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STRONG GROUND MOTION IN THE EPICENTRAL REGION OF THE M_W 6.3, APR 6 2009, L'AQUILA EARTHQUAKE, ITALY

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ABSTRACT

In the night of Apr 6 2009, a M_w 6.3 earthquake struck the Abruzzi region and the whole Central Italy, causing about 300 deaths and vast destructions in the town of L'Aquila, one of the largest urban centres in Central Italy, and its surroundings. As most destructive earthquakes in the Italian Central and Southern Apennines mountain chain, this was caused by a normal fault rupture, the epicenter of which was estimated at less than 5 km from the center of L'Aquila.

Several 3-components digital strong motion instruments were installed around L'Aquila at few km distance from the epicenter: 3 of them recorded the earthquake along a transept crossing the Aterno river valley, while two of them are located in the town centre. The near-fault conditions, the complex geological setting – L'Aquila lies on a fluvial terrace, consisting of calcareous breccias and conglomerates, lying on the top of lacustrine silty sediments – and the availability of several very good quality near-fault records, make this earthquake an important benchmark that provided an impressive and instructive picture of strong ground motion in the epicentral region of a normal fault earthquake.

This paper illustrates some of the most interesting features of the L'Aquila earthquake near-fault dataset, including (i) peak values and spectral ordinates, together with their relationship with respect to some of the most up-to-date ground motion prediction equations, (ii) long period components, (iii) vertical vs horizontal ground motion. Finally, since the L'Aquila shallow subsoil is characterized by frequent natural buried cavities of karst origin, we briefly investigate their potential role on the seismic response.

INTRODUCTION

In the night of Apr 6 2009, at 3:32 am local time, a M_w 6.3 earthquake struck the Abruzzi region and the whole Central Italy, causing about 300 deaths and vast destructions in the town and surroundings of L'Aquila, one of the largest urban centres in Central Italy, with about 80,000 inhabitants. The earthquake occurred along a NW-SE trending normal fault, 15-18 km long, dipping about 45° SW (Chiarabba et al., 2009). The hypocenter depth was estimated at 9.5 km, and the epicenter at less than 5 km SW from the town center. The causative fault of the mainshock is associated with the tectonic depression of the Aterno river valley, sited between two main calcareous ridges, the Velino – Sirente to the southwest and the Gran Sasso to the north-northeast. The surface projection of the inferred rupture surface is shown in Fig. 1 and lies right below L'Aquila. In Fig. 1 the epicenters of the thirteen events with $M_w > 4$ of the L'Aquila earthquake sequence are plotted as well, together with the focal mechanisms of the three strongest earthquakes of the sequence. Besides the mainshock, they occurred on April 7th (M_w=5.6) and April 9th (M_w=5.4).

Historical destructive earthquakes since the XIV century have been documented in the L'Aquila region (Stucchi et al., 2007), with the three strongest events before 2009 occurring in 1349 (maximum MCS intensity: IX-X), 1461(X) and 1703 (X).

The L'Aquila earthquake represents the third largest event recorded by strong-motion instruments in Italy, after the 1980, M_w 6.9, Irpinia and the 1976, M_w 6.4, Friuli earthquakes, but it is for sure the best documented, form an instrumental point of view. The mainshock and its aftershocks have been recorded by several digital stations of the Italian Strong-Motion Network (Rete Accelerometrica Nazionale, RAN), operated by the Italian Department of Civil Protection (DPC), by the Italian Seismometric Network (Rete Sismometrica Nazionale, operated by INGV-CNT; http://cnt.rm.ingv.it), and by a temporary strong-motion array installed by the INGV MI-PV (http://www.mi.ingv.it). The mainshock provided a total of 56 three-components digital strong-motion records within 280 km distance, 23 of them being within 100 km from the epicenter. Presently, the ITalian ACcelerometric Archive (ITACA), the new Italian strong motion database (http://itaca.mi.ingv.it), includes more than 900 waveforms from the L'Aquila earthquake sequence, including the M > 4 aftershocks.

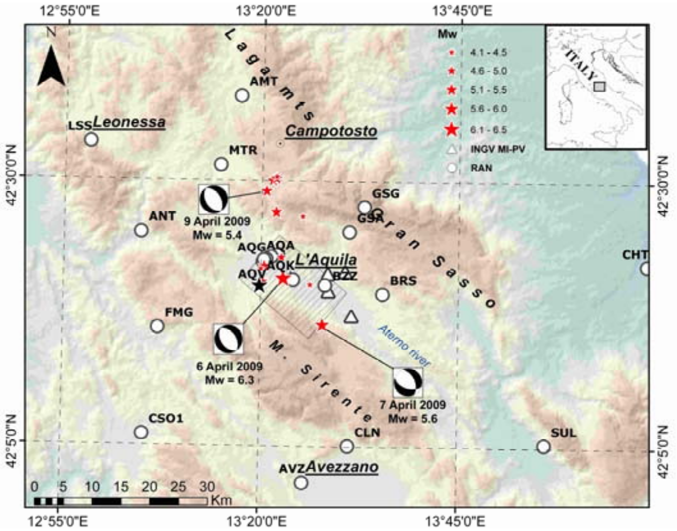

Fig. 1. Location of the main events ($M_w > 4$) of the L'Aquila sequence (red stars) and of the accelerometric stations belonging to RAN (triangles) and to INGV MI-PV (dots). The surface projection of the fault is also shown. Focal mechanisms are shown for the three strongest events. After Ameri et al. (2009).

A strong-motion array consisting of 6 stations was installed in 2001 by the National Department of Civil Protection (DPC), across the upper Aterno valley. Although 3 of these stations either did not trigger or malfunctioned during the earthquake, recordings from this array, together with the AQK and AQU stations located close to L'Aquila downtown (Fig. 2), provide a near-fault strong-motion data set never recorded to date in Italy for events with M > 5, and one of the few ones worldwide.

The goal of this paper is to illustrate some of the most interesting features of this near-fault dataset, including (i) peak values and spectral ordinates, together with their relationship with respect to some of the most up-to-date Ground Motion Prediction Equations (GMPEs), (ii) long period components, (iii) vertical vs horizontal ground motion.

Since, at the time of preparation of this paper, many site investigations for the seismic characterization of the L'Aquila region and of the recording stations are still under way, the analysis of site effects is omitted in this work. We will limit here to shortly focus on a relatively poorly studied and understood problem related to site effects on seismic ground motion, i.e., the role that buried cavities of carsic origin, frequently present in the L'Aquila shallow subsoil, may have played in the seismic motion at ground surface.

