LOCAL AMPLIFICATION EFFECTS RECORDED BY A LOCAL STRONG MOTION NETWORK DURING THE 1997 UMBRIA-MARCHE EARTHQUAKE

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SUMMARY

The earthquake of 26 September 1997 in central Italy is one of the largest seismic events of the last 20 years in Italy. It caused significant damages in a large area of Umbria and Marche regions and site amplification phenomena were recorded even at large distances from the epicenter. After the emergency period, was installed in the main damaged area a temporary strong motion array to detect the aftershocks. As the damaged area is located on the Apennine mountains, local soil amplification, due both to topographic and basin effects, were highlighted. Particulary in two small towns, Cesi and Sellano, were positioned instruments on different geological and morphological conditions to investigate the considerable selectivity in damage conditions. In the meanwhile was carried out geological investigations to determinate the geological sections under the strong motion sites. During the nine months of activity of the network was recorded some significative events.

The recorded waveforms have been analyzed with spectral techniques evaluating both spectral ratios using reference stations and H/V ratios on P and S waves. A two dimensional code, based on the indirect boundary element method, has been used to confirm the recorded data and also to investigate the effects of geometrical parameter changes in order to generalize the results.

The recordings confirmed the importance of the site conditions in the damage distribution in sites very close between them.The results of numerical analysis, according to the sperimental data, have allowed to generalize. We observed a large amplification in the basin border of Cesi site, in opposite small amplification due to topografic effect in Sellano site.Finally a criteria to generalize both the numerical results of real cases and those of parametric studies is presented.

INTRODUCTION

The National Seismic Survey emergency strong motion network has the purpose to detect the most important after-shocks related to all the strong events happening in Italy. The instruments are deployed in order to get information about ground shacking in near field condition and to possibly relate it to the geological characteristics of surface terrain. This information can be very useful both for addressing the work of Civil Defense in the epicentral area for helping the development of safety criteria to be used in the reconstruction operations.

The Umbria-Marche (Central Italy) earthquake was the first opportunity to test the capability of SSN emergency network, since on September 26, 1997 two earthquakes (Mw = 5.7 at 00.33 GMT and Mw = 5.9 at 09.40) shaked the area located 100 Kilometers NE of Rome causing several casualties and important damages, (Figure 1a.).

Few minutes after the night event the Civil Defense received the first damage reports and started to organize the emergency activities; the following morning the SSN people was already in the epicentral area to recover data from the instruments operating in Assisi since 1994 and to deploy some temporary stations.

The Mw 5.9 main shock occurred at 09.40 and found the SSN people, fortunately without any injury, into the Assisi church during data downloading procedures from the dynamic monitoring system realized to study the seismic behavior of the monument.

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During the following days the temporary strong motion network was deployed on rock sites located on limestone in the cities of Nocera Umbra, Annifo, Cesi, and Forcella, (Figure 1b).
In the village of Cesi that suffered important damages in the part of the city located on an alluvial valley an extra instrument was installed on soft soil conditions.
After the bigger aftershock of October 14(Mw = 5.6), that activated the southern termination of the fault area, two new temporary stations were installed in the city of Sellano due to its vicinity to this late epicenter and to the severe damages suffered from the city that was already damaged during the 1979 (Mw = 5.6) Norcia earthquake.
The temporary network operated until the end of June 1998 recording several aftershocks including the activity of March and April 1998 characterized by several quite strong after shocks and by a magnitude 5.6 deep event quite unusual for the area.
Regarding the soil amplification problem the data recorded at Cesi showed important differences between rock and soft soil conditions that can be easily interpreted with a quite simple 2D model, also the observation made in Sellano show some effects but, in this case these can not be interpreted in terms of simple models and three dimensional effects have to be invoked.

GEOLOGIC AND GEOMORPHOLOGIC CHARACTERISTIC OF THE INVESTIGATED AREAS.

Sellano.

