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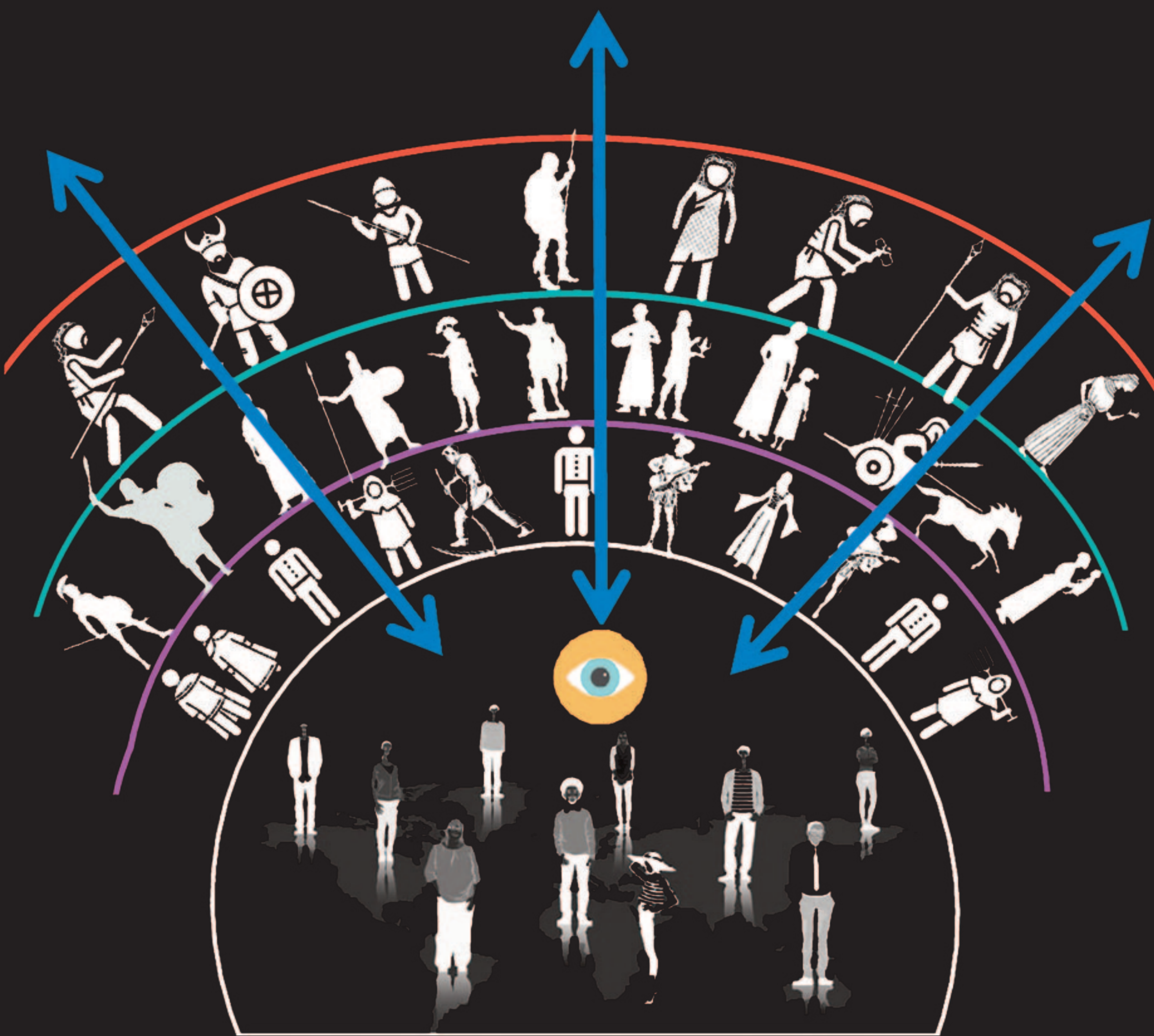

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Andrea Arrighetti*, Marco Repole**

Expeditious archaeoseismological analysis of a medieval town centre. The case of Siena and the PROTECT project

