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Historical cities and earthquakes: Florence during the last nine centuries and evaluations of seismic hazard

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Abstract
The authors' aim in the following study is to contribute to the assessment of the seismic hazard of historical cities. From this preliminary analysis the general characteristics of the seismicity affecting Florence and the evaluation of its seismic hazard may be deduced. Florence is a «mythical» city of world tourism, and its extraordinary artistic value and its ability to be utilized constitute a great economic resource. From this perspective, the authors have tackled some aspects of its urban features (demography and main building types, successive phases in the growth of the city, etc.), aimed at the pooling of information as a basis for further, more specific analyses of seismic risk. The study is based on a review of 131 seismic events of potential interest for the site of Florence from the 12th century. In the case of each of these earthquakes, it was possible to verify the real seismic effects sustained, and thus to assess the seismic intensity on the site. This also enabled the limits in the application of the standard attenuation laws of to be checked. Of all the earthquakes analyzed, those which caused the greatest effects on the urban area have also been identified: namely, the earthquake of 28 September 1453, and those of 18 May and 6 June 1895, both with I_0=VIII MCS. From their overall analysis the authors have further extrapolated the necessary data to statistically evaluate the probabilities of any future earthquake occurring, according to intensity classes.

Key words *Florence – historical seismicity – seismic hazard – seismic damage*

1. Research objectives

It is a well-known fact that Italy possesses the highest percentage of the world's artistic, architectural and archeological heritage (over 65%). This heritage is spread throughout the Italian territory. Yet it does have particular concentrations of major importance in various cities with an ancient artistic and historical tradition, such as Rome, Florence, Venice, Naples and Palermo.

To the already serious problems of how to manage, preserve, and exploit this extraordinary heritage on an ordinary day-to-day basis are added the further risks connected with the possible destructive seismic effects of earthquakes. How to safeguard art treasures is well known to be a problem of great complexity. The protection of historic monuments of specialized type, and of building resources in their individual units and in terms of urban environment as a whole, constitutes in itself an enormous problem of management. To this is added the response of the artistic heritage under conditions of seismic input. In this context there are aspects which affect both the security and the stability of the «containers» in which works of art are housed, and of the «behaviour» of the works of art themselves within these structures.

A significant example, in our view, of the seismic hazard posed to historical cities is that of Florence. This is a city subject to levels of seismic hazard which are by no means negligible, and yet which are largely unknown at the present time. It is in fact subject not only to its own characteristic «local» seismic activity, but also to the long-range effects of the most powerful earthquakes of the Northern Apennines, from the Casentino to the Garfagnana areas. Our aim in the present study is to contribute to the evaluation of the seismic hazard of Italy's historical cities as a way of supporting the institutions concerned. From this initial analysis may be deduced the general characteristics of seismicity affecting Florence and the probabilities of potentially destructive seismic effects of earthquakes recurring in the future.

The measure of Florence's «weakness» has recently been ascertained by the stress caused by the bomb exploded in the attack of May 1993. On the buildings next to the place where the bomb exploded, the effects caused by the windage were comprehensively similar to those caused by a low intensity seismic event. Howewer, many works of art in the Uffizi Gallery were seriously damaged.

2. Method

To evaluate the *seismic hazard* of the site of Florence, we assumed by hazard the probability of the occurrence of a seismic event of intensity greater or equal to a given intensity threshold, within a defined area and during a fixed period of time. The estimate of seismic hazard is thus based essentially on the frequency and intensity of the effects of the earthquakes which have been attested within the area and during the period in question, or on the seismic effects of earthquakes which occurred in adjacent areas and which were propagated as far as the area in question.

Often the level of seismic hazard of a site or an area is calculated merely by applying standard attenuation laws to catalogue data. This procedure becomes more questionable when intensity is considered as a continuous quantity, forgetting its discrete and ordinal character. The method used here introduces the concept of uncertainty in the intensity evaluation in a site, as the probability that for a given earthquake the assessed intensity on the site is right.

If detailed historical research can be developed on the seismic effects really sustained, the results are particularly significant and also permit the attenuation laws in use for a particular area to be evaluated and improved. The exhaustiveness of the results is obviously dependent on the documentary situations and types of sources available for the different historic periods and different areas.

It is of fundamental importance for the evaluation of seismic hazard to be able to have at one's disposal a chronological sequence of the seismic effects on the site and their intensity as complete and precise as possible. To compile a complete picture of these effects, research at the local level on the effects on the site of the various earthquakes being studied is not always sufficient. In fact two important factors need to be borne in mind: first, the incompleteness of the historic series of seismic effects documented on the site; second, the variability within the seismogenetic area of the possible epicentres of future recurrence of historically registered earthquakes.

The first factor has various possible causes; these include, in the most frequent cases, documentary lacunae or the insignificance, and hence meagre records, of the seismic effects sustained. The second factor, *i.e.* the tendency for the epicentres of earthquakes both large and small to migrate within a seismogenetic structure, is a characteristic peculiar to each geological structure linked to the mechanism of the accumulation and release of seismic energy within it.

With a view to a thorough evaluation of seismic hazard, we considered it important to delineate, for each earthquake examined, not only the seismic effects registered at the site, but also its epicentral area and the characteristics of its propagation toward the site.

The site catalogue for Florence has been edited in two stages: firstly, in 1991 (SGA report, 1991), the catalogue of epicentres of the PFG Catalogue (Postpischl, 1985) was adopted as reference catalogue for the historical revision. Then, the site catalogue was updated (in 1993) taking into account the new parameters, both synthetic and analytic, coming from the research to be found in the recent *Catalogue of strong earthquakes in Italy* (Boschi *et al.*, 1995).

The historical research collected information on the effects caused within the city of Florence by each of the earthquakes selected; however, in the absence of these historical records, or in the presence of insufficient and/or imprecise data, we estimated the intensity at the site on the basis of the maximum or epicentral intensity reported in the PFG Catalogue appropriately revised.

3. Catalogue of earthquakes of interest for Florence

The site catalogue of Florence was compiled as the combination of two types of data:

– the data resulting from an interpretation of the descriptions of the seismic effects at the site documented by the historical sources;

– the data resulting from the application of an attenuation law of the intensity values with distance, for the earthquakes for which site data are not available.

The study was conducted by compiling a list of all the earthquakes of the PFG Catalogue which may have generated effects greater than or equal to the V grade of the Mercalli Cancani Sieberg (MCS) intensity scale at Florence, and the epicentres of which were located at a distance less than or equal to 200 km. These events were selected according to the attenuation law proposed by Magri *et al.* (1994). The catalogue obtained in this way was updated with the epicentres – excluded by this selection – whose particular propagation characteristics may have affected the area of Florence; this is the case, for instance, of the Polverina (Marche) earthquake of 1873 (IX MCS), over 160 km from Florence, where some damage was reported (VI MCS).

This catalogue, including 131 events (table I), was the starting point for historical research aimed at creating the site catalogue. Historical research reconstructed for each event the territorial scenario of the effects, allowing the review of the epicentral location and of maximum and epicentral intensities. Where data were available, particular attention was paid to the intensity assessment to the effects at Florence.

A particular problem of seismic hazard analyses is the assessment of completeness with reference to the historical area examined. In order to evaluate the completeness and the quality of seismic information of the catalogue, the following scheme was chosen;

– precise analysis of the information included in the selected catalogue;

– development of a systematic historical research on available sources, starting from the 12th century;

– analysis of the possibility that an earthquake causing some damage (not under VII grade MCS) may have been passed unnoticed by the rich Florentine historiographical tradition;

– analysis of the possibility that written sources of destructive earthquakes might have been accidentally lost.

4. Procedure of the historical research

The historical research and the analysis of the data were conducted on three themes:

1) verification of the bibliography to check possible errors in the attribution of seismic intensity or localization;

2) research on the original written sources of information and on the historiographical tradition in order to identify the whole of data useful for the correct attributions of seismic parameters:

3) delineation of the contextual demographic, historical and urbanistic data with a view to gathering relevant material for the assessment of the seismic impact.

The historico-archival and bibliographical research was conducted in numerous archives and libraries. For a checklist of the documentary materials analyzed, see Appendix; the sta-

Table I. List of the earthquakes affecting the site of Florence, selected from the PFG Catalogue. The list consists of 131 seismic events, reviewed in the course of the present research.

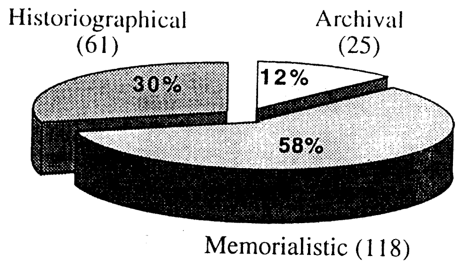
Year	Month	Day	h	min	s	Lat.	Long.	I_0	Epicentral area
1148	–	–	–	–	–	43 45	11 15	VII	Impruneta
1289	–	–	–	–	–	43 55	10 55	VII	Pistoia
1293	7	11	–	–	–	43 55	10 55	IX	Pistoia
1298	–	–	–	–	–	43 55	10 50	IX	Pistoia
1325	5	21	2	–	–	43 45	11 15	VI	Impruneta
1383	2	4	4	–	–	43 45	11 15	VI	Impruneta
1383	2	4	17	–	–	43 45	11 15	VI	Impruneta
1408	–	–	–	–	–	43 45	11 15	VII	Impruneta
1413	8	8	–	–	–	43 20	11 20	VII	Siena
1420	–	–	–	–	–	43 20	11 20	VII	Siena
1426	–	–	–	–	–	43 45	11 15	VI	Impruneta
1430	8	12	5	–	–	43 20	11 20	VII	Siena
1436	3	–	–	–	–	43 20	11 20	VII	Siena
1453	9	28	23	–	–	43 45	11 15	IX	Firenze
1456	8	22	–	–	–	43 20	11 20	VIII	Siena
1463	9	–	–	–	–	43 45	11 15	VII	Impruneta
1467	8	22	20	–	–	43 20	11 20	VII	Siena
1467	9	3	–	–	–	43 20	11 20	VII	Siena
1486	9	30	–	–	–	43 20	11 20	VI	Siena
1496	6	4	–	–	–	43 20	11 20	VII	Siena
1496	6	4	–	–	–	43 20	11 20	VII	Siena
1504	11	1	–	–	–	43 45	11 50	VIII	Chiusa Verna
1527	10	–	–	–	–	44 00	11 00	VIII	Montale
1530	11	11	–	–	–	43 20	11 20	VII	Siena
1542	6	13	9	–	–	44 00	11 20	X	Scarperia
1551	9	26	16	–	–	43 45	11 15	VI	Impruneta
1554	11	28	1	–	–	43 45	11 15	VII	Impruneta
1597	8	3	23	–	–	44 00	11 20	VII-VIII	Borgo S.Lorenzo
1600	7	6	–	–	–	43 45	11 15	VI	Impruneta
1603	1	25	–	–	–	43 20	11 20	VII	Siena
1611	9	8	17	–	–	44 00	11 20	VI	Borgo S.Lorenzo
1611	9	8	17	–	–	44 00	11 20	VIII-IX	Borgo S.Lorenzo
1630	5	–	–	–	–	43 55	10 40	VII	Villa Basilica
1648	1	13	13	–	–	44 00	11 00	VI	Montale
1697	6	18	18	30	–	43 45	11 15	VI	Impruneta
1697	9	20	15	–	–	43 20	11 20	VI	Siena
1697	9	20	16	–	–	43 20	11 20	VII	Siena
1697	9	30	12	30	–	43 20	11 20	VII	Siena
1697	10	1	–	–	–	43 20	11 20	VI-VII	Siena
1697	10	27	–	–	–	43 20	11 20	VI	Siena
1697	12	21	3	–	–	43 20	11 20	VII-VIII	Siena
1705	4	14	–	–	–	43 20	11 20	VI	Siena
1729	6	23	–	–	–	43 50	11 15	VI	Firenze

Table I (*continued*).

