Archaeology and earthquakes in Siena (Italy). Preliminary results from the survey of the historical buildings in the Terzo di Città

Andrea Arrighetti[1], Valeria Razzante[2], Hélène Dessales[3]
[1] École Normale Supérieure – Université PSL (AOROC UMR 8546)
[2] Università degli Studi di Padova
[3] École Normale Supérieure – Université PSL (AOROC UMR 8546)

Abstract
The archaeoseismological study of a number of contexts affected by historical earthquakes provides a more complete understanding of the seismic impacts had on architecture, as well as restoration techniques used in the aftermath of these events. The PROTECT project is part of this line of research, funded by the Horizon 2020 research and innovation program of the European Union, and aims to apply, on an experimental basis, methods of archaeoseismological analysis to a portion of the historic center of Siena (Tuscany), in order to acquire further knowledge on the context of study from the point of view of seismic prevention. In this paper only the first steps of the project, begun in December 2021 and focused on the study of the Terzo di Città, are presented. The contribution focuses in particular on the proposal of a theoretical framework for the creation of a database, linked to a GIS platform, designed to answer precise chrono-typological queries.

Keywords
Archaeoseismology, archaeology of architecture, Siena, earthquakes, antiseismic techiques.

In the field of archaeology, in recent decades, increasing value has been placed on the concept of archaeoseismology. This is a term used to indicate the archaeological study of the effects of earthquakes on ancient buildings, being in a state of ruin or preserved (wholly or in part). The concept has seen significant use in the context of archaeological excavations. In contrast, there is a distinct difference when considering the archaeological study of historical buildings. The archaeology of architecture has attempted to develop general procedures in the analysis of individual case studies through a theoretical and methodological approach, thus integrating archaeology while at the same time safeguarding historic buildings from seismic effects. These architectural features constitute specific solutions employed in buildings to resist, mitigate or prevent the effects of earthquakes. Although these techniques were already used in the past, probably as a form of empirical experimentation applied in the formation of widespread aspects of seismic damage, there is still no clear understanding of their actual development and diffusion across specific geographic areas and chronological periods.

RA 1 | 2022, pagg. 14 | 31 - ISSN 1724-9686 (print) | ISSN 2465-2377 (online)

10.13128/RAR-13099 • https://oaj.fupress.net/index.php/ra

Fig. 1
The city of Siena, Google Earth, 2020.
Satellite image processed by E. Menicagli.
below
Geographical location of the city. Graphic E. Menicagli.

During the Middle Ages, elements such as these were frequently found in buildings but rarely referred to in written sources, thus complicating their study. Consequently, architectures themselves became the main source from which we now can understand the spread, as well as the historical and geographical development, of this building phenomenon. This constitutes an element of great interest, characterized by a dual-status: on the one hand, as a form of historical evidence associated with political, economic, and social dynamics that affected the context of study in a given historical period. On the other, as a technical-scientific profile originating from the documentation, characterization, and assessment of these elements because of future restoration or intervention projects compatible with ancient structures. The PROTECT project (www.protect.altervista.org), funded through the Horizon 2020 research and innovation program of the European Union, has been structured with a view to this idea[1]. The project aims to apply, on an experimental basis, the methods of archaeoseismological analysis to the architectural structures in a portion

of the historic center of Siena (Tuscany), to establish new procedures for damage documentation and post-seismic repair techniques of historical buildings. The analysis of this context will focus on edifices from the Late Middle Ages in view of the fact that during this historical period, and specifically in the 15th century, a significant seismic event occurred in Siena (fig. 1), with an estimated intensity of VII. The project is based on a highly interdisciplinary methodological approach, which allows complete analysis and documentation of the identified cases. This is followed by a series of technical, scientific and historical-archaeological results.
What is presented here is the first step toward analyzing the context of the study. The first survey results of those features that could be defined as post-seismic conservation elements, in particular, are visible on the external surfaces of historical architectures present in the center of Siena in an area known as Terzo di Città. As illustrated in detail below, the autoptic analysis of the buildings was carried out through an expeditious archaeological reading of the buildings' street fronts. That was followed by recording elements of interest and their registration in a GIS platform. The possibility of documenting and geolocating these elements, and comparing them with a series of detailed cartographic sources, has permitted the first considerations on the use of these techniques in specific areas, according to the characteristics of soil and architecture.