GEOLOGICAL SETTING AND AVAILABLE NEAR-FAULT STRONG MOTION RECORDS

L'Aquila lies on a fluvial terrace, some tens of m thick, consisting of calcareous breccias and conglomerates with limestone boulders and clasts in a marly matrix. The terrace lies on the top of lacustrine sediments, mainly consisting of silty and sandy layers and minor gravel beds (De Luca et al., 2005). As shown in Fig. 2, the terrace is at the left bank of the Aterno river valley, which flows about 50 m below downtown L'Aquila.

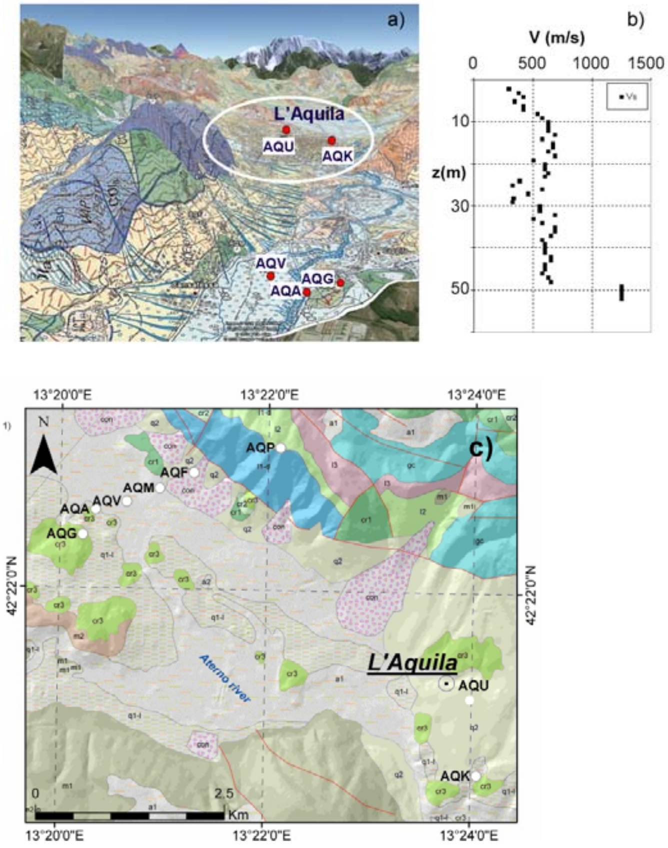

Fig. 2. a) and c): geological sketch of L'Aquila and location of the available strong motion stations. trong ground motion stations of the Aterno Valley array plotted on local geology. b) Cross-hole V_S (m/s) profile at the station AQV.

For the single station AQV, located at the center of the valley, a cross-hole Vs profile is available (Fig. 2c). An alternance of gravels and sands, with average Vs ~ 500 m/s, is present down to a depth of 47 meters, where bedrock is found. In contrast, according to the available geological surveys, the lacustrine sediments reach their maximum thickness (around 250 m) below the center of L'Aquila (De Luca et al., 2005), roughly corresponding to station AQK.

Due to a malfunctioning of the power supply, 2 stations of the network, i.e., AQF and AQP, did not trigger during the mainshock, while station AQM, set to 1g full-scale, saturated although set on outcropping rock. However, the survey carried out within this station after the earthquake proved that the largest phases of recorded ground motion have been affected by the earthquake-induced damage at the basement of the installation site.

Horizontal and vertical time series of acceleration, velocity and displacement obtained at the array sites (AQG, AQA, AQV) and at the downtown stations (AQK, AQU) during the mainshock are shown in Figg. 3, 4 and 5, respectively. To avoid the onset of spurious arrivals in the displacement waveforms from acausal high-pass filtering and to possibly recover reliable permanent displacements from double integration of accelerations, records were processed by a baseline correction technique, consisting of least-squares fitting the velocity time histories by three consecutive line segments, and removing them from the velocity itself (Boore, 2001). As shown in Fig. 5, coherent displacement time series are obtained, especially along the Aterno river transept, showing a downwards permanent displacement in the SE direction, in agreement with the GPS-based findings by INGV (Cirella et al., 2009).

As shown by the recorded values in Table 1, peak ground acceleration (PGA) ranges from about 0.25-0.35 g in downtown L'Aquila to 0.40-0.60 g along the Aterno river valley. Lower values of PGA close to the center of L'Aquila, are likely related to the high-frequency filtering effect due to the stiff calcareous breccias overlying softer lacustrine sediments. As a confirmation of this, note that peak ground velocities (PGV) recorded at the various stations are similar (horizontal values range from about 20 to 40 cm/s), with a remarkable difference in terms of PGV for the vertical component: while it is around 10 cm/s along the Aterno river, in L'Aquila downtown vertical PGV attains 23-26 cm/s in both available records. As apparent in Fig. 4, PGV at both AQK and AQU stations is related to a long period, one-sided pulse which produces a downwards permanent displacement at both stations of about 15 cm, coherent with GPS measurements.

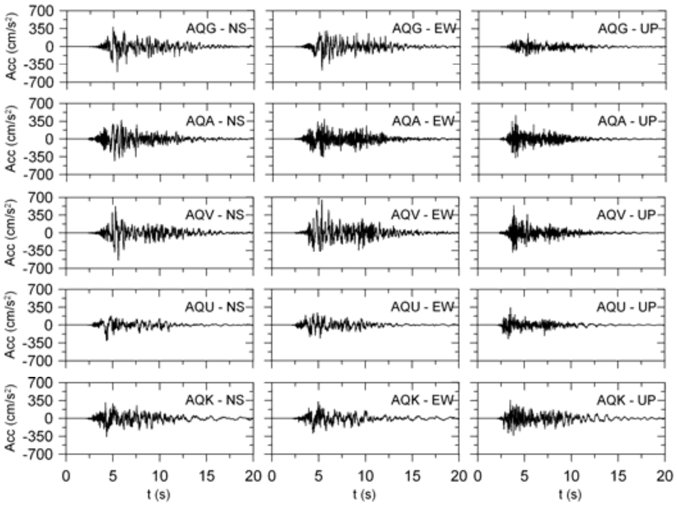

Fig. 3. Acceleration time histories for the Aterno Valley stations, namely AQG, AQA, AQV, AQU and AQK: NS (left panel), EW (centre) and UP (right) components.