The general layout of the town of Sellano is shown in Figure 2. It is located on a hill composed mainly of limestone and marly limestone well stratified and interested by an extended fracturing. Steep slopes characterize the morphology, see Figure 2 where are also shown layers formed by different kind of

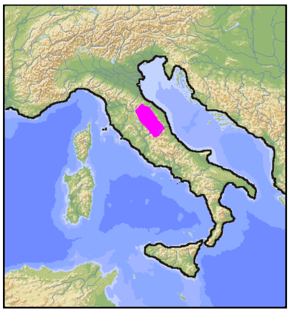


Fig. 1 Epicentral area

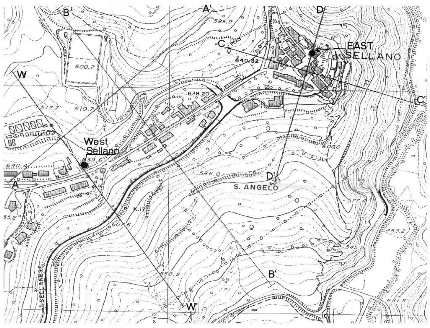


Fig 2 Map of Sellano

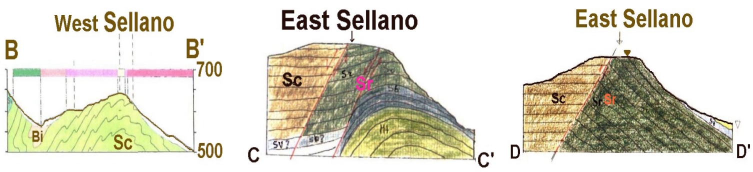


Fig. 3 Sellano: B-B', C-C' and D-D' sections

limestone like Red Scaglia, Sr, Cinereous Scaglia, Sc, White Scaglia, Sb, Variegate Scaglia, Sv and marly limestone, Bisciaro formation Bi. As shown in Figure 3 in the eastern part of Sellano an important fault, in NNW-SSE, separates the Red and Cinereous Scaglia.

Cesi

The town of Cesi is located on the border of an alluvial valley (figures 4 and 5). The first station was installed in downtown on a 35 m thick alluvial layer while the second was on a rock site in a locality called "Villa", about 350 m. apart from the first.
The town of Cesi has got enormous damages (macroseismic intensity MCS of about IX degree) while Villa experienced only few damages (about VI –VII degree)

Both for Sellano and Cesi, the mechanical characteristics of soil are not precisely defined, but only the general information, given by the local technicians, have been taken into consideration.

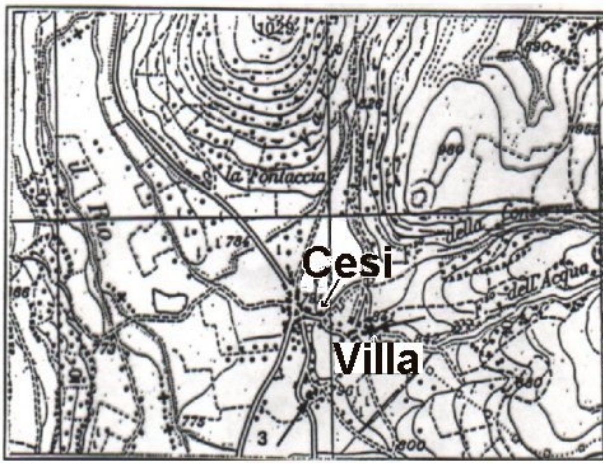


Fig. 4 Map of Cesi

DATA COLLECTION AND ANALYSIS

Sellano

The strong motion stations were installed at Sellano after the October 14 aftershock in two different location few hundred meters apart. One station was deployed in the historical centre of the city on the Red Scaglia formation and very close to the slope that borders the eastern edge of the Sellano hill. The second station was located on the Bisciaro formation on a gently dipping slope elongated in the East-West direction.

