Risposta sismica locale analizzata dal confronto tra due codici numerici: il caso di Castelnuovo Garfagnana (Toscana)

Seismic site response analysis carried out by two numerical codes comparison: the case of Castelnuovo Garfagnana (Tuscany)

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Riassunto. In questo lavoro sono state elaborate alcune modellazioni numeriche allo scopo di valutare la risposta sismica locale su una sezione del territorio di Castelnuovo Garfagnana (Lucca). La zona, molto importante da un punto di vista storico, è caratterizzata da un'alta sismicità. Le proprietà del suolo, relative alle caratteristiche stratigrafiche ed ai parametri meccanici, sono state ottenute mediante diverse indagini geognostiche. Allo scopo di ottenere una migliore comprensione dei fenomeni sismici locali, sono stati utilizzati due codici commerciali, sviluppati con metodi numerici di diversa concezione. Pertanto è stato applicato il FLAC2D i cui risultati sono stati quindi confrontati con i risultati ottenuti mediante il QUAD4M. Il primo codice si basa su un approccio alle Differenze Finite, mentre il secondo è stato sviluppato mediante il Metodo agli Elementi Finiti con possibilità di considerare diversi tipi e filosofie di condizioni al contorno. Inoltre sono state studiate due differenti forme analitiche delle accelerazioni associate alle onde sismiche. Questo tipo di approccio ha consentito una ottimizzazione della risposta sismica locale del sito oggetto dello studio, allo scopo di ottenere migliori indicazioni per piani di controllo territoriale e di microzonazione.

Parole chiave: amplificazione locale, risposta sismica, FLAC2D, modellazione numerica

Abstract. In this paper we have performed numerical calculations to estimate the local seismic response along a section at Castelnuovo Garfagnana (Tuscany - Italy). The area, very important by a historical point of view, is characterized by a high seismicity. The soil properties regarding the stratigraphic feature and the dynamical mechanical parameters have been provided by many geognostic surveys. In order to achieve a better understanding of the local seismic phenomena, two numerical codes based on differently conceived numerical algorithms have been utilized. Firstly FLAC2D code has been applied and then the results have been compared with QUAD4M calculations. The former is based on a Finite Difference procedure, while the latter is built up by a Finite Element Method approach with different boundary constrains philosophy. Furthermore different wave accelerations have been studied. This kind of approach has allowed an optimization of the Castelnuovo's seismic site response in order to provide better indications about territory management and microzoning planning.

Keywords: local amplification, seismic site response, FLAC2D, numerical modelling.

INTRODUCTION

The Castelnuovo's site has been analysed through a very detailed geological, geotechnical and geophysical surveys which enhanced a particular peculiarity of its underground stratigraphy, composed by several kind of lithotypes, each very different to the other ones by both physical and mechanical points of view. Fig.1 shows the analyzed section with the implemented numerical grid suited to the geological heterogeneities. Along this section a tectonic discontinuity links clay formation with a stony formation. The complexity of the system implies, naturally, the employment of a 2d numerical tool in order to carry out local seismic amplification. Thus a Finite Difference Method computer code (FLAC_4.0, 2000), suitable to make integrated bi-dimensional modelling regarding mechanical, geotechnical, hydrodynamic and seismic problems has been applied. An important feature of this numerical tool is to work by a lagrangian approach in evaluating non homogenous and time variable displacements.

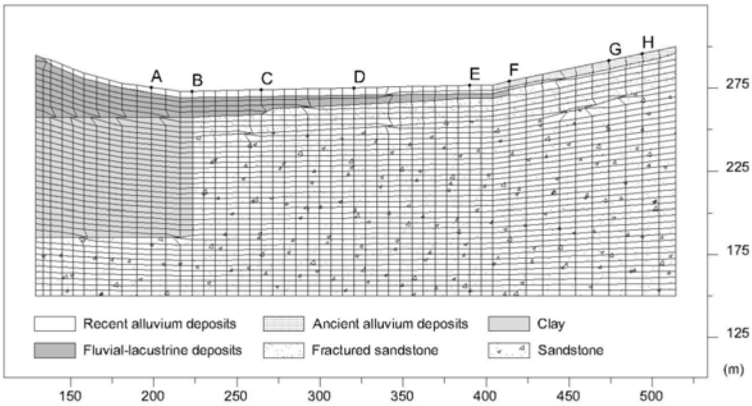

Fig. 1. Simplified modelling section with monitored points labeled A-H.
Fig. 1. Sezione semplificata di modellazione con indicati i punti monitorati.