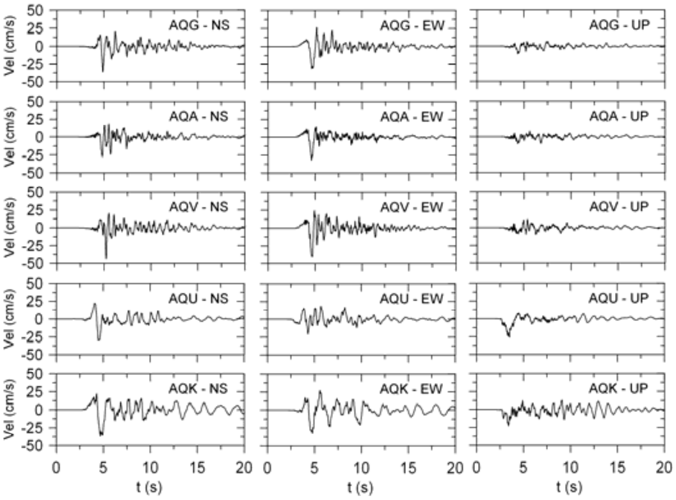

Fig. 4. As in Fig. 3. in terms of velocity time histories.

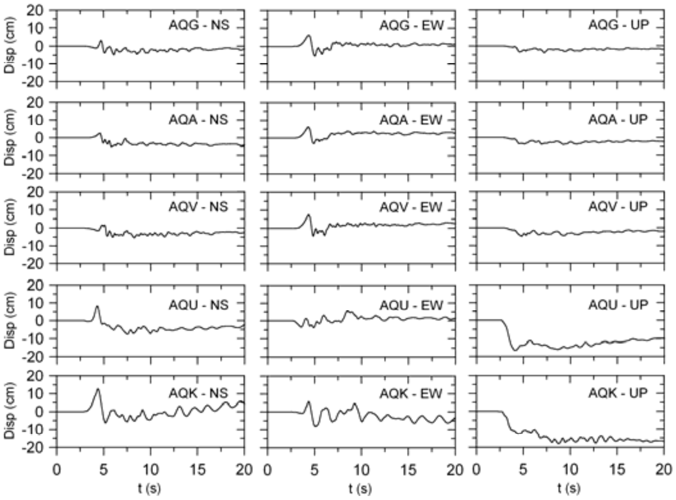

Fig. 5. As in Fig. 3 in terms of displacement time histories.

Table 1. Recorded values of Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV).

	PGA (cm/s^2)			**PGV (cm/s)**		
	EW	**NS**	**UP**	**EW**	**NS**	**UP**
AQA	396.8	435.8	466.9	31.8	27.4	10.0
AQG	463.5	501.3	266.5	31.1	36.3	10.9
AQV	652.2	538.5	540.4	40.3	43.5	12.0
AQU	261.5	307.3	345.5	20.9	30.6	26.0
AQK	330.8	357.3	361.9	32.5	36.8	22.8

SOURCE-RELATED EFFECTS AND LONG PERIOD GROUND MOTION

To investigate the source-related effects on the L'Aquila records, ground motion has been decomposed into its strike normal (SN) and strike parallel (SP) components, assuming a 147° fault strike angle, whence the predominant period T_{SN} and T_{SP} of the main velocity pulses, along with the corresponding peak ground velocities (PGV), were calculated. Results are summarized in Table 2, showing T_{SN} around 1.0 s for stations AQA, AQG, AQV and AQU, and increasing significantly up to about 1.5 s for station AQK. The longer period ground motion at AQK is likely the combined effect of the seismic source radiation and the interaction with the deep lacustrine sediments of the Aterno valley, addressed to in the previous section, that reach their maximum depth below the L'Aquila fluvial terrace. As highlighted by in-field monitoring after the earthquake (G. Milana, INGV, personal communication), the long period amplification in L'Aquila is apparent with similar features as at AQK at all sites of downtown L'Aquila closer to the Aterno valley, while sites on the uphill side of the town, as for AQU which is located at the basement of the L'Aquila castle, do not show similar features.

The ratio T_{SP}/T_{SN} is about 0.75, in agreement with similar observations from other worldwide earthquakes recorded in near-fault. Observed PGVs from about 30 to 45 cm/s in the SN and from about 20 to 30 cm/s in the SP directions are also in reasonable agreement with available empirical prediction equations (e.g., Bray and Rodriguez-Marek, 2004). Note that all records show a predominant velocity peak in the SN direction. Fig. 6 shows the comparison of the observed values of T_{SN} in L'Aquila against the values predicted by the empirical relationship developed by Somerville (2003) for both soil- and rock-like conditions. The observations are in reasonable agreement with the empirical relationship, although the strike-normal period observed at AQK is remarkably larger than the empirical estimates. This discrepancy may be reasonably explained by coupling of source-related effects with complex local site conditions, leading to pronounced lengthening period phenomena.

Fig. 7 shows the velocity particle trajectories in the horizontal plane (EW vs. NS component) associated to the observed ground motion at the stations listed in Table 1 in the most severe phase of shaking (namely, between 2.5 and 8 s referring to the time scale of Fig. 4). For comparison purposes, in Fig. 7 the fault-strike direction (=147°) is also shown. The orientation of ground motion along the strike-normal direction is rather clear at all stations, especially at AQK and AQU.

Table 2. Observed values of the period of the strike normal (SN) and strike parallel (SP) largest velocity pulse, along with the corresponding Peak Ground Velocity (PGV).

	AQA	**AQG**	**AQV**	**AQU**	**AQK**
T_{SN} (s)	1.0	1.10	0.90	1.05	1.55
T_{SP} (s)	0.7	0.78	0.80	0.85	1.30
PGV_{SN} (cm/s)	32.6	34.8	40.7	33	44.7
PGV_{SP} (cm/s)	21.0	28.2	31.6	19.8	20.5

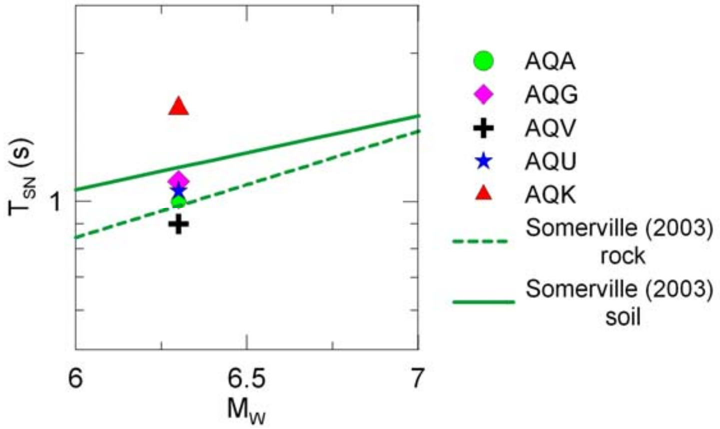

Fig. 6. Comparison of the observed values of the period of the strike-normal largest velocity pulse (T_{SN}) with the prediction of the empirical relationship proposed by Somerville (2003), for both rock- (dashed line) and soil- (continuous line) like conditions.