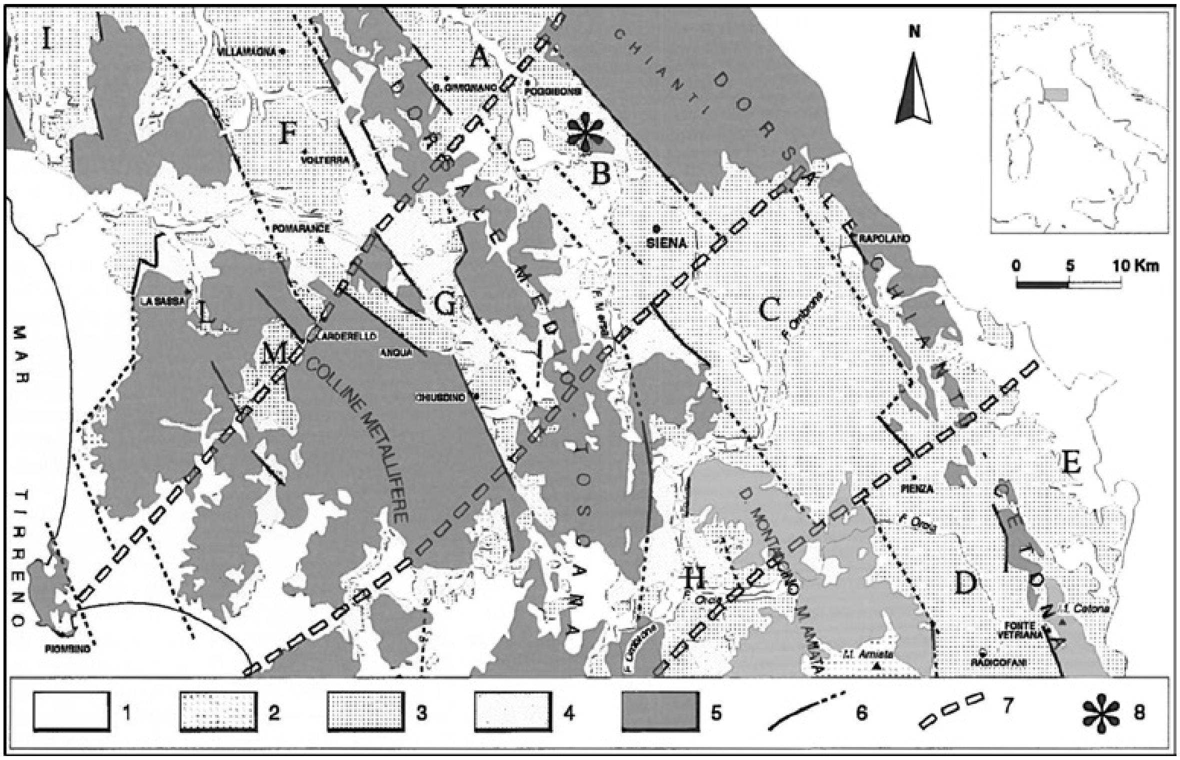
opposite page
above
Fig. 2
Representation of the Graben boundary faults (6) and the transversal deformation faults (7).
(Bossio et al., 2002).
below
Fig. 3
Diagram of the earthquakes recorded in the Sienese territory between the 14th and 21st centuries.
(Locati et al., 2022).

A historical-seismological overview of Siena: an assessment of earthquakes between the Middle Ages and the Modern Age

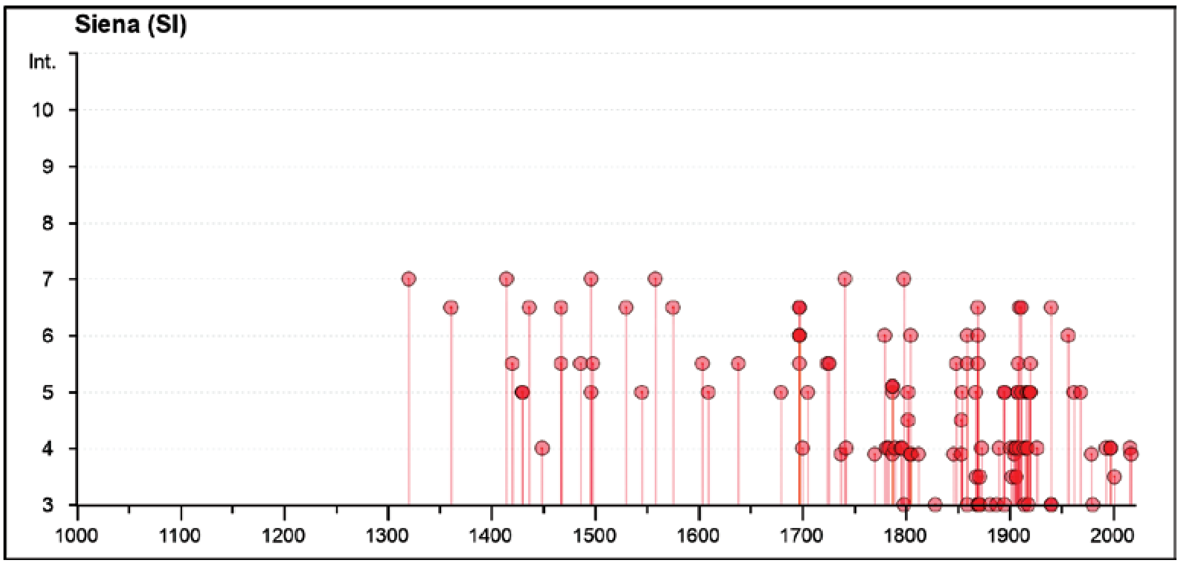
Examining the main tectonic lines of Tuscany (fig. 2), the peculiar position of Siena within an area circumscribed by two deformation faults, namely the Monteriggioni threshold to the north and the Arbia line to the south, cannot be overlooked (Benucci, 1986, p. 281). Among the elements of the Sienese subsurface distributed in the Terzo di Città and linked to seismic activity, it is possible to note the Duomo-San Domenico fault. This last belongs to a group of faults that cross the lower part of the district of Fontebranda, reaching the area below the bell tower of the church of San Domenico. As reported in various chronicles and documentary sources dating to the 18th century, this part of the city appears to be one of the two that suffered the most damage during the May 1798 earthquake. One is the most notorious in the history of Siena (Gennari, 2005): "the coinciding of the path of the fault and the distribution of instabilities speaks clearly in favor of its reactivation in historical times" (Bartolomei, 2009, p. 33).
Considering local or regional earthquakes that have historically affected the Sienese territory, the city would have suffered seismic damage with a maximum intensity equal to the VII degree of the MCS scale. As Castelli (2009, 2016) has argued on several occasions, two main types of seismic events would have taken place over the centuries:

1. Earthquake swarms: characterized by a prolonged sequence (weeks or months) of numerous low or moderate energy tremors.
2. Isolated seismic episodes: earthquakes with a higher emission of energy that can be associated, in the days immediately after the seism, to lower intensity tremors.