The dynamic numerical modelling by FLAC implies, besides the identification of the most appropriate constitutive equations (linear and non linear elasticity, perfect plasticity and so on), to fix the value of some other parameters and characteristics like for example:

- global damping depending on the material type, on the system morphologies, on the "radiation term" through the boundaries, on the seismic wave: among others different options, "local damping" for wave with a simplified shape or "Rayleigh damping" for a more realistic simulation, as in our cases, are available;
- the setting of non congruent volumetric strain accumulation (baseline correction);
- "G modulus degradation" due to the different deformation level of numerical grid.

Fig. 2 shows system constrains and the three different selected directions of the seismic waves input as well. The employed accelerogram regarded a 5.5 magnitude earthquake 4.2 km in depth (PERGALANI et al., 2000; FERRINI et al., 2001) fig. 3. Conformally with the Italian Earthquake Catalogue (GRUPPO DI LAVORO CPTI, 1999), seismic inputs have been defined as the uniform probability spectrum characterized by a 475 years recurrence time (FERRINI et al., 2001). Then, seismic inputs have been calculated considering the influence of seismogenetic bordering areas as well (SCANDONE, 1999), in accordance with the attenuation law due to SABETTA & PUGLIESE (1996). Tables 1 and 2 show the numerical values of the parameters included in the calculations. From table 2, on the base of an exponential correlation law, variations of the G/G_o ratio and the D damping numerical values, utilized by the "equivalent linear model" implemented in FLAC, have been deduced as a function of the shear strain γ, equations 1-4:

sandstone: $$\frac{G}{G_o}=\frac{1}{1+10\cdot\gamma^{0.98}}\,; \qquad D=1.2\cdot10^{6}\cdot e^{-17\frac{G}{G_o}} \qquad (1)$$

fractured sandstone: $$\frac{G}{G_o}=\frac{1}{1+65\cdot\gamma^{1.26}}\,; \qquad D=17\cdot(1+0.2\cdot\gamma)^{-1.2} \qquad (2)$$

clay, fluvio – lacustrine deposits, ancient alluvium: $$\frac{G}{G_o}=\frac{1}{1+65\cdot\gamma^{1.15}}\,; \qquad D=25\cdot e^{-2.26\cdot\frac{G}{G_o}} \qquad (3)$$

recent alluvium: $$\frac{G}{G_o}=\frac{1}{1+16\cdot\gamma\cdot(1.2+10^{-20\cdot\gamma})}\,; \qquad D=0.8+18\cdot(1+0.15\cdot\gamma^{-0.9})^{-0.75} \qquad (4)$$

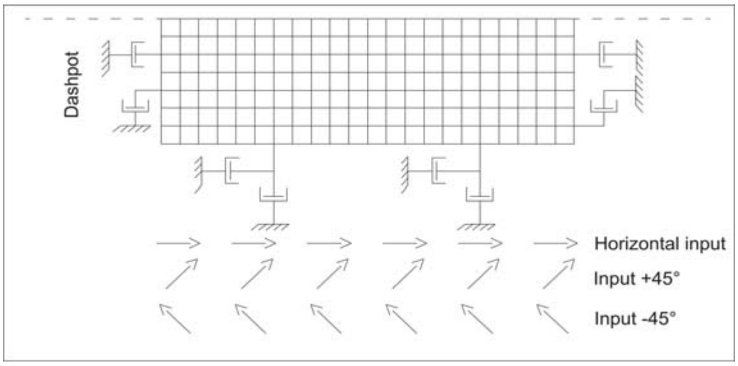

Fig. 2. FLAC numerical gridding with boundary viscous conditions and the selected directions of the seismic inputs.
Fig. 2. Griglia numerica utilizzata con il FLAC considerando condizioni al contorno viscose e differenti direzioni dell'input sismico