Year	Month	Day	h	min	s	Lat.	Long.	I_0	Epicentral area
1731	12	–	–	–	–	44 00	11 00	VI-VII	Montale
1737	6	11	11	–	–	43 45	11 15	VI	Impruneta
1741	10	1	6	–	–	43 20	11 20	VII	Siena
1759	3	18	–	–	–	43 55	10 55	VI	Pistoia
1759	4	18	–	–	–	43 55	10 55	VI	Pistoia
1762	4	14	–	–	–	44 00	11 20	VI	Borgo S.Lorenzo
1762	4	15	22	30	–	44 00	11 20	VII	Borgo S. Lorenzo
1762	4	15	22	45	–	44 00	11 20	VI	Borgo S. Lorenzo
1762	4	17	–	–	–	44 00	11 20	VI	Borgo S. Lorenzo
1762	4	17	–	–	–	44 00	11 20	VI	Borgo S. Lorenzo
1767	–	–	–	–	–	44 10	11 20	VI	Passo Raticosa
1768	11	30	–	–	–	43 35	11 00	VI	Certaldo
1770	12	27	23	–	–	43 30	11 30	VIII	Mercatale
1771	8	13	–	–	–	44 10	11 10	VI	Camugnano
1779	12	24	22	–	–	44 00	10 50	VI	Pistoia
1779	12	31	21	–	–	44 00	10 50	VI	Pistoia
1781	1	3	2	30	–	43 20	11 20	VII	Siena
1781	1	3	3	–	–	43 20	11 20	VII	Siena
1781	4	4	21	20	–	44 15	11 45	IX	Montecchio
1781	6	3	10	–	–	43 34	12 37	X	Cagli
1781	6	3	10	10	–	43 34	12 37	VIII-IX	Cagli
1781	7	17	9	10	–	44 17	11 58	VIII	Faenza-Forlì
1787	10	20	–	–	–	43 20	11 20	VI	Siena
1787	12	26	–	–	–	43 45	11 45	VI	Bibbiena
1787	12	26	–	–	–	43 45	11 45	VI	Bibbiena
1798	5	26	12	10	–	43 20	11 20	VIII-IX	Siena
1804	10	18	20	–	–	43 20	11 05	VII	Tegoia
1804	12	17	20	–	–	43 20	11 05	VI	Tegoia
1812	9	11	12	–	–	43 45	11 05	VIII	Romola
1812	9	12	2	–	–	43 45	11 05	VII	Romola
1815	8	1	–	–	–	44 00	11 00	VI	Montale
1830	1	26	4	30	–	44 05	11 00	VI	Treppio
1835	2	6	18	50	–	43 56	11 23	VII	Borgo S. Lorenzo
1835	2	6	18	50	–	43 56	11 23	VII	Borgo S. Lorenzo
1843	10	25	3	30	–	44 00	11 15	VI	S. Piero
1843	10	25	4	10	–	44 00	11 15	VI-VII	S. Piero
1849	1	6	3	–	–	44 05	11 30	VI	Casaglia
1853	5	17	15	17	–	43 20	11 20	VI	Siena
1854	12	4	1	–	–	43 20	11 20	VII	Siena
1859	1	30	–	–	–	43 20	11 20	VII	Siena
1859	4	12	3	28	–	43 20	11 20	VII	Siena
1859	4	12	13	3	–	43 20	11 20	VII	Siena
1864	12	12	15	49	32	44 05	11 20	VI	Ronta
1867	11	1	16	15	–	43 20	11 20	VI	Siena

Table I (*continued*).

Year	Month	Day	h	min	s	Lat.	Long.	I_0	Epicentral area
1869	2	7	5	–	–	43 20	11 20	VI-VII	Siena
1869	2	7	5	15	–	43 20	11 20	VII	Siena
1869	6	25	13	58	–	44 20	11 05	VII	Vergato
1869	9	26	20	45	–	43 30	11 05	VIII	Colle Val D'Elsa
1871	10	22	13	–	–	43 25	11 20	VII	Radda
1871	10	23	–	–	–	43 25	11 20	VI	Radda
1873	3	12	20	4	–	43 07	13 05	VIII	Polverina
1877	3	3	1	9	26	43 40	11 50	VI	Chiusa Verna
1887	11	14	5	48	–	43 44	11 16	VI	Impruneta
1892	12	29	13	48	–	44 10	11 30	VI	Castel Del Rio
1892	12	29	20	11	–	44 04	11 39	VI	Marradi
1895	5	18	19	55	12	43 45	11 15	VII	Impruneta
1895	6	6	–	35	5	43 45	11 15	VI	Impruneta
1907	12	15	13	6	55	43 29	11 22	VI	Radda
1907	12	20	10	29	15	43 29	11 22	VII	Radda
1911	3	26	21	35	–	43 47	11 49	VI-VII	Pratovecchio
1911	9	13	22	29	2	43 23	11 24	VII	Lucignano
1911	9	13	22	35	10	43 23	11 24	VI	Lucignano
1913	2	13	16	39	50	44 06	10 54	VI	Lizzano
1914	5	15	13	50	–	43 24	11 24	VI	Lucignano
1917	4	26	9	35	59	43 29	12 07	X	Monterchi-Citerna
1918	1	22	19	39	–	43 40	10 50	VI	Empoli
1919	6	29	8	15	–	43 57	11 23	VI	Borgo S. Lorenzo
1919	6	29	15	6	13	43 56	11 27	IX	Vicchio
1920	9	7	5	55	40	44 15	10 17	IX	Garfagnana
1925	3	15	17	14	54	43 48	11 15	VII	Firenze
1929	7	18	21	1	58	43 57	11 23	VII	Borgo S. Lorenzo
1931	9	5	1	25	53	44 04	11 23	VII	Ronta
1931	12	15	3	31	22	43 58	11 23	VI	Borgo S. Lorenzo
1939	2	11	11	16	54	44 04	11 39	VII	Marradi
1940	1	31	11	–	–	43 24	11 18	VII	Monteriggioni
1949	3	9	4	16	30	44 06	11 23	VI	Firenzuola
1953	2	13	16	29	45	44 02	11 31	VI	Casaglia
1956	2	22	22	55	6	43 20	11 20	VI-VII	Siena
1956	4	26	3	–	3	44 09	11 19	VI	Passo Futa
1956	5	26	18	40	–	43 57	11 47	VII	Premilcuore
1959	3	24	10	24	11	43 40	11 11	VII	Romola
1960	10	29	–	8	39	44 00	11 18	VII	S. Piero
1962	5	11	1	5	31	44 12	11 10	VI	Camugnano
1962	9	16	14	49	45	43 36	11 18	VI	Mercatale
1964	9	5	21	8	44	44 00	11 18	VI-VII	S. Piero
1973	11	7	17	6	17	43 59	11 25	VI-VII	Borgo S. Lorenzo
1974	1	28	19	57	22	44 05	10 53	VI	Pracchia
1975	4	4	9	10	53	44 05	10 55	VI	Pracchia



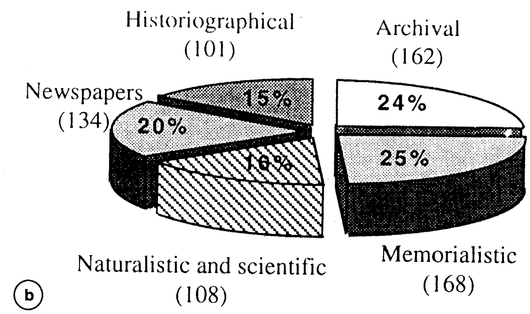


Fig. 1a,b. Types and statistics of the sources which have furnished new data for the evaluation of the seismic hazard of Florence: a) from the 12th to the 16th century; b) from the 17th to the 20th century. Archival sources have given a high quality, but numerically low contribution, because most seismic events did not involve public administrations as they caused slight damage (from SGA report, 1991).

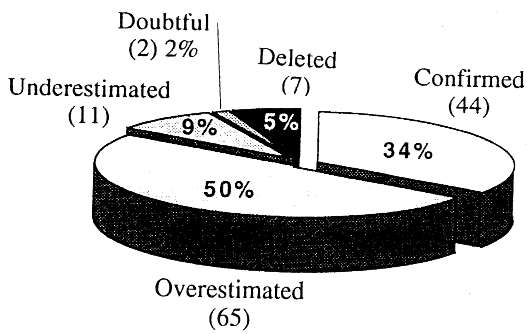


Fig. 2. Modifications of the seismic intensity and localization relating to the 131 earthquakes affecting Florence selected from the PFG Catalogue (Postpischl, 1985).

tistical distributions of the types of source are presented in the fig. 1a,b.

As a whole the results permitted a number of significant revisions to be made to the previous state of research: for a synthesis of the results concerning the adjustments made to the seismic intensity and localization values see fig. 2.

5. Main phases in the growth of Florence

We used the extensive historical and urbanistic bibliography of Florence for some basic information concerning the main phases in the growth of the city: from its first medieval nucleus to its present-day appearance. The aim of this part of the study was to emphasize three particular aspects:

a) the character of the Florentine urban structure and of its minor civil constructions, as the result of historical contingencies and planning measures not always calculated to improve the city's overall building quality;

b) the general features of the context of the urban scenario in relation to the seismic effects sustained in the past;

c) the relationship between extension of the urban area and number of inhabitants (fig. 3).

5.1. *12th-13th centuries: the medieval period and the birth of the city's characteristic building features*

The rapid economic development which characterized Florence since the 12th century did not derive only from demographic growth. With the influx of population from the surrounding countryside, the city became, in few decades, an 'industrial' and 'financial' capital (in the medieval sense of the terms) of first importance in Europe. The urban realities which were to distinguish the history of Florence for centuries were gradually consolidated in the course of the 13th century. The heavily built-

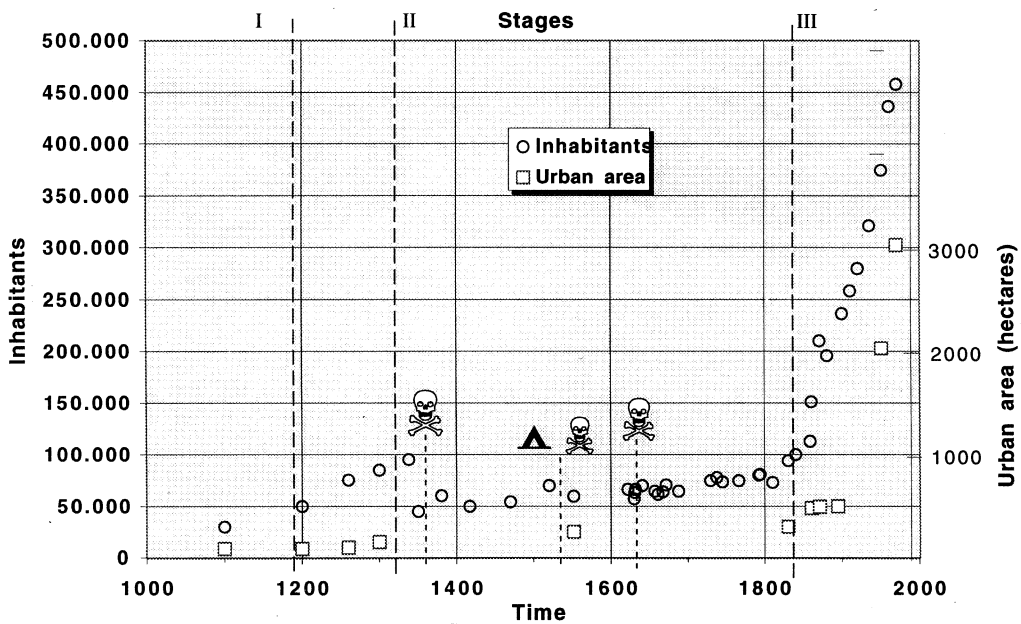


Fig. 3. Relationship between the number of inhabitants and the extent of the urban area of Florence from the 12th century to the present day. Until the 19th century Florence kept growing within the circle of walls of the 14th century, filling spaces which had never been built on before. Stage I: circle of walls of the 12th century. Stage II: circle of walls of the 14th century. Stage III: addition out of the walls. From stage II to stage III the urban area is the same, but the graph takes into account the width of the areas *actually* built. The fall in the demographic trend was due to plague epidemics in 1348, 1417, 1529, 1630; in 1529 it was due also to a military siege.

up areas along the banks of the Arno were the most populous and thriving. The presence of the river, which was both a trade route and a source of energy for the textile industry, determined in large measure this development which was accompanied, since the last decades of the 12th century, by the construction of bridges to connect the opposite banks of the Arno.

The intensive building up of the whole central area, superimposed over the urban plan of Roman origin, soon became insufficient to contain the effects of the city's demographic and economic growth. Thus the circuit of town walls of the period of Matilde of Canossa, dating to 1078, no longer defined nor could delimit the growth of the city's population in the course of the 12th century; this growth led to urban expansion beyond the walls, along the main roads leading into the city.

In 1172 the city magistrates deliberated the construction of a new circuit of walls. Completed in 1175, this new and expanded outer boundary incorporated for the first time the territory of the Oltrarno – the area on the bank of the Arno opposite to that of the city centre – even though for many decades it was enclosed by a simple palisade (fig. 8). The surface area of the city was almost tripled, rising to some 85 hectares for a population which had already exceeded 30000 residents (Fanelli, 1980). During the following century the population of Florence increased further: from approximately 50000 inhabitants in the first half of the 13th century it rose to some 75000 inhabitants in 1260, 85000 in the early years of the 14th and

95000 in 1338 (Romano, 1974). According to the estimates of Giovanni Villani (14th cent. edited in 1979) the city comprised almost 100000 inhabitants in the early years of the 14th century. These figures, even if taken with the necessary caution for medieval historical demography, place Florence among the most populous cities of Europe in the 14th century.