Proceeding backwards with the support of the seismic catalogues[2], it is possible to reconstruct the historical course of seismicity in many Italian localities. As far as the Sienese context is concerned, the following is a synthesis of the earthquakes grouped by century and known thanks to a thorough review of archival documents (fig. 3).



I
A
B
C
D
E
F
G
H
L
M
N
0 5 10 Km
VILLAMAGNA
POGGIBONSI
VOLTERRA
POMARANCE
SIENA
RAPOLANO
LA SASSA
LARDERELLO
ANQUA
CHIUSDINO
CHIANTI
COLLINE METALLIFERE
MAR TIRRENO
PIOMBINO
PIENZA
RADICOFANI
1
2
3
4
5
6
7
8



Siena (SI)
Int.
10
9
8
7
6
5
4
3
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000

• 14th century: the first historic evidence referring to earthquakes in the territory of Siena dates back to the beginning of this century. Unfortunately, due to gaps in the archival sources, the historical-seismological profile of this phase still appears quite obscure and poorly defined. Nevertheless, thanks to studies combined with the seismic catalogues, it has been possible to rediscover and provide clearer knowledge concerning some seismic events. The first recorded earthquake dates to 1320: an important contribution was provided by Mario Baratta, one of the Italian pioneers in the historical study of seismic phenomena. Having gathered evidence from various late 19th century authors, Baratta notes that strong earthquakes occurred between October and December of 1320, with a danger peak reached on the 16th of December. Among the direct sources par excellence is the anonymous Sienese chronicler: «a ogni ora della notte sonava la champana del Duomo a martello per li grandi tremuoti che venivano [...] molta giente moriva sotto le chase, le quali chascavano per li detti tremuoti. E molta giente andoro ad abitare a chanpo, e tutto el prato della porta a Camolia era pieno di padiglioni»[3]. (Castelli et al., 1996, p. 1). Baratta noted another seismic event on the 27th of December 1361, for which a review of the sources would lead to hypothesize a degree of VII MCS intensity, considering the widespread and severe damage caused to houses (Castelli et al., 1996, p. 51).
• 15th century: the seism that took place on the 7th of August 1414, felt both in Siena and Florence, with the epicenter in the area of the Colline Metallifere to the west of Siena, was the first recorded at the beginning of the century (Guidoboni et al., 2018, p. 577). The degree of uncertainty that shrouds the historical sources related to earthquakes which occurred up to the middle of the 15th century, does not allow scholars to distinguish with certainty the real extent of the damage related to every individual event. However, details on the earthquake of the 3rd of September 1467 constitute an exception as they provide an articulated picture of the material effects that the event caused in the city of Siena. The documents referable to this earthquake, both textual and iconographic[4], have allowed to attribute to the earthquake swarm an intensity equal to the VI-VII degree of the Mercalli scale (Castelli et al., 1996, p. 85-87). Moving forward in the century, further earthquakes are documented, including that of the 30th of September 1486 (Castelli et al., 1996, p. 92), as well as the two earthquakes of June the 4th, 1496, and April the 11th, 1498, of which the chronicle of a Sienese contemporary minutely describes the effects on important ecclesiastic buildings situated in the city. In 1496 the Basilica of San Francesco recorded new lesions and the widening of pre-existing ones, the detachment of a ceiling vault from the walls and the overturning of a side wall (Camassi et al., 2011, p. 10) while in 1498 the same chronicler noted the presence of lesions inside the Duomo (i.e. the city Cathedral) along with the fall of a keystone ashlar near the organ (Camassi et al., 2011, p. 13).
• 16th century: the first earthquake of this century occurred on the 11th of November, 1530. The main written sources are several Sienese chronicles and a Bolognese historical compilation which list damages in the church of San Domenico, including the rotation of the bell tower steeple and the detachment of portions of the decorative apparatus. The silence of the Florentine chroniclers suggests the localization of the epicenter south of Siena (Camassi et al., 2011, p. 22). The two earthquakes of the 27th of November, 1545 (Camassi et al., 2011, p. 25) and the 14th of June, 1575 (Camassi et al., 2011, p. 44) can be considered minor affairs. The earthquake swarm of the 13th of April, 1558, on the other hand, led to damages on an entirely different scale: from recent research

carried out by the Istituto Nazionale di Geofisica e Vulcanologia and the Dipartimento della Protezione Civile, the localization of the epicenter has been hypothesized to be in Val d'Ambra. Besides the accurate testimonies of the Sienese nun Girolama Caterina Bocciardi and the Florentine priest Agostino Lapini, for the historical-seismological reconstruction of the events, a series of letters sent to Cosimo I de' Medici from the south-eastern part of Tuscany proved to be of fundamental importance, describing the correlation between damages and repair works carried out after the 13th of April (Castelli, 2004).

