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The 1930 earthquake and the town of Senigallia (Central Italy): an approach to seismic risk evaluation

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Abstract

The town of Senigallia is located on the Adriatic coast of the Marche and Romagna regions (Central Italy), an area affected by offshore seismicity. This city was almost completely destroyed by an earthquake of IX degree intensity on the Mercalli-Cancani-Sieberg scale (MCS) on October 30, 1930. This quake is the most recent and the best documented. In particular, this shock was characterized by strong differences in the damage levels at a scale of hundreds and tens of metres. The geographic position of Senigallia at the mouth of a river and its soil conditions, similar to many other coastal historical and tourist centres in the region, make this earthquake an important case history, useful for a better understanding of the seismic risk of the entire coastal area. This note reports the first results of a study on the possible causes of the different damage levels. The research started with the history and town-planning evolution of Senigallia, then, the regional or local geological characteristics were considered by geological, geotechnical and geophysical investigations.

Key words *historical seismicity – seismic risk evaluation – Adriatic coast, Central Italy*

1. Introduction

On 30 October 1930, a very strong earthquake struck the Marche between Pesaro and Ancona, causing severe damage in Senigallia and almost completely destroying the town. The maximum intensity reached the IX MCS degree (Oddone, 1930). This was the most relevant event which took place off the Marche-Romagna Adriatic coast (fig. 1). In order to understand the relationships between a seismic event and its effects, Senigallia is an excellent case-study for a multidisciplinary approach. In fact it is affected by seismic activity and is located at the mouth of a river, on clayey alluvium with interbedded sands, a typical situation of many other Adriatic coastal towns. The great wealth of seismological (macroseismic and instrumental) information, geophysical, stratigraphical, hydrogeological and geotechnical data allowed us to investigate the differentiated seismic effects for an evaluation of the seismic hazard.

2. The town history

The origins of Senigallia are very old, going back probably to the Neolithic age. However, Senigallia – the ancient Sena – derives its name from the *Galli Senoni* (Celts), who founded it in the fourth century B.C. on an island surrounded by a coastal swamp at the mouth of Misa river (the swamp is now an al-

