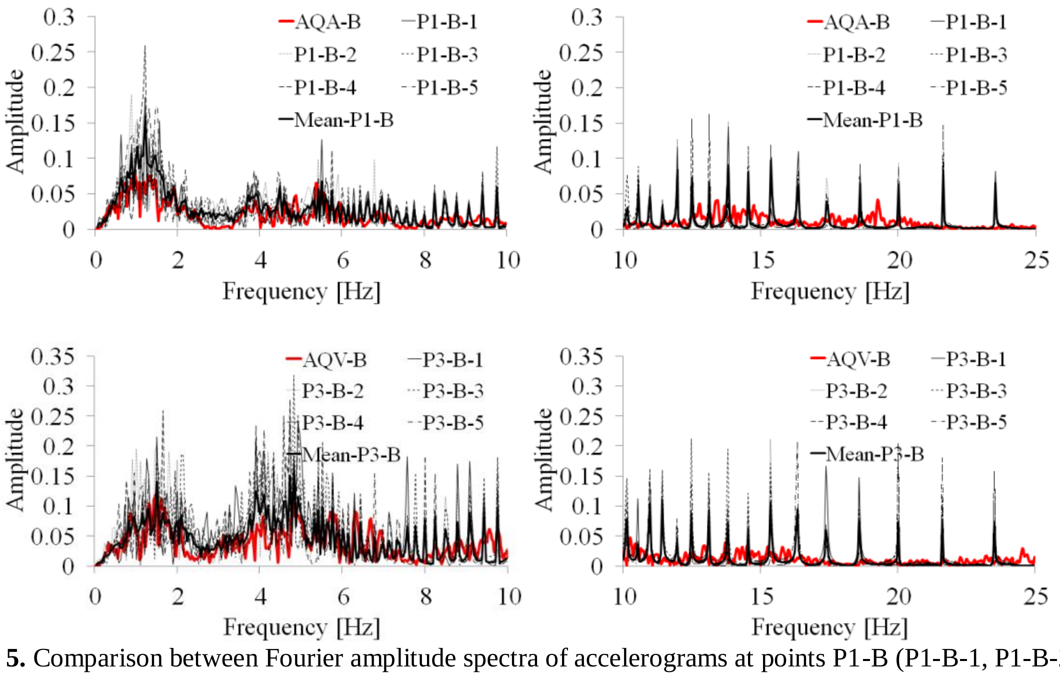

Figure 5. Comparison between Fourier amplitude spectra of accelerograms at points P1-B (P1-B-1, P1-B-2, P1-B-3, P1-B-4, P1-B-5) and P3-B (P3-B-1, P3-B-2, P3-B-3, P3-B-4, P3-B-5) of five array of bedrock signals generated by GAS, mean curves of the five amplitude spectra in P1-B and P3-B (Mean-P1-B, Mean-P3-B) and Fourier amplitude spectra (AQA-B, AQV-B) of accelerograms obtained at bedrock by deconvolution of recorded signals at P1-S and P3-S.

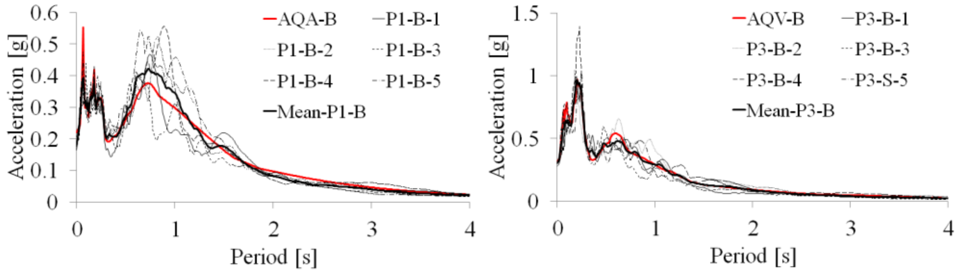

Figure 6. Comparison between acceleration spectra of accelerograms at points P1-B (P1-B-1, P1-B-2, P1-B-3, P1-B-4, P1-B-5) and P3-B (P3-B-1, P3-B-2, P3-B-3, P3-B-4, P3-B-5) of five array of bedrock signals generated by GAS, mean curves of the five spectra in P1-B and P3-B (Mean-P1-B, Mean-P3-B) and acceleration spectra (AQA-B, AQV-B) of accelerograms obtained at bedrock by deconvolution of recorded signals at P1-S and P3-S.