• 17th century: as for the earthquakes that occurred in 1603, 1609 and 1638, either the description in the sources is contradictory or the magnitude of the events themselves was so insignificant that they remained in the background compared to other narratives of greater interest[5]. More favorable outcomes for historical and seismological research were obtained from further in-depth work on the seism of the 24th of March, 1679. This was felt in the localities of Montepulciano and Pienza and the tremor was also reported in Siena with «great fear», according to the contemporary chronicler Ghiselli (Camassi et al., 2011, p. 89). The most well-documented earthquake, also for the considerable effects it had on the anthropic context, took place in 1697, in the form of a seismic period that lasted from September to December. The tremors seriously damaged the city center; many buildings suffered lesions or wall detachments, while the falling of cornices, chimneys and masonry was reported throughout the city[6] (Guidoboni et al., 2018).

• 18th century: the earthquakes of 1700 (Camassi et al., 2011, p. 124) and 1704 (Molin et al. 2008, p. 64) were felt by the Sienese population but did not affect buildings across the city. The following earthquakes of 1726 and 1727 reached an intensity of the VI degree on the MCS scale: the first earthquake, which occurred on the 11th of December, caused minor damage in the city with lesions on some buildings, including the convent of the Discalced Carmelite Fathers (Guidoboni et al., 2018); the second took place on the 19th of April, in the form of an earthquake swarm (Camassi et al., 2011, p. 149). Leaving aside the seismic event of June 1737, also barely perceived (Guidoboni et al., 2018), the episode of 1741 was of greater consequence. The latter, in fact, caused the sliding of roof covers and widespread lesions along the ceilings of various structures, including the Duomo, San Domenico and the convent of the nuns of San Girolamo. In view of the damage threshold at the time, an intensity of the VII degree MCS has been hypothesized (Castelli et al., 1996). Almost forty years after the last major episode, the 26th of June 1779, a number of tremors damaged the convent of Santa Maria dei Servi (Camassi et al., 2011, p. 232). An important seismic sequence was recorded at the beginning of the following decade. If tradition is to be believed, the main event would have taken place on the 3rd of January, 1780, while recent research has instead postdated the entire sequence to the following year. Furthermore, through a survey of the rich documentation from the Abbazia of Monte Oliveto Maggiore together with the State Archives in Siena, a clear picture of the damages recorded between the area of the Crete Senesi and the city of Siena has been traced (Camassi et al., 2011, p. 246). On the 26th of May, 1798, a strong earthquake of magnitude[7] 4.8 struck Siena, causing damage within a 10 km radius of the city and arousing dismay in most of central-northern Italy. The effects on the natural and anthropic contexts were significant, with structural damage recorded on religious and civil buildings. The poorer neighborhoods such as Fontebranda and Porta Ovile, due to the structural fragility of the walls made with low quality binders and problems related to foundation soils, suffered more from the impact of the earthquake (Guidoboni et al., 2018). For these reasons, the earthquake of the 26th of May represents an exceptional event because, despite the medium-low seismic hazard attributable to it, it was precisely the high vulnerability of the architectural structures that determined an exponential growth in the number of damages recorded in the urban center (Castelli, 2016).

Analysis strategies for restoration interventions with preventive functions

Before proceeding with the discussion of data garnered during survey, it is important to formulate some clarifications with regard to operational methods adopted and the motivations behind the choice of the study context.

Beginning with this last consideration, the choice to concentrate the analysis on the Terzo di Città stems from the fact that, according to historical sources reported in seismological catalogues, the greatest number of effects on architecture correlated to the earliest earthquakes (i.e. those that took place in the 14th and 15th centuries) were to be found in this part of the city. Obviously this evidence is closely linked to a series of factors such as the composition of the subsoil, the characteristics of the earthquakes, the state of conservation as well as the building types of the architecture, all of which is of great interest in the reconstruction of the dynamics triggered by seisms in different periods. The other important premise regards on-site work. Given the rather extensive size of the area, featuring a wealth of well-preserved and stratigraphically readable Medieval architecture, the recording of evidence was based on the autoptic analysis of restoration interventions with preventive functions, correlating these last to the constructive features of buildings. Compatibly with the type of structures documented, tools and methods characteristic of the archaeology of architecture and the more recent discipline of archaeoseismology have been chosen, suitable for the identification and typological characterization of these interventions (Arrighetti, 2015). Once evidence was documented through survey drawings, field datasheets and photographs, the next step involved the registration and geolocalization of all data acquired on a GIS platform database[8]. As for evidence documentation, it was essential from the beginning, to establish the questions to be addressed to the selected subjects. Regarding the restoration interventions with preventive functions, the setting up of a system of datasheets, edited on the GIS under form of attribute, proved rather complex due to the range of typologies, further divided into sub-categories according to materials and functions carried out in relation to a seismic event (prevention, restoration or containment) (Arrighetti, 2015). Therefore, in this case, the categories were chosen by way of comparison with the anti-seismic datasheet intervention features elaborated by the Archaeology of Buildings Lab of the University of Siena (Arrighetti, 2018)[9], used during the field recording phase and subsequently optimized to be logged into the GIS platform. Initially these datasheets were conceived for a detailed study of a single architectural complex. Given the extensive nature of the survey, the principle used to document the intervention features had to be readjusted to a macro-scale level. In this sense, having to submit the entire system of elevations facing out on streets and alleys of the Terzo di Città to survey observations, it was of fundamental importance to select *a priori* only a few categories of intervention, and for these to choose only some fields of reference for their precise description. Excluding intra-mural systems[10], which can be traced only through the archeological study of a single building, and solutions