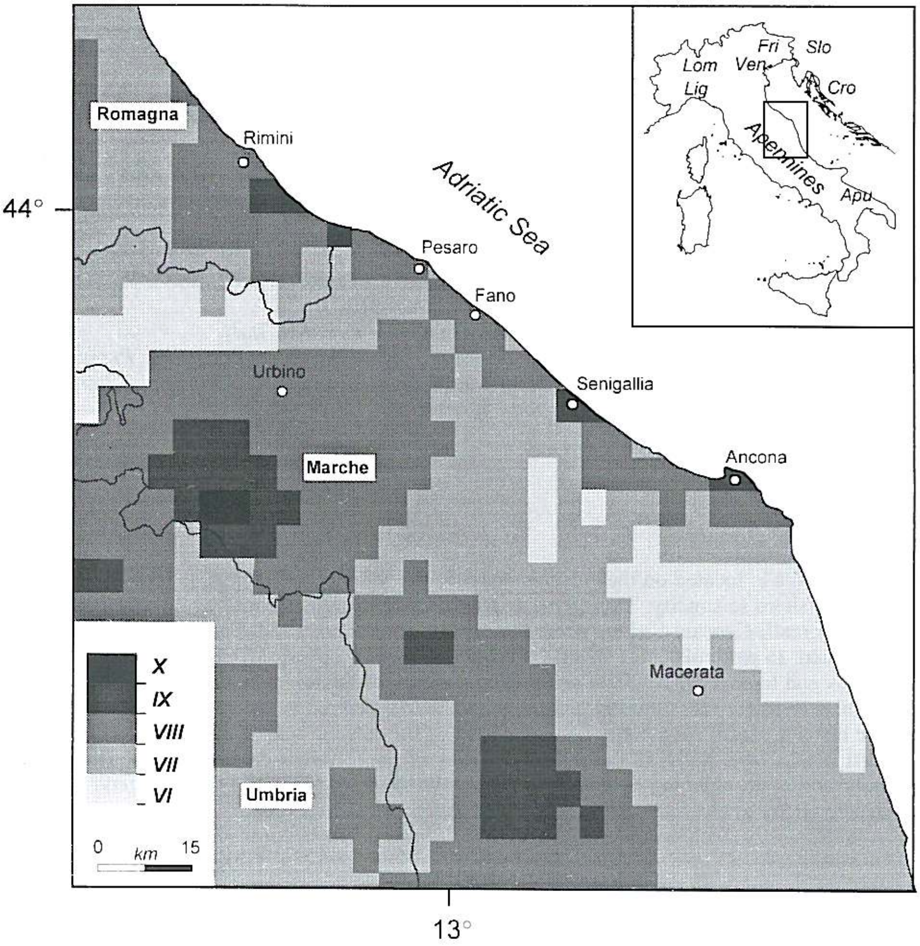


Fig. 1. Map of the maximum intensities felt in the Marche-Romagna region (the rectangle shown at the top right corner), using the ING seismic databases. The time span considered is between 1000 and 1990 years. The scale of greys on the left bottom corner of the figure indicates the values of intensities, according to the MCS scale ($I \geq$ VI). At the top right corner are also reported the other geographic names used in the text (Apu = Apulia, Lig = Liguria, Lom = Lombardia, Ven = Veneto, Fri = Friuli-Carnia, Slo = Slovenia, Cro = Croatia).

luvial plain). Subsequentely, it became a Roman colony and its urban development started. In 409 A.D. the town was completely destroyed by the Goths of Alarico. There followed a long period of ups and downs until the 8th century when Senigallia went under the domination of the Church. With the destruction of the city ordered by Manfredi in 1264, the town knew another long period of decline worsened by the floodings of the Misa river which turned the region into a swamp. The renaissance of Senigallia had to wait until 1445, when under the rule of Sigismondo Malatesta, followed by the Della Rovere dynasty (1474-1631), and later under the direct power of the Popes, the town underwent a period of growth and prosperity through maritime and commercial activities. It became one of the most important trading settlements in the northern Adriatic area. The mid 18th century signified the «Golden Age» of Senigallia. Drainage of the swamp and straightening of the river took place along with the expansion of the town. At the beginning of this century, it changed from a commercial town into a tourist and seaside resort.

Figure 2 shows the town-planning evolution from the Roman age to 1940, ten years after the quake (Giarrizzo, 1963). The oldest area (zone 1), south of the Misa river, is characterized by a 15th century centre, with some Roman remains, and buildings from the 16th and 17th centuries. In the 16th century, after the drainage and reclamation of the swamps close to the river, the fishermen's and sailors' village (Borgo Pace), built along the left bank of Misa on filling material used to drain the swamp, was included within the walls of the town. Zones 1 and 2 represent the city at the end of the 16th century. Subsequentely, the town developed along the bend of the river (zone 3); the three areas show Senigallia at the middle of 18th century under Pope Benedetto XIV who promoted the architectural development of the town and the enlargement of the port. After that period, the city expanded essentially towards the Adriatic Sea as shown in zone 4. The four zones, as a whole, outline the extent of Senigallia during the time of the Pope's rule until 1870, when the territories were incorpo-

