ECCOMAS Congress 2016
VII European Congress on Computational Methods in Applied Sciences and Engineering
M. Papadrakakis, V. Papadopoulos, G. Stefanou, V. Plevris (eds.)
Crete Island, Greece, 5–10 June 2016

SEISMIC HAZARD OF URBAN AREAS: A CASE-STUDY

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Keywords: urban seismic hazard, urban vulnerability, seismic assessment, vulnerability map, data collecting, data management.

Abstract. *This work deals with the evaluation of the seismic vulnerability of urban areas. The city of Florence has been selected to be the case-study of the analysis. The work is organized in two main parts. The first one consists of the representation of the area hazard. Starting from the PGA of the area, a map of the amplification factors and of the fundamental frequencies has been made, by performing an extensive experimental campaign. The second step is focused on the buildings properties, and on the increase in the seismic hazard – and the consequent vulnerability – due to the possible occurrence of resonance. A large data-bank of the buildings has been collected, and they have been classified after their structural material (masonry versus reinforced concrete) and height. As a result of the collected information, a map of the fundamental period of vibration of the buildings has been obtained, by adopting the expressions provided by the current International Codes. The comparison between the period of each building and the one of its foundation soil has provided the resonance index (RI), which can be considered as an hazard parameter related to each building.*

1 INTRODUCTION

The evaluation of the safety of urban areas is one of the most important challenges that the Community is facing in these decades. The increase of the scientific and technical knowledges, together with the outstanding development of the capacity to collect and to manage databases, let the territory protection more affordable than it never was in the past. Many different retrofitting techniques [1, 2, 3] have been developed, suitable to be applied to all types of existing buildings. Nevertheless, the achievement of a satisfactory safety level of the building population is totally impossible, at the current time. If the inadequacy of the economical sources is certainly the first reason of this impossibility, also the lack of an intervention plan plays an important role. In many Italian towns, in fact, the buildings population is made mostly by ancient or, anyway, pre-normative structures. If the historical buildings, made in the past centuries, have been made without any anti-seismic criteria, even the pre-normative ones present, in many cases, an unsatisfactory safety level. The Italian country, indeed, experienced an economic boom in the 1960s, which was characterized by a great expansion, and by the construction of many buildings. Many of them have been made with poor materials [4], which did not comply with the technical requirements of the time. As a consequence of these observations, the Italian towns are, in most cases, vulnerable, i.e. they have an unsatisfactory seismic capacity. In the last decades, many procedures have been developed to check the seismic vulnerability of urban areas [5, 6, 7, 8, 9], which can be divided into three main groups: the empiric, the analytical and the hybrid methods. The vulnerability analyses are focused on the reliability of the buildings with regard to the seismic actions expectable for the area.

The current work deals with the urban vulnerability of the city of Florence, (Italy), which is an example of complexity, both for the outstanding architectural heritage and the for multilevel dimensions. The work develops a previous research [10], aimed at evaluating the urban vulnerability of Florence through an empirical approach based on a simplified vulnerability index. The analysis was based on the database available at the time, consisting in the information collected by GIS, which was very basic, providing only the total height and the age of the building population.

This work is focused on the seismic hazard of the buildings located in the area of Florence. The maximum seismic acceleration expected for each point of the urban area has been defined by assuming a PGA equal to 0.13g over the entire urban area, according to the Code [11] classification, and determining the amplification factor map, which is a function of the specific geological features of each micro-zone of the area.

A further development has been achieved, by determining the maximum acceleration which each building of the Florence area can experience as an effect of the relationship between its own dynamical properties and the ones of the foundation soil. To obtain this information, the maps of the fundamental period both of the soil and of the buildings would be needed. The map of the fundamental period of the soil has been found after an extensive experimental campaign made on the Florence area. The map of the fundamental periods of the buildings, in turn, has been found by applying a simplified approach to the buildings population. To this purpose, further information has been achieved on the buildings population, like their structural system and material. As a consequence of the more detailed classification, a reliable evaluation of the main frequencies of the building population has been made. The comparison between the maps of the fundamental periods of the area and of the buildings pointed out the probability of the buildings to experience resonance phenomena during seismic events. A "resonance index" (*RI*) has been defined to measure the sensitiveness of the buildings to this phenomenon, and a *RI* map of the area has been consequently drawn.