Figure 7 shows comparison 1 in terms of Fourier amplitude spectra for the signals at the surface. The amplitudes of the signals P1-S-CB and P3-S-CB resulting by amplification of the ones generated by GAS at the bedrock are greater at points P1-S and P3-S near the frequency of 3Hz and for frequencies above 7 Hz. The greatest differences at P1-S are of about 0.291 and 0.131 for the frequencies of 2.95 Hz and 7.98 Hz, whereas at P3-S the differences are of about 0.342 and 0.277 for the frequencies of 2.7 Hz and 8.79 Hz. In Figure 8 comparison 2 in terms of Fourier amplitudes spectra is shown. At the point P1-B and P3-B the agreement between the two sets of signals is good and there are not great differences as found in case of comparison 1, exception of a few frequencies.

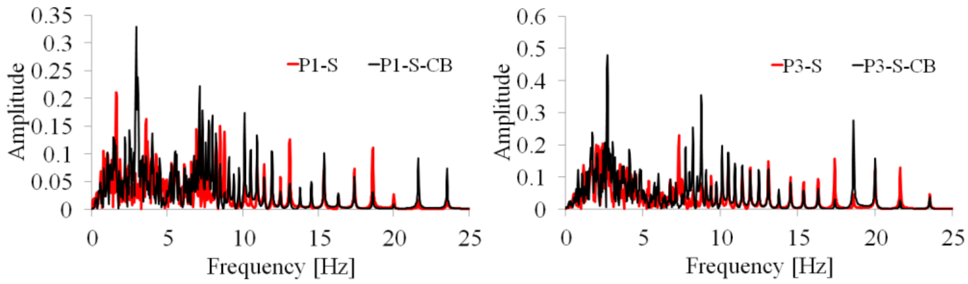

Figure 7. Comparison 1 between Fourier amplitudes spectra of accelerograms at P1-S and P3-S generated by GAS on surface (P1-S, P3-S) and ones obtained by convolution of the bedrock accelerograms generated by GAS at P1-B and P3-B (P1-S-CB, P3-S-CB).

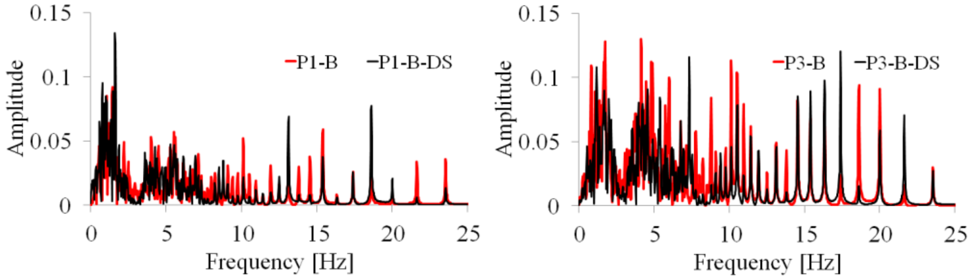

Figure 8. Comparison 2 between Fourier amplitudes spectra of accelerograms at P1-B and P3-B generated by GAS on Bedrock (P1-B, P3-B) and ones obtained by deconvolution of the surface accelerograms generated by GAS at P1-S and P3-S (P1-B-DS, P3-B-DS).

In Figure 9 the comparison 1 between the acceleration spectra for the points P1-S and P3-S on the surface is presented. From this comparison a good agreement in P1-S and P3-S is observed. The greatest differences are of about 0.792 for a period of 0.13s and of 0.4866 for a period of 0.34s at P1-S where the spectrum P1-S-CB is greater. In the point P3-S the spectrum P3-S-CB is greater and a difference of 0.846 for a period of 0.12s is observed whereas for the period of 0.44s the spectrum P3-S is greater with a difference of 0.314.

In Figure 10 the comparison 2 between acceleration spectra at the bedrock at points P1-B and P3-B is shown. The spectra are comparable with differences contained and maximum values smaller than ones observed for comparison 1 at the surface. A better comparison is possible by comparing average curves for n signals generations.