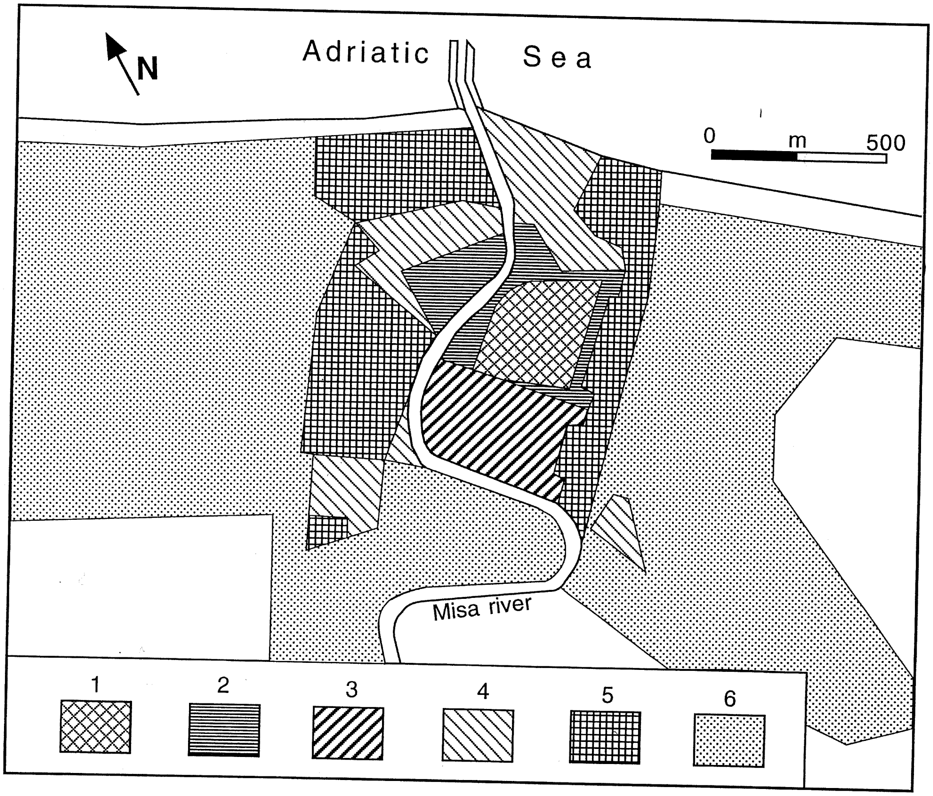


Fig. 2. Historical evolution of Senigallia from the Roman age to 1940 (ten years after the earthquake): 1) Roman age; 2) end of the 16th century; 3) middle of the 18th century; 4) the annexation to the Italian kingdom (1870); 5) at the beginning of the 20th century; 6) 1930-1940 (after Giarrizzo, 1963 – simplified).

rated into the Italian kingdom. In the years that followed, the city expanded on both sides of the river and along the shoreline (zone 5, at the beginning of the 20th century). Finally, zone 6 shows the city in the Forties, just ten years after the earthquake.

3. The 1930 earthquake

The Adriatic coast of the Marche and Romagna regions, almost corresponds to the buried front of the external thrusts in the Northern Apennines and is often subject to offshore seismicity. Some historical earthquakes have caused inland effects with intensities which have reached the IX degree MCS; table I lists the major earthquakes which have occurred since 1300 offshore between Rimini and Ancona (Postpischl, 1985; ING, 1991). The maximum felt intensity map (fig. 1), computed following the methodology described in previous papers (*e.g.*, Basili *et al.*, 1990; Favali *et al.*, 1990), shows two bands with comparable maximum values. The first along the coast and the second along the Apenninic chain.

The 1930 Senigallia earthquake is the most recent of the largest quakes. The seismic energy released, the size of the damaged areas, the strongly differentiated damage levels, and the number of chronicles and instrumental records make the study of this quake significant to better understand the seismic characteristics and hazard of the region. The magnitude (M_s) of this event has been recently reassessed using all the available original seismograms as 6.0 by Margottini *et al.* (1993). This value makes the Senigallia earthquake comparable with others which have characterized other well known Italian seismogenic zones (*e.g.*, Friuli-Carnia, May 6, 1976 $M_L = 6.4$). The 1930 shock is completely different from the last important earthquake which occurred offshore Ancona in 1972 (see table I). In fact, the

Table I. Major earthquakes which occurred from 1300 in the Adriatic Sea, near the Marche-Romagna coast, between Rimini and Ancona (see fig. 1). The localities listed as epicentral areas simply show the area of heaviest damage.

Year	m.d.	I_M (1)	M (1)	I_M (2)	M (2)	Epic. area
1303	08 08	9	6.1	nr	nr	Rimini
1308	01 25	8	5.2	8	5.2	Rimini
1507	06 —	8	5.3	nr	nr	Rimini
1572	07 13	8	5.4	8	5.1	Pesaro
1672	04 14	9	5.7	9	5.6	Rimini
1688	05 31	8	5.4	8	5.1	Fano
1690	12 24	9	5.9	8	5.1	Ancona
1692	10 24	7	4.9	8	5.1	Fano
1786	12 25	9	5.7	8	5.2	Rimini
1875	03 17	8	5.2	8	5.2	Rimini
1916	08 16	8	5.2	8	5.2	Rimini
1924	01 02	7-8	4.8	7-8	4.8	Senigallia
1930	10 30	9	5.6	9	5.6	Senigallia
1972	02 04	8	5.1	8	5.1	Ancona

I_M = maximum felt intensity according to MCS scale; M = magnitude derived from the intensity; (1) = catalogue of the *Istituto Nazionale di Geofisica* (ING, 1991); (2) = catalogue of the *Progetto Finalizzato Geodinamica* (Postpischl, 1985); nr = non reported.