2 THE CASE-STUDY: FLORENCE

Florence is a city of about 353,000 inhabitants, with a larger number of people (supposed to almost achieve 700,000 units), living in the whole urban area. This work is focused on the vulnerability of the buildings population of the urban area of Florence, made by about 55,000 units. The area has been historically subjected to earthquakes, with local magnitude ML until 5, and maximum intensity equal to VIII MCS (Mercalli-Cancani Sieberg scale).

Despite the high density of population and the not negligible seismicity, the buildings of the area do not present any anti-seismic criteria, since most of them are ancient or – anyway – built before the seismic regulations have been introduced.

In this study each building is ranked by the Florence municipality database through few main parameters, i.e. the total height and the range of the construction year. This research does not include the area of the historical center (UNESCO protected area), since it is object of another survey. The current investigation, therefore, has been applied over about 40,000 buildings. The town lies in a valley (about 50 m a.s.l.) crossed by Arno river and surrounded by hills. Many investigations [12, 13] have been made on the soil of the Florence area, providing a detailed knowledge of the lithostratigraphic subsurface, of the lithoid substrate profile and of the geotechnical properties of its soils. In these years all the available drilling data have been collected and implemented into a GIS. Each data has been expressed in terms of unconformable boundary stratigraphic units [14] and unified soil classification system (USCS), and then transcribed into a geodatabase (UBSU).

The Florence basin had been developing since late pliocene thanks to the role played by the Fiesole faults on its NE border; these faults have no any sign of tectonic activity in the last 200ky. This geological evolution led to the filling of the basin by plio-pleistocene palustrine and alluvial deposits, followed by two sedimentary cycles related to the paleo-Arno river and the holocene geomorphic evolution, respectively (Fig. 1).

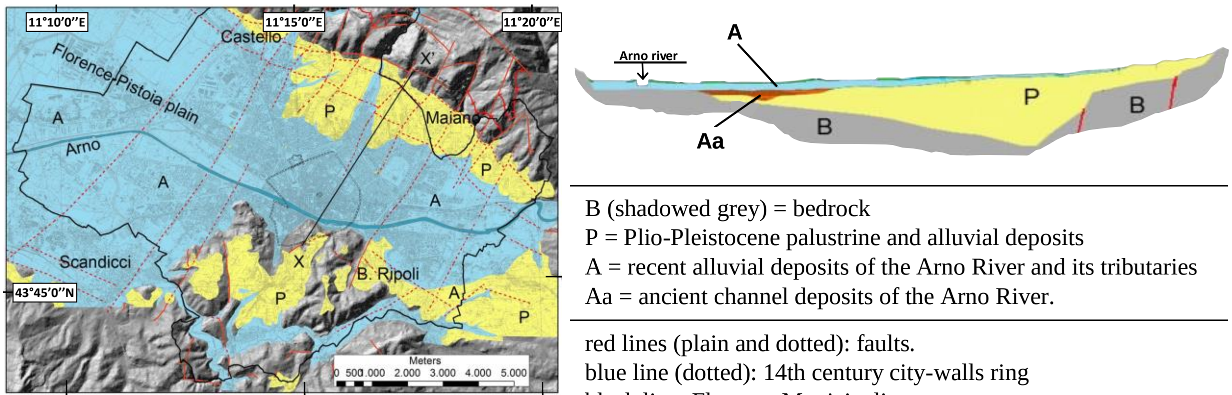

Figure 1: Geological sketch map and cross-section of the Florence area (from: [12]).

3 HAZARD MAPS OF THE SOIL

The seismic hazard of the area of Florence has been checked by performing an extensive experimental investigation [12], consisting in a 1,850 drillings, whose location has been shown in Figure 2, enhanced by 32 downhole proofs. For each test the maximum peak of the transfer function has been found, which has been combined with information provided by the downhole proofs about the stratigraphy of the area. A seismic-stratigraphic analysis has been performed, which provided the transfer function of the area. By integrating the transfer function found over a range of periods between 0,1s and 0,5s (the range of major interest as regards the buildings interaction), the amplification factor of each test has been found. Figure 2 shows the map of the amplification factor obtained after the experimental investigation [12]. In the map the values below the unity have not be evidenced, while the red area represents the points with the highest amplification.