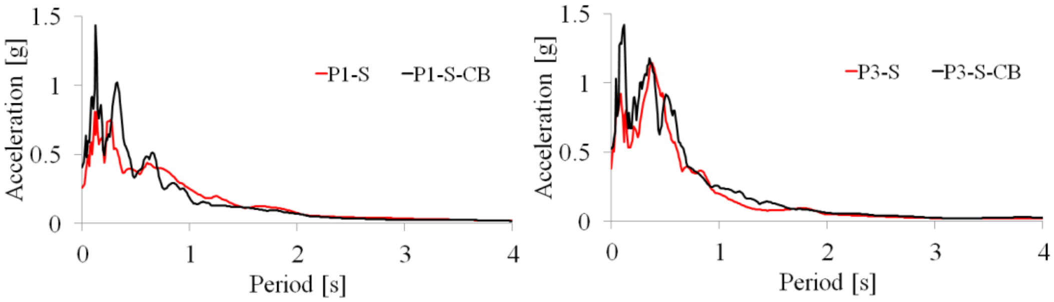

Figure 9. Comparison 1 between acceleration spectra of accelerograms at P1-S and P3-S generated by GAS on surface (P1-S,P3-S) and ones obtained by amplification of the bedrock accelerograms generated by GAS at P1-B and P3-B (P1-S-CB, P3-S-CB).

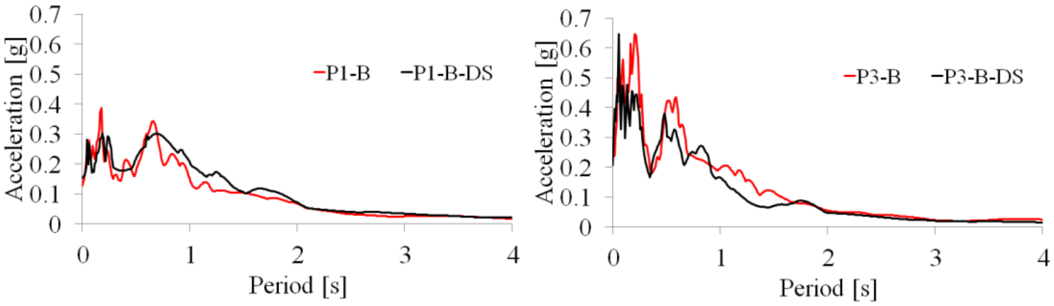

Figure 10. Comparison 2 between acceleration spectra of accelerograms at P1-B and P3-B generated by GAS on bedrock (P1-B,P3-B) and ones obtained by deconvolution of the surface accelerograms generated by GAS at P1-S and P3-S (P1-B-DS, P3-B-DS).

6. CONCLUSIONS

Asynchronous seismic actions are a very important issue for the design of structures with great extension as bridge or dams. The software GAS, a program implemented in MATLAB for the generation of asynchronous seismic signals, has been already successfully used assigning as inputs the EC8 response spectra.

This program has been updated solving some numerical problems, considering propagation trough different type of soils and using the numerical power spectrum to build the covariance matrix necessary for the signals generation, more suitable in case of irregular natural accelerograms.

The calibration of an appropriate coherence function necessary to improve the program results requires many experimental data not available.

In this study a procedure for increase “artificially” the number of natural accelerograms for a given earthquake on the base of a few registrations has been proposed.

In particular the accelerograms recorded at two stations AQA and AQV of the Aterno Valley during the Main Shock of the L'Aquila earthquake (06-04-2009), have been used to test this procedure. The characteristics of the soil below these stations are known well by cross hole tests and soil perforations. The procedure is simple: calculating bedrock signals by deconvolution of the surface accelerograms; using these signals as input in GAS to generate an array of asynchronous accelerograms at the bedrock and amplifying the bedrock signals considering for each point the above stratigraphy and soil characteristics. The propagation at the bedrock through one type of soil with more controlled characteristic is more reliable. The amplification of signals by means of EERA is well verified.

The procedure permits to obtain superficial signals also in case of propagation in different soil if the soil characteristics are known by tests.