1. Introduction

In recent decades, archaeoseismology has become increasingly important in archaeology and beyond. The term refers to the archaeological investigations related to the effects of earthquakes on ancient buildings, preserved either as ruins or standing structures. Although this field plays a very important role in the documentation, safeguarding, and conservation of cultural heritage, it has not so far had a methodological and practical development comparable to that of other 'historical' approaches to seismology (Guidoboni, Ebel 2009). This disparity not only affects the disciplines as such but also causes clear diversifications within them. This is the case in archaeology, where the situation is extremely heterogeneous, both in the development of the methodological framework used for archaeological analysis and in its practical applications in the field. In particular, a clear difference can be observed between many archaeological excavations both in and outside Europe, where the use of archaeoseismology is now an established practice and applied in many case studies, as opposed to the archaeoseismological analyses applied to buildings located in historical urban and rural centres. Concerning the latter point, the literature offers only a few valid attempts to define general methods of analysis by means of theoretical and methodological investigations that integrate archaeoseismology with the knowledge of the effects of earthquakes on historical buildings located in ancient and medieval urban and rural realities[1].

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[1] By way of example, on a territorial level and in addition to the PROTECT project, the following archaeoseismological projects can be mentioned: the "ArMedEa – Archaeology of Medieval Earth-

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In recent years, numerous projects have been developed in selected areas of Tuscany, the Italian region where the case study presented in this paper is located, leading to the organization of, or participation in, national and international conferences and conventions on specific archaeological and historical topics[2]. These events were organized in response to the earthquakes of 2009 in Abruzzo, 2012 in northern Italy, and 2016 in central Italy[3].

The thoughts expressed, albeit briefly, in the previous paragraphs formed the basis for the creation, design, and development of the project PROTECT – Knowledge for Prevention: Techniques for repairing seismic damage from the Medieval period to the modern era, a two-year research project financed by the European Union Horizon 2020 Research and Innovation Programme, together with a Marie Skłodowska-Curie Individual Fellowship at the École normale supérieure - Université PSL, Paris. The project's research aim is to apply the methods of archaeoseismological analysis to the historic town centre of Siena. (fig. 1), Tuscany, in order to thoroughly document some of its buildings from the perspective of seismic prevention. The final objective of this ongoing project is to create an operational protocol for historic town centres, based on a multidisciplinary approach and using different analytical techniques at varying degrees of detail. The protocol will facilitate the recording and documentation of single buildings, street fronts, neighbourhoods, and urban centres in line with specific methodological criteria defined according to different objectives that are set on a case-by-case basis[4].

quakes in Europe (1000-1550 AD)" project developed by the Department of Archaeology at the University of Durham (Forlin *et al.* 2015; Forlin, Gerrard 2017; Gerrard *et al.* 2021); the "ACROSS – ArChaeology, inventory of RecOnstruction, Seismology and Structural engineering" project developed in the Mugello area by an Italian-French team (Montabert *et al.* 2020; Montabert *et al.* 2022). Also worth mentioning in relation to Italy are two projects that conducted extensive analyses of the archaeological sites of Pompeii, with the RECAP project (Dessales 2022), and Ostia Antica (Pecchioli *et al.* 2022). There are currently no large-scale archaeoseismological projects targeting entire historic centres.

[2] With particular reference to the areas of Mugello, Casentino and the town of Florence. The projects were developed in collaboration with the Department of History and Cultural Heritage (DSSBC) of the University of Siena and the Department of Architecture (DIDA) of the University of Florence.

[3] To mention only the most significant: the conference SAMI held in L'Aquila in 2012 (Redi, Forgione 2012); the Italo-French convention held in Cascia and Le Mans in 2019 and 2020 (Soussignan *et al.* 2021); the Mantua conference focusing on the earthquake of 1117 (Calzona *et al.* 2018); the seminar held at the Istituto Storico Italiano per il Medioevo in Rome, the proceedings of which are included in the 2020 Bullettino, no. 122; the convention on 'Economie e Tecniche della Costruzione' held in Siena in 2018 and the resulting proceedings published in the journal Archeologia dell'Architettura, XXIII; the convention 'I Beni Culturali della Capitanata' held in Foggia, in 2017 (Zullo 2018).

[4] The complete operational protocol, based on three levels of analysis of the historic centre of Siena, was presented in a preliminary form at several national and international conferences throughout 2023 and 2024 and is broadly described in a recent publication (Arrighetti 2023a). The present paper represents the outcome of one of these contributions and illustrates the protocol in greater details. Additionally, further publications detailing the individual aspects comprising the proposed work practice are planned for 2024.

Fig. 1. Drone photograph of the town centre of Siena (Image: Gianluca Fenili).