In the 12th century and for much of the 13th century, numerous towers were erected within the walls of the city. They helped to define the city's substantially vertical image. Built adjacent to the houses, whose façades were tall and narrow, the towers reproduced, at least initially, the types of aristocratic fortifications found in the countryside (Comba, 1985; Benevolo, 1993). The towers were remarkable both in elevation (one which rose to a height of 75 m was demolished in 1258) and in number (there were more than 150 in the 13th century). They represented in fact the organizational centres of the power of the leading noble families over the various *insulae* (or blocks) of the city. These towers, abutting onto the houses, and communicating with them by overhead passages, grew in the midst of a homogeneous urban structure informed by the choice of *verticality* (figs. 4 and 5).

The various types of building became intermixed: the patrician tower or tower-house flanked or abutted onto the two-storey houses of the merchants, the warehouses and the flimsy houses of the poor built of wood and thatch. As to the characteristics of minor civil urban building in the 12th century, the information we have about Florence at the present time is rather meagre (Nada Patrone, 1990).

The sources of the following century are better documented and transmit to us an image of a Florence in which the poorer classes lived in wooden houses, while the emerging middle classes had at their disposal houses with wooden structures combined to a limited extent with masonry in stone or brick, mainly of two storeys and with a narrow front: dictated by the fact that the width of the front determined the family's tax burden.

Timber was the predominant material in the upper storeys of buildings, constituting an all too common fire hazard and fuelling a number of devastating fires, such as the one that destroyed some 1700 buildings in the centre of Florence in 1304 (Fanelli, 1980).

The use of *wooden superstructures* also spread as a result of enlargements made to the towers and tower-houses in the form of overhanging structures (known as «*sporti*»), which projected the building's presence beyond the area covered by its actual ground-plan, suffocating the streets below and threatening them militarily. The building workers represented by Ambrogio Lorenzetti in his fresco «The Effects of Good Government» (in the Public Palace in Siena) are shown in the process of raising a tower-house in height, almost as if to emphasize construction developed in the vertical sense as the paradigm of building progress.

The measure of Florence's first Republican government, that of the *Primo Popolo*, stipulating the maximum permitted height of private towers as 50 Florentine *braccia* (*c.* 29 m), while at the same time decreeing the demolition of several such towers, was not certainly inspired by chance or by any concerns about the buildings' stability. This was the beginning of a campaign, conducted in the course of the 13th and pursued right up to the 16th century, aimed at the vertical development of the city and hence controlling the overall evolution of the urban structure.

5.2. *14th century: end of building verticalism and beginning of horizontal urban development*

The aspiration to the order, cleanliness, spaciousness and rectilinearity of the streets prevailed in civic statutes and regulations. Curbs were placed on wooden superstructures, and the use of stone and brick in the lower storeys of buildings was made obligatory. Structures widespread in the older city centre, such as overhead galleries, bridges, vaults in brick and wood which performed a function of providing reciprocal support to buildings, were regulated by the municipal Statutes of 1324, 1355 and 1415. In 1333, after various interruptions, the enlargement of the circuit of walls ordered by

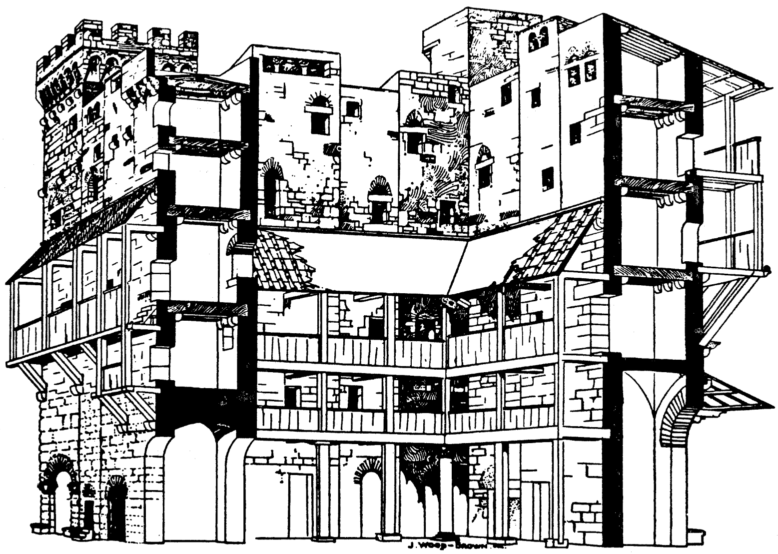


Fig. 4. Types of tower-houses in Florence (from Benevolo, 1993, p. 262).

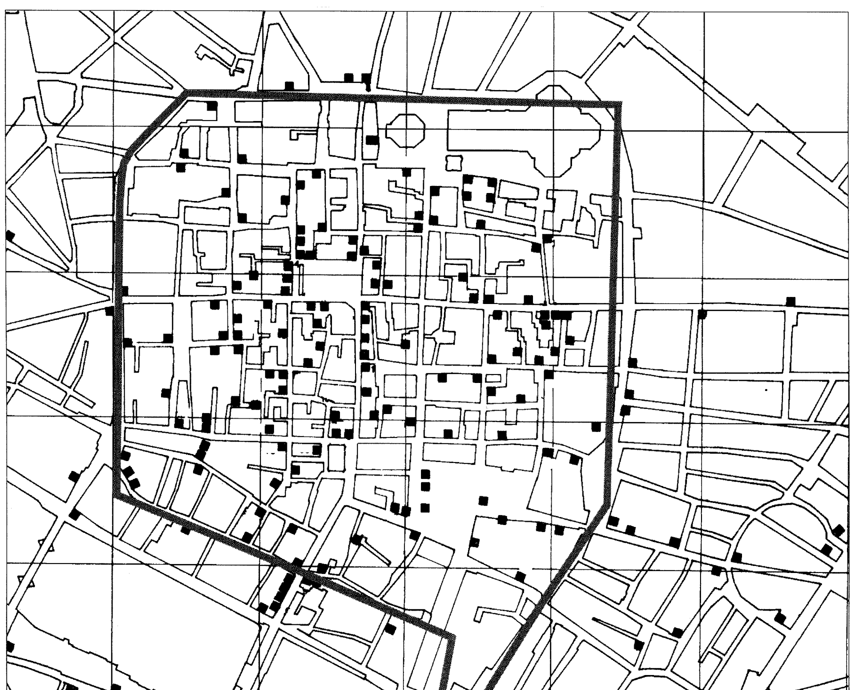


Fig. 5. Localization of medieval tower-houses (black squares) reported in the historical sources, within the 12th century circle of walls, represented by the bold line (new elaboration from Benevolo, 1993, p. 263).

the government of the *Secondo Popolo* in February 1284 was finally completed. The new walls had a circumference of 8500 m and enclosed an area of approximately 430 hectares, thus quintupling the area of the city enclosed by the older walls.

The government of the *Secondo Popolo* in the 14th century shifted its attention to major public building projects, which took the form of the construction of the great public buildings of Florence (the Bargello, Orsanmichele and Palazzo Vecchio). The first measures for the regulation of the banks of Arno, the paving of the main streets and the reconstruction of Ponte Vecchio, were all decided on during these years. But well before the Black Death in 1348, which caused a sharp contraction in the city's population, the period of grave famine in the years 1313-17 had arrested its economic and demographic development (Del Panta, 1980). The plague epidemic finally prostrated a city which was already afflicted by serious difficulties: in the mid-14th century the population of Florence was around 45000 inhabitants; in 1380 some 60000 individuals were residing within its walls (Fanelli, 1980).

5.3. *15th-17th centuries: the functional specialization of the urban area*

The process of the city's remodelling also led to an evolution in the middle and lower building types. Thus, intensive building activity aimed at providing housing for the middle and lower classes took place in the Oltrarno between 1425 and 1520. Most of the new palatial buildings, taking the place of entire blocks, arose in the area comprised between the present-day Via del Proconsolo, Borgo Albizi, Via Ghibellina and Via de' Benci. More than 450 buildings were erected thanks to the division into lots promoted by the monastic order of the Camaldolensians, who in this way made a considerable investment in urban development.

On rectangular lots of ground, with a frontal length of 8-9 Florentine *braccia* (5.23 m, the standardized length of wooden beams of the period) and a variable depth of between 30 and 50 *braccia* (*c.* 18-30 m), two-storey stone houses were built with an external staircase and an inner garden (Fanelli, 1980); they were mainly aimed at providing housing for the families of craftsmen and artisans. Durable building materials were also used in the construction of single-room dwellings for the poorer classes. In general, the roofs were supported on load-bearing lateral walls (Klapisch-Zuber, 1978; Sanfilippo, 1987).

The general improvement of the building types did not however have any effect on the wooden hovels and shacks inhabited by the victims of the economic and social crisis which severely struck the city from the early decades of the 14th century.

The various areas of the city were subsequently subjected to a process of *functional specialization.* The administrative activities, the running of government affairs, the official residences and the places of work of the mercantile bourgeoisie were maintained in the old city centre. The residential areas allotted to the new ruling classes (city villas) were located along the new thoroughfares, between the first and second circuit of town walls, to the north and in the Oltrarno. The popular classes, on the other hand, were concentrated in the areas to the east, in the Santa Croce quarter and in the older housing nuclei in the Oltrarno. The city was thus stripped of its medieval homogeneity and, at the same time, a diversification of building types took place (Francovich, 1976). These complex developments were registered within an urban extension which had remained substantially unchanged since 1333.

The progressive abandonment of the old city centre as a place of residence of the well-to-do classes led, especially in the 16th and 17th centuries, to the diffusion of seignorial residences *intra muros* (*i.e.* in the open ground between the first and second circuit of walls).

The age of fortifications had profound repercussions on the urban structure and on the overall life of the city. In response to the siege – laid by French troops – of Florence in 1529, a series of drastic provisions were taken, such as:

– the *lowering* of the towers which rose over the city gates, so as not to offer easy targets to the enemy;

– the *demolition* of hundreds of houses in proximity of the walls to facilitate the movements of the defending forces and to extend the unbuilt-over buffer zone.

The damage caused by the long siege was enormous, and entire districts, especially in the Oltrarno, were only reclaimed and reinstated in the life of the city a century later, in the 17th century. The destruction was accompanied by a considerable demographic decline: at the end of the Republic, the population within the walls amounted to 70 000-80 000 inhabitants; in the census of 1552, 59 500 persons were registered (excluding Jews); and in 1561 the city comprised 8741 houses and 2172 workshops (Beloch, 1937/1994).

5.4. *18th century: new building features*

The overhanging superstructures (the *sporti*) characteristic of the medieval city had by now virtually disappeared. Among the innovative building features represented by the cartography of the period were the utilization of terraces and upper storeys with stone cornices and saddle roofs, in substitution of loggias.

These features were further refined during the wave of reconstruction in the years spanning the 18th and 19th centuries. The presence of buildings along the streets laid out in an irradiating pattern and the definition of the major suburbs outside the walls already anticipate the future course of urban development in the 18th and 19th centuries (fig. 6a,b).

In the 17th century the existing city was reconstructed. A population of 66 056 and a total of 9038 houses were registered in the census of 1622. The plague epidemic of 1630, which caused the death of some 9000 inhabitants (12 800 according to some estimates cited by Del Panta, 1980), contributed to further depress the city's socio-economic situation.

It was the enlightened government of the House of Lorraine, and in particular the work of Pietro Leopoldo (1765-90), that later introduced the first elements of modernity into the urban situation of Florence. The Leopoldine urbanistic policy curbed the capacity of the religious orders to dictate the urban development of the city. The contraction of the religious confraternities and congregations and the suppression of their property released new space within the walls, which was used by the grand-ducal government for measures aimed at improving and refurbishing the urban structure, such as:

– the increase of areas allocated to public recreation (the parterre outside the Porta San Gallo and the periodic opening to the public of the grand-ducal park of the Cascine);

– the utilization of the existing building stock aimed at an organic policy of public services (Fanelli, 1980).

The *refurbishment* and *improvement* of the existing structures contributed to the evolution of building types. The following features became widespread:

– the stuccoing of façades;
– the plastering of ceilings;
– the enlargement of staircases.

The general stability of buildings was improved by the elimination of the structures abutting onto them. The reconstruction measures in general, from the 16th century to 1800, were inspired by criteria of regularity and uniformity, leading to the union of multiple building units built in series into constructions with a greater cubic capacity. A considerable effort on the part of the public administration to survey and document seismic damage can be observed in the 18th century. The administrative documentation formed the basis for deciding on fiscal intervention. This attention was addressed not only to urban, but also to rural property (for example, for the earthquake of 23 June 1729, see the account of the Capitani di Parte of Florence on the damage in the extraurban area and in the city, ASF, Capitani di Parte Guelfa).