1930 quake had much less aftershocks than the 1972 one. This last event lasted many months with hundreds of aftershocks. From these different patterns it is possible to hypothesize a deeper focus for the 1930 seismic event connected with deeper structures below the sedimentary covers. The shock occurred offshore and a coseismic high tide was reported by the newspaper «Corriere Adriatico» on November 1st, 1930. The IX degree was reached in Senigallia and its neighbourhoods, and the VIII degree over a wide area between Fano to the north and Ancona to the south. The III degree was felt throughout almost the whole Italian peninsula, from Apulia to Liguria, and Lombardia to Veneto, as well as in Slovenia and Croatia (Molin and Mucci, 1990); see fig. 1 for a geographical framework. The isoseismal map is reported in fig. 3a,b in two versions according to different authors (Oddone, 1930; Molin and Mucci, 1990). In our opinion, Oddone's map, based on the analysis of more than 25 000 buildings in the area shown in fig. 3a, represents a more detailed picture; while the other map (fig. 3b) points to a more regional trend, with a study essentially focused on Ancona.

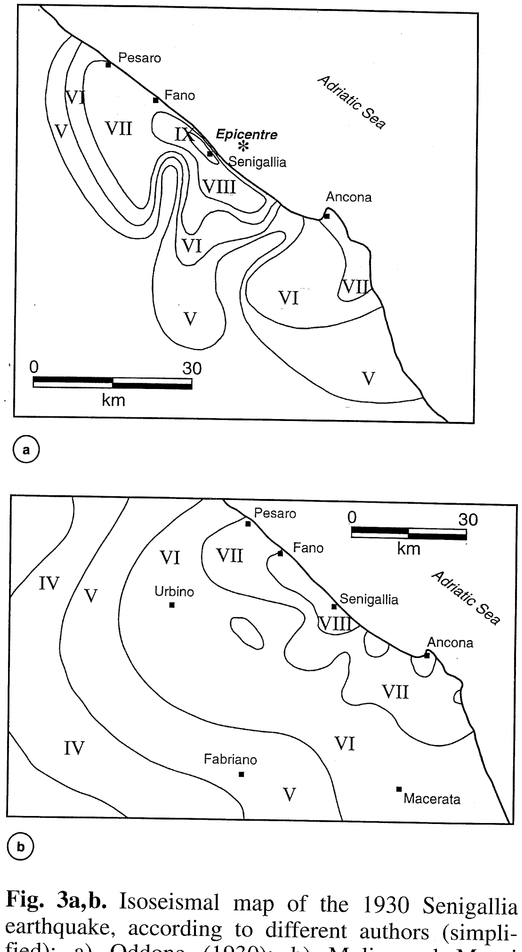
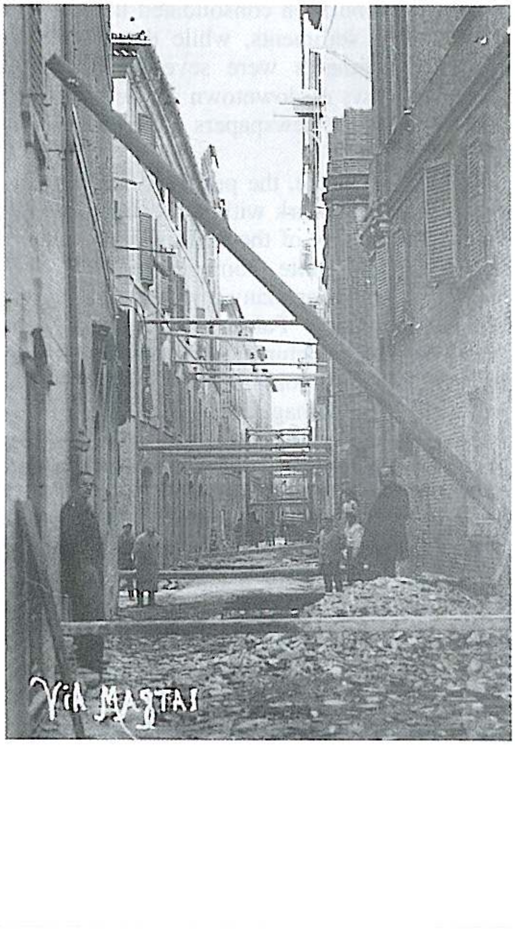


Fig. 3a,b. Isoseismal map of the 1930 Senigallia earthquake, according to different authors (simplified): a) Oddone (1930); b) Molin and Mucci (1990).

