LOCAL INTENSITY VARIATIONS IN THE CITY OF ROME DURING THE 1997-1998 UMBRIA-MARCHE (ITALY) SEISMIC SEQUENCE AS INFERRED BY SCHOOL QUESTIONNAIRE SURVEYS

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SUMMARY

Two high density macroseismic surveys were performed in Rome during the September 1997-April 1998 Umbria Marche (Central Italy) seismic sequence. This work was developed by the cooperation among Istituto Nazionale di Geofisica (ING), Università Roma Tre and public high schools of Rome. The study was carried out for the October 14, 1997 (15:23 GMT) earthquake (M_w=5.6; I_0=VIII MCS; $h \approx 10$ km), located about 115 km far from Rome, and for the March 26, 1998 (15:25 GMT) earthquake (M_w=5.3; I_0=VII MCS; $h \approx 50$ km), 150 km far from Rome. The aim of the work was to investigate local macroseismic variations by means of school questionnaire surveys, collecting significant data to test historical issues and numerical modelling and to integrate, when available, ground motion and weak motion measurements. A sort of macroseismic network in the urban area was arranged in 27 public high schools, where suitable questionnaires were delivered to students after the two events. A large amount of macroseismic information was synthesized in 669 and 928 observation points, respectively. The sample reliability was checked considering the data distribution versus urban framework discontinuities and the frame of outcropping geological formations. The analysis on seismic effect distribution versus geological conditions outlined a preferential distribution of major effects on Holocene alluvial deposits. Recent alluvium are characterized by a higher MCS intensity (one degree, on average) with respect to volcanic and sedimentary formations, for both earthquakes. In particular, low intensity effects are largely predominant on pliocenic bedrock formations. Macroseismic variations were also investigated as a function of alluvium thickness and distance from the edge of the Tiber valley. A new tight correlation between largest effects and alluvium emerged in correspondence of the minor hydrographic network in modern suburban areas of Rome. All results seem to confirm the role of local geological heterogeneity in the seismic response of the area.

INTRODUCTION

Many urbanized areas display a geological complexity often responsible for locally significant amplification of ground motion during earthquakes. In fact, in regions where the near-surface geology presents lateral hard-rock to soft-soils transitions, site effects were observed to vary sharply and significantly, producing locally important increment of intensity. Evaluation of effects can be correlated with strong motion recordings and mapped geology on a very fine scale. Nevertheless, strong motion data are not always available, especially in large urban areas. In these cases, the use of macroseismic data in site effects studies can play an important role, particularly in the identification of sites where amplifications occur.

The geologic setting of the Roman area is characterized by the presence of three different domains: the Plio-Pleistocene regional sedimentary bedrock, the Middle-Late Pleistocene volcanic plateau and the holocenic alluvial plain of the Tiber River. Marine and continental sedimentary units outcrop in the western part of the city, while Sabatini and Alban Hills volcanic products, spread up from 0.6 Ma, have blanketed especially the eastern portion of the area. In the last glacial low-stand (Würm), the Tiber River and its tributaries excavated the plio-pleistocenic bedrock down to a maximum deepening of -50 m below the present sea level. During Holocene, in

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the last 10.000 years, this articulated hydrographic network was backfilled with a maximum of 60 m thick coarse alluvial deposits, subsequently covered by man-made fills accreted from the early history of the town. Holocene deposits are mostly

unconsolidated and water-saturated and present a lower density, as compared to the pre-holocenic sedimentary and volcanic formations. Moreover, recent deposits filling the minor valleys present a poorer geotechnical characterization with respect to Tiber River valley alluvium [Bozzano *et al.*, 1997]. In all these cases, such a different mechanical behavior may cause a significant difference in seismic impedance of the geological units outcropping in Rome.

During the September 1997-April 1998 Umbria-Marche (Central Italy) seismic sequence, the city of Rome felt many of the shocks. Highest intensity reached the V-VI degree Mercalli-Cancani-Sieberg (MCS) in many parts of the city, producing large emotion in most people. Following two aftershocks of the sequence, the 14 October 1997 (M*w*=5.6; I_0=VIII MCS; *h*≈10 km) and the 26 March 1998 (M*w*=5.3; I_0=VI-VII MCS; *h*≈50 km) events, located 115 km and 145 km N of Rome, respectively (see Figure 1), Istituto Nazionale di Geofisica (ING) and Università "Roma Tre" undertook a detailed research to determine intensity levels in Rome by using macroseismic surveys.