As regards the demographic size of the city, the first census figures relating to the period of the House of Lorraine date to 1738: on that date the population of Florence was calculated as 77 835 inhabitants (Beloch, 1937/1994). The thorough census in 1745 assigned to Florence a number of inhabitants equivalent to 8.3% of the overall population of the State (Del Panta, 1980). In 1766 the city comprised no more than 74 300 individuals.

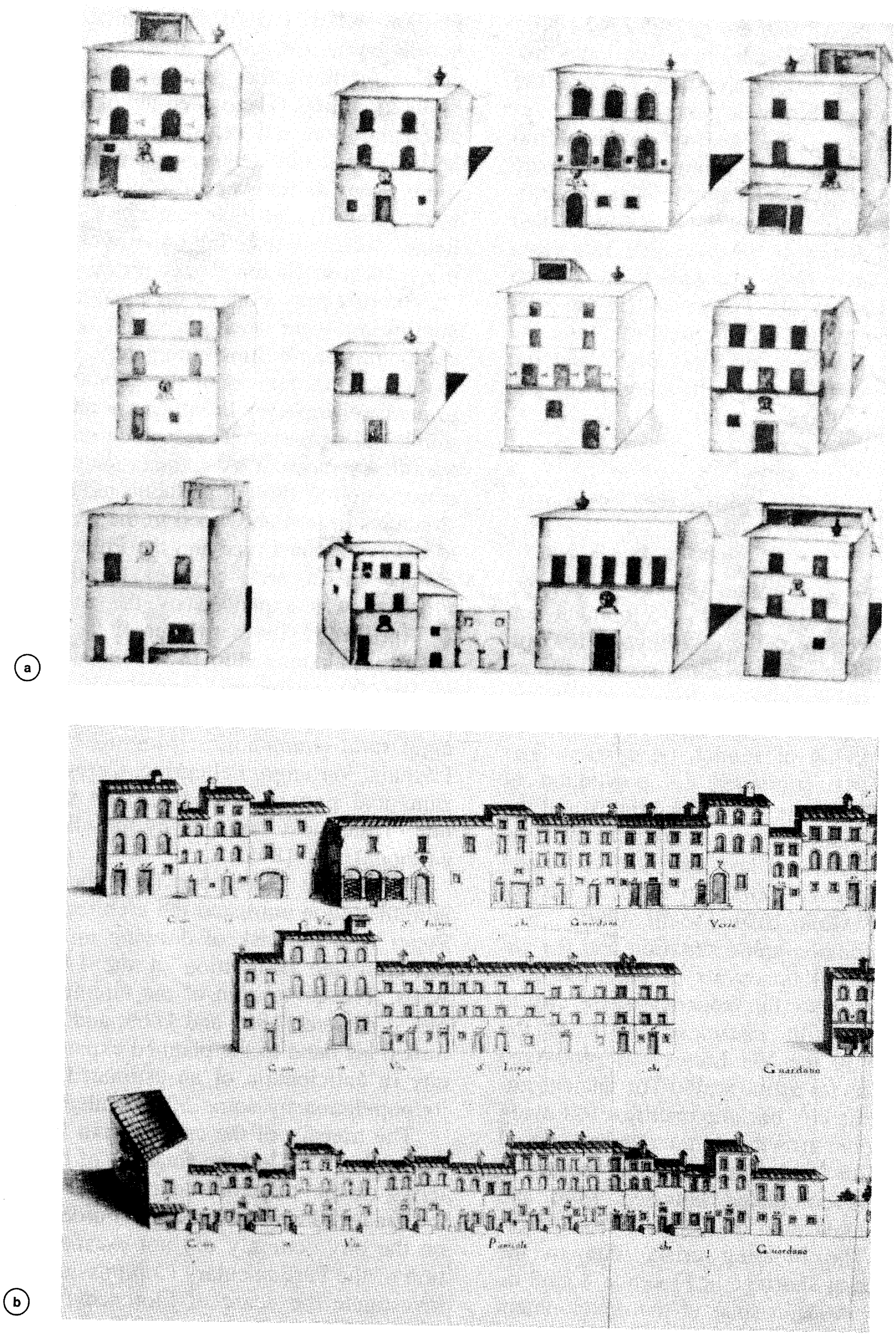


Fig. 6a,b. Florence: a) houses drawn in the land registry records of the 18th century (from Benevolo, 1993, p. 286); b) types of urban houses from the 18th to the 19th century (from Fanelli, 1980, p. 167).

It is well known that the growth of the population of the Grand Duchy in the period 1784-94 was due not to any tendency towards the city's expansion, but to a generalized and remarkable demographic growth in the rural areas. The inhabitants of Florence represented only 7.6% in 1794 (Del Panta, 1980). In absolute figures, the inhabitants of the city totalled 80195 in 1792 (Pardi, 1916), while two years later they have been estimated by Beloch (1937/1994) as 80560. The growth in the population of the main Tuscan cities was, with the exception of Livorno, less than that registered in the countryside and in the smaller towns and settlements.

5.5. *19th century: new projects and Florence as capital city*

The Napoleonic period marked the beginning of a renewed building development and the first projection of the city beyond its 14th century circuit of walls. The registration for assessment of the territory of the city and its environs was begun, according to modern criteria, in the period of French occupation. The census of 1810 computed the population of Florence as 73000 resident inhabitants and the number of its building units as 8025. In 1831 the number of Florentines had risen to 94000, and numbered just over 100000 in 1840, to reach a figure of 113000 in 1859 (Fanelli, 1980).

The new demographic situation and the social and political upheavals of the time concurred to accelerate the tendency of the city to develop beyond its circuit of walls. In the period 1826-30 the Via Larga was prolonged to the north as far as the walls. The ancient imbalances of the city became manifest following its demographic growth and the damage caused by the flood in 1844. The residential quarter of Barbano was completed between 1844 and 1855, and linked with the centre by new thoroughfares. The building crisis, due to the chronic housing shortage in Florence, found no adequate solution, in spite of the development of the new suburban district of the Cascine in the years 1850-55.

In the years immediately following the unification of Italy (1860), the municipal administration continued, albeit amid growing financial difficulties, the previous urbanistic and building policy. The widening of streets, and the demolition and incorporation of buildings in the historic city centre, were promoted at the same time. A number of residential quarters were planned, and their realization became no longer deferable once the transfer of the capital from Turin to Florence was proclaimed.

The first provisions of the local and national authorities were without doubt intended to cope with the resulting emergency. The proclamation of the transfer of the capital caused an immediate wave of building speculation. The municipal administration decided on a first extraordinary measure by commissioning the rapid construction in 1866 of prefabricated houses with structures in iron and wood in the areas adjacent to the Porta alla Croce and the Pignone.

The urban area covered by the city of Florence was expanded by the State law of 27 April 1865; the perimeter of the new outer circuit was extended to 14867 m. A population of 194000 inhabitants resided within this circuit, which incorporated the territories of some eight rural communities: Montughi, La Pietra, Legnaia, Varlungo, Pellegrino, Careggi, Rovezzano and part of Galluzzo. This village was one of the most damaged by the effects of the earthquake of 1895.

Already in November 1864 the municipal administration entrusted the architect Giuseppe Poggi with the task of drawing up a plan for the complete demolition of the 14th century walls. The demolition of the circuit was completed between 1865 and 1869, and Poggi then turned his hand to the planned expansion of the city in anticipation of an estimated growth of its population by some 50000 inhabitants.

The transfer of the capital from Florence to Rome, in 1871, left the finances of the city tottering on the verge of bankruptcy. The scale of the financial and patrimonial burden imposed on the city certainly did not escape the attention of the Parliamentary Commission set up to investigate the «case of Florence»: in the period 1865-69, out of an overall municipal budget equivalent to Italian Lire 125419000, a fifth had been allocated for urbanistic projects.

The municipal project for the gutting of the old city centre, which derived its origin from the undeniable need to reclaim some particularly run-down areas, became executive in 1888. The more ancient structures were almost completely swept away in the process, arousing protests from leading intellectuals throughout Europe.

The reclamation plan, documented by photographic plates (Fanelli, 1980) of the photographic campaign promoted by the Commune and carried out by G. Baccani, led to the expulsion of the inhabitants of those areas. The popular classes were in large part absorbed by the Santa Croce and San Frediano quarters, with the consequent local increase in housing density and the deterioration of building types. These urban areas were seriously damaged by the earthquake in 1895 (fig. 8).

5.6. *20th century: demographic growth and urban expansion*

The area of Florence and of its immediate environs comprises not only an architectural and artistic heritage of the highest value, but also a series of industries, services and structures of strategic importance for the area's economic and productive levels. The census data relating to the growth in population of the communes of the Florence's green belt (Fiesole, Scandicci, Bagno a Ripoli, Impruneta, Sesto Fiorentino and Prato) for the fifty-year period 1861-1911 may be interpreted in this sense (Mercandino and Mercandino, 1976); but is it the only possible interpretation?

Here we remember some characteristics of this area in order to stress their exposition to seismic risk.

The dynamics consolidated in the 19th century did not change during the first decades of the 20th. The urban development plan, drawn up in 1915 and approved in 1924, made reference to urban growth up to *c.* 1960. The tangible result was the development of the new residential districts of Romito, Piazza Vieusseux, delle Cure, Campo di Marte and Gavinana. The provision, adopted on 1 November 1928, for the revision of the municipal borders formed part of this context; it led to a further substantial expansion of the administrative borders of the Municipality of Florence. The territories of Bagno a Ripoli, Brozzi, Casellina and Torri (now Scandicci), Galluzzo (where the local town council was suppressed), and Sesto Fiorentino were all incorporated in the city. As a whole 34014 individuals were added to the city's resident population. The area covered by the Commune of Florence was fixed as the current 10241 hectares in 1939.

The territorial policy measures that motivated the considerable expansion of the city's administrative borders also included the planning and realization of the industrial quarter of Novoli. At the end of the II World War, the signs of demographic growth soon became manifest: in the space of two decades, the population of Florence swelled from 374625 residents in 1951 to 436516 in 1961 and to 457803 in 1971 (ISTAT, 1985). The growth was accompanied by the urbanization of huge areas, which in effect destroyed the old urban balances.

The demographic figures for 1981 assign 448331 residents to Florence. The data of the 6th general census of industry, commerce, services and handicrafts of 1981 demonstrate how the country's third main industrial pole had come to be consolidated in the area comprised between Florence, Prato and Pistoia: an area with 278000 employees in manufacturing industry, of whom 203000 in the province of Florence alone.

The interconnections between the manifestation of economic dynamics and the evolution of settlement patterns can foster more precise seismic risk elaborations. The statistical data relating to 1981 testify that in the Florentine urban area at least 1 out of 5 houses were built in the decade 1971-81 (Bianchi, 1986). In 1952 the Commune of Florence comprised 2028 hectares of urbanized terrain below 100 m a.s.l., of which 1797 hectares were residential and 231 allocated to industrial zones and green areas. In 1986 the urbanized area had grown by 49%, rising to 3026 hectares, of which 2214 for residential use (+23% over 1952), and 812 for industrial, recreational, infrastructural and administrative purposes (+250% over 1952) (Poggiali, 1990).

Table II. Statistical processing of the site catalogue. Historical series of felt reports in Florence. For each earthquake the probability that the effects felt in Florence were greater than or equal to a given grade MCS is reported. Seismic damage effects in the city of Florence are documented for each event marked with an asterisk. The I_{Florence} column lists the intensity values corresponding to these effect at Florence. The last column (VI_{PFG}) lists the probability that the effects at Florence had been ≥ VI MCS; this probability was calculated with an attenuation low (Magri *et al.*, 1994) from the data of the PFG catalogue.