The two stations recorded several aftershocks but we have chosen the 17 events recorded simultaneously at the two stations for the analysis. have chosen the 17 events recorded simultaneously at the two stations for the analysis. In addition to strong motion data a short campaign for collecting weak motion data was performed in November 1997 installing four short period station in a continuous recording mode to detect differences in ground motion in the centre of the city in the position reported in fig. 6. The V2,V3,V4 stations were located on the Red and White Scaglia formation while the V1 station was located on the Cinereous Scaglia formation. During the operation time the weak motion stations recorded several tenths of small magnitude aftershocks, we selected for the analysis about 40 events that presented a good signal to noise ratio.

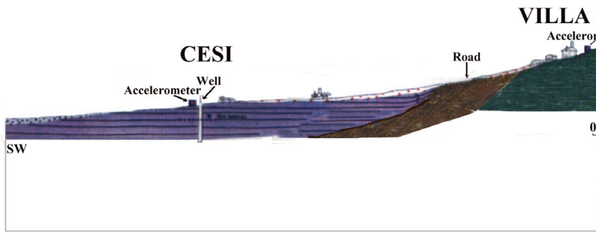


Fig. 5 Section of Cesi

As a preliminary analysis both for strong and weak motion data we evaluated H/V ratios in order to detect amplification effects.

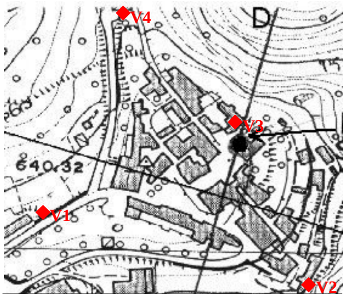


Fig. 6 Weak motion stations location

As a result of this preliminary analysis for both weak and strong motion station located in the centre of Sellano a quite sensitive difference between the two horizontal components of motion is found (Fig. 7-8).

In fact while the NS components do not show any significant amplification effect, the EW components indicates some important amplification factor in the 2-5 Hz frequency range for the stations located in the north-eastern part of the city centre (stations V4,V3 and Sellano East) where the presence of a morphological effect can be more important. Moving away from the city centre (stations V1, and Sellano West) those effect disappears and only an amplification effect in the 8-10 Hz frequency range appears at the Sellano West station. In order to define a unique vibration ground motion for the two stations, we tried to use the average value of the acceleration response spectra at 5% level of damping of all records, but it wasn't possible to identify a common characteristic of the ground motion in each station [8]. A great peak at high frequency of about 12 Hz was noticed on the mean value of West Sellano recorded motion and it was justified as a probable defect at the accelerometric station. So we decided to consider only those records that do not have such anomaly. In figure 9 the three spectral components of one aftershock recorded on November 1997 are shown. The component in E-W direction has a similar form to the N-S one except for the very high frequencies.

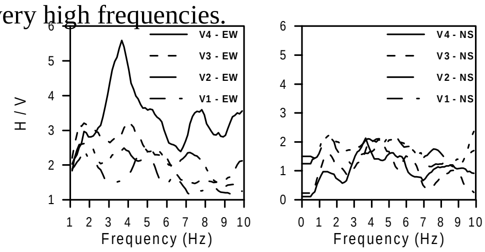


Fig. 7 H/V ratios from weak motion data.

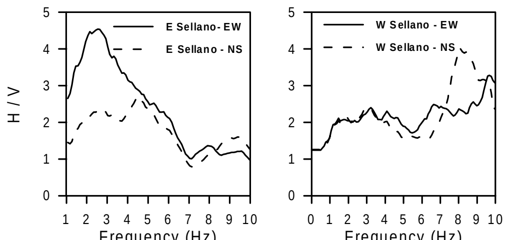


Fig. 8 H/V ratios from strong motion data.