A macroseismic network was set up and arranged in cooperation with 27 public high schools of Rome, where *ad hoc* macroseismic questionnaires were delivered to students. We performed high-density macroseismic surveys for both events, obtaining 669 and 928 intensity points, respectively, and reaching a density of 3.4 data/km^2 in the first survey and 4.7 data/km^2 in the second one. The data distribution was largely representative of the urban setting of Rome [Cifelli *et al.*, 1999]. It is important to emphasize that such amount of data was hardly achieved in previous macroseismic surveys in large cities.

Data collected were then used to analyze the intensity distribution in Rome of the October 14, 1997 and March 26, 1998 earthquakes in relation to the nearsurface geology. Finally, we correlated intensity to shape and dimensions of the sediment-filled valleys of the Tiber River and its tributaries, with the aim to identify the presence of edge effects and 2-D resonance phenomena in small alluvial basins.

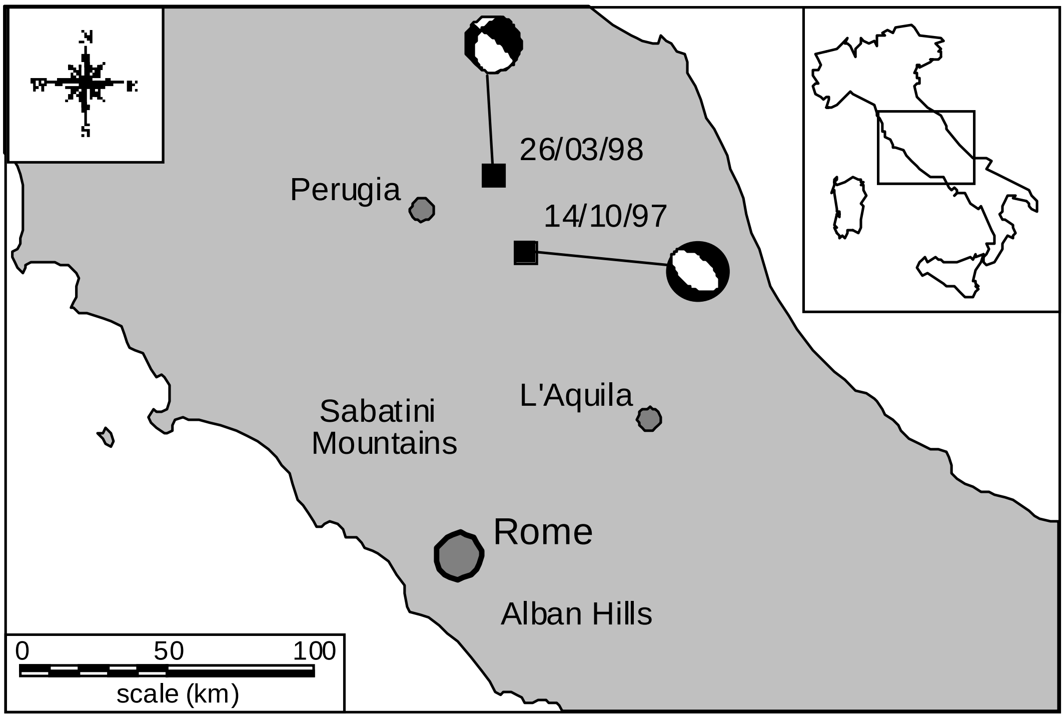

Figure 1: Map of Central Italy with the epicentres and the focal mechanisms of the 14 October 1997 (Mw=5.6; I_0=VIII MCS; *h*=10 km) and the 26 March 1998 (Mw=5.3; I_0=VII MCS; *h*=50 km) earthquakes (Morelli *et al.*, 1999). The first event occurred 115 km north of Rome, while the second one occurred 145 km north of the city.