Elastic 5% damped displacement response spectra of the recorded ground motion were calculated for the SN and SP components, and compared in Fig. 8 with the theoretical displacement response spectrum according to Faccioli et al. (2004). The latter authors proposed analytical displacement spectral shapes, simply based on the following ingredients:
(i) a theoretical prediction equation of peak ground displacement (d_{max}), based on the classical Brune (1970) model of the seismic source, which, in its simplest expression, takes the form:

$$\log_{10} d_{\max} = -4.3 + M_W - \log_{10} r \qquad (1)$$

where d_{max} is in cm, M_w = moment magnitude and r = hypocentral distance (km);
(ii) an empirical relationship between Mw and the period τ of the largest velocity pulse of recorded ground motion, which, as proposed by Somerville (2003), takes the form:

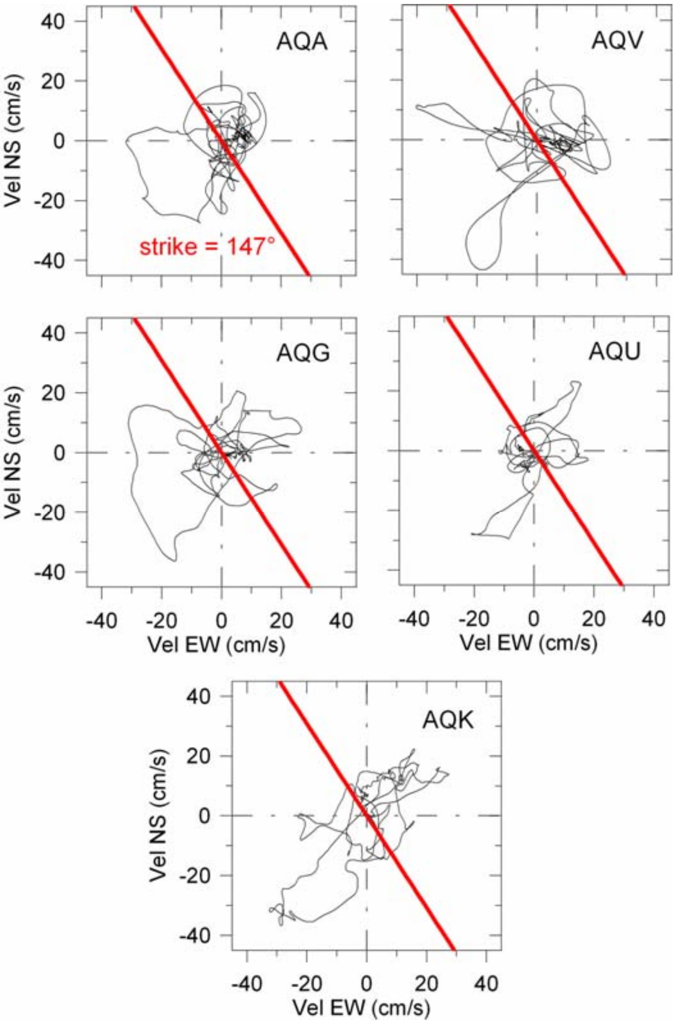

Fig. 7. Velocity particle motion for the stations under consideration (see Table 1). The fault strike direction (= 147°) is also superimposed for comparison purposes.

$$\log_{10}\tau = -3.17 + 0.5M_W \qquad (2)$$

(iii) the analytical expression of the displacement response spectrum of simple acceleration pulses of period τ.

The analytical curve in Fig. 8 is obtained using the values $d_{\max}$ = 0.1 m and τ = 0.95 s, obtained according to eqs. (1) and (2) with the values M_w=6.3 and r = 10 km. For simplicity, the Aterno valley spectra are plotted in terms of average values for both components. There is a striking similarity of theoretical and observed spectral ordinates, both in terms of shape and values, showing that long period ground motion recorded in L'Aquila is close to the expectations based on simple physical considerations. Due to the location of the hypocenter and of the seismic fault with respect to the stations (see e.g. Ameri et al., 2009), the effect of directivity on recorded ground motion at stations considered in this paper is likely not relevant, while the focal mechanism effect is more relevant, with a significant difference between SN and SP components.

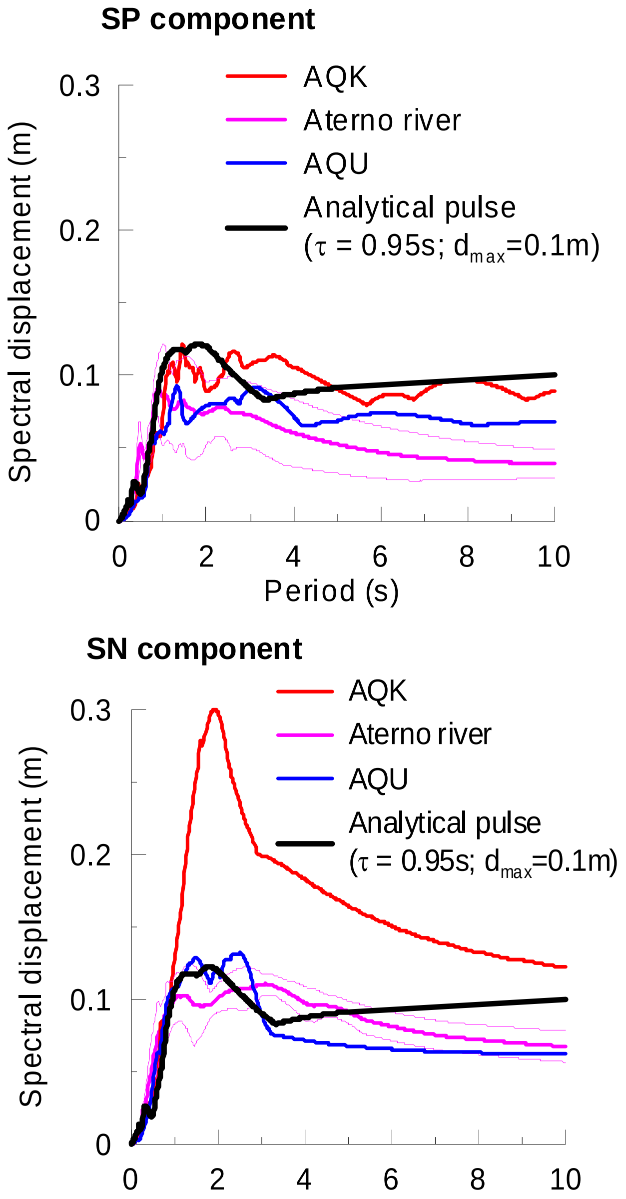

Fig. 8 Comparison of 5% damped displacement response spectra along the SN and SP components. Magenta: average ± 1σ of the three records along the Aterno river. Red: AQK. Blue: AQU. Black: analytical pulse according to Faccioli et al. (2004), for M_w=6.3 and r = 10km.