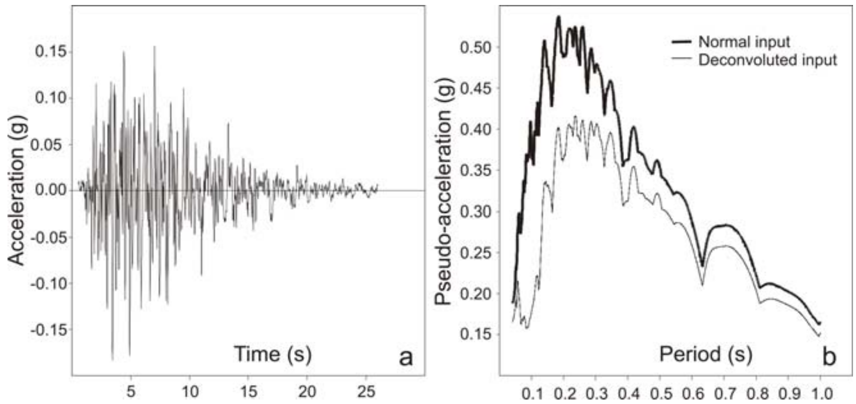

Fig. 3. Input accelerogram (a); normal and deconvoluted inputs spectra (b).
Fig. 3. Accelerogramma di input (a); spettri di input normali e deconvoluti (b)

Tab. 1. Physical and mechanical parameters: V_s (shear wave velocity); γ_n (unit weight); ν (Poisson's coefficient); G_o (initial shear stiffness modulus).
Tab. 1. Parametri fisici e meccanici: V_s (velocità onde di taglio); γ_n (peso di volume); ν (coefficiente di Poisson); G_o (modulo di rigidezza iniziale al taglio).

Litotype	V_s (m/s)	γ_n (kN/m^3)	ν	G_o (MPa)
Sandstone	1000	25	.4	2100
Fractured sandstone	600	23	.4	756
Clay	800	21	.4	1344
Fluvial-lacustrine deposits	500	21	.44	525
Ancient alluvium	380	19	.44	274.4
Recent alluvium	250 – 300	19	.3	143.7

Tab. 2: Values of stiffness (G normalized by G_o) and of internal damping coefficient ξ (%) functions of the shear strain γ (%).
Tab. 2. Valori della rigidezza (G normalizzato rispetto a G_o) e del coefficiente di smorzamento interno ξ (%) funzioni della deformazione al taglio γ (%).

Geological Formation	Shear strain (γ %)					
		.0001	.001	.01	.1	1
Sandstone	G/G_o	1	1	0.8	0.75	
	ξ (%)	0.05	0.05	1.5	4	
Fractured sandstone	G/G_o	1	1	0.77	0.35	
	ξ (%)	0.05	0.05	2	8	
Clay, Fluvial-lacustrine deposits, ancient alluvium	G/G_o	1	.97	.75	.17	.015
	ξ (%)	2.6	2.7	4.5	16	22
Recent Alluvium	G/G_o	.98	.95	.78	.38	.06
	ξ (%)	.95	1.5	3.9	10.8	17

FLAC CODE VALIDATION

To test capability in analyzing sites dynamical response, a simple FLAC modeling has been compared with the results obtained by QUAD4M (HUDSON et al., 1994), a much more widely applied code in the seismic analysis field, based on Finite Element Method approach. The testing section was built up by two horizontal layer: an upper recent alluvium deposits on a lower intact bedrock, (fig. 4). Two different kind of seismic inputs have been successively applied: a simple harmonic wave (fig. 5a) and then a more realistic seismic input, fig. 5b. The following equations are the related accelerograms:

$$a = 0.2\sin(2\pi t) \qquad (5)$$

$$a = \sqrt{0.375e^{-2.2t} \times t^{8.0}} \times \sin(6\pi t) \qquad (6)$$

Further, to compare the two code results, three different points, labeled as 1, 2 and 3 (fig.4), have been virtually “monitored” by an amplification point of view. Regarding the first type of seismic input, equation (5), FLAC response, displayed in fig. 6, shows two set of spikes, one at 0.4 s period and the other at 1 s period.
The results obtained by QUAD4M, considering seismic input just applied only on the base of the section shows a spike at 1 s period as well, whose amplitude is comparable to the corresponding FLAC value, while at 0.4 s period the spike value is very low and actually it is absent, fig. 7a. Calculated amplifications at points 1 and 3 by FLAC are coincident, while at point 2 the amplification is slightly higher than the others. Anyway the maximum pseudo-acceleration value oscillates around 2.4g. Applying seismic inputs on both the base and the lateral boundary of the simplified section, QUAD4M results display spikes at high frequency as well and a clear differentiation of the seismic response at points 1 and 3 which are, however, deamplified, while the central point 2 is extremely amplified (around 2.9g), fig. 7b. About results obtained by a more actual seismic input, equation (6), maximum acceleration value calculated by FLAC is 5.9g at the central point and 3g at the external points, fig. 8. Although QUAD4M application shows a similar differentiation among calculated amplification values at the three points, a lower value (5.0g) at the central point is obtained, fig. 9a. If seismic input is applied laterally, as well, QUAD4M maximum pseudo-accelerations are clearly higher, fig. 9b.
From the previous discussion it follows that the modeling difference between the two codes depends essentially on how the lateral boundaries are considered. FLAC uses the quiet-boundary scheme proposed by LYSMER (1978) involving dashpots attached independently to the boundary in the normal and shear

direction; while QUAD4M considers the "borders grids" as finite elements similarly to the other ones without any further specific constrains. In order to obtain similar results it would be necessary to work, each time, on lateral boundary of the models.

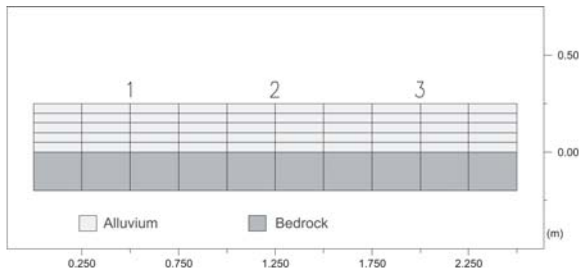

Fig. 4. Simplified testing section utilized to compare FLAC and QUAD4M results obtained at the three selected monitored points labeled 1, 2, 3.
Fig. 4. Sezione semplificata utilizzata per il confronto tra i risultati ottenuti con il FLAC ed il QUAD4M nei punti 1, 2, 3, selezionati per il monitoraggio.

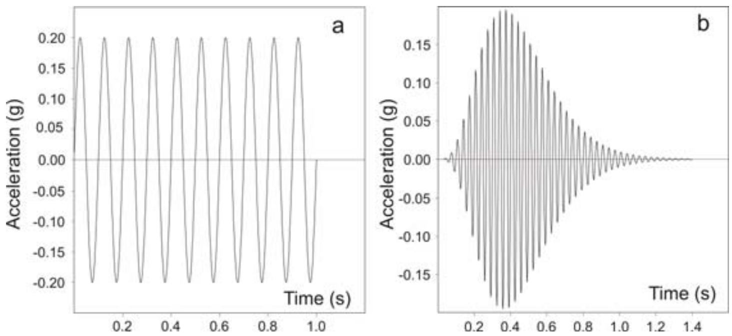

Fig. 5. Wave shapes of the comparison analysis: a) equation (5); b) equation (6).
Fig. 5. Forme delle onde utilizzate per le analisi di confronto:a) equazione (5); b) equazione (6).

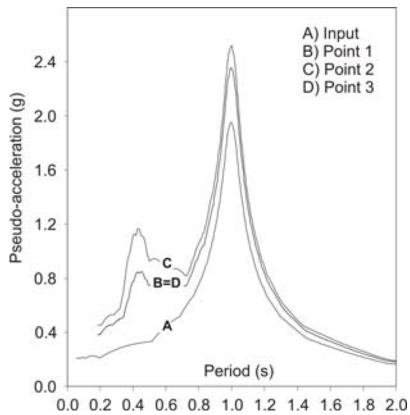

Fig. 6. FLAC spectra related to equation (5) with the evidence of identical responses of points 1 and 3.
Fig. 6. Spettri del FLAC relativi all'equazione (5) che evidenziano la similitudine di risposta tra i punti 1 e 3