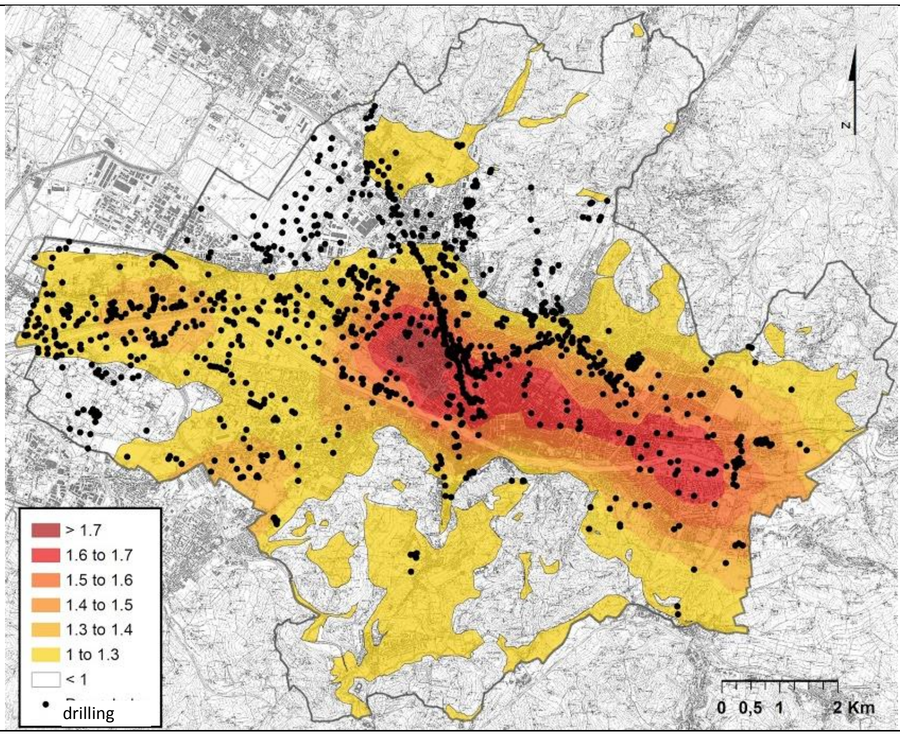

Figure 2: Map of the amplification factor (from: [10])

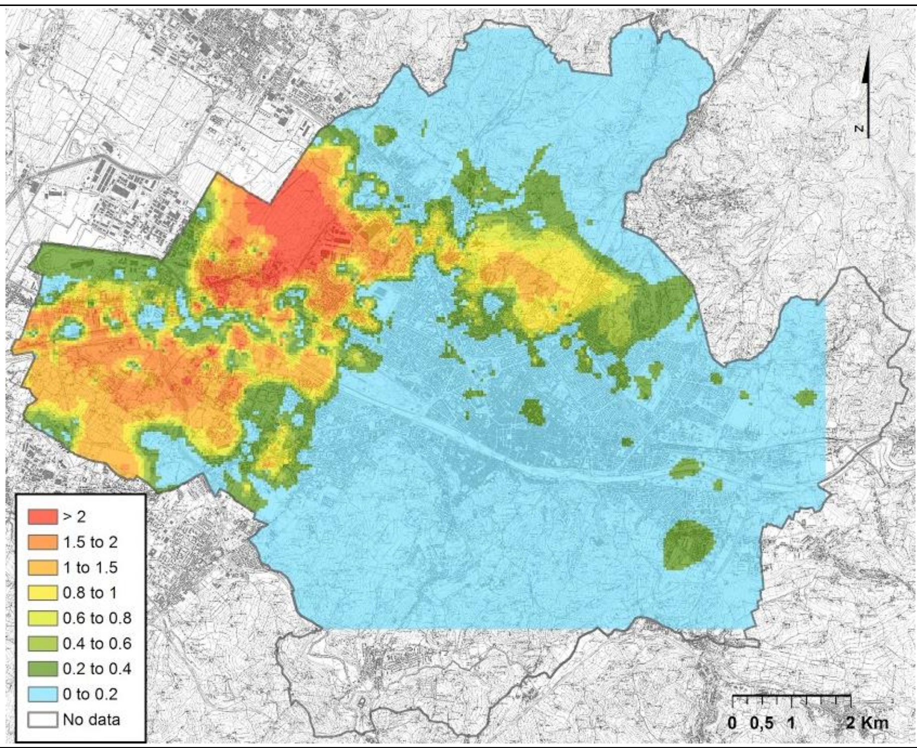

Figure 3: Map of the proper period (in seconds) of the soil.