Emilio Oddone, seismologist and engineer, was in charge of surveying the damaged areas a few days after the quake, and has left a detailed study. He pointed out the systematic damage to the higher floors (over second) of buildings in the downtown area, the strong attenuation of the effects (from IX to VI degree) towards the shoreline, even though the earthquake was localized offshore, and the differentiated levels of damage on a scale of hundreds and tens of meters. For similar types of well-made buildings, he observed minor damage to constructions built on consolidated lithology or on soft thick sediments, while those built on soft thin sediments were severely damaged. Moreover, news of downtown surface fractures were reported in newspapers (Corriere Adriatico, 1930).

Before the quake, the prevalent building typology was brickwork with main walls in solid bricks. The quality of the buildings was generally good and quite homogeneous all over Senigallia. However many important buildings, such as the Ducal Palace or the town hall, show complex structural characteristics due to changes and additions made throughout the centuries. The damage was widespread irrespective of the quality of construction. Many downtown dwellings were heavily spoiled (46% on a total of 3948), many suffered partial or total collapse of the higher floors with more marked cracks at their corners (figs. 4 and 5), and many rooms were declared uninhabitable (53% on a total of 27 126). In the reconstruction program the authorities decided to reduce the number of floors and the height of buildings. Figure 6 shows the centre of Senigallia, distinguishing the complex structural units

Fig. 4. The «Albergo Roma» after the 1930 quake. Located along the Misa river, it had its second floor completely destroyed.



from the other types of buildings, and the distribution of damage divided into four classes: total demolition, prevalent demolition of the higher floors, widespread demolition and partial collapse. The third class of damage was prevalentely concentrated in Borgo Pace which was built on a landfill.

4. Geological setting

The Marche-Romagna coastal region is located between the eastern front of the Apenninic chain and the middle part of the Adriatic foredeep, and from a structural point of view lies on the external portion of the Apenninic Thrust Belt (Ori *et al.*, 1991). The tectonic lineaments that characterize the area at the surface are east-verging folds, thrusts, and minor

Fig. 5. «Via Mastai» after the 1930 quake. This central street of Senigallia roughly strikes E-W, and reported almost systematic damage especially on the higher floors.