Year	Month	Day	h	min	s	VI	VII	VIII	IX	I_{Florence}	VI_{PFG}
1293	7	11	–	–	–	0.43	0.16	0.05	0.01	–	–
1414*	8	7	13	–	–	1.00	0.50	0.00	0.00	VI-VII	0.08
1420	–	–	–	–	–	0.11	0.03	0.01	0.00	–	–
1436	3	–	–	–	–	0.03	0.01	0.00	0.00	–	–
1453*	9	28	23	–	–	1.00	1.00	0.00	0.00	VII	1.0
1504	11	1	–	–	–	0.32	0.11	0.03	0.01	–	–
1527	10	–	–	–	–	0.16	0.04	0.01	0.00	–	–
1530	11	11	–	–	–	0.03	0.01	0.00	0.00	–	–
1542*	6	13	9	–	–	1.00	0.00	0.00	0.00	VI	0.94
1554*	11	28	1	–	–	1.00	0.00	0.00	0.00	VI	1.00
1600*	7	6	–	–	–	1.00	0.00	0.00	0.00	VI	1.00
1697	9	30	12	30	–	0.03	0.01	0.00	0.00	–	–
1697	10	1	–	–	–	0.03	0.01	0.00	0.00	–	–
1697	10	27	–	–	–	0.03	0.01	0.00	0.00	–	–
1705	4	14	–	–	–	0.03	0.01	0.00	0.00	–	–
1729*	6	23	–	–	–	1.00	0.00	0.00	0.00	VI	0.18
1741	10	1	6	–	–	0.03	0.01	0.00	0.00	–	–
1770*	12	27	23	–	–	1.00	0.00	0.00	0.00	VI	0.43
1771	8	13	–	–	–	0.03	0.01	0.00	0.00	–	–
1779	12	24	22	–	–	0.03	0.01	0.00	0.00	–	–
1787	12	26	–	–	–	0.04	0.01	0.00	0.00	–	–
1804	10	18	20	–	–	0.03	0.01	0.00	0.00	–	–
1812*	9	11	12	–	–	1.00	0.50	0.00	0.00	VI-VII	0.74
1815	8	1	–	–	–	0.04	0.01	0.00	0.00	–	–
1830	1	26	4	30	–	0.04	0.01	0.00	0.00	–	–
1859	4	12	3	28	–	0.03	0.01	0.00	0.00	–	–
1859	4	12	13	3	–	0.03	0.01	0.00	0.00	–	–
1871	10	22	13	–	–	0.04	0.01	0.00	0.00	–	–
1871	10	23	–	–	–	0.04	0.01	0.00	0.00	–	–
1873*	3	12	20	4	–	1.00	0.00	0.00	0.00	VI	0.07
1877	3	3	1	9	26	0.03	0.01	0.00	0.00	–	–
1887*	11	14	5	48	–	1.00	0.00	0.00	0.00	VI	1.00
1895*	5	18	19	55	12	1.00	1.00	0.00	0.00	VII	1.00
1907	12	15	13	6	55	0.05	0.01	0.00	0.00	–	–
1911	3	26	13	51	2	0.04	0.01	0.00	0.00	–	–
1911*	9	13	22	29	2	0.50	0.00	0.00	0.00	V-VI	0.12
1913	2	13	16	39	50	0.03	0.01	0.00	0.00	–	–
1918	1	22	19	39	–	0.04	0.01	0.00	0.00	–	–
1919*	6	29	15	6	13	1.00	0.00	0.00	0.00	VI	0.80
1956	2	22	22	55	6	0.03	0.01	0.00	0.00	–	–
1960	10	29	0	8	39	0.50	0.00	0.00	0.00	V-VI	0.19

6. Major seismic effects at Florence

In order to draw the best indications for seismic risk assessments from historical data, it is necessary in our opinion to take into account the territorial changes of the examined area. As far as Florence is concerned, the present urban system actually defines a metropolitan area which is much larger than the old city of Florence.

This type of area is the result of a growth which is not only demographic and spatial, but also of a complexity of roles and functions of pre-existent included urban centres. In this case, the damage caused by the earthquake of 1453 in the villages is generically recorded in the sources by the urban-centered point of view which tended to give more emphasis to the effects in the cities than in the «countryside». Now, the damage has to be evaluated within the present context.

Research has not constantly made available information on seismic effects, particularly for earthquakes felt in Florence without damage. The circular neighbourhood of Florence with a 10-km radius has been assumed for the site of Florence, including over 3000 hectares of urban building area and many villages of Florence's urban area.

As it has been previously mentioned, in this way it was meant to privilege the available historical record for each earthquake in each locality of this neighbourhood, compared to the analytical value provided by the attenuation law used. On the other hand the conventional choice of that radius does not conflict with the space resolution of the intensity attenuation laws.

The seismic effects on the site are summarized in table II, with the aim of providing a general picture for rapid consultation. By comparing it to table I, it is possible to recognize the changes that have been made (already summarized in the graph of fig. 2). On the basis of these new indications, the seismic scenarios of the two important earthquakes that struck Florence have been further investigated on: the 1453 and the 1895 ones, located within a 10-km radius from the city (the area we have defined *site*).

Earthquake of 28 September 1453

Catalogue	I_0	Epic. area	I_{Florence}
Postpischl (1985)	IX	Florence	not available
After revision	VIII	Impruneta	VII

This seismic event caused a rather pervasive pattern of destruction in Florence, even if clearly overestimated by the PFG Catalogue: the previous IX grade MCS, according to our estimate, should be lowered by one grade. The greatest seismic effects have been located in the environs of Impruneta, and are equivalent to VIII MCS. The effects in Florence were assessed of VII grade, therefore the impact of this event on the site has been cut down to 2 grades.

Vivid memories of the earthquake of 28 September 1453, which made a great impression on the city, are preserved in the Florentine chronicles of the period. The main shock occurred at night: the sources, almost unanimously, record it at 22:45 GMT. This was followed by a long series of aftershocks, which persuaded most of the population to leave their homes and sleep in the open. A very authoritative eye-witness source is the chronicle of Antonino Pierozzi (1587). At the time of the earthquake the author was in Florence and he records that it struck all buildings and opened up fissures in the walls. It was therefore necessary to spend a lot of money – the author affirms – on the reinforcement of many buildings. The explicit statements of this eye-witness on how destructive the event was are important: he testifies that no building in the city collapsed, but only many chimneys and many merlons on palaces collapsed.

Various other testimonies confirm this type of damage, at least as far as the city is concerned. More serious levels of damage and even some victims (2 in Camerata), on the other hand, are reported in the surrounding villages, now in part incorporated in the urban area of Florence. A manuscript chronicle (BNCF, Matteo Chiari, 15th century) records that more than a thousand chimneys collapsed in Florence and that «many» houses were ruined in the surrounding countryside.

In the *Ricordanze* (memoirs) of a Florentine merchant, found among the *Carte Strozziane* in the Archivio di Stato in Florence (ASF, Tommaso Giovanni di Francesco, 15th century), we read that, as a result of this earthquake, churches and many houses collapsed in the *contado* of Florence (the rural area surrounding the town). The houses that escaped with no damage were few; the victims, whose number is not specified, were all in the countryside.

The sources records the collapse of part of a tower and other buildings at Bagno a Ripoli, Impruneta, Camerata, Vincigliata. (BNCF, *Nota de' tremoti...*, 15th century; ASF, *Priorista a tratte...*, 15th century).

All the sources identified agree in pointing out that this seismic period lasted over a month. In one of the manuscripts already cited (ASF, Tommaso Giovanni di Francesco, 15th century), a series of aftershocks is mentioned: at least eight between 28 and 30 September, and further shocks between 30 September and 28 October, the day on which the shocks were described as «great and terrifying». Another powerful shock «with a rumble and a strong shock» was recorded on 8 November. The sources agree in affirming that many other aftershocks were felt, though without damage, up till May 1454.

Damage to the artistic heritage of Florence

In the church of Santa Reparata, the ancient name of the Cathedral of Santa Maria del Fiore, several stones fell from the ceiling vaults; in the Convent of San Marco (since 1869 seat of the Museo del Beato Angelico) cracks were caused to the walls and the vaulting of the famous library (fig. 8).

Earthquakes of 18 May 1895

Catalogue	I_0	Epic. area	I_{Florence}
Postpischl (1985)	VII	Impruneta	not available
After revision	VIII	Impruneta	VII

The effects of the two earthquakes that struck Florence less than a month apart in 1895 (18 May and 6 June) are very well documented by contemporary sources, administrative, scientific, historiographical and newspapers. Our research has indicated that the epicentral intensity has been underestimated by one grade. The earthquake had an area of destructive effects in practical terms limited to the municipal territory (fig. 7). The damage suffered by the buildings within the city, numerous and widespread, was serious; there were four victims. The buildings that suffered the greatest damage were the older ones, especially those readapted for other purposes or with superstructures built onto them, but also houses of recent construction, considered by the eye-witnesses themselves to be «defective and poor» (Raddi, 1897). The quarters of San Salvi, San Frediano, Santo Spirito and San Jacopino were those most badly affected (see in the order in fig. 8, B, C, D).

Immediately after the earthquake, the municipal administration appointed a special Commission charged with assessing the damage and adopting the necessary provisions. The documentation of the inspections carried out and the Commission's findings (ASCF, *Affari sfogati al tempo del Sindaco marchese P. Torrigiani 1895*) comprise, *inter alia*, the final report sent to the Mayor on 28 June 1895, in which it is reported that, with only a few exceptions, all the buildings in the various localities of the Commune had suffered damage. Very detailed information on the levels of damage was obtained from the reports of the engineer in charge of the Technical Department of the Intendancy of Finance, and from the reports of the various sections of the Municipal Police (ASCF, *Affari sfogati al tempo del Sindaco marchese P. Torrigiani 1895*; file 1474). These data confirm the gravity of the effects observed in various zones of the Oltrarno, where numerous apartment blocks were made uninhabitable or seriously damaged. Fissures in the walls, collapsed ceilings, cracks of various kinds were also reported in the upper storeys of buildings in the historic city centre. Another area of very serious damage, with apartment blocks classified as «uninhabitable», has been identified in the north-western quarters of the city, from the Cascine to San Jacopino and Romito (D in fig. 8) and further to the north in the areas of Il Pellegrino and Le Cure (A in fig. 8).

The buildings erected after 1860 by the Società Anonima Edificatrice were particularly badly damaged (see above, section 5.5); 145 tenants were evacuated from these buildings: in the eyes of contemporaries, the reason for such a «débacle» suffered by relatively recent building structures was due not only to the violence of the earthquake, but to social rather than natural causes: speculation, the poor quality of the building materials and of the construction methods used, especially of the mortars, poor-quality bricks, and poor maintenance. Analysis of the «General Register», which reports the «Claims for damages from the earthquake» (ASCF, *Affari sfogati al tempo del Sindaco marchese P. Torrigiani 1895*, file 1474), confirms the widespread incidence throughout the city's housing of fissures in walls, cracks in ceilings, collapsed chimneys, unsafe terraces, and isolated buildings which were seriously damaged, even within areas little affected by the shock, and characterized by bad building practices, as at Santa Croce.

A recent study (Cioppi, 1995) presents data on this earthquake, drawing on the scientific documentation alone (however valuable) or on the journalistic one, without thorough research on administrative documentation. Moreover, as far as damage in the city

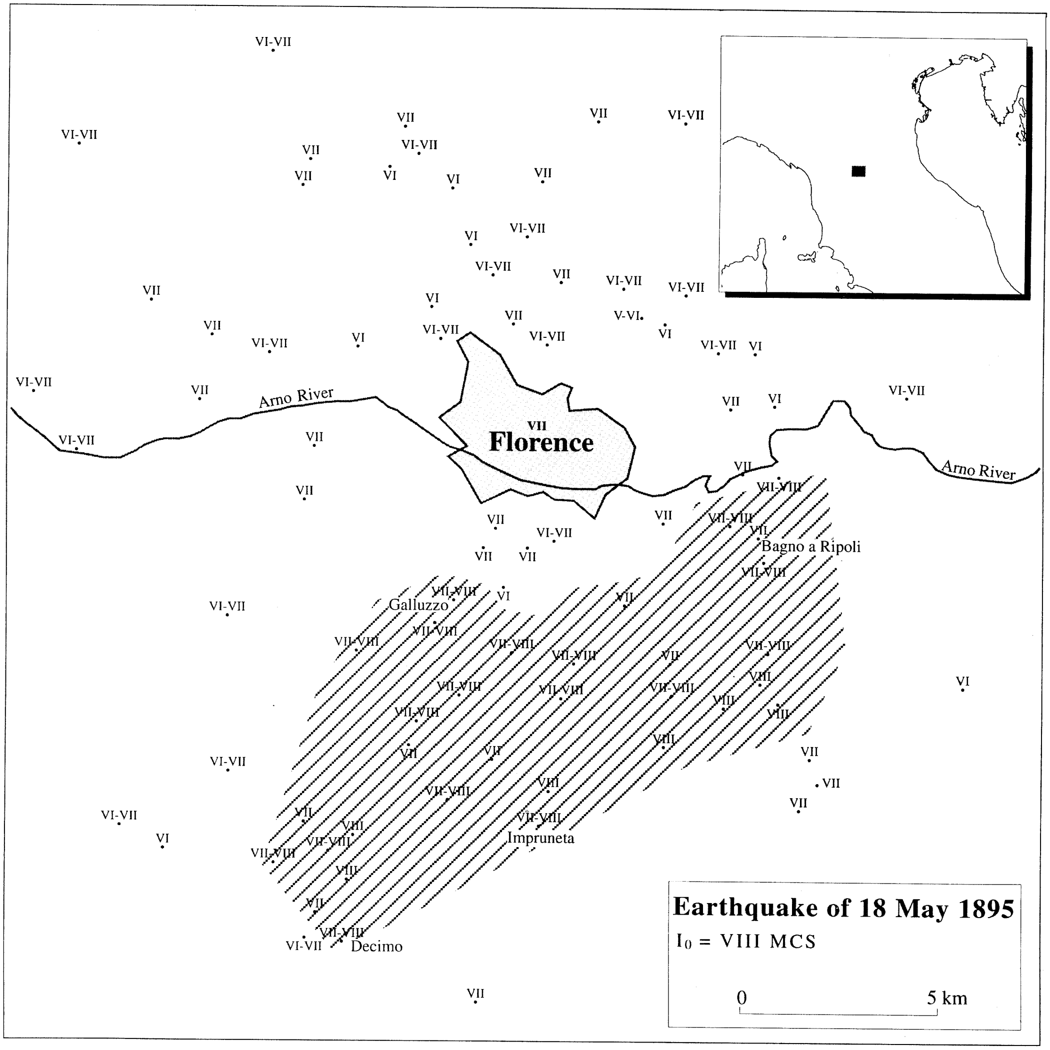


Fig. 7. Distribution of the effects in MCS scale; 232 sites comprehensively evaluated, 86 of which on map; the major effects area is hatched.

is concerned, the attention is drawn on the effects on single monumental buildings.