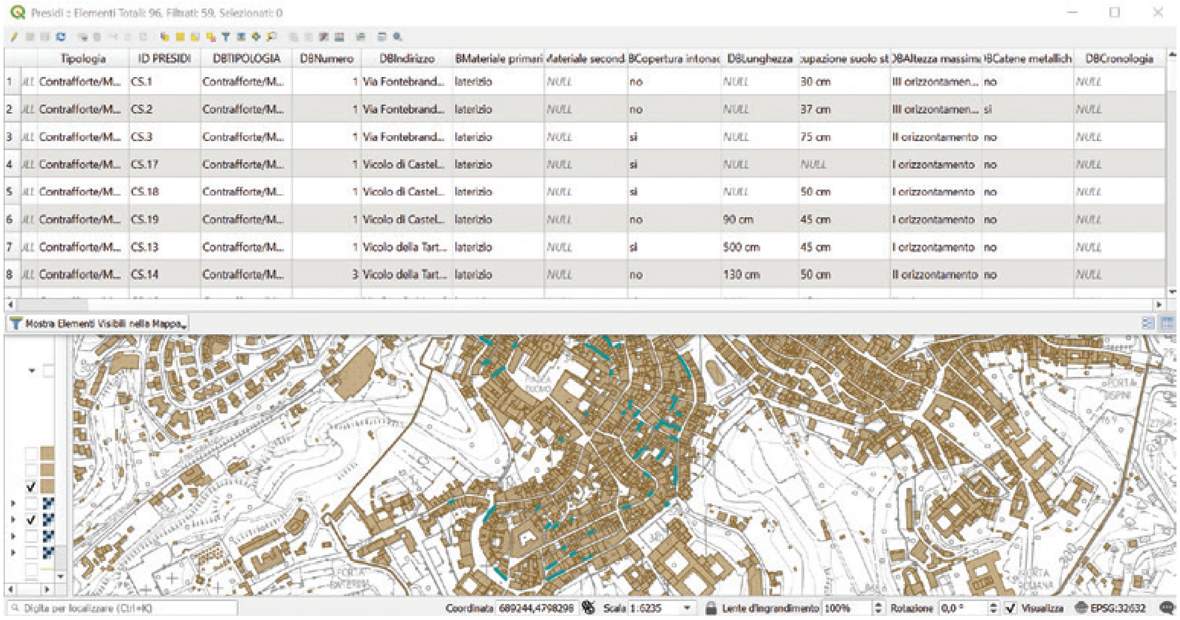


Fig. 4
Table with elements characterizing buttresses and scarped walls.
Cartography: GEOscopio WMS - Regione Toscana.
Data processing: V. Razzante.

such as metal or stone chains, quite common, but often not visible in the masonry due to coatings and coverings, it was decided to focus the research on the following categories: buttresses and scarp walls, relieving arches, buttress arches, wooden beams and metal tie-rods. Together with the characterization parameters for each of these restoration interventions, of paramount importance for temporal and geographical identification (such as the ID, street address and chronology), were associated other fields that synthetically describe structural features as well as qualitative and quantitative aspects (fig. 4). For the metal tie-rods and wooden beams, for example, it was necessary to introduce two other fields describing the materials employed. For the relieving arches the same information listing the characterization parameters and materials employed is repeated, while there is a first entry for the recording of the number of arches and a second with the maximum height in relation to the floor of the building; the last question was reserved for the possible association with metal chains. In the datasheets for the buttressing arches, the characterization parameters, material and quantitative information are repeated while a section was added to describe the presence or absence of possible surface coverings. Lastly, given the greater complexity of buttresses and scarp walls, it was decided, in the case of this specific group, to collect all the analysis parameters illustrated so far, increasing the information with two additional sections: the length compared to the supporting wall surface and the maximum length of occupation of the road surface.

Fieldwork: the urban survey of the Terzo di Città

The application of archaeoseismology not just to a single building but to an entire historic center can be considered akin to a model of light archaeology, adapted to an urban scale (Arrighetti, 2015). Such an approach requires that the territory be explored through non-invasive archaeological methods such as those employed in landscape

opposite page
Fig. 5
Example of a wooden beam set inside wall masonry.
Photo: A. Arrighetti.
p. 24
Fig. 6
Example of contrast arches.
Photo: A. Arrighetti.
p. 25
Fig. 7
Example of buttress inserted above wall.
Photo: V. Razzante.