INTENSITY DISTRIBUTION AND LOCAL GEOLOGY

The distribution of the effects in Rome for both the 14 October 1997 and the 26 March 1998 Umbria-Marche earthquakes displays a large variability of the macroseismic intensity, ranging from not felt (NF) to V-VI MCS. Major effects show a higher frequency of occurrence on the recent alluvial deposits. In particular, the intensity distribution of the 14 October 1997 earthquake outlines a correspondence between highest effects (V degree in MCS scale) and Holocene alluvium in both the Tiber River valley and the minor hydrographic network. Alluvial deposits were comprehensively prone to a higher intensity, equal to one degree of difference in MCS scale, on average, with respect to volcanic and sedimentary bedrock formations. Almost 60% of intensity points on Holocene alluvium was around V (see Figure 2). Pre-holocenic units were mainly affected by moderate effects (IV, III and NF); in particular, no remarkable effects (V) occurred on pliocenic bedrock formations. Results for the 26 March 1998 earthquake confirm the influence of the local geology in the seismic response of the city. Highest effects (IV and V MCS) show a preferential concentration on recent alluvium, while lower effects spread all over the bedrock formations. The data analysis (Figure 3) shows the higher intensity values on alluvial deposits with respect to the remnant formations (IV MCS vs II-III MCS, on average).

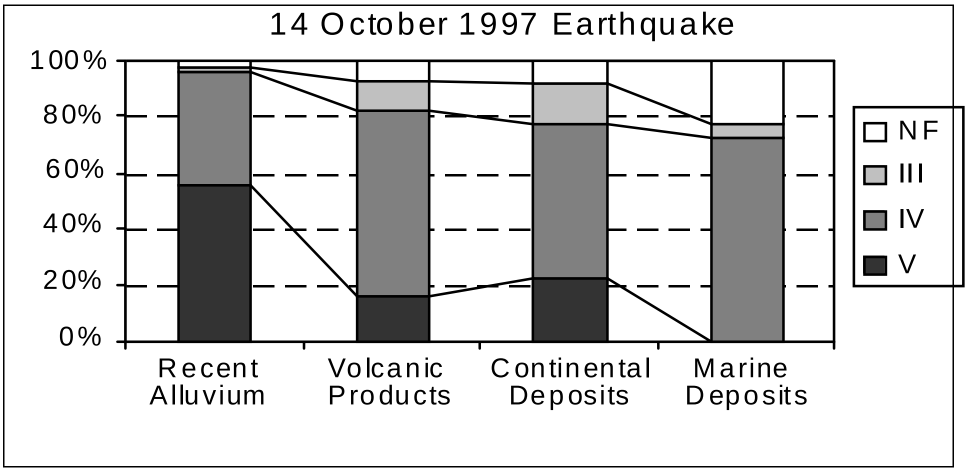

Figure 2: Normalized MCS intensity distribution in Rome of the 14 October 1997 earthquake vs lithologic units. Alluvial deposits are prone to a higher ground motion (one MCS degree, on average) with respect to bedrock formations.

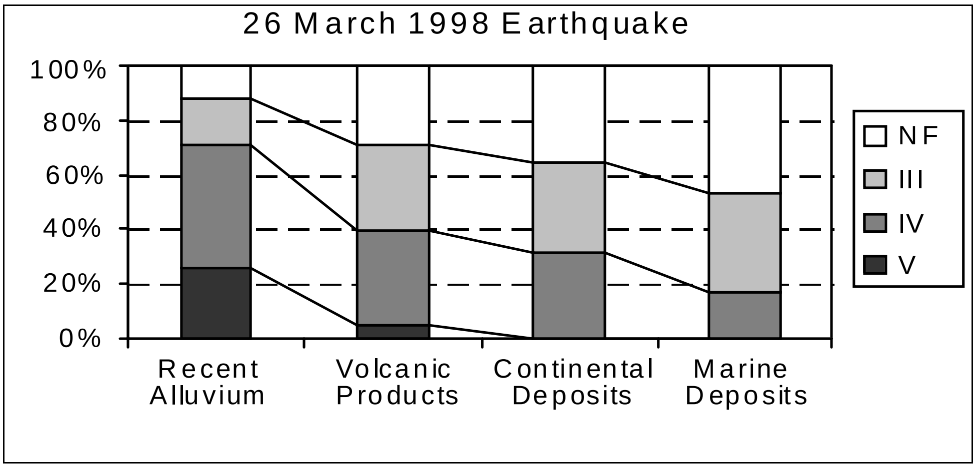

Figure 3: Normalized MCS intensity distribution in Rome of the 26 March 1998 earthquake vs lithologic units. The higher shaking on Holocene alluvium, with respect to pre-holocenic formations (IV MCS versus II-III MCS, on average), is confirmed.