Damage to the artistic heritage of Florence

Journalists and scholars devoted particular attention to the effects of the earthquake on the artistic and historical heritage of the city. An examination of the archival documentation has confirmed that the damage in Florence was of slight extent, but extended to almost all the buildings of artistic or cultural interest. The documentation preserved in the Archivio Storico Comunale (ASCF, *Affari sfogati al tempo...*, files 1473 and 1475; *Chiese monumentali cedute al Comune...*, file 5309), concerning the decisions taken about which monumental buildings to restore, permit an initial mapping of the effects of the earthquake on the artistic heritage of Florence (see fig. 8).

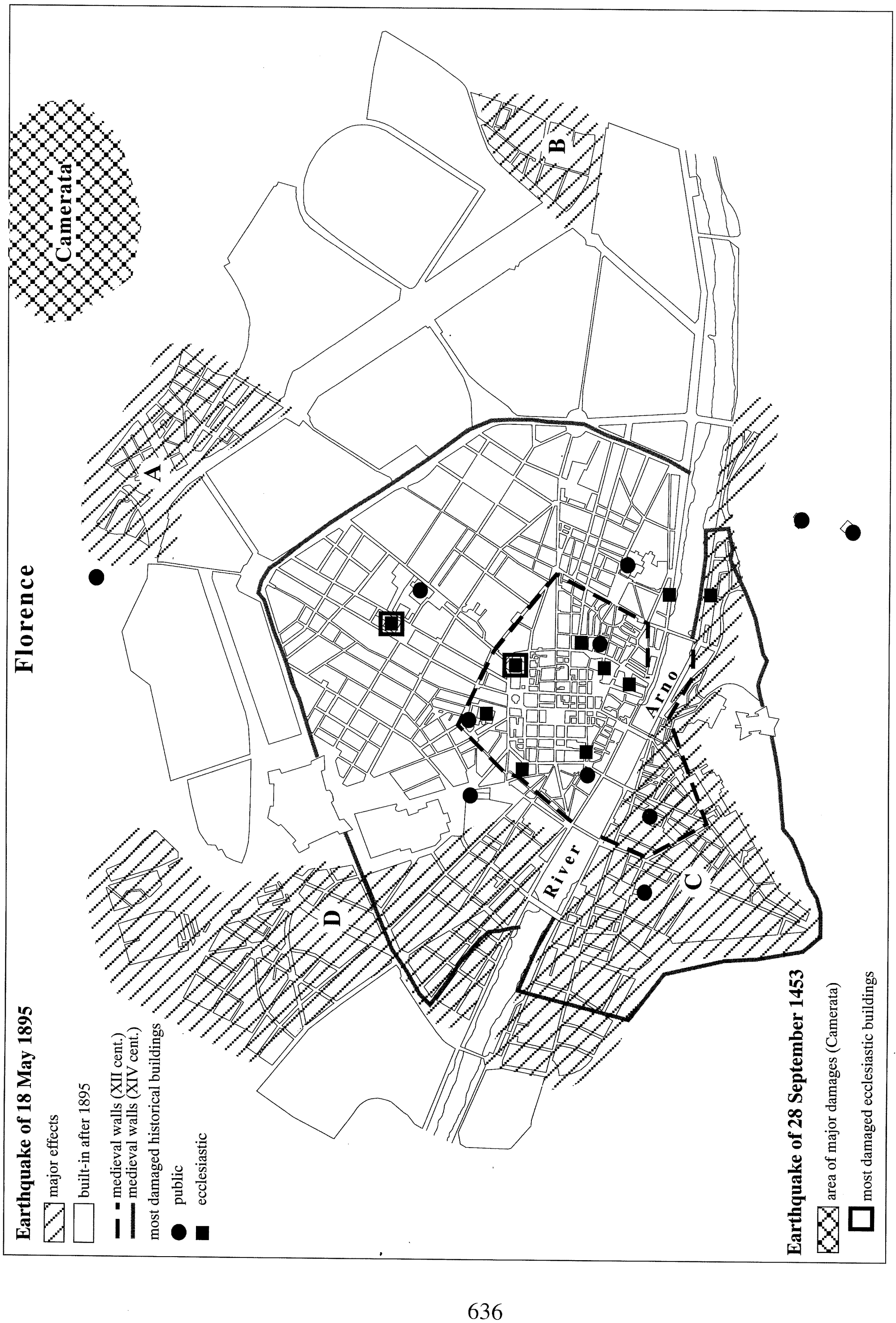


Fig. 8. Localization and assessment of the effects caused by the earthquake of 1895 in the urban area of Florence. Even though in the limit of Medieval descriptions, some concordances between the 1453 effects and the 1895 ones are stressed; the hatched areas include some quarters of the city: A = Il Pellegrino and Le Cure; B = San Salvi; C = San Sepolcro, San Frediano and San Niccolò; D = San Jacopino and Romito.

Serious damage without collapse to the following churches and monasteries: Santa Maria Novella, San Giovannino degli Scolopi, San Salvatore al Monte, Santa Trìnita, Santo Spirito, Santa Firenze, Santa Croce, Santa Maria del Carmine (including the Brancacci Chapel), and SS. Annunziata. A series of reports on the damage suffered by the Santa Maria del Fiore: breaking of the iron tie-beam of one of the bays of the central nave, detachment of plaster and stucco, is contained in the detailed reports published by the *Deputazione Seculare* of Santa Maria del Fiore and in administrative documentation of the Commune of Florence (Del Moro, 1895; ASCF, *Chiese monumentali cedute al Comune...*, file 5309).

Moreover, public and private buildings were damaged: the Uffizi Gallery, Palazzo Vecchio, Palazzo Buondelmonti, the building of the Biblioteca Nazionale, the Biblioteca Laurenziana, the Museo San Marco (or Museum of Beato Angelico) the Spedale degli Innocenti (fig. 9a) and the Museo del Bargello, were damaged with some of the works on display. Gerpasch (1896) reports the fall of the bronze eagle, emblem of the guild of the Calimala, from the façade of the church of San Miniato al Monte.

Particularly serious damage was caused to a number of historical villas and ecclesiastical monuments in the environs of the city: among the former the Villa Demidoff, Antinori, Duprè, Rossi, Bossi; and among the latter the Certosa of Galluzzo, where one side of the large cloister completely collapsed (fig. 9b), destroying in the process sixteen terracotta heads by Luca della Robbia (Gerpasch, 1896), and the parish church of San Pietro a Ripoli.

7. Quantitative representation of the effects at the site

The information regarding how each earthquake was felt has been expressed through a data stripe which, together with the time setting of the event, represents the probability that this event has been felt with an intensity greater or equal to each of the possible values of the MCS intensity scale. For instance, an earthquake felt with an intensity of IX MCS is represented by a stripe in the form:

Intensity	VI	VII	VIII	IX	X	XI	XII
Probability	1.	1.	1.	1.	0.	0.	0.

This formulation allows to take into account the uncertainties that may be present in the attribution of intensity. For instance, in case of uncertain assessments like VIII-IX MCS, equal probabilites can be assigned to each of both values VIII and IX, and the stripe of that event will take the form:

Intensity	VI	VII	VIII	IX	X	XI	XII
Probability	1.	1.	1.	0.5.	0.	0.	0.

Of course the interval of uncertainty may have arbitrary extension (within the interval of definition of the macroseismic intensity scale used).

The historic series of felt reports at the site of Florence was created with the felt reports corresponding to each of the examined earthquakes. The method of construction of this series assumes for each earthquake the intensity value assessed for Florence. When it was impossible to reconstruct on a historical basis the felt report of an earthquake at Florence, its intensity value was calculated as the maximum among the values attributed to localities included in the 10 km-radius circular area around Florence. When even this neighbourhood was empty, we used empiric relations that take into account the space localization of the event and of its epicentral intensity. In particular, relations of logistic type proposed by Magri *et al.* (1994) were used. These relations allow the calculation of the probability P that, given a certain epicentral intensity of the earthquake (I_0), and the distance r from Florence, the intensity I_s felt at the site is greater than or equal to a value I:

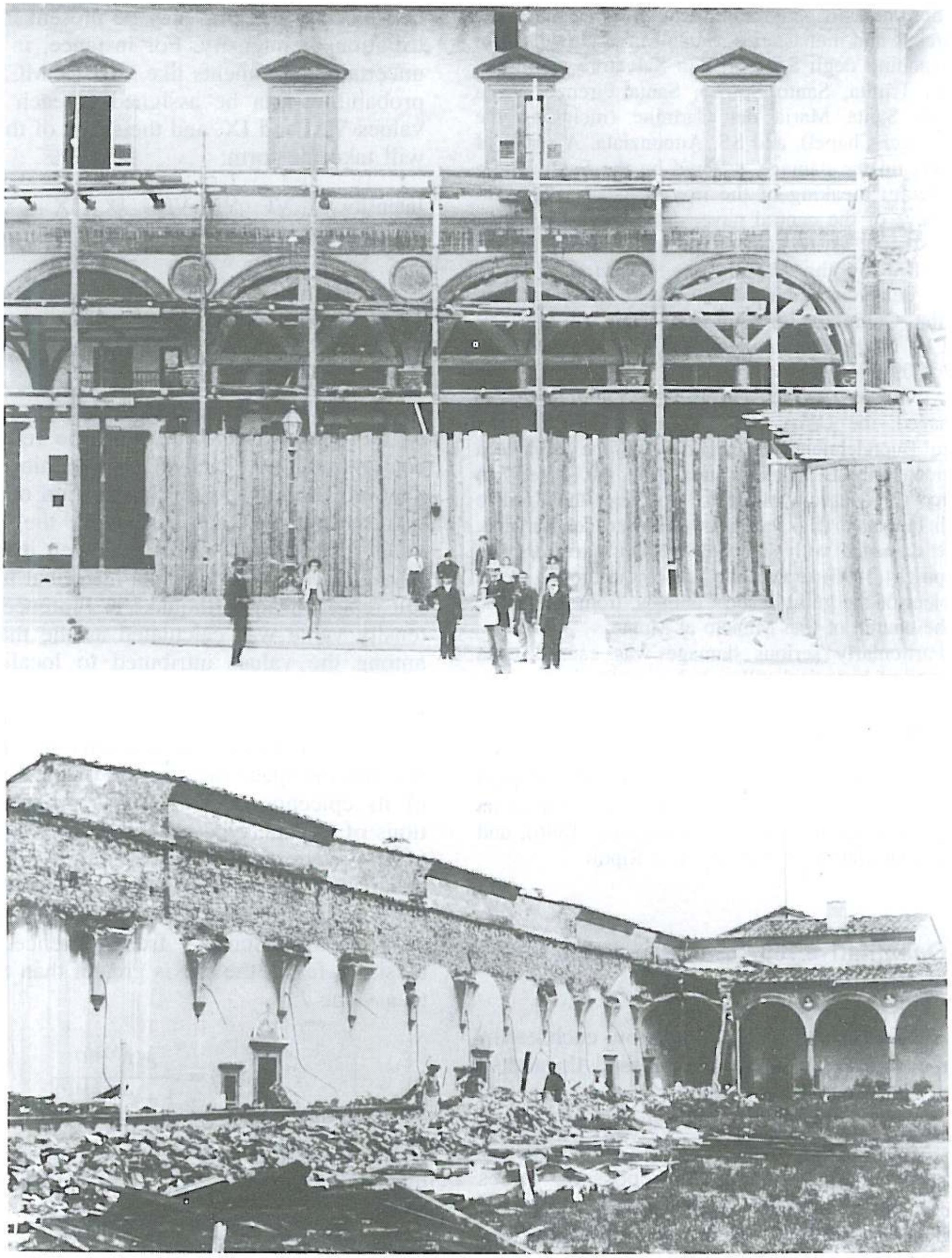
$$P(I_s > I) = \frac{e^{a+b\ln(r)}}{1+e^{a+b\ln(r)}} \tag{7.1}$$

where a and b depend on I_0 and I according to the relations:

$$a = \quad 1.00 + 1.95\,(I_0 - I) \tag{7.2}$$

$$b = -\,1.15 - 0.16\,(I_0 - I) \tag{7.3}$$

The various probabilities P calculated for a given seismic event for all of the intensity



(a) (b)

Fig. 9a,b. Effects of the earthquake of 18 May 1895: a) Florence: *Spedale degli Innocenti*: buttressed front during the restoration works. This building, by Filippo Brunelleschi (1419-26) and completed by Francesco della Luna, is of great importance for the history of architecture in the Renaissance; b) Certosa of Galluzzo: collapse of the north-western end of the great cloister. The building of the 14th century was enlarged during the 16th century. Now it retains a valuable art gallery.