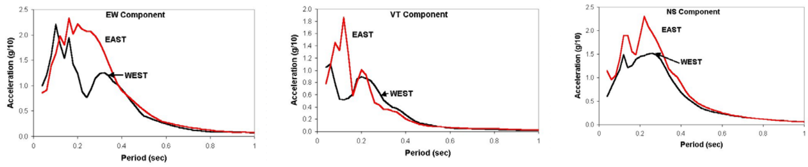


Fig. 9 Spectra of records in Sellano

The great difference of the characteristic motion is evident here. At the accelerometric station of West Sellano a generally lower amplification does occur with a maximum at low periods, near 0.1 sec, while the station in East Sellano has a large amplification for periods of 0.2 sec. The spectrum in N-S direction was chosen for the following amplification analyses.

CESI

Since the spectra of recorded signals show a uniform shape, only the records of the 7th of September 1997 have been taken into consideration (fig. 10). They show a clear different amplification in the two sites. The spectra on soft soil, Cesi, are about twice greater than in Villa. Also the shapes are different as the spectra on soft soil show a larger period range of amplification a widening toward higher periods. It is worthwhile to note the evident amplitude of vertical spectra comparable to those of the horizontal motion. It can be justified by the closeness of the source at about 3 km.

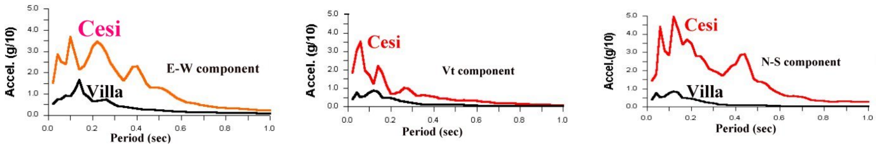


Fig 10 Spectra of records in Cesi and Villa

Methodology of analysis

A simple 2D scheme was used and the analyses were performed through the computer code BESOIL [2] using an indirect boundary formulation for dynamic elasticity. It is based upon the integral representation of the diffracted elastic waves in term of single-layer boundary sources [3]. Although in literature this approach is called indirect BEM, it provides far more insight into the physics of diffraction problems than does the direct approaches. This is because diffracted waves are constructed at the boundaries from which they are radiated. The 2-D space is divided in zones where the mechanical properties are constant. From boundary conditions on the free field and on each boundary between the zones, a system of integral equations for boundary sources is obtained. Subsequently a discretization scheme based upon the numerical and analytical integration of exact Green's functions for displacements and tractions is used. The method is suitable for the analysis of an irregular ground, since it can easily formulate an obliquely incident wave and outgoing scattering waves. Both the anti-plane model for incident SH-waves and the plane strain model for incident SV-waves can be analyzed.

The analyses were performed in two phases. Firstly we faced an inverse problem, that is, knowing the motion in one accelerometric station, we computed the motion on an hypothetical outcropping plane rock (reference motion). In the second phase we computed the response in the other location and compared the computed motion with the recorded motion. The input used was the plane outcropping rock motion computed in phase one.

AMPLIFICATION ANALYSIS IN SELLANO

We performed a lot of parametric analyses in order to match the recorded data [8]. We changed the geometry and the material characteristics of soil. In this paper only the main results are presented.
(Fig. 3 and 4) and is suitable to be representative of a 2-D plane system since it is perpendicular to the longitudinal axis of the hill. On the contrary the second section, East Sellano, is located on the top of the terminal part of the cylindrical hill (Fig. 2) in such a way that only a 3-D scheme can represent its geometry. However we analyzed both the sections, D-D' and C-C', Fig. 3, as 2-D geometry, but the results have been assessed considering the used approximations. Firstly we have faced the inverse problem, that is, knowing the motion in the West Sellano accelerometric station, we computed the reference motion. To reach this goal we considered the W-W' section and the average motion as described in the previous chapter (Fig. 6). The W-W' section was chosen because it allows, with very good approximation, a 2-D analysis. In the second phase we computed the

response in the location of the East Sellano station and it was compared with the recorded motion. We then have made a few parametric analyses to highlight the effect of some variation of geometry. In such analyses we have also considered the section C-C' as being part of geometric variations[8]. The scheme of section W-W' used for the BESOIL analyses is shown in Figure 11. As already seen it is similar to the section B-B' in Figure 2. For the homogeneous case we used the same mechanical characteristics of the soil in both the sections W-W' and D-D'. They are the same ones used in the '*analisi speditiva'*, that is: shear