2. Research aims

Within the framework of the PROTECT project, several predefined lines of analysis were developed that are valuable for understanding and documenting the town of Siena, with a view to planning and scheduling operations for seismic risk knowledge and prevention[5]. Only a portion of the proposed general protocol for the analysis of the historic centre of Siena is presented here. Specifically, this contribution deals with the level of analysis of the context defined as 'medium', which involves reading moderate-sized portions of the city centre, specifically the road fronts, through the trial of an investigation protocol that combines digital data with archaeological information (fig. 2). This process, described in detail in the following paragraphs, involves an expeditious archaeoseismological analysis, i.e. an investigation aimed at gaining knowledge through the digital documentation and archaeological analysis of the street fronts, and also at collecting the data needed to formulate preliminary and practical suggestions on their conservation and vulnerability[6]. The purpose of the experiment proposed here is to test which practices in archaeological reading and surveying can be used to

[5] The project's planning and design strategies in relation to the knowledge of seismic risk are discussed in the concluding paragraphs. For more information on this issue with regard to the entire project please refer to Arrighetti 2023a.

[6] The data processed by this project must be read in accordance with the archaeoseismological documentation of the road fronts, based on a digital survey and an archaeological reading of the buildings. This practice, therefore, needs to be accompanied by interpretations at a structural level in light of its practical application for possible vulnerability analyses or for the design of restoration works.

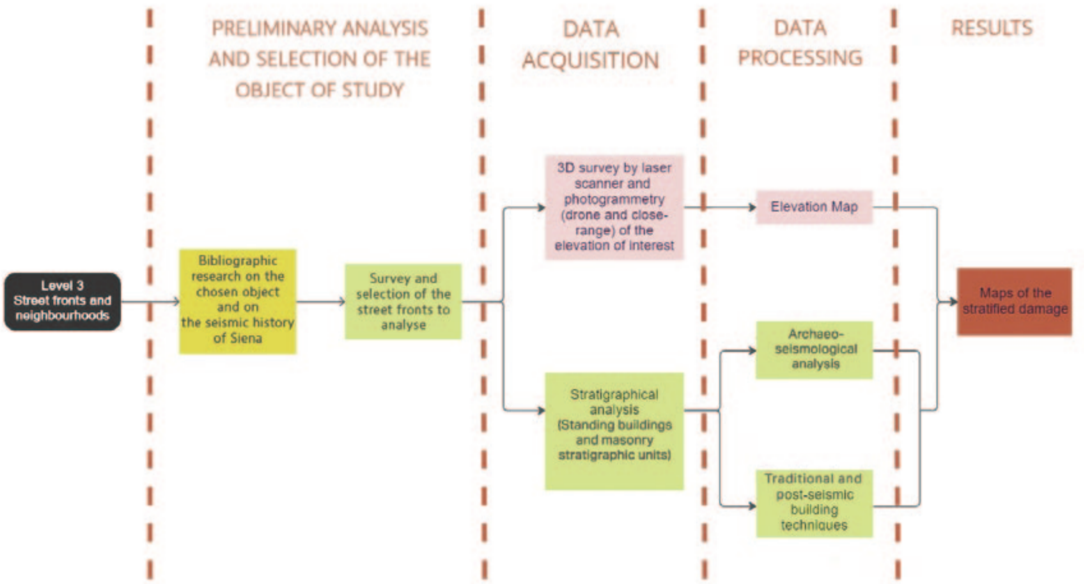

Fig. 2. Flow chart illustrating the conceptual framework underpinning the expeditious investigation of street fronts. Only the general outline of the framework is shown here and a detailed description is given in sections 3 and 4. This protocol was tested in the field to understand its limits and potentials in the various macro-phases of investigation.

document the external façade alone of a stratigraphically complex element such as a street front and using it as a knowledge base, emphasising step by step the advantages and disadvantages of the individual choices made. This approach was applied to selected streets in the medieval town centre of Siena, Via Pendola and Via Fontebranda, leading to specific results discussed at the end of the paper, with particular reference to the methodologies adopted, the results obtained, and the possibilities for developing the processed data at the technical-operational level. The main methodological guidelines and results that characterize this approach are discussed below.