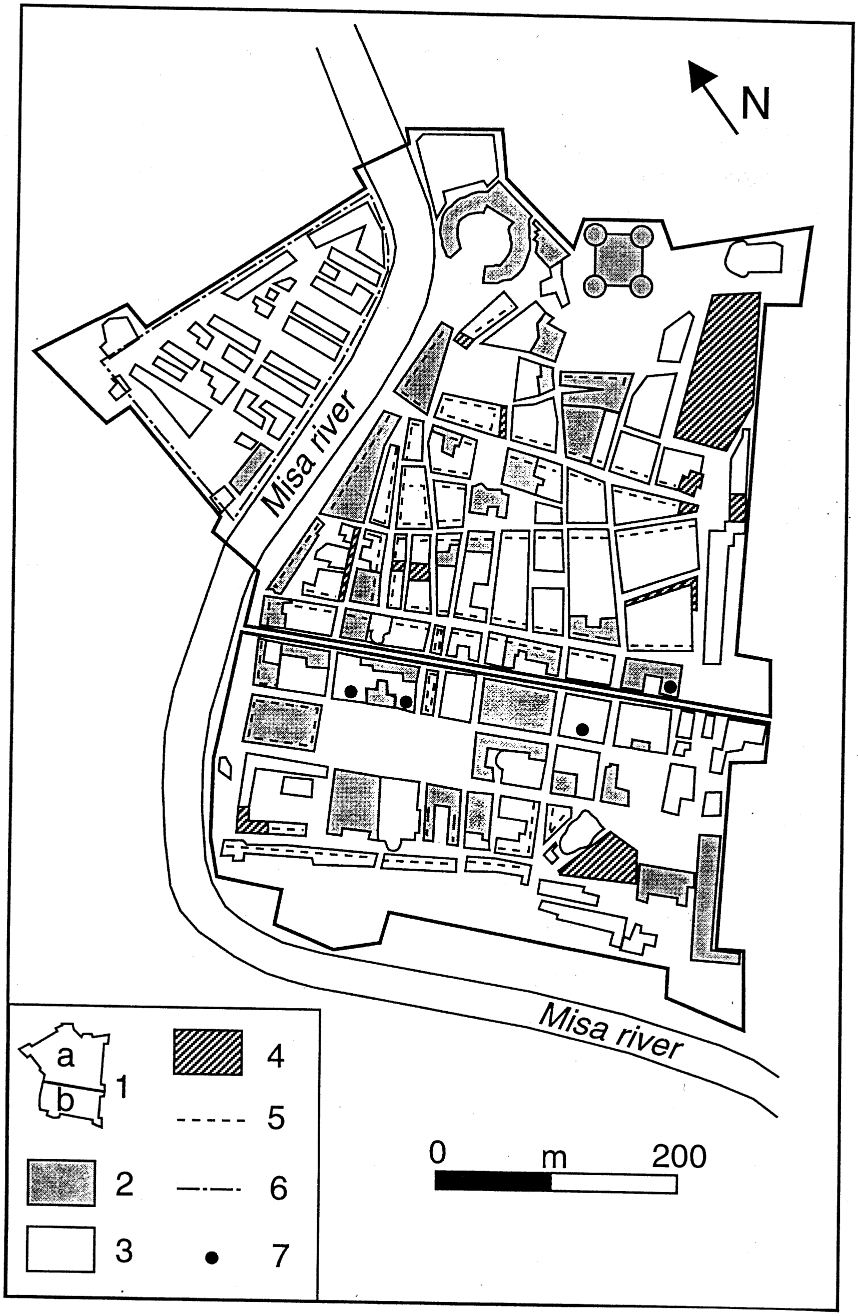


Fig. 6. Map of downtown Senigallia: 1) ancient walls of the city: a) 15th-17th centuries (zones 1 and 2 of fig. 2); b) 18th-19th centuries (zone 3). Building typologies: 2) complex structural units; 3) other buildings. Classes of damage: 4) total demolition; 5) prevalent demolition of the higher floors; 6) widespread demolition in Borgo Pace; 7) partial collapse.

NW-SE compressional faults (imbricate fan). These structures reflect a regional structural style which can also be found in the Adriatic offshore (Bally *et al.*, 1986), mainly due to the strongest phase of the Middle Pliocene Apenninic tectonics (Casnedi *et al.*, 1984; Centamore and Deiana, 1986; AA.VV., 1991).

In the Senigallia area two anticlines, located to the north and south of the Misa river and cored by Tortonian-Langhian p.p. calcareous marls (Schlier), reflect the structural trends of the region (fig. 7). These two outcrops can be considered the superficial expression of the same structure dislocated by anti-Apenninic (NE-SW) tectonic lines at the northern and southern edges of the Misa alluvial plain. The Misa valley can therefore be defined as a structurally controlled valley. This situation is peculiar to the region's geological framework (Nanni *et al.*, 1986). Finally, the structural setting of the area is characterized by Adriatic verging and narrow spaced thrust faults. Generally, the throws of faults are greater than 100 m and connect the Schlier sediments with Upper Messinian or Pliocene sediments, and in some cases, as north of Misa, with Plio-Pleistocene deposits.

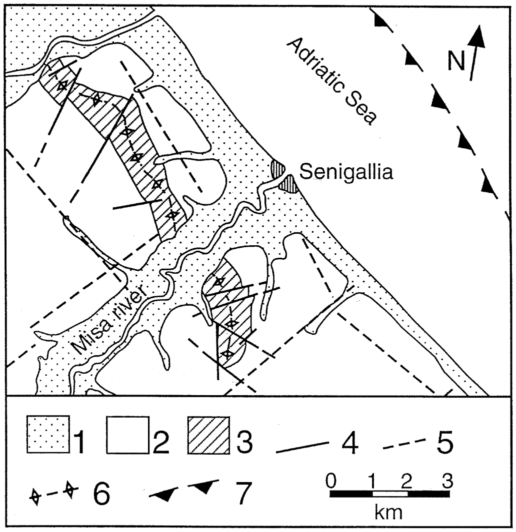


Fig. 7. Schematic geological map of the Senigallia area (after Nanni *et al.*, 1986; AA.VV., 1991 – simplified): 1) recent terraced alluvial deposits; 2) Plio-Pleistocene sediments; 3) pre-Pliocene sediments; 4) faults; 5) presumed faults; 6) axis of anticline; 7) sub-surface thrust unit front.