The same experimental campaign has provided the map of the fundamental periods of the area, shown in Figure 3.

Even in this case the information provided by the two types of investigation have been integrated, i.e. the strathigraphies found through the drilling proofs have been represented by the mechanical properties and the shear velocity (v_s) values provided by the downhole investigations. For each drilling the filtering process through the soil columns has provided the fundamental frequency of the soil. The map of the fundamental periods of the soil cannot be considered as an hazard map; nevertheless it has a crucial role in the evaluation of the buildings vulnerability, since it affects the intensity of the seismic acceleration which each building will face at the occurring of an earthquake.

As can be observed in Fig. 3, only a relatively small area, represented in green, presents a period compatible to the buildings ones (0.20s - 0.60s). The amount of the seismic acceleration expectable by each building as an effect of its position can be related both to the relationship between the fundamental period of the building and the one of its foundation soil, and to the amplification factor. The maps shown in Figs 2 and 3, therefore, should be compared to the map of the fundamental period of the buildings, shown in the next section.

4 HAZARD MAPS OF THE BUILDINGS

4.1 The buildings population

The buildings population consists of about 55,000 unities. No distinctions are made about their use: residential, scholastic, commercial and industrial buildings have been considered as well. Each unity has been classified through an *ID*, and the parameters adopted in the database are the total height, the surface, the volume and the age range. Fig. 4 shows the classification of the buildings population of the entire city referred to the age of construction and to the total height.

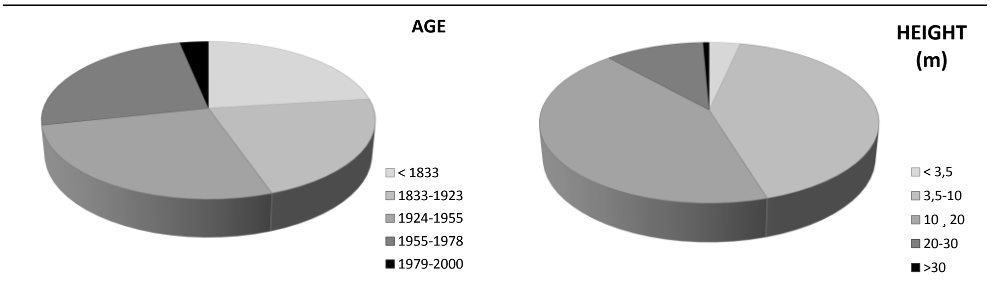

Figure 4: Database referred to the entire city of Florence.

In this work, a more detailed classification has been made on the residential buildings of the city, external to the most historical center - which is the object of another research - i.e. about 40000 buildings. In this database, the number of information has been upgraded, by the introduction of the type of structure. The buildings, indeed, have been classified after their main technology/material. The considered classes are: masonry (*M*), reinforced concrete (*RC*) and other structures (*OS*). The *OS* class comprehends buildings below 3.5m, and the structures not belonging to any of the previous classes. The buildings population of the area basically does not present any steel unities, which, anyway, would belong to the *NC* class. Fig. 5 shows the classification of this more specific database. The total height of the buildings, together with their material, leads to achieve an evaluation of their fundamental period of vibration. It should be noted that only few buildings exceed the height of 30 m. This evidence depends on an ancient law, passed in the XIII century, still in force, which topped the height of the civil buildings to 50 "florentine braccia" (about 30 m).