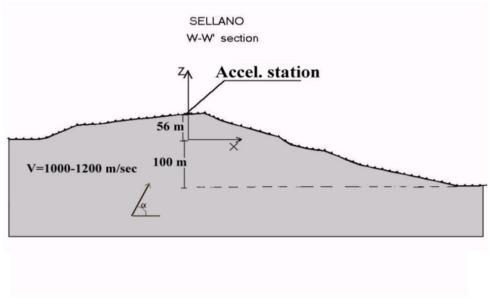
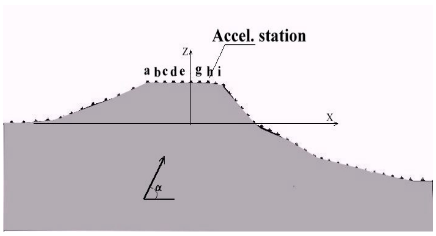


Fig. 11 Scheme of W-W' section

velocity V_s=1200 m/s and damping β= 0. In Figure 12 the scheme of section D-D' is shown with the location of the stations where the output is computed. They are labeled with figures from a to i included the accelerometric stations, East Sellano, labeled as h. As input motion we used the N-S component of the ground motion and therefore we have made the assumption that the incoming motion from the infinity is made of SV waves impinging with an α angle on the horizontal soil surface and that the whole NS record is made of shear waves. Accordingly we have assumed that the W-W' and D-D' were in the plane in a NS direction.



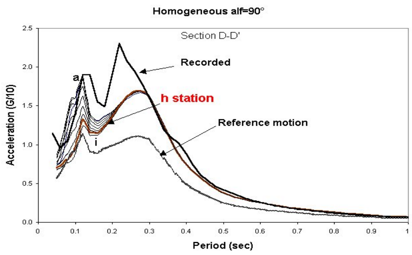


Fig. 12 Scheme of D-D' section **Fig. 13 Case of homogeneous soil**

Case of homogeneous soil and vertically impinging waves

The results of the analyses, in case of vertically impinging waves after the solution of the inverse problem on section W-W' and then the direct one on section D-D', as described in the previous chapter, are shown in the Figure 13. They are always represented as response spectra with 5% damping in a few stations in East Sellano and are compared with the average spectrum of the recorded accelerograms (see chapter 3). The curve labels refer to the stations of Figure 12. The curve labeled: 'reference spectrum' refers to the motion on the hypothetical horizontal outcropping rock, therefore it represents the results of the inverse problem. There is a noticeable difference between the computed and recorded motion. We can distinguish two different period ranges, the one at high frequency or periods less then 0.15 sec and the other at 'low' frequencies or periods grater than 0.18 sec. In the frequency range at low period, 0.10 sec, there is a greater amplification while there is a lower amplification in the period range, 0.15-0.25 sec where the spectrum of the recorded accelerograms has its maximum. The difference between the recorded and computed values probably derives from the 3-D effect in Sellano East site, which has been ignored in the analyses. The great variability of the computed spectra can be observed in a range of distance of almost 100 m, and the values change from 0.5 to 1.2 G/10 in the low frequency range. The higher values are for the stations on the left side, stations a, b, c, d and e, which are so far from the steepest slope on the right as to show a focussing of the high frequency waves caused by such declivity. The amplification of the computed motion on the south stations (a,b..) varies from 1.5 for the medium period range of 0.2-0.35 sec to 3 for the low period range less then 0.2 sec, while is about constant, 1.5 for the north stations (h,i). How the following parametric analyses will show, the variation of the shape of section D-D' will only change the response at low periods leaving nearly unchanged the response at high periods. The assumed shear wave velocity, V_s=1200 m/sec, affects only the low periods, that is the wave lengths less than the horizontal dimension of the hill of Sellano.