In the first part of the study some comparisons between recordings and signals generated by GAS have been presented considering five array of signals generated at surface and at bedrock respectively and their mean values. The signals generated are in good agreement with the records used as inputs in term of acceleration spectra but differences still arise especially in term of Fourier amplitudes spectra due to the coherence function used (Luco et al. 1986). Therefore it will be necessary to calibrate a new suitable coherence function. In the second part of the study two types of surface signals have been compared (comparison 1) to verify the procedure for the data extension: a) array of signals at different points obtained propagating with GAS the surface recordings; b) array of signals at different points resulting by amplifying with EERA the signals propagated with GAS at the bedrock. The first results of this extension procedure are good and these results can be improved calibrating a coherence function on the base of the recorded accelerograms at different stations for more seismic events.

Finally two types of bedrock signals have been compared (comparison 2) to control the deconvolution procedures: c) array of signals resulting by the propagation with GAS using as inputs the signals obtained by deconvolution of the surface registrations; d) array of signals resulting by deconvolution of the signals obtained with the propagation by GAS on the surface on the base of the surface records.
The results are encouraging but there are some differences. However a better confrontation will be done considering more signal generations and the mean values. Furthermore noise in signals due to the type of seismic event considered (near-fault), may justify some differences. After removing this noise the comparison 1 and 2 will be repeated.

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REFERENCES

Bardet, J. P., Ichii K., Lineera, C. H. (2000) Equivalent-linear Earthquake site Response Analysis , University of southern California, Department of Civil Engineering.
Carnevale L., Lavorato D., Nuti C., Vanzi I. (2010) Response of continuous deck bridges to non-synchronous seismic motion, Sustainable Development Strategies for Constructions in Europe and China, Rome 19-20 April 2010.
Chiarini,M., D'onofrio,A., Evangelista,L., Penna ,A., Silvestri,F. (2011) The role of site effects and near source seismic actions on ground and buildings response at some sites across the Aterno river valley (italy),5ICEGE Santiago, Chile.
Clough, R. W., Penzien, J., (2002) Dynamics of structures, McGraw-Hill, Inc., New York, 1975, 634 pages Comité Européen de Normalisation, CEN, Eurocode 8: design of structures for earthquake resistance, Draft n. 2, doc cen/tc250/sc8/n320, May 2002
Der Kiureghian, A., Neuenhofer, A., (1991) A response spectrum method for multiple-support seismic excitations, UCB/EERC-91/08, Berkeley: Earthquake Engineering Research Center, University of California, Aug. 1991, 66 pages
Der Kiureghian, A., Neuenhofer, A., (1992) Response spectrum method for multi-support seismic excitations, Earthquake Engineering & Structural Dynamics, 21, 8, Aug. 1992, pages 713-740
Gómez, J. E., Filz, G. M. and Ebeling, R. M. (2000a). Development of an improved numerical model for concrete-to-soil interfaces in soil-structure interaction analyses, Report 2, Final study. ERDC/ITL TR-99-1, US Army Corps of Engineers, Engineer Research and Development Center.
Hao, H., (1998) A parametric study of the required seating length for bridge decks during earthquake, Earthquake Engineering & Structural Dynamics, 27, 1, Jan. 1998, pages 91-103
ITACA (ITalian ACcelerometric Archive, http://itaca.mi.ingv.it) INGV, National protection
Luco, J. E., Wong, H. L., (1986) Response of a rigid foundation to a spatially random ground motion, Earthquake Engineering & Structural Dynamics, 14, 6, Nov.-Dec. 1986, pages 891-908
Luco, J. E., Mita, A., (1987) Response of circular foundation to spatially random ground motion, Journal of Engineering Mechanics, 113, 1, Jan. 1987, pages 1-15
Monti, G., Nuti, C., Pinto, P.E., Vanzi, I., (1994) Effects of non Synchronous Seismic Input on the Inelastic Response of Bridges, II international workshop on seismic design of bridges, Queenstown, New Zeland, 1994
Monti, G., Nuti, C., Pinto, P. E., (1996) Nonlinear response of bridges under multisupport excitation, Journal of Structural Engineering, 122, 10, Oct. 1996, pages 1147- 1159.
Nuti, C., Vanzi, I., (2005) Influence of earthquake spatial variability on differential soil displacements and sdf system response, Earthquake Engineering and Structural Dynamics, John Wiley and Sons, Volume 34, Issue 11, 1353-1374.