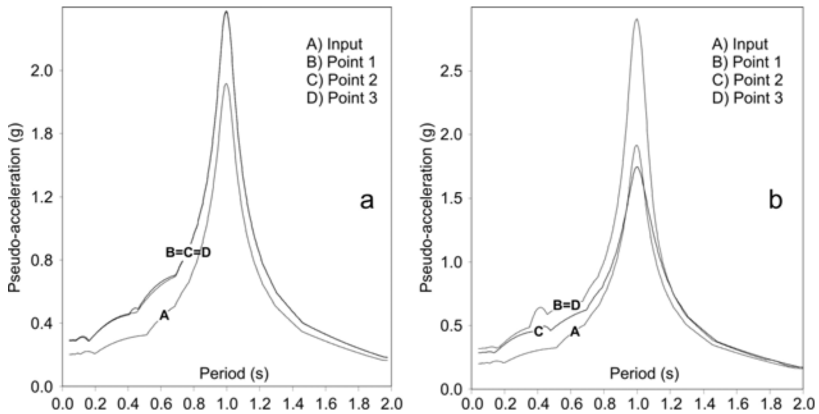

Fig. 7. QUAD4M spectra regarding equation (5): (a) seismic input only on the base, considering free the lateral boundary (the three points responses are identical); (b) seismic input both on the base and on the lateral boundary (responses of points 1 and 3 are identical).
Fig. 7. Spettri di risposta del QUAD4M relativi all'equazione (5): (a) input sismico solo alla base considerando liberi i bordi laterali (le risposte dei tre punti sono identiche); (b) input sismico sia alla base sia sui bordi laterali (solo le risposte dei punti 1 e 3 sono identiche).

RESULTS ANALYSIS

Numerical results have been carried out considering seismic inputs (in terms of acceleration) applied both horizontally and inclined by ± 45° at the base of the section reported in fig. 1. The possibility to introduce inclined seismic inputs is a feature particularly important regarding sections showing a complex geology and an asymmetric topography. Also, the parameters G/G_o and D have been considered both as constants and as functions of shear strain. The results, obtained by linear and equivalent elastic analyses later discussed, are reported in the successive figures showing the pseudo accelerations (defined as the elastic response spectra with a 5% damping) function of the period, at specific points on the topographic surface as reported in fig. 1.

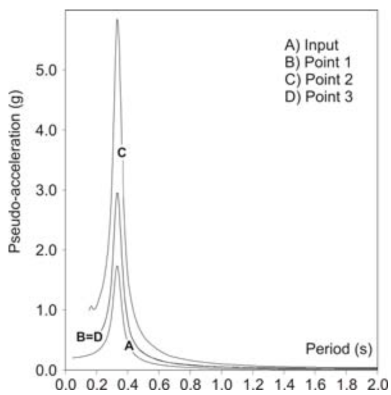

Fig. 8. FLAC spectra regarding equation (6); responses of points 1 and 3 are identical.
Fig. 8. Spettri del FLAC relativi all'equazione (6); le risposte dei punti 1 e 3 sono identiche.

– *Linear elastic analysis*
This kind of analysis considers G/G_o and D as constant parameters. Their values are deduced on the base of the maximum shear strain calculated in a preliminary phase step that, for our system, was equal to 0.01 %. For a horizontal seismic input, fig. 10a shows response spectra with absolute maximum values as higher as closer to the central point of the section. The highest pseudo-acceleration value (1.36g) is experienced at the point D with a 0.3 s period. Point H pseudo-accelerogram is deamplified. The +45°

inclined seismic input induces response spectra whose absolute maximum is experienced, among virtually monitored points, at point C (0.94g), fig. 10b. Then it follows points D (0.82g) and B (0.6g), all at 0.3 s period. For a -45° inclined seismic input different diagrams, from the above ones, have been obtained, with pseudo-accelerations focused at points G and F, showing similar maximum values (0.77 and 0.78g) at a 0.25 s period, fig. 10c.

– *Equivalent linear analysis*

The previous analysis have been carried out again but, this time, varying G/G_o and D at each iteration, as a function of γ, following the specific lithotypes equations (1, 2, 3 and 4) to perform an equivalent linear analysis. For a horizontal seismic input points E, C and D still show maximum values of pseudo-acceleration, fig.10d. The absolute maximum value is found at point E (1.36g) for a 0.12 s period. Point H is still deamplified. The +45° inclined seismic input induces equal maximum values at points B and C (0.82g, T=0.24s). Maximum values are concentrated in 0.15-0.35 s periods range, fig. 10e. The -45° input induced, as in the case of constant parameters, maximum values at points E (0.74g) and F (0.7g) both of them at a 0.24 s period, fig. 10f.