INTENSITY DISTRIBUTION IN ALLUVIAL VALLEYS

Further investigation of the effects on recent alluvium of Tiber River and its minor hydrographic network was undertaken by considering shape and dimension of the alluvial basins. Intensity points on Holocene alluvial deposits for the 14 October 1997 and the 26 March 1998 earthquakes were 232 and 229, respectively. For every observation point, we measured the width of the alluvial basin and the distance of the point from the edge of the valley. The main Tiber River valley has a mean width of about 2200 m (ranging from about 1000 m, within the historic centre of Rome, to more than 3500 m, in its lower reaches). Each side of the valley was divided into 4 longitudinal bands, characterized by different width, in order to consider the lateral variations of both the alluvium thickness and the shape of the basin. Data coming from both sides were then cumulated.

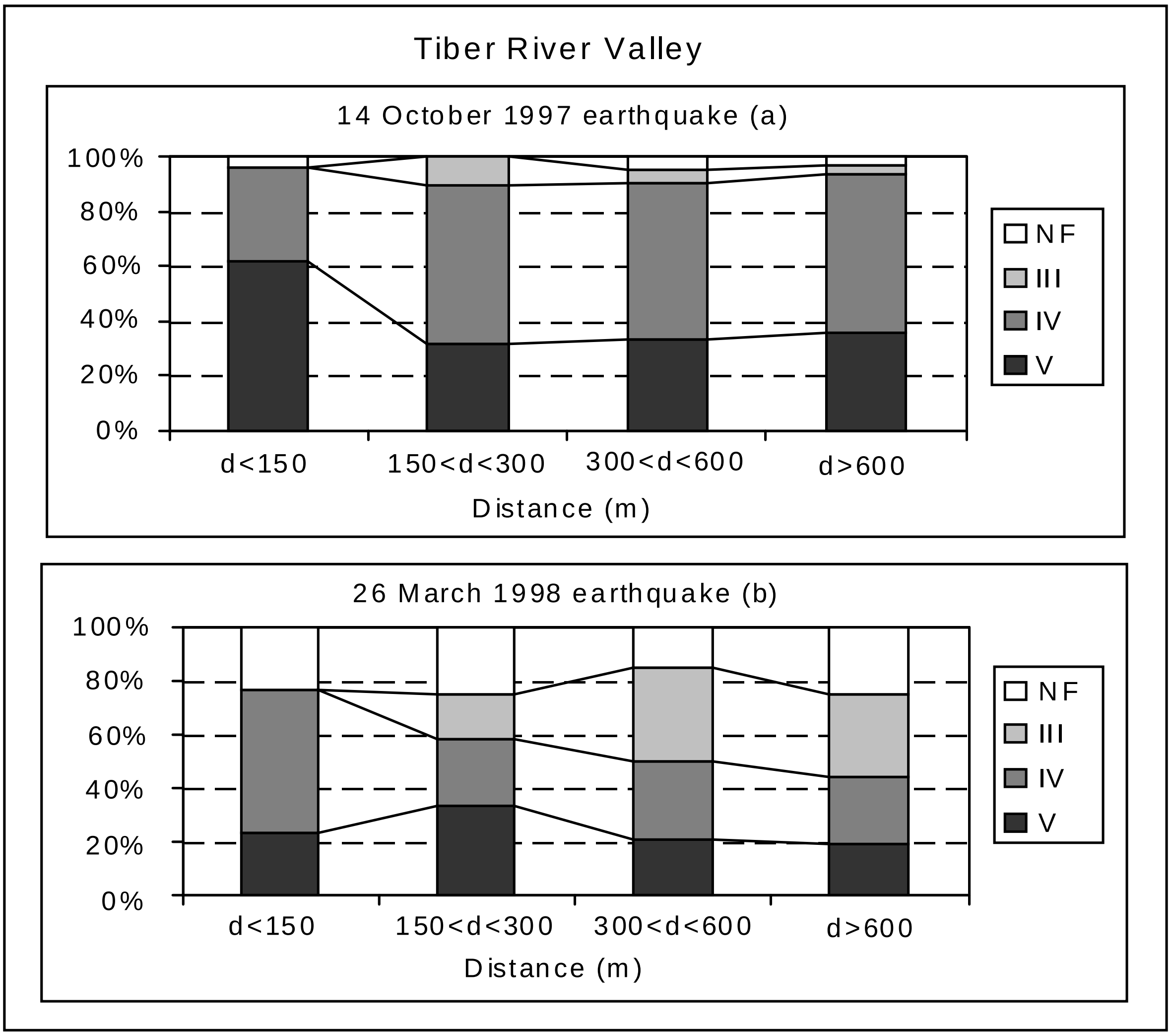

Figure 4: Normalized intensity distribution of the 14 October 1997 (a) and 26 March 1998 (b) earthquakes within the Tiber River alluvial valley. The edge band (d < 150 m) is affected by higher effects than those in the central part of the basin.

The intensity distribution of the first survey versus the distance from the edge of the valley (Figure 4, a) shows a remarkable concentration of highest effects (V MCS exceeds 60%) in the 150 m wide band near the bedrock-alluvium limit. The other bands, towards the centre of the basin, outlined more moderate and homogeneous effects. Data from the second event (Figure 4, b) confirmed the higher intensity on the