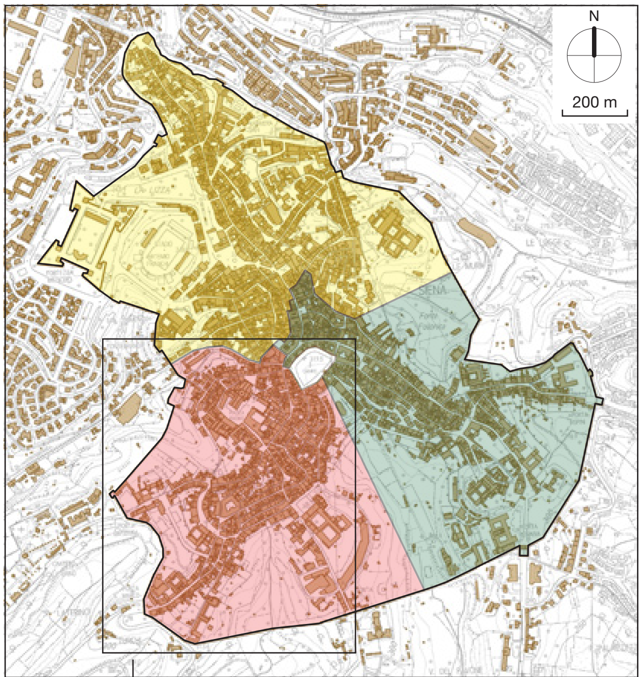
archaeology and the archaeology of architecture, supplemented by stratigraphic observations carried out only on a select number of sites (Nucciotti, Vannini, 2020). Starting from these methodological premises and with the aim to materially identify the archaeological and seismic traces in the city of Siena, a vast and complex area from both an historical and architectural standpoint, it was decided to prefer for a survey of the urban context within the walls and limited to the area known as Terzo di Città. Approaching a macro-scale work, it was important to establish the level of detail, which consequently led to a district-type of research. The following is a critical review of the data collected from the urban survey and recording of the four categories of restoration interventions with preventive functions, documented in the elevations of the buildings analyzed along the roads of the Terzo di Città. Among the various roles played within buildings, metal tie-rods and wooden beams (fig. 5) make it possible to counteract anomalous thrusts that occur in vaulted structures. Specifically, the introduction of metal tie-rods increases the degree of connectivity between the walls and contrasts potential overturning phenomena[11]. In order to join these elements to the wall face, key heads are used, designed according to the type of architectural element to which they are connected (wall, column or pillar) (MIBAC, 2011). Four types of interventions were identified during the survey that can be included in this first group. The process of recording tie-rods and beams followed a more elementary, schematic approach, also due to the low number of elements distributed in the area of interest. As for chronologies, it was possible to advance some hypotheses of relative chronology[12] for two of the recorded elements. The first case concerns the metal tie-rods and wooden beams in Via Fusari, for which it is hypothesized that they were put in place after 1408; the construction of the brick overpass which runs over the same street, commissioned by the Opera del Duomo, dates to this period (Gabbrielli, 2010, p. 277). The second dated element consists in the installment of wooden beams and buttressing arches in Vicolo di Vallepiatta. The *Statuto dei Viari*[13] refers to a number of works that between 1290 and 1298 involved Via del Costone, Via and Vicolo di Vallepiatta and Via del Pozzo (Balestracci, Piccinni, 1977, p. 48). By correlating this information with *in situ* observations, it would be possible to chronologically ascribe both intervention features to a temporal phase after 1290.
The buttress arches (fig. 6) can be defined as masonry or brick elements, the use of which is functional to counteract overturning mechanisms (Arrighetti, 2015, p. 78). In the past these elements were widely used as structural supports between two buildings. Once put in place they could undergo further changes and from a single arch it was possible to proceed with the construction of entire overpasses: in this way, while counteracting the horizontal thrusts caused by earthquakes, it was also possible to enlarge living areas inside the buildings (Ferrigni et al., 2005, p. 304). In the Sienese context of the Terzo di Città such interventions appear to be the most widespread, confirmed during the field survey that allowed the documentation of a total of seventeen. Among the records identified, once again interrogated on GIS through qualitative and quantitative characterization parameter datasheets, only in two cases was it possible to advance a proposal of relative chronology: the already cited case of Vicolo di Vallepiatta, in association with wooden beams which had been dated to after 1290, and the walkway built near Chiasso del Bargello which is considered as subsequent to the enlargement of the road section that occurred in 1328 (Balestracci, Piccinni, 1977, pp. 48-49).
A narrow passageway inside a building can determine a break in its linear continuity.


14

If subjected to specific stresses, the arches are able to redistribute the forces generated toward the floor plane (Ferrigni et al., 2005, p. 196). Arches with this particular function can be defined as relieving arches and, by reducing the weight of the overlying loads, fulfill the role of protective curtain for the structures below (Arrighetti, 2015, p. 78). The survey conducted in the Terzo di Città led to the recording of eight interventions pertaining to this category, despite the general difficulty of tracing them in cases where, over time, building facades have been covered by mortar or plaster coating. Two further aspects have been highlighted through direct field analysis and data recording in the *ad hoc* datasheets. The first concerns the construction technique in the form of bricks arranged in a radial pattern and connected by thick mortar joints; the second involves the presence of metal chains alongside relieving arches, understood to be additional elements used to contain and stabilize the masonry.
Buttresses and spurs (fig. 7) ideally create a truncated-pyramidal geometry that absorbs horizontal seismic actions. Referring to the aforementioned 'virtual arch model', these structures counteract the thrust that the angular semi-arches exert on the corners of the building. The increased use and spread of these elements in the pre-Modern Age can be attributed to the technical simplicity of their construction and the availability of material. For Siena, the building of buttresses and scarp walls provide the opportunity to observe concrete examples of how an entire group of adjacent buildings can respond to telluric stresses through compression and distention. Indeed the city responded to the presence of natural slopes with the spread of building nuclei that, when subjected to seismic stress, perform an "containment dam effect" (Cangi, 2018). In relation to the survey activities carried out in the Terzo di Città, 67 units were documented as buttresses and scarp walls. Also in this case, the primary recording parameters were accompanied by observations on the materials employed. While most of the structures are made of brick, only in four buttresses the alternation of sandstone and locally quarried cavernous limestone was used. As far as dimensional aspects are concerned, if the longitudinal development and occupation of the road surface were measured directly from the ground, the maximum height is related to the alignments of the buildings examined. Lastly, regarding the more strictly structural aspects, in fourteen cases it was noted that buttresses in elevation are associated with metal chains that, as Cangi (2018) points out, might be interpreted as additional containment elements.

opposite page
above
Fig. 8
Cartography of the historical center. Highlighted the *Terzi of Siena*.
Cartography: GEOscopio WMS - Regione Toscana.
Graphic: E. Menicagli.
below
Fig. 9
GIS-based framing of the Terzo di Città.
Cartography: GEOscopio WMS - Regione Toscana.
Data processing: V. Razzante.