The difference of SN and SP ground motion is magnified at station AQK, as it is apparent from Fig. 8, because of the strong polarization of ground motion, as already pointed out in the trajectories of Fig. 7. Most likely, the AQK record is affected by a complex coupling of the source mechanism and the deep structure of the Aterno basin, where the lacustrine sediments reach around 250 m depth right underneath L'Aquila, as previously mentioned. Although numerical simulations of near-fault seismic wave propagation in such complex geological environments is still demanding (see e.g. Stupazzini et al., 2009), because it requires 3D numerical models and computational tools, they are expected to shed light on this important effect on earthquake ground motion, that may play a major role in some of the mostly active seismic areas in Central and Southern Italy.

COMPARISON WITH GROUND MOTION PREDICTION EQUATIONS

We aim now at comparing the previous L'Aquila strong motion records with, on one side, the observed levels of ground motion recorded in near-fault conditions from other recent worldwide earthquakes and, on the other side, with the empirical predictions from some recent GMPEs. To this end, we have considered near-fault records from earthquakes with magnitude M_W ranging from 6 to 6.3 and hypocentral distance (R_{hy}) less than about 20 km, similar to the range of the L'Aquila records. Specifically, the following earthquakes have been selected: (i), (ii) Friuli seismic sequence of Sept. 15 1976 (M_W 6 and M_W6.1), (iii) Parkfield, California, Sept. 2004 (M_W 6), (iv) Iceland May 2008 (M_W 6.3) earthquakes. A summary of the relevant data for these earthquakes and corresponding records, including the range of hypocentral distance (R_{hy}) of the records ranges and the Peak Ground Horizontal and Vertical Accelerations (PGA_H and PGA_V, respectively) are given in Table 3.

Fig. 9 shows the comparison of the observed response spectral acceleration ordinates for such records, at 5% damping PGA, and for different structural periods, with the values predicted by the following empirical attenuation relationships: Cauzzi and Faccioli (2008), on the left-hand-side, Boore and Atkinson (2008) and Ambraseys and Douglas (2003) on the right-hand-side. Note that the GMPE by C&F2008 is defined as a function of the hypocentral distance, while the other two relationships (B&A2008 and A&D2003) make use of the Joyner-Boore distance, i.e., the distance from the surface projection of the fault trace. The GMPEs are calculated for M_W 6.2 and stiff soil conditions (class B according to Eurocode 8 for C&F2008, S_S=1 for A&D2003 and V_{s30} = 450 m/s for B&A2008). It is worth to underline that, among the considered GMPEs, the one proposed by Ambraseys & Douglas (2003) alone has been calibrated on a near-fault earthquake ground motion dataset (42 earthquakes for 186 recordings), while the other two ones have a wider application field. Further details about the adopted GMPEs can be found in Table 4.

It is noted that, for all periods considered, the observed values are in reasonable agreement with predictions. This suggests that the L'Aquila earthquake recordings in the near-source region do not present significant deviations neither from the most recent worldwide observations nor from the predictions with recently calibrated empirical GMPEs.

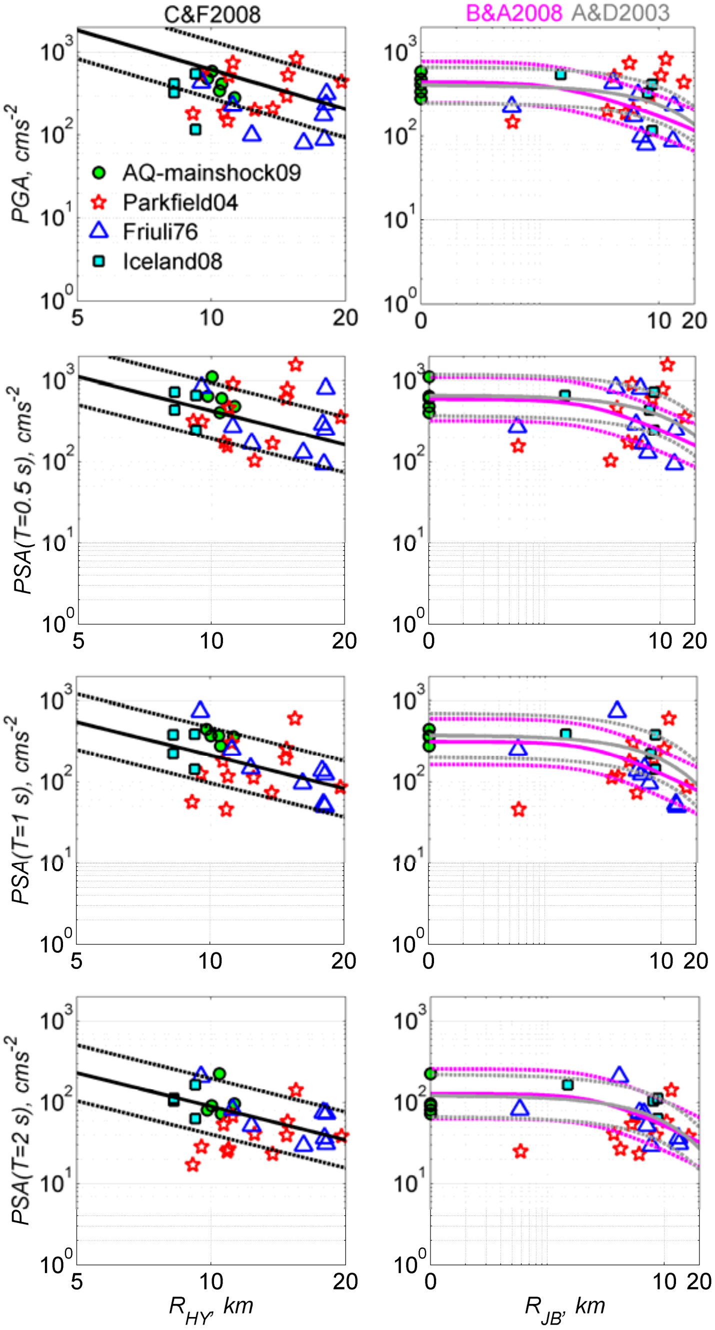

Fig. 9. Comparison of some selected spectral pseudo-acceleration ordinates (PGA, T=0.5 s, T=1 s and T=2 s) predicted for M_W6.2 and stiff soil condition by the ground motion attenuation relationships by Cauzzi & Faccioli (2008), in black, Boore & Atkinson (2008), in magenta, and Ambraseys & Douglas (2003), in grey, with the recordings in the near field of some recent earthquakes, listed in Table 3.