edge band (IV and V reach almost 80%) and showed a growing contribution of very weak effects (III and NF) towards the centre of the valley. Subsequently, the response of all the alluvial valleys was analyzed as a function of their width and thickness (*h*). In the studied sediment-filled basins of Rome, the thickness of Holocene alluvium and man-made fills ranges from a maximum of 60-70 m, in the Tiber valley, to a minimum of 30-40 m, in minor alluvial basins [Funiciello *et al.*, 1995; Marra and Rosa, 1995]. We classified the sediment-filled alluvial valleys into 5 different typologies, according to their narrowness (see Figure 5): type A (width < 150 m), type B (width between 150 and 300 m), type C (width between 300 and 600 m), type D (width > 600 m) and the main Tiber River valley.
The distribution of the intensity on the different alluvial basins for the 14 October 1997 earthquake (Figure 5, a) shows that the response of the Tiber valley is remarkably lower with respect to other minor sedimentary basins. On minor streams (type A, B, and C), intensity seems to be roughly proportional to the narrowness of the basin. The narrowest streams (type A), for instance, present more than 80% of highest effects (V MCS). Secondary valleys (type D) also show a much higher response with respect to the Tiber valley.

Results for the second survey (Figure 5, b) confirmed the lower response of the Tiber valley with respect to the minor basins. Higher effects (IV and V) exceeded 95% in the narrowest streams (type A). Also the peculiar seismic behavior of the secondary valleys (type D) was confirmed.