The results discussed so far, carried out by FLAC code, have been compared with data obtained by PERGALANI et al. (2000) and FERRINI et al. (2001) applying QUAD4M on the same Castelnuovo's site section. The results obtained by these Authors well matching the results achieved by the FLAC equivalent linear analysis for similar calculation method approach.

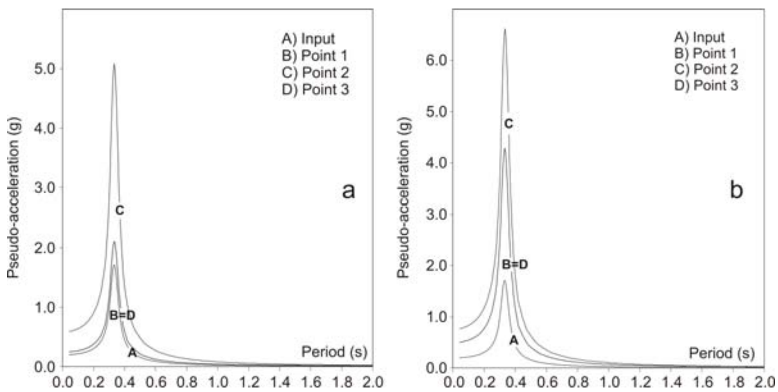

Fig. 9. QUAD4M spectra regarding equation (6), seismic inputs applied: (a) only on the base (responses of points 1 and 3 are identical); (b) both on the base and on the lateral boundary (responses of points 1 and 3 are identical).

Fig. 9. Spettri relativi all'equazione (6), input sismico applicato: (a) solo sulla base (le risposte dei punti 1 e 3 sono identiche); (b) sia sulla base, sia sui bordi laterali (le risposte dei punti 1 e 3 sono identiche).

FLAC maximum pseudo-accelerations are slightly higher and with a lower associated frequencies (T≅0.3s) than QUAD4M evaluations, as it is inferred observing in fig. 11 comparison diagrams regarding the two most amplified points in both the analysis (E and D). Point H is deamplified in all FLAC simulations, while it displays an anomalous behavior compared with the other points and translated to high period in QUAD4M calculations. This kind of response, reasonably, is due to boundary effects associated to the utilized algorithm type.