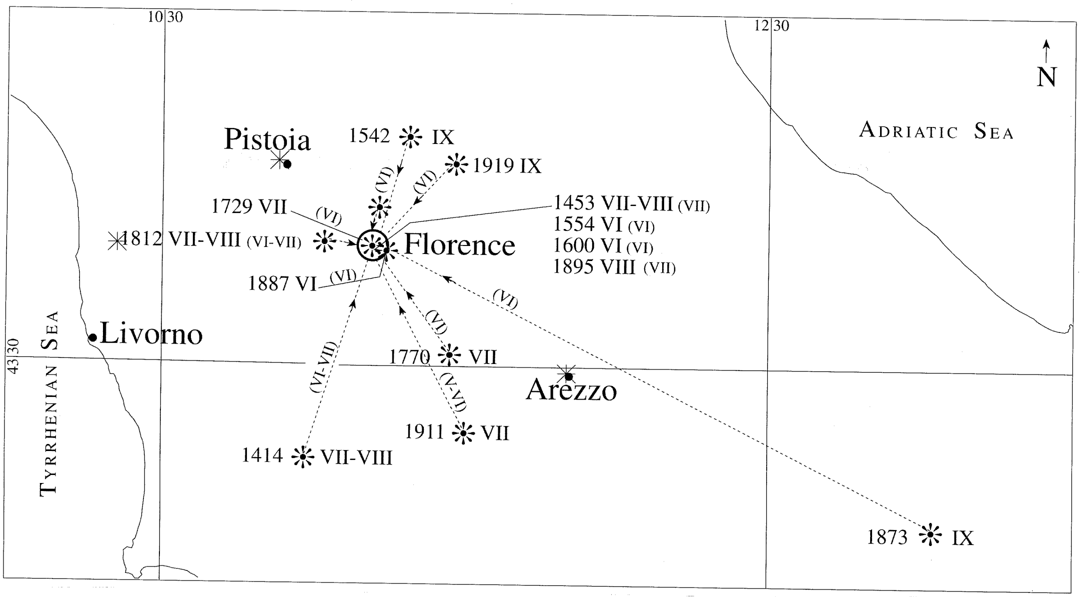


Fig. 10. Localization of the earthquakes which caused damage within the area of definition of the site of Florence. The asterisk defines the epicentre of the earthquake, the Roman figures define the epicentral intensity and the Roman figures in brackets define the intensity of the effects of the earthquake in Florence.

values I_s greater than or equal to VI MCS (the threshold of damage effects) allow the assessment of the values to be inserted in the stripe that characterizes each single earthquake.

In the historic series reported in table II, the different felt reports are represented by the probability that effects greater than or equal to VI, VII, VIII, IX etc. grades of the MCS scale have occurred at Florence. The 41 listed events are the ones for which an intensity value greater than V MCS at Florence site was assessed. For approximately one third of these events (13 out of 41) historical sources bear evidence of effects at the site of Florence greater than or equal to VI grade. Such events are localized in fig. 10. For the remaining 28 events intensity was calculated with the previous formulae, always starting from a general framework of seismic effects on the territory reappraised by historical research.

The results of the revision were compared and updated to the ones of the most recent Italian seismic catalogue (Boschi *et. al.*, 1995).

In brief, for the interval 11th-20th century the major effects recorded for Florence do not go beyond VII MCS, and are generally caused by seismogenetic structures close to the city and the major effects of which are located within the 10-km area of the defined site of Florence.

8. Assessment of the seismic hazard of Florence

Seismic hazard has been assessed calculating, on the basis of the historic series of felt reports at the site (table II), the number of earthquakes that affected Florence for each intensity greater than or equal to VI grade.

Given the probabilistic character of the proposed formalism, the number of seismic events felt at Florence having intensity greater than or equal to a given value cannot be *calculated* but only *assessed* following the approach defined below.

The fact that a given seismic event is or is not observed at the site (Florence) with an intensity greater than or equal to a given threshold value, can be considered as an event belonging to a Bernoullian sequence. The probability distribution $P(N)$ related to the number of times that event (exceeding the threshold intensity) occurs is assimilable to a Binomial distribution:

$$P(N) = \frac{N_{\text{tot}}!}{N!\,(N_{\text{tot}} - N)!} P(I)^N\,[1 - P(I)]^{(N_{\text{tot}} - N)} \qquad (8.1)$$

where N_{tot} is the total number of the considered earthquakes characterized by probability $P(I)$ of exceeding the intensity threshold. The value of $P(I)$ comes from the historic series of felt effects at the site or from the assessments obtained through the above described logistic models (in this case $P(I) = P(I,r)$). The expected number $<N_i(I)>$ of earthquakes that have exceeded the threshold I of intensity, among the ones characterized by a probability of going beyond the threshold equal to $P_i(I)$, is given by the relation

$$<N_i(I)> = N_i(I)\,P_i(I) \qquad (8.2)$$

A measure of the uncertainty connected to the assessment can be given by the standard deviation of the binomial distribution

$$\sigma_{N_i(I)} = \sqrt{P_i(I)\,[1 - P_i(I)]} \qquad (8.3)$$

The total assessed number $<N(I)>$ of earthquakes which have exceeded the I at the site will be given by the sum of the values $<N_i(I)>$; therefore:

$$<N(I)> = \sum_{i=1}^{N_{\text{tot}}} [(P_i(I)] \qquad (8.4)$$

As the events are assumed to be independent, the total uncertainty on the assessment of $N(I)$ is given by the standard deviation calculated by

$$\sigma_{N(I)} = \sqrt{\sum_{i=1}^{N_{\text{tot}}} \{P_i(I)\,[1 - P_i(I)]\}} \qquad (8.5)$$

It is worth noting that when there are no uncertainties in the attribution of the intensity values, $P_i(I)$ is equal to 1 for each i and the previous relation is reduced to the sum of the number of earthquakes that have exceeded the intensity I at the site. In this case $\sigma_{N(I)}$ is equal to 0.

Hazard function

The *seismic hazard* function is the function $H(I,t)$ defining the probability that in a given site intensity I is exceeded in a time interval t one time at least. The function H can be calculated assuming:

1) a probability function $F(I)$ that a certain intensity I is exceeded given a certain sample of earthquakes: this function $F(I)$ is exponential in the form

$$F(I) = e^{-\beta(I - I_t)} \qquad (8.6)$$

where I_t is the minimum intensity considered in the analysis;

2) the number of earthquakes exceeding the threshold I_t at the site in the time unit is a Poissonian variable with media λ.

It has been demonstrated (for instance, Epstein and Lomnitz, 1966) that in these assumptions, the hazard function $H(I,t)$ adopts the form:

$$H(I) = 1 - e^{-\lambda t F(I)} \qquad (8.7)$$

Evaluation of the hazard function parameters

The two parameters β and λ of (8.6) and (8.7) have to be evaluated on the basis of the historical series of the seismic effects at the site: β, defining the distribution of the earthquakes felt in the various intensity classes and λ, defining the seismic rate. β should be evaluated keeping in mind the ordinal and discrete character of the intensity.

On the discrete field, the equivalent of the exponential distribution $F(I-I_t)$ is provided by the geometrical distribution (Tinti and Mulargia, 1986) from which a good estimator of β can be calculated as follows:

$$<\beta> = -\ln(<I>-I_t) + \ln(<I>-I_t+1) \qquad (8.8)$$

where $<I>$ is the average intensity observed in the time interval Δt covered by the available seismic history.

The parameter λ can be estimated as follows:

$$<\lambda> = \frac{<N(I_t)>}{\Delta t} \qquad (8.9)$$

Estimate of hazard

The hazard function H can therefore be estimated on the basis of the historical series of seismic effects of the examined site.

Two methods to estimate $H(I,t)$ are proposed here: an indirect one, based on the above-described evaluation of λ and β, and a direct one, based only on the evaluation of λ and on the number of earthquakes actually observed on the site, having an intensity greater than I.

Indirect method

If $<\beta>$ and $<\lambda>$ are known and evaluated according to the above-described methods, $H(I,t)$ will be given by:

$$H(I,\ t) = 1 - e^{-t<\lambda>e^{-<\beta>(I-I_t)}} \qquad (8.10)$$

Direct method

This method (Cornell, 1968; Dargahi-Nourbary, 1989) needs no assumptions on the form of the function F: therefore, it is not connected to the parameter β. This method can be applied when the number of earthquakes having an intensity greater than I and happened in the time interval Δt is greater than 0. In this case, the function H can have the form:

$$H(I,\ t) = 1 - e^{-<N(I)>t/\Delta t} \qquad (8.11)$$

where $<N(I)>$ is the number (observed or estimated) of earthquakes happened at the site with an intensity greater than or equal to I.

9. Results

The elaborations have been led for forecast intervals of 50 and 100 years, with the above-described methods, both the direct and the indirect one. These elaborations have been carried out on both previously available data (epicenters of the PFG Catalogue) and data (epicentres and felt reports) carried out by this study.

Former knowledge assigned to the 1453 earthquake, located at Florence, an epicentral intensity of IX MCS, which on the basis of this study turns out to be overestimated by two degrees.

On the whole, 7 seismic events proved to be errors of the PFG Catalogue, drawn from unreliable texts; 2 events are uncertain; 66 proved to be overestimated, 11 underestimated and 45 confirmed (fig. 2).

The outline that can be inferred from the final results of the revision and from our seismic hazard assessment at the site is as follows:

a) the maximum expected seismic event was lowered by two intensity grades (from IX to VII);

b) the average return time in which a seismic event is expectable having an intensity greater than or equal to VI MCS is approximately 66 years; for an event greater than or equal to VII grade, it is approximately 240 years; for an event greater than or equal to VIII grade, approximately 6183 years; this last assessment and the ones for higher grades recorded in the former tables are merely indicative, and considerably depending on the adopted forecasting method, as they concern a return period that widely exceeds the considered chronological span and for which there is historical documentation;