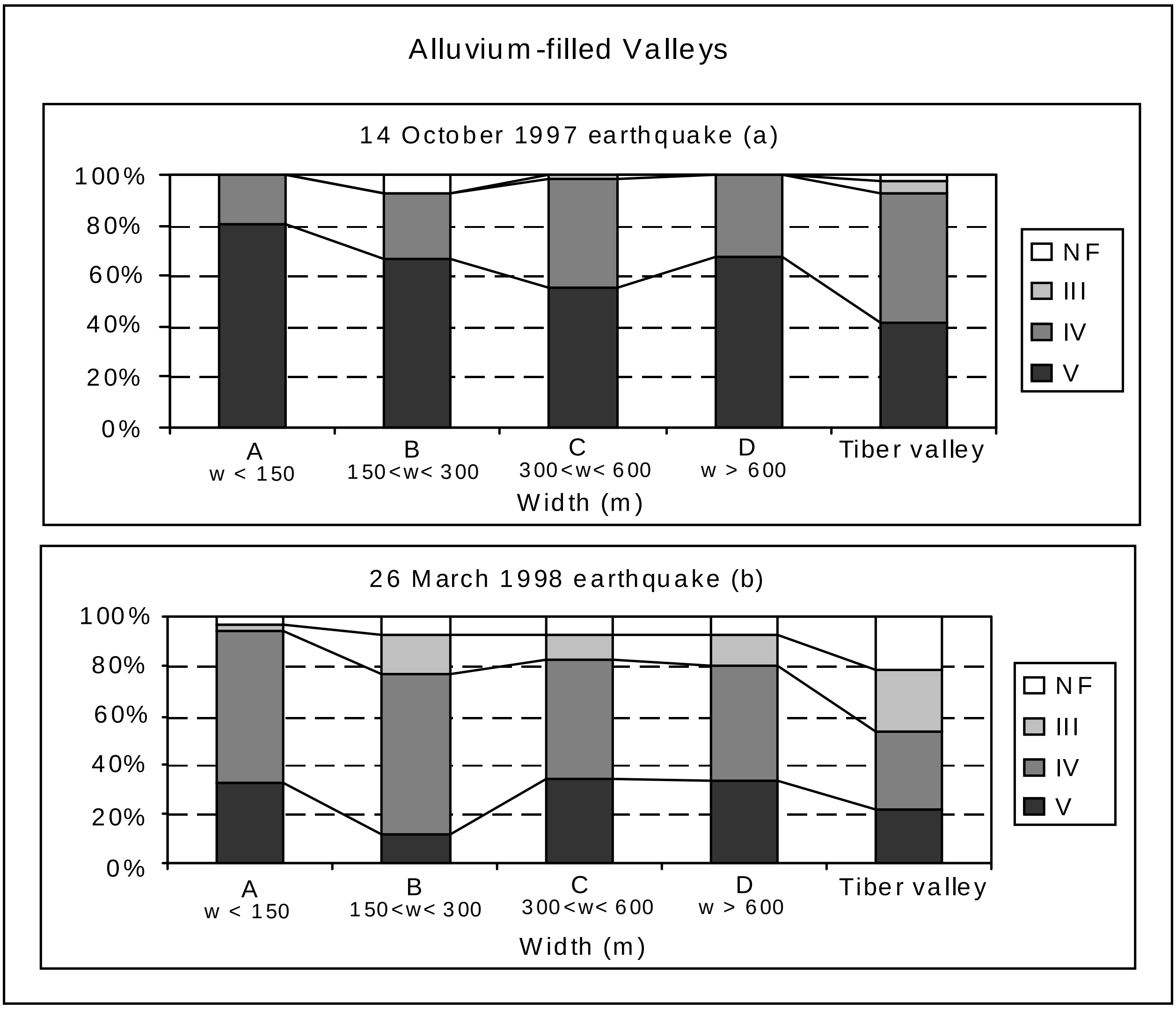

Figure 5: Normalized intensity distribution of the 14 October 1997 (a) and the 26 March 1998 (b) earthquakes on the different alluvium-filled valleys of Rome as a function of their width and shape ratio (*h/l*). Narrowest streams (type A), widely diffuse in the modern suburban areas, display the worst seismic response.

DISCUSSION AND CONCLUSIONS

High-density macroseismic surveys carried out for the 14 October 1997 and the 26 March 1998 earthquakes [Cifelli *et al.*, 1999] provided very similar and homogeneous results.

The analysis of intensity stresses the occurrence of site effects in the Rome urban area. Higher effects (V MCS) are well correlated with lateral variations of the local geology. Recent alluvial deposits are characterized by a marked difference in intensity (one MCS degree, on average) with respect to the pre-holocenic sedimentary and volcanic formations. Such a difference is noteworthy, especially in a low intensity macroseismic field. The different response of the outcropping units could be related to the seismic impedance contrast between bedrock units and Holocene deposits. The latter is estimated to be around 4:1 [Bozzano *et al.*, 1995] and can be responsible of local amplification phenomena. All the data suggest that Holocene deposits in Rome present a higher level of hazard than Plio-Pleistocene bedrock units.