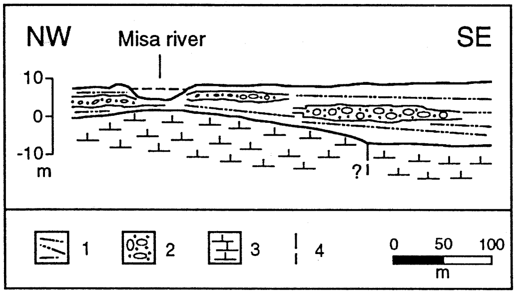


Fig. 8. Typical geological cross-section in downtown Senigallia. Alluvium: 1) silty and sandy clay; 2) sandy-gravel lenses. Bedrock: 3) pelitic-arenaceous unit (Lower Pliocene); 4) presumed fault.

The 4th order alluvial terrace of the Misa river, where downtown Senigallia lies, is composed by silty and sandy clay, and sands with sandy-gravel lenses which have a thickness ranging from 10 to 20 m. These deposits are related either to periodic flooding of the Misa, or to aggradation phases in pre-Roman times (Coltorti, 1991). The bedrock is a layered pelitic-arenaceous unit intensively fractured, probably dating from the Lower Pliocene. A typical geological cross-section in downtown Senigallia is shown in fig. 8. An unconfined aquifer is located in the alluvial sediments.

5. The approach to seismic risk evaluation

With the aim of linking causes to different damage levels, the physical and mechanical soil characteristics of the alluvial deposits and bedrock were first defined. The downtown of the city rests over uniform lithology that shows differences in the thickness of the alluvial deposits. An analysis of seasonal freatimetric variability disclosed an unsaturated zone with a depth ranging between 3 and 6 m from the surface.

Refraction seismic prospecting, using P and SH waves (according to Cherubini *et al.*, 1983), was carried out. The computed velocities of the P and SH body waves, combined with the elastic dynamic modules classify the soils as having generally poor characteristics. In particular, the alluvial deposits have high spreading velocities ($300 \leq v_p \leq 1200$ m/s; $120 \leq v_s \leq 200$ m/s) with a highly fractured bedrock ($1800 \leq v_p \leq 2500$ m/s; $v_s \simeq 300$ m/s); the shear dynamic modules for both lithotypes are, on average, low. This pattern is confirmed by the existing geognostic and geotechnical analyses on samples. The interaction between the released seismic energy and soils with such poor characteristics could explain the superficial fractures falling in the field of the permanent deformations.

The recent reassessment of the earthquake magnitude, classifying the event with magnitude 6.0 (Margottini *et al.*, 1993), raises many questions about the seismic energy release and the actual peak site accelerations. The analysis of the history of the town and its planning evolution excluded a direct connection between the structural quality of the buildings, generally very good, and the level of damage, except for widespread damage which occurred in areas built on filling material. On the other hand, the width and mainly the height of the buildings played a major role. Therefore, an attempt was made to classify the building structures on the basis of their dominant frequencies. For this purpose, some field investigations were planned, having chosen some examples of buildings representative of specific structural typologies. 3-D geophones (1 Hz natural frequency) were used to record the oscillations. These sensors seem to be suitable to vibrometer measurements in seismology because it is also possible to obtain data with frequencies of around 1 Hz, unlike the sensors (4.5 Hz natural frequency) commonly used in the classical vibrometric tests. The data were analyzed with the technique of average density spectrum. Figure 9a,b shows a typical example of spectra from the two horizontal components, recorded on the top of the watch tower of the Senigallia town hall. Both spectra have about 3 Hz as their dominant frequency, corresponding to the free oscillation of the tower.