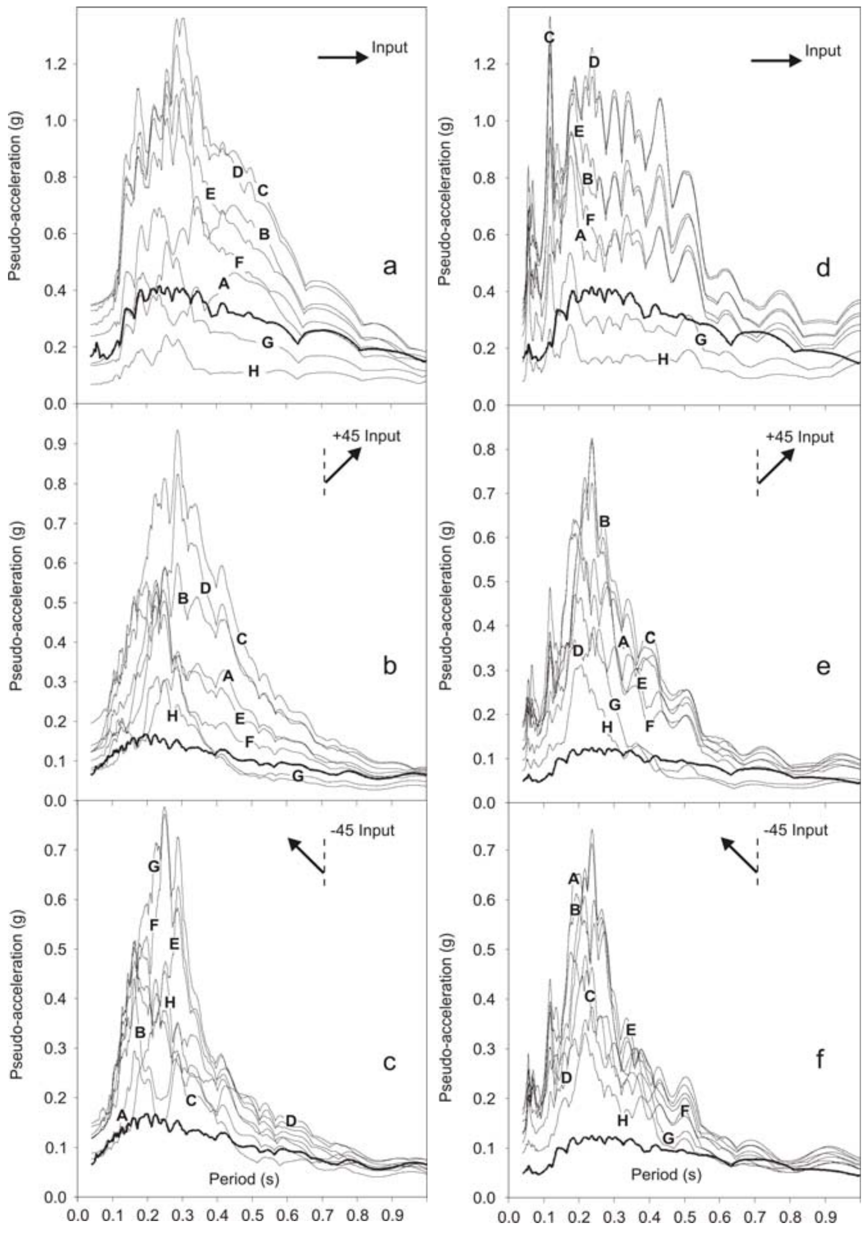

Fig. 10. Response spectra regarding “linear elastic analysis” imposing: (a) horizontal input; (b) +45^0 inclined input; (c) -45^0 inclined input. Response relative to “equivalent linear elastic analysis”: (d) horizontal input; (e) +45^0 inclined input; (f) -45^0 inclined input.

Fig. 10. Spettri di risposta relativi ad “analisi elastiche lineari” imponendo: (a) input orizzontale; (b) input inclinato di +45^0; (c) input inclinato di -45^0. Spettri relativi ad “analisi elastiche lineari equivalenti” imponendo: (d) input orizzontale; (e) input inclinato di +45^0; (f) input inclinato di -45^0.

CONCLUSIONS

In this paper a Finite Difference Method approach code (FLAC) has been applied on a representative section of Castelnuovo Garfagnana’s site (Tuscany – Italy), in order to refine investigation about local seismic response. Thus the FLAC results have been compared with the results carried out by QUAD4M, a much more widely applied code in the seismic analysis field. The analysis of the results allow to state that

FLAC code seismic calculation are comparable to QUAD4M evaluations. The comparison based on the same damped pseudo-sinusoidal wave input, equation (6), pointed out a well matching of the two code results, in particular regarding the frequency in correspondence of the maximums of pseudo-acceleration. On the other hand the intensity of the amplification was affected by the modality of the selected QUAD4M seismic inputs. For QUAD4M evaluations, the importance of the particular input type and, overall, how it is applied, is clearly pointed out comparing fig. 6 to 7b in which higher frequencies peaks appear only when lateral boundary seismic inputs are applied. FLAC analysis, carried out by a variable seismic incident angle, show different surface responses and different surface seismic polarization points, highlighting the code capability to consider, in a sufficiently reasonable way, diverted seismic inputs as well.

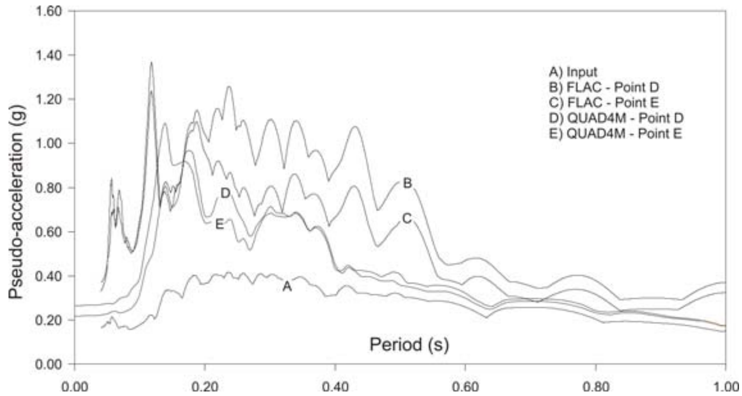

Fig.11. Comparison between numerical spectra calculated by FLAC and QUAD4M.
Fig.11. Confronto tra gli spettri numerici calcolati con FLAC e QUAD4M

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