3. Materials and methods

3.1. Preliminary analysis and selection of the object of study

The case study identified for the application of the PROTECT project is the town of Siena, an urban centre in southern Tuscany that has been on the UNESCO World Heritage list since 1995. Siena was chosen as the perfect case

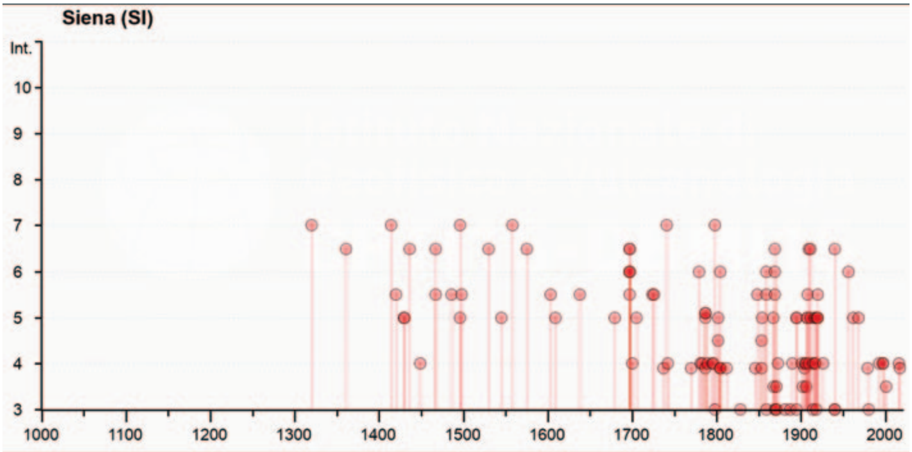

Fig. 3. Seismic history of Siena from 1000 AD (Source: INGV https://emidius.mi.ingv.it/CPTI15-DBMI15/place/IT_47956).

study for the application of archaeoseismological analysis for several reasons: the city has been affected by numerous seismic events throughout its history, some of which were of medium to high intensity (fig. 3); the architecture is well-preserved in its original features and is therefore also easily readable from an archaeological point of view; the city's state archive holds an incredibly large and detailed collection of texts covering the period from the Middle Ages to the present day; several studies in the field of historical seismology and archaeology have already been published and can be used as starting point for the investigation. Focusing on historical seismology, the town and its territory are an area historically affected by numerous seismic events. The seismological databases drawn up by the National Institute of Geophysics and Vulcanology, and we reference here its latest edition, namely the Italian Macroseismic Database – DBMI15 (Locati *et al.* 2022), propose a seismic history for the city characterised by over 145 events with documented effects from 1300 A.D. to the present day (fig. 3), of which at least 6 were responsible for significant damage to the town's buildings (grade VII on the Mercalli-Cancani-Sieberg scale, that ranges from I to XII). As Castelli has argued on several occasions (Castelli 2009; Castelli 2016), two main types of seismic events have occurred over the centuries:

1. Seismic swarms: characterised by a persistent series (over weeks or months) of numerous distinct tremors of low or moderate energy.
2. Isolated seismic episode: earthquakes with higher energy output followed by tremors of lower intensity in the immediate aftermath.

Many of these events left traces in the material structure of the buildings, although not all of them in ways that can still be identified and documented today by reading the wall palimpsests.

Fig. 4. Aerial view of the historic centre of Siena with the two road fronts under investigation highlighted: Via Fontebranda and Via Pendola. (Map data Google, Landsat / Copernicus).

At an operational level, once the historical-seismological analysis of the city of Siena[7] had been completed, it was decided to begin the investigation by subdividing the historic centre into the three Terzi of reference (Terzo di Camollia, Terzo di San Martino, and Terzo di Città) and by identifying areas in which the architecture showed clear evidence of the effects of historical earthquakes. After this preliminary work, the research focussed on the identification of the contexts to be analysed, choosing the ones that would provide the most relevant data for the study, aiming to adopt a multi-scalar approach set at three levels: historic centre, road fronts, and architectural complexes (Arrighetti 2023a). In this article, we present the work and results obtained from the second level of investigation, namely the medium-range survey of road fronts. For the latter, because of time constraints, it was not possible to analyse the historic town centre of Siena in its entirety. Therefore, after an initial survey, several streets were selected which, from an archaeological and seismic point of view, displayed attributes compatible with those required by the project's objectives. These were areas of the town characterised by the presence of buildings with a material component that was clearly visible and readable from an archaeological point of view and that enabled the