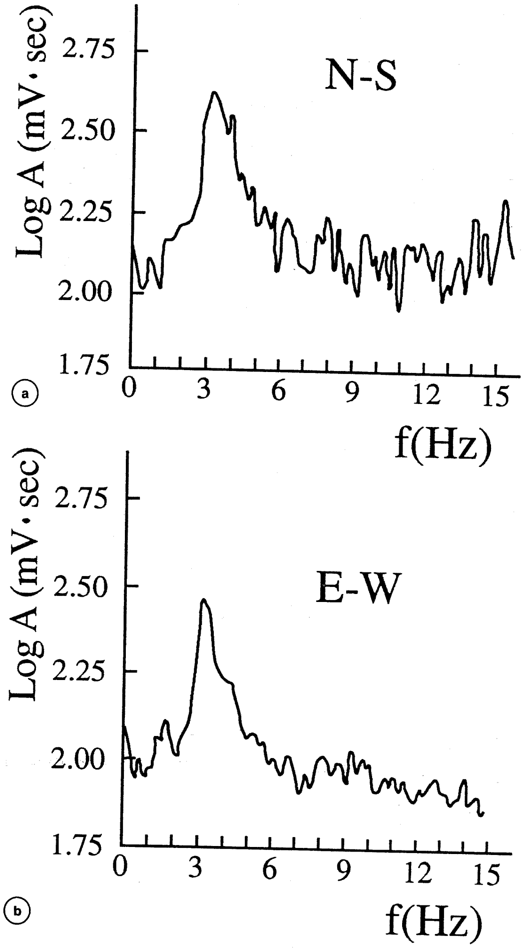


Fig. 9a,b. Example of Amplitude spectra (mV · s) versus frequency (Hz) derived from data recorded on the top of the watch tower of Senigallia town hall: a) N-S component; b) E-W component. A peak around 3 Hz is clearly dominant in both spectra.

Another important aspect linked to the seismic risk evaluation is connected with geological and geomorphological characteristics of the area. The geology seems to point out a bedrock rise which corresponds with the Misa bend, a heavily damaged zone. The geometry of the

Senigallia alluvial plain, which is imbricated in two wedges with coastal verging thrusts (see fig. 7), could have focused the seismic effects, giving a possible explanation of the different damage levels. The frequency range of the Misa valley was estimated by a simplified method (Bard and Tucker, 1985; Bard *et al.*, 1986). The expression used for the frequency (*f*) is:

$$f = \frac{\beta}{4h} \cdot \left(1 + \frac{h^2}{l^2}\right) \simeq \frac{\beta}{4h} \qquad (5.1)$$

where β and h are respectively the S wave velocity and the thickness of the alluvial cover, and l is the semi-width of the valley. Taking into account the geometry of the valley (1.5 km wide), the thickness range (10-20 m) and the shear wave velocities ($120 \leq v_s \leq 200$ m/s) of the alluvial cover, the frequencies of the Misa valley range between 1.5 and 5 Hz.

6. Conclusions

The data collected confirm the interest in studying the Senigallia earthquake as a case history for a better evaluation of the seismic risk of the whole Adriatic coast, and at the same time the need for an integrated and multidisciplinary approach. The observed different damage levels, the geological and geomorphological hazard conditions, and the preliminary building classification support the hypothesis that the 1930 earthquake had differentiated site effects at a scale of hundreds and tens of metres. This hypothesis is supported even if some damage could be explained by other causes. For instance, the widespread damage in Borgo Pace because this borgo was built on landfill; damage occurred in area 1b (fig. 6), close to the river, because there the Misa was straightened and therefore the sediments are very incoherent. The minor damage along the shoreline could be explained by the prevalent presence of two-floor buildings, the damage on higher floors was almost systematic over the second.

In any case, the explanation for the damage has to be referred to a more complex frame. The geological setting of the Senigallia area characterized by an alluvial plain imbricated in two wedges, could have focused the seismic effects. The very low values of the elastic shear modules in the surface sediments could justify the possibility of having permanent deformations. The interaction between the dominant building frequencies and the frequency range of the Misa valley could support the hypothesis of resonance phenomena.

Many questions remain open and warrant further studies: the different seismic ground responses; the role of the thickness of the unsaturated zone; the soil-structure interactions; seismic energy focusing mechanisms. These questions are very important, since in recent years many high buildings (6-8 floors) have been built in areas along the shoreline, closer to the seismogenic zone, or in areas in which a swamp was previously located (essentially characterized by soft sediments). What would happen to these buildings if another earthquake of the same energy as the 1930 shock occurs?

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