Cartographic and typological restitution of the archaeosesimological evidence
After completing the survey of evidence related to the seismic history of Siena and the recording of restoration interventions with preventive functions, the data obtained was organized and returned in the form of digital cartography (figg. 8-9) through the use of QGIS software. In application terms, an initial response of content structuring and drafting the datasheet was followed by the graphic and geographical restitution of this information. The data obtained from the field survey was then interpolated in the software through a join operation of the field "ID presidio", specific for each intervention and present both in the vector file drawn in GIS and the datasheets of the four categories of interventions, separately pre-compiled in an Excel file.
On a cartographic basis, the possibility of mapping and returning the evidence which emerged from the survey permitted a series of reflections to be carried out, closely correlated to historical-architectural data as well as to the characteristics of the sub-



Terzo di Città

Terzo di Camollia

Terzo di San Martino

Enlarged area

Architectural features

- Wooden chains
- Buttresses
- Discharging arches
- Counter-arches

soil and layout of the city center. The presence of specific areas in which these features are used is evident, probably referable to areas where the effects of earthquakes or other structural issues were especially amplified, as the area behind the Duomo or the neighborhood of Castelvecchio. Another point to be taken into consideration in relation to the evidence which emerged during this research is the probable precariousness of the state of conservation of some of the architecture, that has certainly contributed to the formation of instabilities (both of natural and structural origin), conditioning the choice in the use of certain protective expedients for the structures involved. Moreover, it is interesting how the use of certain techniques to the detriment of others allows us to understand the probable correspondence between a post-seismic intervention and an earthquake, thus allowing the formulation of some hypotheses on the use of specific expedients as chronological reference markers. In this sense, from the macro-area reading of the data, an integrated use of the buttress arches and wooden tie-rods seems to be visible in the area near the Duomo, with an almost total absence of wood in the external wall surfaces throughout all the other parts of the Terzo di Città. The buttresses, on the other hand, show an almost homogenous distribution in the whole area but represent, for the purpose of this work, an element that is of little use for chronological characterization. Conversely, an element of significant interest is the extensive use of buttressing arches, which apparently saw greater employment in the area near the city center. Given their constructional characteristics, these can be classified into two macro-types (fig. 10): simple arches, characterized by a rounded or lowered arch made with vertically set bricks and an upper wall surface of 10-15 rows of bricks with no further decorative apparatus, and complex arches composed of rounded or lowered arches with a well characterized decorative apparatus, sometimes featuring a small cover in the upper portion. In both cases there are sub-variants based on the size of the section of the arch, which could in some cases present a passage located above, useful for connecting rooms between buildings, or on the curvatures of the intrados, if rounded or lowered. From a chronological point of view there is little information that permits a periodization of the identified elements. Only for the buttress arches some dates are available linked to documents produced in the wake of the earthquake of 1798, allowing us to identify the complex arch type as contemporary to the reconstructions that took place following the late 18th century earthquake. On the contrary, the use of the simple form in this type of intervention appears to be backdated.

opposite page
Fig. 10
The two types of contrast arches present in the Terzo di Città. Photo: A. Attighetti.

The archaeoseismological project for Siena between premises and future developments

The present contribution constitutes a first result of an extensive archaeoseismological analysis carried out on the Terzo di Città area in the historic center of Siena and aimed at recording, documenting and characterizing elements that could be assimilated with post-seismic prevention. Clearly, this represents only a first step in the analysis of the context and its understanding at an archaeoseismological level. The following stages will involve an in-depth historical analysis of the seismicity of Siena through archival research centered on the chronological periods referable to the currently known major earthquakes, and a definition of areas of interest in which to carry out more detailed archaeological readings of entire road fronts. The final objective is to create a protocol of archaeoseismological reading for a city center, or a portion of it, that can also be employed in other Italian and European urban realities with the aim towards better understanding, safeguarding and preserving cultural heritage from seismic risk.

Aknowledgments
The present contribution stems from the rielaboration in the PROTECT project of a BA thesis discussed during the academic year 2018/2019 by Dr. Valeria Razzante at the University of Siena, titled: "Proposta per una gestione informatizzata delle evidenze archeosismologiche nelle architetture del centro storico di Siena". In particular, paragraphs 2, 3 and 4 of the present article can be referred to Dr. Razzante. The Introduction and the other paragraphs can be referred to the other authors