[7] The historical-seismological analysis of the historic centre of Siena and some of its unpublished findings are currently being printed in the journal 'Mélanges de l'École Française de Rome - Moyen Âge'. This research is the result of a collaboration between Dr Viviana Castelli of the INGV and Dr Barbara Gelli of the University of Siena. Preliminary findings were published in the volume "Siena e i terremoti. Punti di vista multidisciplinari per la lettura archeosismologica del centro storico" in 2023 (Castelli 2023; Gelli 2023).

identification of instabilities or damages relating to probable seismic events through a preliminary assessment of the masonry[8]. Two specific areas of the town were identified: Via Pendola in Terzo di Cittá and Via Fontebranda, limited to the stretch from Via di Cittá to Via Diacceto, in Terzo di San Martino (fig. 4). These portions of street façades are roughly 100 metres in length and were used as a testing ground for different methods of data acquisition and palimpsest analysis.

3.2. Data acquisition

As far as the recording of information was concerned, different technologies were applied to assess which was the most suitable for the objective required by this phase of the project. Mobile and traditional terrestrial laser scanners were used, accompanied by a photogrammetric survey carried out using ground and drone acquisitions. After the initial processing of the point clouds generated by the mobile scanner with SLAM technology (Simultaneous Localization and Mapping), it became apparent that, although very fast in acquisition, this instrument did not produce data accurate enough to be used for archaeological reading. This is probably due to the fact that this type of scanner uses proximity sensors, which are simpler and less accurate than those used by terrestrial scanner models, and also to what is normally called "drift", which is the tendency of the scanners to accumulate errors during acquisition in the field. The excessive noise of the model and the failure to acquire certain parts of the façades because they were too distant or too inclined, did not offer the accurate morphometric basis needed for the archaeological documentation of the street front. Therefore, the choice fell on the phase-shift laser scanner by the merit of its very high accuracy, with measurement errors below 0.1 mm. From an operational point of view, the plan to acquire the data of the façades in Via Pendola by means of a 3D laser scanner (fig. 5) was developed with a view to capturing all the data necessary to read the surfaces of the street fronts while minimising the number of scans (approximately 20). This method of "expeditious" surveying, already tested in other urban contexts both in Italy and internationally, has reduced the amount of time required for the field survey and the data processing and recording, thus streamlining the entire workflow.

The archaeological analyses of the masonry carried out in the field were characterized by an initial division of the street fronts into Standing Buildings, followed by a detailed study by means of Masonry Stratigraphic Units (abbreviated to USM, from the Italian 'unità stratigrafiche murarie'). For example, in Via Pendola, the façades were divided into 7 Standing Buildings, one of which could be further subdivided into three elements (fig. 8). Additionally, a considerable portion of the street front had to be excluded from the investigation because the

[8] This initial assessment was carried out by means of a rough reading of the areas of interest with the compiling of specific reference sheets (Arrighetti 2015; Arrighetti 2018).

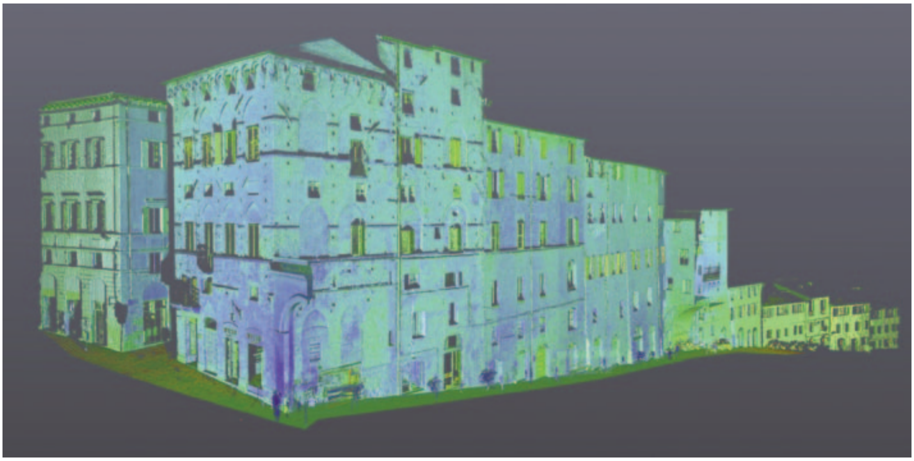

Fig. 5. Screenshot of the point cloud obtained from the laser scanner survey of Via Fontebranda.