The relevant concentration of higher effects in the narrow band (< 150 m) close to the bedrock to alluvium transition of the Tiber River valley (Figure 4) suggests the presence of a characteristic edge effect in the alluvial basin. This observation is in agreement with the edge effects described by previous historical earthquakes

observations [Tertulliani and Riguzzi, 1995] and numerical modeling of the seismic response [Rovelli *et al.*, 1995] for the city of Rome.
An unexpectedly larger seismic response of recent alluvium is enhanced in correspondence of minor alluvial basins in modern suburban areas of Rome, never investigated before with such a detail. In particular, the highest effects occur in correspondence of the narrowest alluvial streams (type A, in Figure 5), while wider basins, especially the Tiber valley, show a relative lower shaking. This observation can be explained considering the shape ratio (*h/l*) of the alluvial basins, as the ratio of the maximum sediment thickness to the half-width of the valley. For very narrow sediment-filled streams of Rome, *h/l* ratio ranges between 0.4 and 0.8. According to Bard and Bouchon [1985], these values of *h/l*, if coupled with a contrast impedance around 4, can induce a 2-D resonance in the valley (see Figure 6).

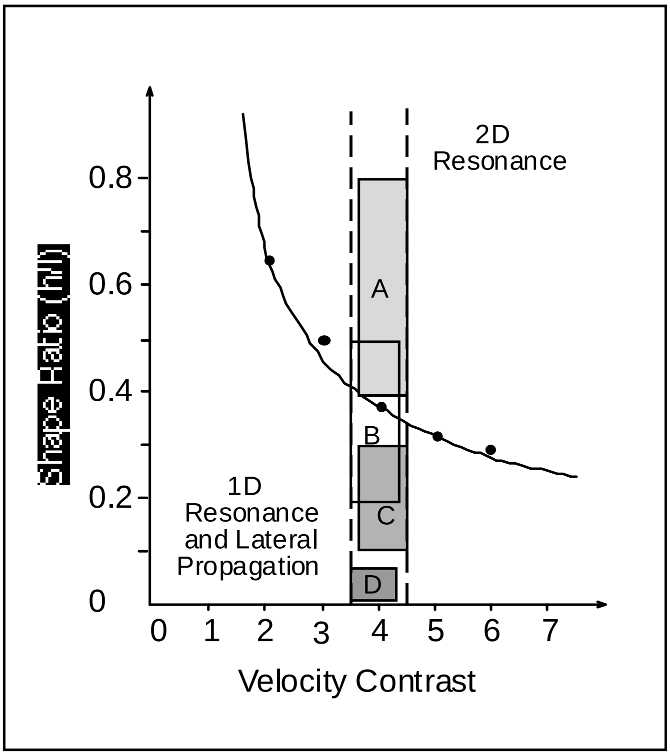

Figure 6: The curve represents the existence conditions of the 2D resonance of sediment-filled valleys as a function of shape ratio (*h/l*) and velocity contrast (redrawn from Bard and Bouchon, 1985). The four rectangles correspond to the different types of studied valleys in Rome (type A, B, C, and D). Dashed lines represent the bedrock-alluvium impedance contrast in Rome (around 4, according to Bozzano et al., 1995). Valleys of type A (width < 150 m), where highest effects occurred, entirely lay in the 2D resonance range.

Such amplifications of the ground motion in minor alluvial streams of Rome were also evidenced by numerical modeling of the seismic response in the Fosso Labicano valley [Moczo *et al.*, 1995] and in the Palatino area [Rovelli *et al.*, 1994]. For other typologies of alluvial basins in the study area (width > 150 m), whose shape ratio cannot exceed 0.2, no 2-D resonance phenomena are expected (see Figure 6). Also the poorest geotechnical characterization of small-size basins filled by alluvium deposits, with respect to the main valleys [Bozzano *et al.*, 1997], could involve a local amplification of the ground motion.
These results can provide a significant contribution to seismic risk evaluation of the urban area for larger events, assessing the correct hazard to recent alluvial deposits. Despite the moderate seismicity of the region, plans for seismic risk mitigation should take into account the seismic behavior of rock to soft soils transitions.

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