Bibliography

Arrighetti A. 2015, *L'archeosismologia in architettura. Per un manuale*, Firenze University Press, Firenze.
Arrighetti A. 2018, *Archeosismologia in architettura. Nuove prospettive di un dialogo multidisciplinare*, «Archeologia dell'Architettura», XXIII, pp. 11-17.
Balestracci D., Piccinni G. 1977, *Siena nel Trecento. Assetto urbano e strutture edilizie*, Clusf, Firenze.
Bartolomei A. 2009, *Valutazione degli spessori dei terreni di riporto o colluviali nel sottosuolo dell'abitato di Siena da misure di rumore sismico ambientale*, Università degli Studi di Siena, tesi di laurea, non pubblicato.
Benucci V. 1986, *Siena città dei terremoti? Rispondono la storia, la letteratura e la scienza*, TAP grafiche, Poggibonsi.
Camassi R. et al. 2011, *Materiali per un catalogo dei terremoti italiani: eventi sconosciuti, rivalutati o riscoperti*, «Quaderni di Geofisica», n. 96, pp. 4-387.
Cangi G. 2018, *Approccio metodologico all'analisi sismica delle strutture murarie in ambito archeologico e monumentale: dall'osservazione alla modellazione*, «Archeologia dell'Architettura», XXIII, pp.63-74.
Castelli V. et al. 1996, *I terremoti toscani dall'anno 1000 al 1880: schede sintetiche*, GNDT, Rapporto interno, Macerata-Milano, p. 314.
Castelli V. 2004, *Hidden behind the Ranges. How the 13 April 1558 "Sienese" Earthquake Was Put in Its Place*, «Seismological Research Letters», vol. 75, n. 3, pp. 342-351.
Castelli V. 2009, *Ricordarsi del terremoto. Tracce senesi di una "memoria sismica collettiva"*, «Bullettino Senese di Storia Patria», CXVI, p. 316.
Castelli V. 2016, *I terremoti nella STORIA: 26 maggio 1798, un terremoto di fine secolo XVIII a Siena*, INGV terremoti, <https://ingvterremoti.com/2016/05/26/i-terremoti-nella-storia-26-maggio-1798-un-terremoto-di-fine-secolo-xviii-a-siena/>.
Ferrigni F. et al. 2005, *Ancient buildings and earthquakes. The local seismic culture approach: principles, methods, potentialities*, Edipuglia, Bari.
Gabbrielli F. 2010, *Siena medievale. L'architettura civile*, Protagon Editori Toscani, Siena.
Gennari M. 2005, *L'orribil scossa della vigilia di Pentecoste, Siena e il terremoto del 1798*, Il Leccio, Monteriggioni.
Guidoboni E. et al. 2018, *CFTI5Med, Catalogo dei Forti Terremoti in Italia (461 a.C.-1997) e nell'area Mediterranea (760 a.C.-1500)*. Istituto Nazionale di Geofisica e Vulcanologia (INGV), <doi: https://doi.org/10.6092/ingv.it-cfti5>.
MIBAC 2011, *Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale: allineamento alle nuove Norme tecniche per le costruzioni*, Gangemi, Roma.
Nucciotti M., Vannini G. 2020, *Light archaeology and territorial analysis: experiences and perspectives of the Florentine medievalist school*, «Archaeologia Polona», vol. 50, pp. 149-169.

Rovida A. et al. 2017, *ASMI, Archivio Storico Macrosismico Italiano. Istituto Nazionale di Geofisica e Vulcanologia (INGV)*, <https://doi.org/10.13127/asmi>.
Szabó T. 1975, *La rete stradale del contado di Siena. Legislazione statutaria e amministrazione comunale nel Duecento*, Mélanges de l'Ecole française de Rome. Moyen-Age, Temps modernes, tome 87, n. 1, pp. 141-186, <https://doi.org/10.3406/mefr.1975.2325>.

Note

[1] The project was funded through the European Union Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No. 101018762.
[2] Considered among the main 'indirect tools' for archaeological use in matters of earthquakes, the seismic catalogues, namely databanks structured in GIS form, integrate cartographic data with historical and detailed seismological information for each recorded earthquake that took place in the past (Arrighetti, 2015).
[3] English translation: "at every hour of the night the bell of the Duomo rang like a hammer because of the great tremors that occurred [...] many people lay dead under the houses that collapsed because of those same tremors. And many people went to live in the Campo, and the whole field of Porta Camollia was filled with pavilions"
[4] Among the best known is a small book cover of Biccherna (the painted cover of the registries of the Biccherna, the chancellery of finance in the city) dated to 1467 and a fresco from the Palazzo Pubblico of Viterbo.
[5] For details on the seisms of 1609 and 1638 see: Camassi et al., 2011. Concerning the earthquake of 1603 the main sources of the time only note a number of earthquake tremors (Rovida et al., 2017).
[6] A full examination of the event was possible thanks to the previous revision of the seismic catalogues, accompanied by a more careful inspection of the chronicles, both published and unpublished. At the end of the research it was understood that the earthquake swarm had repercussions not only in Tuscany, but also throughout central Italy.
[7] In this case the CFTI5Med used the definition of 'equivalent magnitude' calculated following macroseismic observations.
[8] In the current context of study, all data was recorded and re-organized through the use of a QGIS software in its QGIS 3.14.16 version.
[9] LAArch: <http://laarchsiena.altervista.org/>.
[10] Included in this category are wooden tie-beams, diatons and specific wall features.
[11] The function of tie-rods, like buttressing arches and spurs, can be exemplified through the 'virtual arch model': in the presence of coplanar forces, two types of lesions can occur, tearing lesions and sliding lesions; assuming a wall surface as an ideal system for arches and semi-arches, it is possible to hypothesize the dynamics of collapse or displacement of portions of the wall (Cangi, 2018, p. 66).
[12] It should once again be remembered that we opted for an extensive strategy that has opened a parenthesis of reflection on a number of dates susceptible to changes and future developments; in order to obtain absolute chronologies, in fact, it is necessary to subject the individual buildings to precise historical-archaeological queries.
[13] The Statuti can be considered the new form of legislation of the bourgeoning Italian communes of the 13th century: the *Statutum Viarium* is part of the documents regulating the Sienese roads, drafted and constantly updated between 1290 and 1299 (Szabó, 1975, pp. 141-142).