walls were completely plastered and, therefore, unreadable from an archaeological point of view[9]. Following this initial selection and the assessment of the stratigraphic relationships between the various buildings, the analysis became more detailed and reading by masonry stratigraphic unit (USM) was implemented: this identified 1400 remnants of damage and/or repair highlighting the multi-layered nature of the façades. The archaeological analysis documented a construction history teeming with events, both anthropic and natural, involving collapse, rebuilding, rearrangements, and modifications of pre-existing settings. For example, the frequent filling-in of windows and the subsequent installations of new openings characterise many façades and highlight the frequent transformations that affected each building. The observed building activities must also be related to the damages and instabilities that compromised the architecture to the extent that it was necessary, among other repairs, to introduce 38 safeguarding measures, still visible today, to consolidate the masonry (fig. 6); among these recorded techniques, related in many cases to the desire to repair the damage caused by the effects of a specific earthquake[10], we can include: bond stones, iron anchor plates, buttresses, relieving arches and infill operations that involve the

[9] In this specific case, given the experimental nature of the proposed analyses, which aimed at the creation of an expeditious protocol that would relate deformations and stratigraphy, and since the latter element was missing from the plastered portion of the street front under analysis, it was decided to exclude the part covered by plaster from the archaeological reading of the façades. Instead, the latter was considered in the restitution phase of the survey because some evidence of damage was still visible despite the plastering and affected and related to the damage present on the unplastered walls.

[10] On the possible link between the techniques defined as 'post-seismic' and the historical seismic events that occurred in Siena, please refer to the considerations elaborated in Arrighetti *et al.* 2022.

Fig. 6. Examples of anti-seismic repairs documented during the archaeo-seismological analysis: bond stones (11a and 11d) and relieving arch (11b and 11c).

blocking of openings throughout the architectural complex. Moreover, on the basis of the stratigraphic readings, 29 traditional masonry building techniques were identified: these were analysed using dedicated filing systems, which systematised the countless information useful for framing the technological dimension within which the masons operated through the ages. In addition, the data obtained from the field analysis was recorded directly on-site by means of quick filing cards specially designed for this project, based on 3-tier documentation of the structures: road front, standing building, and construction technique.

3.3. Data processing

3.3.1. The digital restitution of the deformations

Following the data acquisition phase, a 3D model of the street façade was produced, which clearly showed how the morphology of the studied street front was strongly characterised by a diverse and complex geometry (elevation, width of each structure), as well as by varying levels of preservation of its buildings[11].

[11] An example of the latter is the clear degradation levels of the wall faces, characterised by the disintegration of the bricks used for their construction. All these considerations, already observed and recorded during the analysis in the field, are even more apparent in the generated models.

Surveying has always been an exceptionally valuable tool in archaeology. Modern technologies enable the acquisition of a great quantity and variety of data and offer the opportunity to work on almost exact replicas of the original object. Working on a digital model, while not replacing the necessary fieldwork, makes it possible not only to document and record the observations made in the field but also to provide information that is useful for the interpretation and ultimately the understanding of how a building was erected and modified over time. In relation to seismic risk assessment, surveying becomes an essential tool, both in the recording phase and also in the difficult stage of interpreting the data acquired in the field. The single most tangible example is the use of Elevation Maps, which can be described as two-dimensional characterizations of three-dimensional source data recorded by various types of tools such as photogrammetry or laser scanner survey. The documentation of damage to buildings by means of Elevation Maps[12] is a technique used by our research team for many years to analyse the structural instabilities caused by natural events such as earthquakes or other natural or man-made causes (Arrighetti 2019; Pancani 2017; Minutoli 2019). To create an elevation map of the building, different types of surveying instruments such as LiDAR (Light Detection and Ranging), GPS (Global Positioning System), photogrammetry or 3D Laser Scanner are used. These instruments, although characterised by different specifications and accuracies, make it possible to detect variations in elevation between the points that constitute the surfaces of an object. The theory behind this technique consists of identifying an ideal reference plane on the surface to be analysed, which is then used as the basis for the measurement that will create the elevation map. The measurements start from a classical Cartesian system composed of a Z coefficient indicating height, an X coefficient indicating width, and a Y coefficient indicating depth. In this space, we find the surveyed model to be analysed. Since this ideal plane is composed only of X and Z coordinates, it is possible to measure all the variations of the points in their Y component, associating their size (Delta) with a given colour of an assigned chromatic scale. Typically, the portion of the gradient leaning towards red identifies the positive deformations, while that leaning toward blue indicates the negative ones; green denotes the points closest to the reference plane and therefore deformation-free. Three-dimensional visualizations of data at this degree of accuracy enable the identification and analysis of the deformations on surfaces, which not only allow for the evaluation of the different issues affecting an architectural structure at the time of the survey but also provides an assessment of the dynamics linked to the seismic events that have affected the building over time. In this regard, the precise recording of deforma-