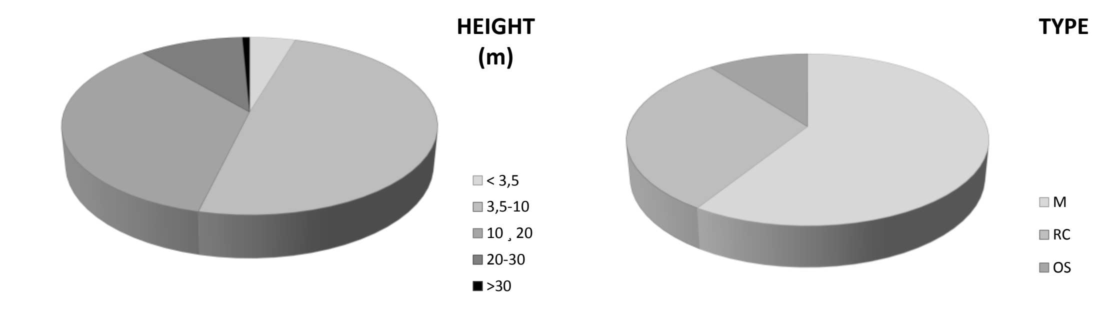

Figure 5: Upgraded database referred to the residential building of the city of Florence (with the exclusion of the historical center)

4.2 The dynamic characterization

The fundamental period (T_0) of the buildings population is a derivative information provided for the database, as a function of the total height of each building and its type class, as explained in the previous section. The vibrational properties of the buildings can be evaluated by performing an eigenvalue analysis on a mechanical model representing the structural behavior, or by calibrating approximate expressions, based on the observation of experimental data [15]. The empirical approach is the most largely adopted so far, and it is followed even by the main International Codes [16, 17, 18, 19]. In this work the simplified relationships proposed by the Italian [10] and European [20] technical Codes, which are identical each other, have been adopted:

masonry buildings: $$T_e = 0.050\ h^{0.75} \quad (1)$$

RC framed buildings: $$T_e = 0.075\ h^{0.75} \quad (2)$$

where h is the building eight (in meters). The provided period depends only on the total height of the building and on its constructive system (masonry vs framed structure). The reliability of (1) and (2) could be argued. It is well known, in fact, that the dynamic response of buildings depends on their stiffness, which experiences a considerable decrease during the seismic excitation; depending on the level of assumed damage, a different amount of stiffness - and consequently of the period - can be assumed [21]. In most cases, the period values provided by the most recent empirical expressions [15] [22] are larger than the ones found by following the Code approach. The most accurate expressions which evaluate the period of buildings, however, require a large number of information, like the amount of walls in the two main directions (wall systems), or the presence and quantity of infilled walls inside the structure (framed systems). Therefore, at the current time, the adopted Code expressions seem to be suitable to the work purpose, and compatible to the collected information.

The obtained T_0 values, however, should be considered as a lower limit for the buildings period. Fig. 6 shows the map of the Period found for the buildings population (the map has been slightly cut, to lead a larger size of the plot). In the same figure, the percentage of the period ranges of the database has been shown.