Table 3. List of recent near-fault earthquake recordings used in this work for the comparison with GMPEs.

EQ. name	**Date time UTC**	**M_W**	**# rec.**	**R_{hy} (km)**	**PGA_H (m/s^2)**	**PGA_V (m/s^2)**
L'Aquila	06/04/09 01.32	6.3	5	9.8-11	6.52	5.4
Friuli	15/09/76 03.15	6	8	9.5- 18.1	5.91	4.48
Friuli	15/09/76 09.21	6.1	4	11.1-18.1	3.18	2.23
Parkfield	28/09/04 17.15	6	12	9.1-19.6	12.85	5.6
Iceland	29/05/08 15.45	6.3	4	8.2-9.2	6.51	4.28

Table 4. Ground Motion Prediction Equations (GMPEs) used for comparison purposes in this work. For each GMPE, the number of records and earthquakes constituting the strong motion database used for its empirical regression, region of application, magnitude and distance ranges are listed.

GMPE	**# rec.**	**# EQ.**	**M**	**Region**	**R [km]**
S&P1996 (1)	95	17	4.6-6.8	Italy	0-100
C&F2008 (2)	1164	60	5.0-7.2	world-wide	6-150
B&A2008 (3)	1574	58	5-8	world-wide	0-400
B&C2004 (4)	443	36	4.7-7.7	world-wide	0-60
A&D2003 (5)	186	42	5.8-7.8	world-wide	0-15
S2003 (6)	rock :16 soil:12	8 6	6-8	world-wide	0-20 0-15

(1) Sabetta & Pugliese (1996); (2) Cauzzi & Faccioli (2008); (3) Boore & Atkinson (2008); (4) Bozorgnia&Campbell 2004; (5) Ambraseys & Douglas (2003);(6) Somerville (2003).

ACCELERATION RESPONSE SPECTRA OF HORIZONTAL AND VERTICAL GROUND MOTION

The 5% damped elastic acceleration response spectra of the near-fault records considered in the previous sections are plotted in Fig. 10, in terms of both horizontal (left panel) and vertical (right) components. To provide an insight of how severe this ground motion has been with respect to the seismic design requirements, these spectra are compared with the elastic design spectral ordinates of the Eurocode 8 (EC8). The design spectra of Fig. 10 are anchored to the PGA value assigned for L'Aquila by the Italian seismic hazard map (Gruppo di Lavoro MPS, 2004) for probability of exceedance of 10% in 50 years. For site class A, PGA = 256 cm/s^2, while for site class B, PGA = 307 cm/s^2, (where EC8 class A: $V_{s,30}$ > 800 m/s, B: 360-800 m/s, C: 180-360 m/s, and D: <180 m/s). Since AQV is the single station for which Vs profile is available (Fig. 2b), corresponding to V_{s30} = 474 m/s Class B, for the other stations we made reference to the preliminary site classification provided in the ITACA database, mainly based on geological surface evidences.

As regards the horizontal components, the Aterno river stations tend to exceed the design spectral ordinates in the short period range, up to about 1 s, with the largest values for the AQV station, where the effect of shallow sediments on the amplification of ground motion is larger. The opposite holds for stations inside L'Aquila town center (AQU and AQK), for which, as previously noted, the stiff surface cap of calcareous breccias and conglomerates seems to have acted as a natural filter of high frequencies. On the long period side (T > 1 s), the observed spectral ordinates at AQK slightly exceed the design values.

The comparison in terms of vertical spectral ordinates is even more intriguing. On one side, very large values are observed at several stations (namely AQA, AQV and AQU) for periods around 0.05 s, up to 2.4 g at station AQV. It is not clear yet whether these vertical peaks are related to the actual free-field ground motion, or to a vibration mode influenced by the interaction with the basement of the station installation. On the other side, AQK vertical ground motion significantly exceeds the design values for periods ranging from 0.5 to 1.5 s, due to the dominant presence of basin-related surface waves, as apparent from the velocity record in Fig. 4. This observation suggests that, in the presence of deep or closed-shape basins that may induce propagation of surface waves, vertical ground motion may be significantly amplified. On the contrary, the site-dependent amplification of the vertical component in terms of design spectra is usually neglected.

To give further insights into the relative amplitude of vertical with respect to horizontal ground motion observed during the L'Aquila earthquake, we show in Fig. 11 the vertical to horizontal (V/H) response spectral ratios, computed as the median ratio of the vertical acceleration response spectra at 5% damping over the horizontal response spectra, for all records. The observed V/H ratios (black line in Fig. 11) are compared with the predictions by some recent empirical attenuation relationships (Ambraseys & Douglas, 2003; Bozorgnia & Campell, 2003; Cauzzi & Faccioli, 2008 and Sabetta & Pugliese, 1996). The V/H values obtained by dividing the corresponding EC8 class B elastic design spectra, are also shown in the plot.