Case of homogeneous soil, effect of the incident angle impinging waves

Numerical results change significantly as the impinging angle α varies from 90° to 60° and to 110° (Fig. 14 and 15). 90 degree refers to vertically impinging waves while 60 and 110 degree refer to oblique directions. The choice of α angle has been quite arbitrary, even if, after an analysis of the initial part of the accelerograms, namely the P waves, it turn out that the incidence angle is nearly vertical with a tolerance of 30 degrees. The angle of 60 degree may refer to a source located at South while the angle of 110 degree to one at North. The former is near to the actual case of the chosen accelerogram.

A rapid inspection of the figures reveals a grater amplification, respect to the previous cases, at low periods in the stations h and i and a large variability also at high periods, up to 0.4 sec. Looking at the Figure 15, angle α equal to 110 degree, a clear reduction of the response can be seen with respect to the rock motion (reference motion) for almost the whole range of periods. A more evident effect, in the case of α equal to 110 degree, is to move the focussing of the waves from the stations on the right hand (a,b,..) to those on the left hand (h and i). For these last ones a significant reduction of the response can be seen. It worth noting the reference motion it almost equal to that recorded at West Sellano, demonstrating that there was no amplification of the motion.

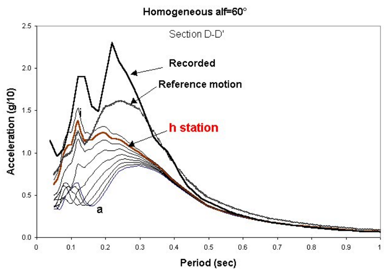


Fig. 14 Results for α=60 degree

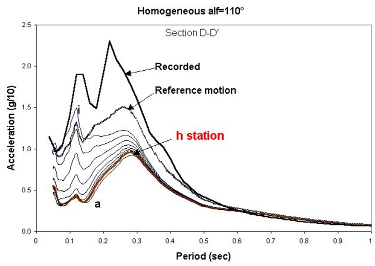


Fig 15 Results α=110 degree

Effect of the material discontinuity.

Finally we have considered the effect of the material discontinuity. As a mater of fact this discontinuity is shown in the Figures 2, 3 and 4 where the materials are marked as Sr, that is red scaglia on the Eastern part of Sellano and Sc, that is cinereous scaglia, The scheme, used in the analyses is shown in the Figure 16.

We investigated the effect of two different contrasts, namely two different couple of shear wave velocities. In the first analysis, for the red and cinereous scaglia respectively, we have chosen V= 800 m/sec and in the second: V= 1000 e 1200 m/s. Such figures are not probably the actual ones, since a great uncertainly on their values still exist, but they have been chosen to the purpose of investigating the effect of the impedance contrast. The results of two analyses are shown in the Figures 17 and 18. It is clear that a great difference of the response exists between the stations at left of the discontinuity and those on the right hand. The curves are clearly separated in two different groups.

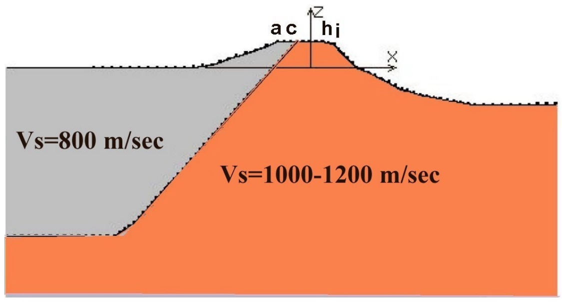


Fig. 16 D-D' section with discontinuity

The effect of the discontinuity is to create a kind of barrier for the medium period waves and to allow only the low period waves to pass through the barrier. The bigger is the contrast the more narrow and distinct are the bundles of curves and larger the difference between the two groups. The result is generally a reduction of the response with respect to the previous cases. With regard to the stations on the cinereous scaglia the amplification is less then one only for the periods grater than 0.18 sec and increase up to 2.0 for very low periods.