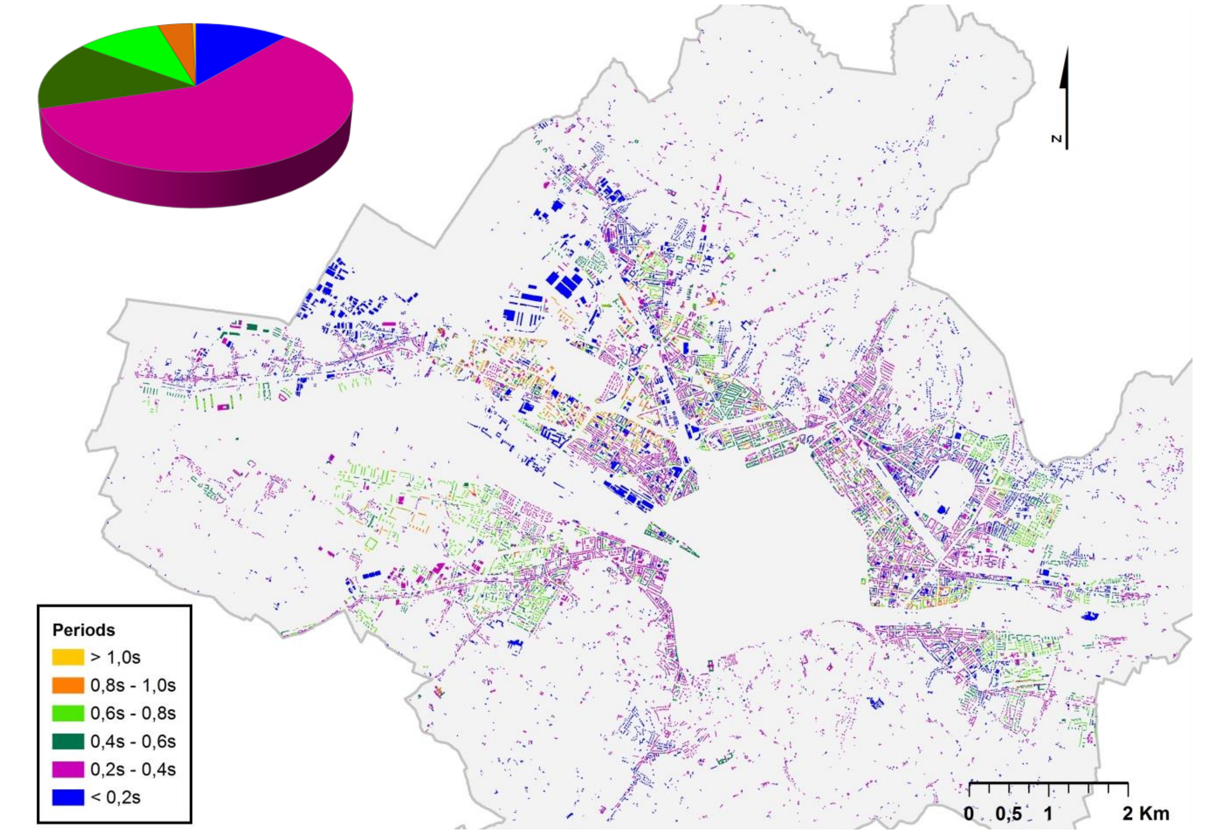

Figure 6. Map of the fundamental periods (T_0) of the buildings population.

4.3 The "resonance index" map

The maps representing the period distribution found for the buildings (Fig. 6) and for the soil (Fig. 3) have been compared, in order to find the "resonance map", which express how much the fundamental period of each building differs by the one of its foundation soil. The resonance index (*RI*) has been expressed as the ratio between the period of the building and the one of the soil (equation 3):

$$RI = T_{building} / T_{soil} \quad (3)$$

The obtained *RI* values have been classified in five different classes, listed in Table 1, which express the vulnerability of the buildings population regard the resonance phenomena. Since the periods found for the buildings can easily lengthen, due to the occurring of structural damage, the *RI* values over the unity are supposed to represent absence of resonance.

Table 1: Assumed ranges for the resonance index (RI)

RI range	Expected resonance phenomenon
0.0 - 0.3	No resonance
0.3 - 0.6	Low resonance probability
0.6 - 0.9	Possible resonance for moderate/strong earthquakes
0.9 – 1.1	Elastic resonance
> 1.1	No resonance

With reference to the introduced *RI* classification, the most "dangerous" ranges, i.e. the ones of the maximum resonance, are the one around the unity (0.9-1.1) and the one between 0.6 and 0.9, which represents the building with a fundamental period slightly lower than the one of their foundation soil. This last *RI* range can be dangerous at the occurring of moderate or strong earthquakes, which could induce a large increase of the elastic period of the buildings. The *RI* values below 0.3, instead, can be assumed to represent a low probability of resonance. The classification proposed in Tab. 1 should be assumed as a simplified instrument to evaluate the resonance problems; to achieve a more affordable classification, a more detailed description should be needed about the buildings, and more accurate expressions should be adopted to estimate the fundamental period of the buildings. Moreover, especially for isolated buildings, the two first periods, along the two main directions, should be considered, to avoid that the second vibrational mode could have resonance problems with the soil.