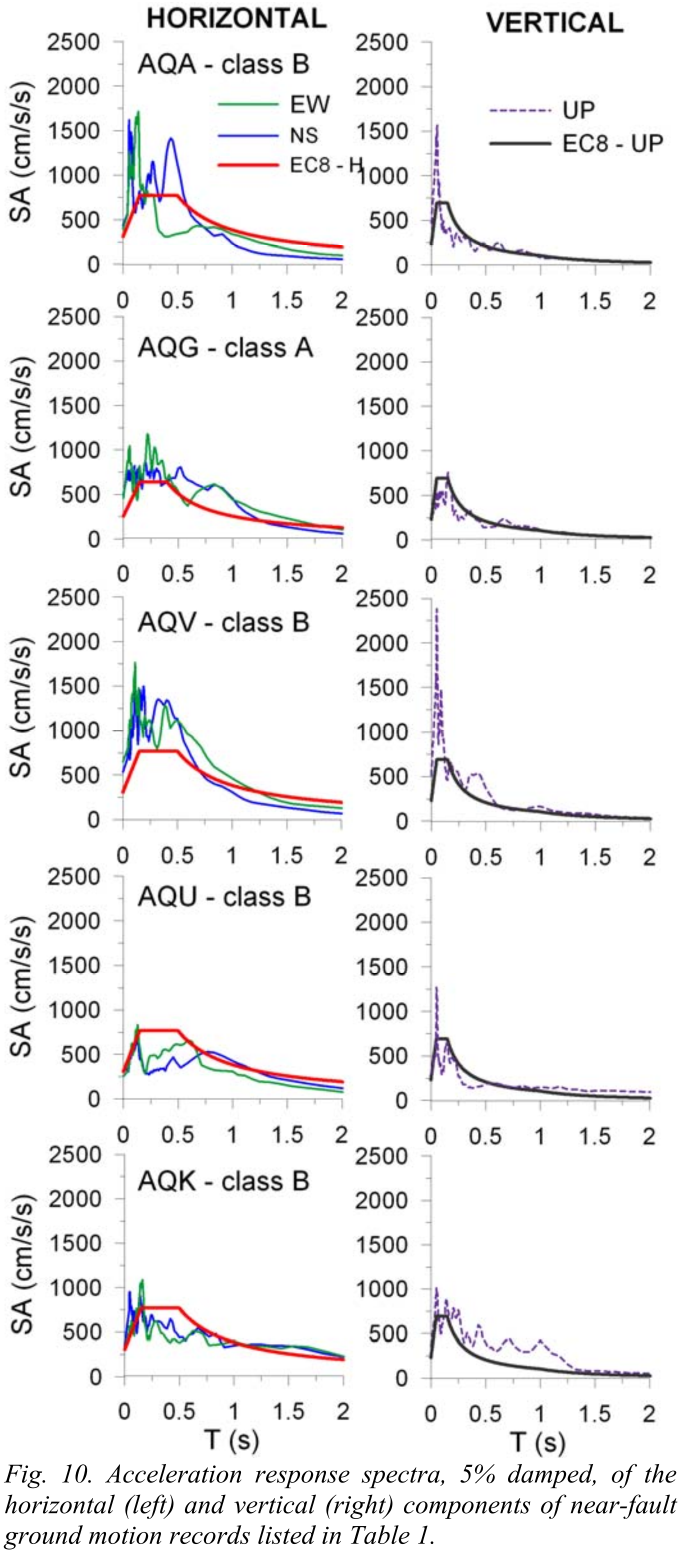

Fig. 10. Acceleration response spectra, 5% damped, of the horizontal (left) and vertical (right) components of near-fault ground motion records listed in Table 1.

At very short periods (T < 0.1 s), the observed median V/H ratio tends to exceed the predictions from GMPEs, with the peak at 0.05 s, the reliability of which should be carefully assessed, as discussed previously. For larger periods, the observed V/H follows reasonably well the GMPEs values. The sharp increase at 2-4 s is a consequence of the long period vertical velocity pulse, especially at AQU and AQK, producing large values of permanent vertical displacements.

As for the EC8 values, they are more conservative than the GMPEs at short periods, and in this case in good agreement with the L'Aquila earthquake observations. However, it must be pointed out that for T > 0.5 s the V/H calculated from the EC8 spectra tends to fall well below the observed median values, with a decreasing trend towards long periods that is contrary to the trend observed not only in the L'Aquila earthquake, but on the median values as well predicted by the GMPEs.

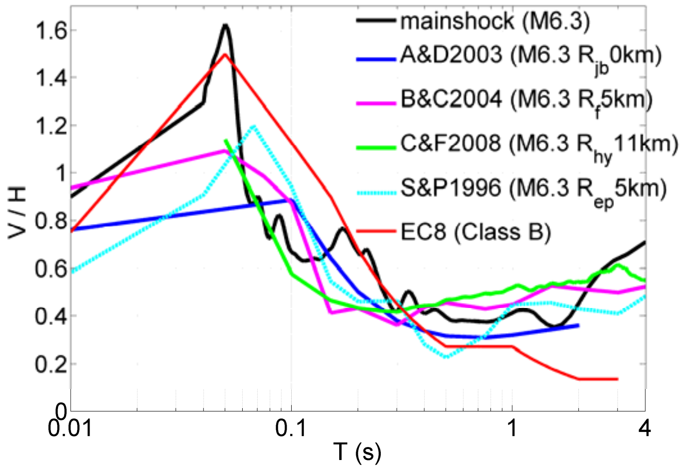

Fig. 11. Observed vertical to horizontal spectral ratios (V/H) for the L'Aquila mainshock, computed as the median value of the available recordings (AQG, AQA, AQV, AQK e AQU). The observed V/H are compared with the median values predicted by several GMPEs (Ambraseys & Douglas, 2003; Bozorgnia & Campell, 2003; Cauzzi & Faccioli, 2008; Sabetta & Pugliese, 1996) and with the corresponding ratio of the V and H elastic design spectra according to EC8, class B.

EFFECT OF NATURAL SUBSURFACE CAVITIES ON EARTHQUAKE GROUND MOTION IN L'AQUILA

As mentioned in the introductory section, detailed geological and geophysical investigations are in progress in different parts of L'Aquila, and on the strong motion station sites as well, to better constrain the effect of the surface geology on seismic ground motion, Therefore, we will limit the conclusion of this overview of L'Aquila earthquake ground motion by addressing the evaluation of the effect of natural buried cavities on surface earthquake ground motion. As a matter of fact, within the largely heterogeneous subsoil of the L'Aquila town center, various geological and geotechnical investigations have pointed out the presence of frequent shallow buried cavities, presumably of karst origin, the dimensions of which may typically range around 3 to 6 m, at least according to some private borehole data available to the authors.

During the earthquake, several large holes opened at ground surface, as shown in Fig. 12, probably due to the extension of the cavity towards the surface, as a possible consequence of water losses in the ground.

Due to their widespread presence throughout the subsoil of L'Aquila, many buildings are expected to be founded on such buried cavities, so that it is desirable to provide an evaluation of their potential effect on surface earthquake ground motion. To this end, we have adopted the analytical approach devised by Smerzini et al. (2009). The approach is based on the expansion of either plane or cylindrical incident SH wave field in terms of cylindrical (Bessel) functions, in the presence of a circular cavity embedded in a homogenous linear visco-elastic halfspace.

In this work, we have considered three representative configurations (see Fig. 13, top panel), namely: a) a cavity of diameter D = 3.5 m and embedment depth H = 9.25 m; b) D = 5 m and H = 12 m and c) D = 3 m and H = 4 m. The shear wave velocity is V_S = 400 m/s and the soil density ρ_S = 2200 kg/m^3. As a representative ground motion in the L'Aquila center we have selected the horizontal (EW and NS) components of the AQK record. To provide a quantitative evaluation of the effect of the buried cavity on the seismic motion at ground surface as a function of period, response spectral amplification factors R_{SA} are provided as the average ratio between output and input 5%-damped acceleration response spectra. $R_{SA} > 1$ denotes amplification of surface ground motion with respect to homogeneous soil conditions, viceversa for $R_{SA} < 1$, while $R_{SA} = 1$ obviously denotes no effects. Fig. 13 (bottom panel) shows the R_{SA} values, calculated as average values of the horizontal components, as a function of period for the three previous configurations, at different horizontal distances (d/r, where r is the radius of the cavity) from the cavity itself.