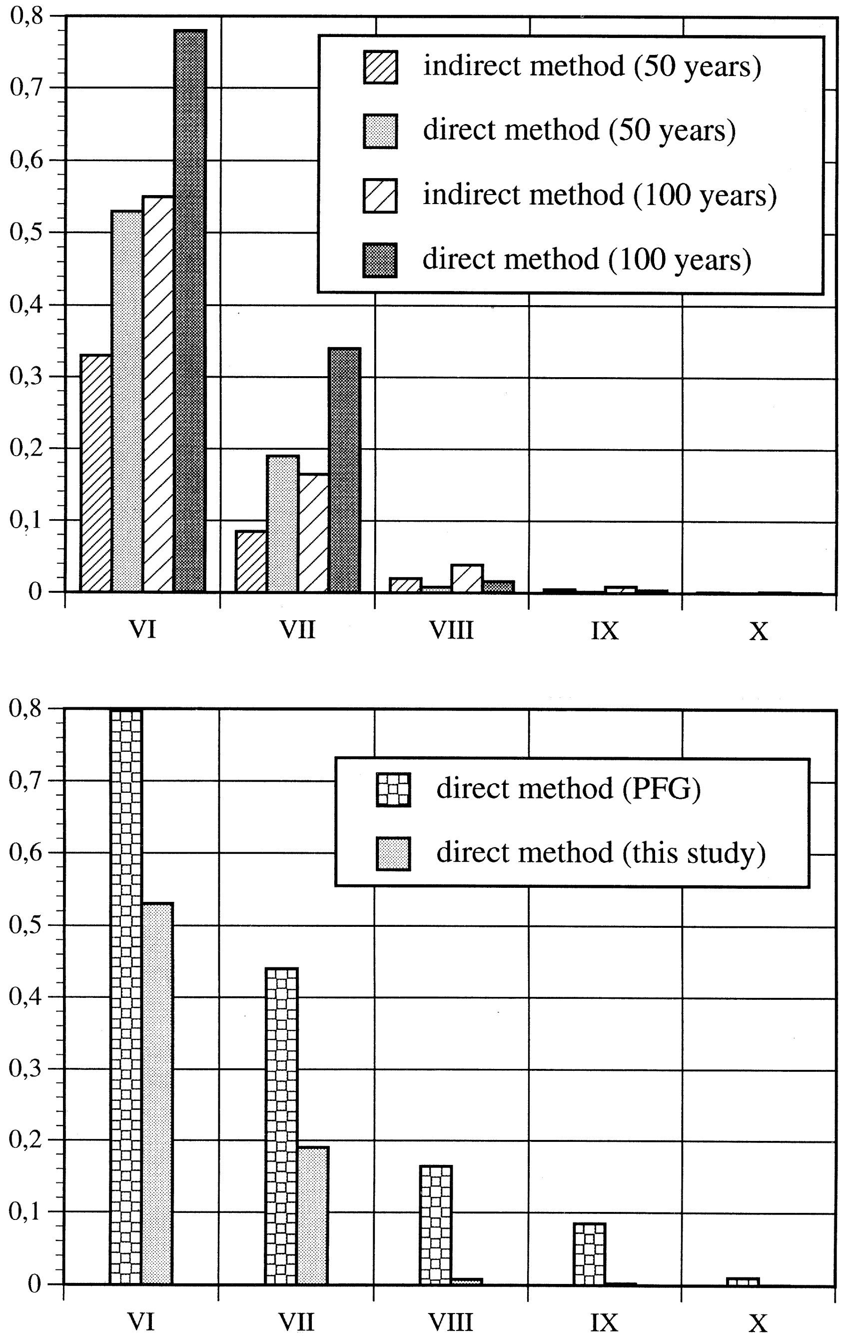


Fig. 11a,b. Seismic hazard in Florence calculated: a) with direct and indirect method, for forecast intervals of 50 and 100 years; b) with direct method before and after the results of this study, for a forecast interval of 50 years.

c) the last seismic event that caused VII grade effects in Florence occurred in 1895.

The return times assessed on the basis of epicentral data drawn from the PFG Catalogue were: 31 years for VI MCS, 86 years for VII MCS and 278 years for VIII MCS. The accuracy in the writing of the site catalogue, that can assure both quality and completeness of data, is a fundamental aspect, particularly in the case of Florence, where destructive events occur with scarce frequency. A thorough and careful historical analysis succeeded in determining, for Florence, events having particular features of effect propagation. This is the case, for instance, of the earthquake of 12 March 1873, having its epicentral area over 160 km off Florence; its effects on the site were of VI MCS. A selection with attenuation laws from the earthquake catalogue would have never given an account of the damage effects occurred in Florence.

As far as hazard is concerned, the direct method (the most conservative of the two methods used) involves the following occurrence probabilities of a seismic event, in 50- and 100-year intervals, from the 11th to the 20th century:

I_s	50 years	100 years
≥ VI	53%	78%
≥ VII	19%	34%
≥ VIII	1%	2%

The comparison of the results of the hazard processing can be found in the graphs of fig. 11a,b.

In fig. 11a, the hazard values assessed through both direct and indirect methods (described above) are compared for forecast intervals of 50 and 100 years. In fig. 11b, the hazard values assessed through direct method (which proved to be the most conservative), based on PFG data are compared for forecast intervals of 50 and 100 years to the ones based on our revision. A perceptible difference emerges in the most probable intensity value for the site (VI grade MCS).

10. Conclusions

The historical approach developed in this study has allowed a quantitative elaboration of new aspects of seismic hazard, introducing significant changes to the former framework of seismological knowledge.

131 events of interest for the definition of hazard at the site of Florence have been revised and reappraised. Only for 13 events out of them effects greater than or equal to VI grade at the site were historically documented. The revision has pointed out previous errors and lack of information concerning the effects in the urban area of Florence. For the other 28 events having an epicentral intensity greater than or equal to VI MCS historical documentation did not provide elements to assess the intensity to the seismic effects at Florence. The probability that such effects for each earthquake had been greater than or equal to VI MCS was calculated with the attenuation law proposed by Magri *et al.* (1994). The elements provided also allowed the assessment of the occurrence probability of the events by classes of intensity.

Such elaborations can be reliable only taking into account the historical evolution of the built-up area of Florence: the city shows particular features that also determined the changes of the extension and of the population density of the urban area, directly affecting the framework of seismic effects.

These elements provide strong indications about the completeness of the site catalogue, since dwelling continuity and the economic levels shared amongst the majority of the population are an important indicator of the possibility to produce historical evidence of seismic effects in a continuative way. This allows to exclude that destructive earthquakes might have occurred in Florence from the 12th century up to now without being mentioned in written texts.

The comprehensive framework of Florence's seismic hazard appears more precise and reappraised, both in frequency characters and in maximum expected intensity values.

Maximum effects evaluated from the PFG Catalogue were equal to IX grade MCS, attributed to the 1453 earthquake, localized in Florence. After this study, the effects of this earthquake in Florence have been assessed of VII grade MCS (I_0 = VII-VIII in Impruneta).

The maximum intensity historically felt in Florence is VII MCS in the 1453 and the 1895 earthquakes. The probability of the return period with which damaging earthquakes are expected is of 66 years for VI MCS, 240 for VII and 6183 for VIII. In this stage a preliminary map has been drawn of the differential distribution of seismic effect on Florence's historic centre.

Other elements that emerged from this study, not developed in this phase in quantitative terms, are susceptible of further elaboration. For instance, further investigations can be done to outline a framework, as detailed as possible, of the effects of the 1895 earthquake in minor civil building, by analyzing the reports that were written for each single building. Moreover, the city's seismic response outlined in the long period can be connected to surface geology to model the behaviour of the whole urban structure.

As an extraordinary artistic heritage is being retained in Florence, kept in its turn in architectonic historical «containers» of enormous value, seismic risk remains very high even in spite of the moderate hazard of its territory. The indications that emerged from this research can be applied also to direct general stategies of intervention and consolidation with preventive function.

Acknowledgements

Basic research was carried out by SGA in 1990-1991, in the «Firenze» project of the «Presidenza del Consiglio dei Ministri, Dipartimento per le Aree Urbane»; then it proceeded in 1993, with data updating on the basis of the new catalogue of earthquakes, at that moment under preparation, now published (Boschi *et al.*, 1995). We wish to thank M. Giovanna Bianchi, Antonella Guarneri, Achille Ludovisi, Dante Mariotti, who took part in this research. Thanks to Dario Albarello who wrote the computer program, with whom the hazard processing was developed. Special thanks to Fabio Sabetta and Antonio Rovelli for useful discussion and suggestions.

Appendix

Below we list the various archives and libraries in which the research was carried out, according to a work project which aimed at the systematic gathering of the relevant information, concerning both the urban site and its surrounding territory.

Archivio di Stato di Firenze

Due to the quantity and importance of the documentation it contains, the State Archives of Florence (ASF) was the research centre where the most important part of the present research was carried out. In spite of the difficulties encountered in the study of sometimes incomplete archival collections (due to the vicissitudes traversed by this Archive as a result of dismemberment, floods, etc.), the documentation found here enabled us to considerably augment the data hitherto available. Various archival collections contained in ASF were taken into consideration. They were explored chronologically, in order to identify descriptions of seismic effects in the city and its territory, and to examine various aspects of the administrative procedures in dealing with them. The archives relating to the land registers offices were inspected especially for historical place-names.

– Catasto (1427-1495);
– Capitani di parte Guelfa, numeri rossi (1335-1544);
– Capitani di parte Guelfa, numeri neri (1545-1773);
– Magistrato Supremo;
– Catasto Generale Toscano;
– Affari Giurisdizionali;
– Regio Diritto;
– Archivio Mediceo;
– Archivio Mediceo del Principato;
– Capitani di parte Guelfa, numeri neri;
– Carte Strozziane;
– Compagnie Soppresse;
– Corporazioni Religiose soppresse dal Governo Francese;
– Magistrato dei Nove Conservatori del Demanio e della Giurisdizione di Firenze;
– Otto di Pratica;

– Senato dei Quarantotto;

– Prefettura (affari ordinari, affari comunali).

The examination of the *Manuscripts* collection turned out to be of particular interest, enabling us as it did to locate important eye-witness accounts from memoirs of the period. We also examined the maps of the *Catasto Generale Toscano* for the localities in the suburbs of Florence, in particular the areas comprised in the territory of Galluzzo.

Archivio Storico Comunale di Firenze

The Historical Archives of the Municipality of Florence (ASCF) contains the administrative documentation of the city from 1782 up till the mid-20th century. The research focussed on those collections in the Archive which document the administrative procedures connected with the urbanistic developments in the city. Major archival collections were systematically inspected:

– Repertorio del Registro Generale di Affari;

– Carteggi del Sindaco e del Segretario Generale;

– Atti del Consiglio Comunale;

– Affari Sfogati;

– Buste Speciali;

– Miscellanee dell'Ufficio Edilizia e dei Lavori Pubblici;

– Cartografico.

Of this latter collection the following plans were used: *former Convent of S. Firenze*, (1890-1900) scale 1:250, 45.8×32.7 cm, coll. 24/78 n. 2623; *former Convent of S. Gaggio*, elementary school, plans of first and second floor (1910-15) scale 1:200, 40.4×64.4 cm, coll. 75/82 n. 7230; *Torrente Mugnone e zone limitrofe Macelli, Romito, Ponte Rosso*, relief plan (1880-90), 48.05×202 cm, coll. 1608 n. 19045-19049.

Among the documents found and analyzed, the following may be mentioned due to the importance of the information they contain: the List of the properties reported to the Commune of Florence due to the dangers of collapse they posed following the earthquake (file 1474);

– the insert of reports by the Police Office (file 1474);

– the fascicule of the Special Commission for emergency provisions following the earthquake, containing the Report of the said Commission, established following the earthquake on 18 May 1895 (file 1474);

– various resolutions relating to buildings owned by the Municipality, including buildings and monuments of particular historical and artistic interest. Among the loose papers of the Special Commission particular interest attaches to the summary reports of the surveys conducted by the city's engineers to verify the damage reported by private citizens (file 1474).

The documents preserved in file 1473 for the most part concern administrative rulings, in some cases accompanied by technical reports, relating to the municipally-owned buildings damaged by the earthquake. The documentation relating to the works carried out after 18 May 1895 in the monumental churches and Convents ceded to the Municipality of Florence are gathered in files 1509 and 5309.

The data on individual buildings, almost all produced by the incidence of various types of dispute between landlords, tenants and the municipal authorities, were selected and regrouped. In this way we proceeded to the selection of an optimum documentary corpus which could be used with a view to the precise localization of the damages registered in the urban structure of Florence.

Archivio Provinciale dell'Ordine dei Frati Minori Cappuccini di Firenze

The manuscripts contained in the archive were examined. Some of them relating to the history of the Order were consulted with a positive result.

Archivio Topografico del Museo «Firenze com'era»

The Archive comprises a huge corpus of iconographic documentation (maps, plans, elevations, drawings, *vedute*, etc.) concerning the city of Florence and its immediate environs. Research was conducted on the extensive subject catalogue. The documentation contained in this Archive provides, in any case, evidence of primary importance for identifying the types of building developed in the urban structure between the second half of the 18th and the early 20th century.

Biblioteca Nazionale Centrale di Firenze, Biblioteche Marucelliana, Riccardiana e Moreniana di Firenze

The most important published and unpublished sources relating to the history of the city of Florence and, more generally, that of Tuscany were examined. Letters, parts of manuscripts, documents and memoirs contained in the following archives proved to be of particular interest from the standpoint of the present research: Banco Rari, Conventi Soppressi, Fondi Magliabechiano, G. Capponi and Palatino-Baldovinetti. A systematic study of the sources and printed works preserved in these libraries was conducted; the choice of texts aimed at the objectives of the present research enabled a sizeable corpus of historical records and eye-witness accounts to be selected.

Istituto Geografico Militare Italiano

The historical records preserved in the Library of the Italian Military Geographic Institute (IGMI) were consulted with the aim of locating and examining the perspective views and topographical representations of the city of Florence. This documentation, in some cases of great historical and artistic value, permitted the urbanistic developments of the city to be followed from the 15th to the early 20th century.

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