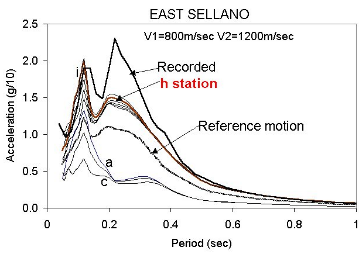


Fig. 17 Case of V_2=1200 m/sec

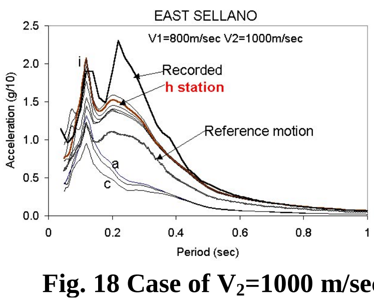


Fig. 18 Case of V_2=1000 m/sec

AMPLIFICATION ANALYSIS IN CESI

In figure19 the scheme used for the analysis is shown. Since it was performed just after the main shock with the aim to give a result as soon as possible, we got few data regarding the soil material and geometry far from the town of Cesi so we extended the data near the station uniformly to all the valley. The valley, about 1 km long, is divided in two layers.

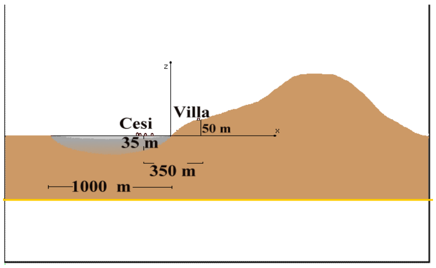


Fig.19 Scheme of Cesi (not to scale)

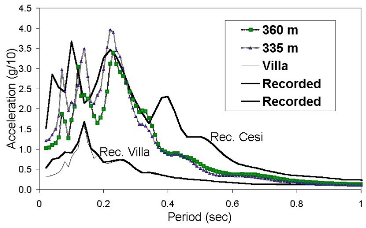


Fig. 20 Computed vs recorded motions

The superficial one, about 10 meter thick, has a low shear wave velocity of 80 m/sec while the lower layer has an average shear velocity of 300 m/sec. The computer code can treat any kind of impinging plane waves incident at any angle but in these analyses only SV waves vertically incident were used, that is we assumed that all the signal is formed by SV waves.

We carried out two analyses. The first one had the aim to check the scheme that we had assumed and in the second we tried to get the response spectra of the main shock, since the stations were not installed at that time, in order to justify the dramatic damages observed in the town.

In the first analysis we didn't faced a real inverse problem to obtain the reference motion, as described in previous chapter, but we simply used the record in Villa reduced in same extent. In fact the slope of the rocky soil in Villa is nearly horizontal so that it can be considered an outcropping horizontal rock. The results of the first analysis are shown in fig. 20.

The comparison in Villa, of course, is very good while on soft soil, Cesi, there are few differences especially in the period range around 0.4 sec. They can be explained by the lack of real data on material and geometry of the valley and by the extreme variability of the response from point to point. As matter of fact this variability is shown in the figure where the response spectra in two stations 25 m distant each other are reported.

In the second analysis we used as input a ground motion similar to that of that main shock. As matter of fact the enormous amplification recorded may be not representative of a stronger excitation, as that of the main shock, where a greater inelastic soil deformation took place with a consequent greater energy dissipation and lower amplification.

The required ground motion has been obtained by the methodology implemented in Italy by Sabetta and Pugliese[5], which, through a statistic of the recorded ground accelerations in Italy, allows to construct response spectra on an outcropping rock by knowing the magnitude and the distance from the fault. We assumed the following parameters of the main shock: magnitude = 5.8 and distance= 3 km. The spectrum of the input ground motion is shown in fig. 21. The dominant frequencies contained in this ground motion are around 5 Hz, that is a period of .2 sec, and the maximum response is equal to what is expected for an Italian second category zone, that is 0.62 g.