It is noted that, for large values of the ratio between the embedment depth and the cavity radius (H/r), as in Fig. 13a, the effect is relatively small, even though at 0.1 s the amplification at d/r = 0 approaches 10%. As far as the H/r ratio decreases, see Figs. 13 b and c, the short period amplification tends to be more important, up to 30% amplification at 0.05 s for case c). As a practical indication, R_{SA} can be significantly larger than 1 for $H/r < 3$ and $d/r < 3$, approximately, while for larger embedment ratios and distances, it tends to unity. As a concluding remark, it is worth underlining that the results shown here are limited to the case of a cylindrical cavity subject to SH wave propagation and may not be directly extended to the more general and realistic case of a spherical cavity under a 3-component input motion.

Fig. 12. Hole formed at L'Aquila city after the Apr 6 2009 earthquake and caused by the opening at ground surface of a buried natural cavity Courtesy of F. Benedettini.

CONCLUSIONS

We presented an overview of earthquake ground motion in the epicentral region of the M_w 6.3 L'Aquila earthquake of Apr 6, 2009, Italy, with special emphasis on some of its most interesting features, such as (i) peak values and spectral ordinates, (ii) long period components, (iii) vertical vs horizontal ground motion. As a matter of fact, the near-fault conditions, the complex geological setting and the availability of several very good quality near-fault records, make this earthquake an important benchmark that provided an impressive and instructive picture of strong ground motion in the epicentral region of a normal fault earthquake.

The analysis of data shows that most of the features of earthquake ground motion can be reasonably well explained in terms of the most up-do-date ground motion prediction equations, as well as by some analytical solutions for long period ground motion.

Comparison with design spectra suggests that near-fault ground motion approached, and in some period ranges exceeded, the no collapse limit state design spectra (10%

exceedance probability in 50 years) both for horizontal and vertical components. For T > 0.5 s the ratio of the vertical vs. horizontal EC8 design spectra tends to fall below the observed median values, suggesting that vertical spectral ordinates for design may be in general under-conservative at long periods.

A more careful investigation of records requires a quantitative characterization of the complex local geology – L'Aquila lies on a fluvial terrace, consisting of calcareous breccias and conglomerates, lying on the top of lacustrine silty sediments – that is not available yet at the time of preparation of this paper. Instead, attention has been focused on the influence that the frequent natural buried cavities of karst origin in the subsoil of L'Aquila may have had on the surface ground motion.
Based on the application of an analytical solution, it was found that, especially for relatively shallow cavities with small ratio *H/r* between the embedment depth and the radius of the cavity, ground motion can be amplified up to about 20-30 % in the short period range ($0 < T < 0.2$ s). Although these results should be strengthened by considering the more general and realistic case of a 3D cavity under a 3-component input motion, this problem seems to be of relevant practical interest, owing to the widespread presence of such cavities in the whole L'Aquila shallow subsoil.

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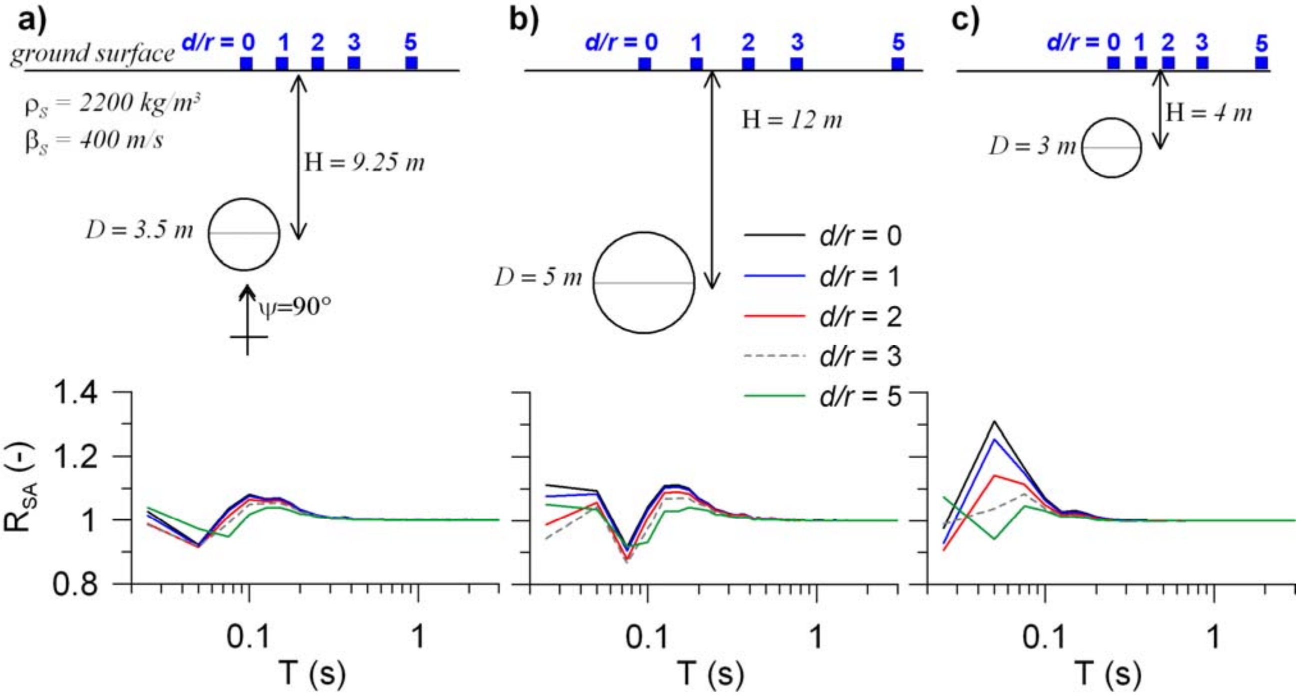

Fig. 13. Bottom panel: average amplification factors (R_{SA}) on 5% damped acceleration response spectra, assuming as incoming excitation the horizontal (EW e NS) components of the AQK record. R_{SA} are calculated at different locations (d/r, where r is the radius of the cavity) and for three different configurations (sketched in the up panel). The shear wave velocity is $V_S = 400$ m/s and the soil density $\rho_S = 2200$ kg/m^3.

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