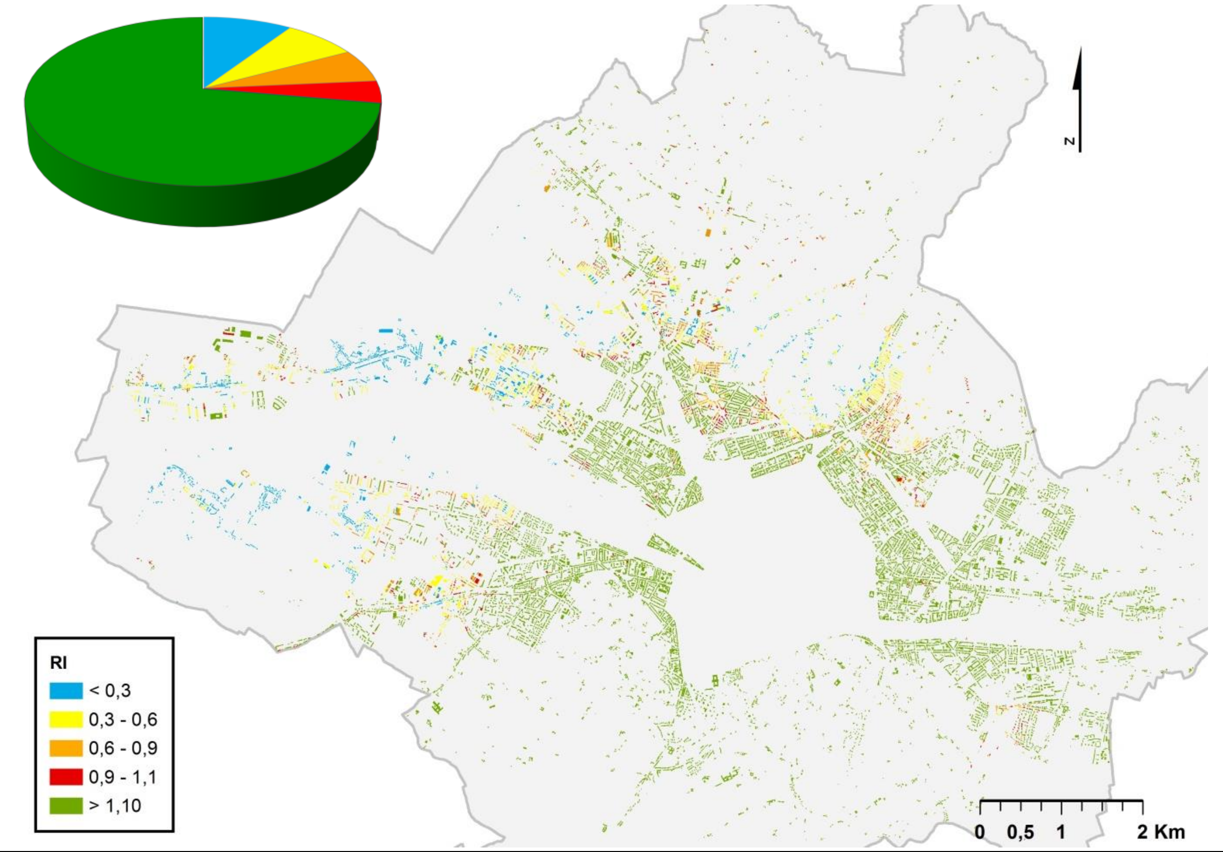

Figure 7. Resonance map.

5 CONCLUSIVE REMARKS

In this work an evaluation of the seismic vulnerability has been made on the area of Florence. To this purpose the dynamic properties both of the soil and of the buildings population of the urban area have been checked.

The hazard of the area has been achieved by performing an extensive experimental campaign over the area soil, consisting of 1,850 drillings and 32 downhole tests. The information provided by the two types of testing have been combined, returning a mapping of the fundamental frequency of the soil all over the Florence area. The same investigation has provided the distribution of the amplification factor over the selected area.

The existing database referred to the buildings population has been upgraded, by introducing further information about the constructive system and the materials of all buildings, and by determining their vibrational period by means of the conventional expressions provided by the Technical Codes. A vulnerability index, *RI*, has been introduced to express the probability of the buildings to experience resonance phenomena. *RI* has been defined as the ratio between the period of the buildings and the one of their foundation soil, and a classification has been introduced to evaluate the resonance probability of each building. A further map, expressing the *RI* classification, has been provided for the urban area of Florence.

The obtained *RI* map should be improved, by introducing further information about the buildings geometric and mechanical properties, and by evaluating the buildings fundamental periods through more accurate expressions.

ACKNOWLEDGMENTS

The financial support of the Cassa di Risparmio di Firenze through the project "SISMED - Modelli sperimentali di valutazione della vulnerabilità sismica di aree urbane complesse: il caso della città di Firenze" is gratefully acknowledged.

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