In order to account for strain compatible soil properties, we performed a preliminary approximate analysis with the computer program PSHAKE [6]. It evaluates the soil response with a 1D scheme, in this case a soil column at the accelerometric station site (see fig. 19), and an iterative procedure to account for the non-linear behavior of the soil. In this case, as we didn't know exactly the shear modulus and the damping and their relationship relating these properties to shear strain, we used a suitable literature data [7]. As output of the preliminary analysis we got a reduction of the shear wave velocity in soft soil from 300 to 250 m/sec and an increase of damping from 1 to 8%. Also the damping of the superficial layer increased to 12%.

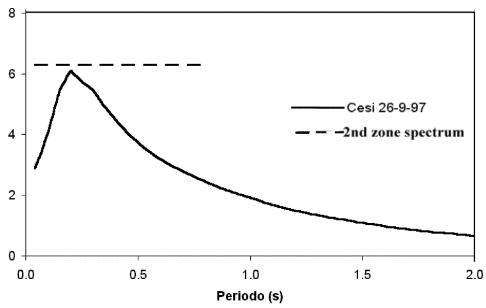


Fig 21 Input ground motion

In fig.22 a detail of the scheme used in BESOIL is shown with the locations where output motions are computed and are labeled from A, toward the center of the valley, to L at its end.

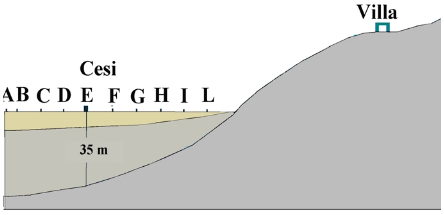


Fig. 22 Detail of Cesi scheme (not to scale)

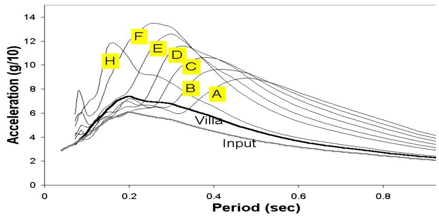


Fig 23 Spectra in Cesi for the main shock

The final results are shown in fig. 23. The labels A to H refer to the stations in figure 22. It is possible to notice that generally the amplification is less than the case of the aftershock shown in fig. 20. The shape and the amplitude of the curves change passing from the central part of the valley, stations A and B, to the final part, toe zone, labeled as H. The maximum is reached in station F, which is near the accelerometric station. Also the frequency range of maximum response change from high period, 0.5 sec at the center of the valley to 0.2-0.3 sec at the stations E, F, H. The shape of the curves explain the selectivity of damages. As matter of fact about all the houses were masonry structures, with probably high frequencies, so the maximum of damage was concentrated in the toe zone near stations E and F.

CONCLUSIONS

The accelerograms recorded in different locations in Sellano and Cesi show a great amplification in the range of period of 0.15-0.25 sec, or frequency range of 4-7 Hz, that are dangerous especially for masonry structures. This confirms the dramatic damages recorded in both towns.

Computer codes using 2D schemes are suitable for some zones, like West Sellano and Cesi, with cylindrical geometry, but they can’t reproduce the amplification in zones, like East Sellano, characterized by a complex geometry. Only a 3D analysis can probably reproduce the real physical phenomenon.

Regarding the numerical analyses the results show that

- The most important parameter is the direction of impinging waves. Changing the direction, we can get, for some analyses, both a great de-amplification and an enormous amplification at very low periods.
- The motion on a hill may be very variable from point to point, in a very short distance, depending on the shape of the hill.
- A little variation of geometry, like changing the slope or the horizontal dimension of a hill affects only the response at high frequency and the space variability of the motion.
- Lengthening of periods in soft soils
- Large amplification in the alluvial valley close to the contact with the rocky slope.

There are still many uncertainties in the understanding of the local amplification phenomenon. A great effort should be done to improve theoretical analyses and computer codes for the analysis of complex geometry

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