[12] An Elevation Map is, in this context, a graphic representation of the differences in elevation between points on a terrain or surface.

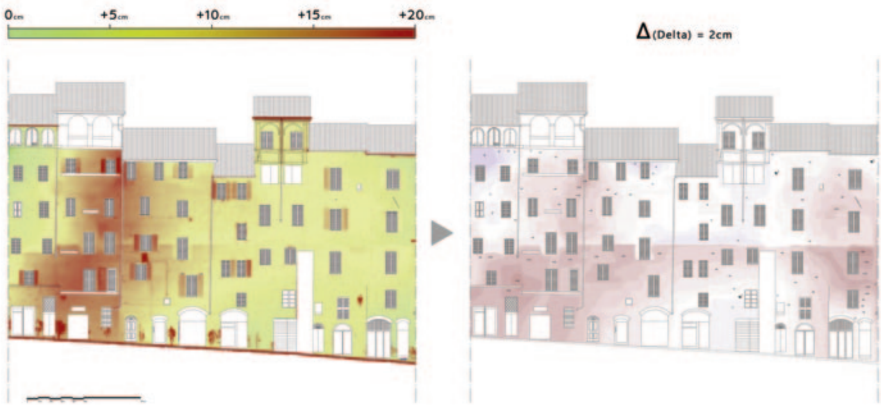

Fig. 7. The image shows the difference in graphic rendering of the deformation data of a portion of the external road frontage related to Via Pendola. In particular, from the image, it is possible to appreciate how the deformations visible on the Elevation Map on the left (composed of a colour gradient that ranges from green corresponding to an elevation of 0 cm to a maximum displacement in red of 20 cm) provide generic information on the trend of the entire frontage, while in the Map on the right (composed of isohypses with a Δ variation of 2 cm) they provide not only a general view but also a precise measurement of the extent of the displacement in that given area. The use of contour lines also allows for more detailed references on the frontage, moving by individual standing building, which made it possible to identify deformations (such as those on the right of the framed frontage) that were difficult to see with the colour gradient method. In our opinion, for the colour gradient to be graphically clear, more detailed measurements on the façade plane are necessary.

tions, as well as of cracks, becomes essential to the understanding of the evolution of the artefact, its alterations and instabilities and, consequently, the dynamics underlying the choices of intervention and transformation of the architectural complex.

In contrast to the 'classic' elevation map described above, which is characterised by colour gradients, the project PROTECT experimented with the use of a map based on a representation system similar to the one used in terrestrial topography, namely "isohypses" (fig. 7)[13]. This type of documentation enables the identification and schematization of all points on the analysed surface, correlating them with a given Delta. The main difference between this kind of representation applied to standing buildings rather than terrains is the scale of application: in the latter, the lines are set to a metre interval, in the former to a centimetre. This method, when applied to the smaller scale of representation, enables the filling and demarcation of each area of a building front that is characterised by the same displacement, thus generating a digital elevation model capable of de-

[13] In cartography or geography, the term 'isohypses' refers to a system of representation based on contour lines that show in detail the elevation profile of a surface and its relative altitudes.

scribing the deformations in detail. The advantage of using this specific type of elevation map lies in the precise identification of the size of each isostatic anomaly that describes the precise dimension of each deformation of the surface, thus documenting the direction and extent of each alteration visible on the analysed masonry.

3.3.2. The archaeoseismological analysis

Archaeoseismological analysis applied to historic buildings deploys tools that have been progressively refined by the archaeology of architecture over the last few decades and have, therefore, become integral to this disciplinary field (Brogiolo; Cagnana 2012). However, these traditional methodologies have been modified to determine which operative practices are best suited for the context and purpose of the investigation (Arrighetti 2015). Different neighbourhoods of historic town centres comprise buildings that are inevitably complex and composite. As described in paragraph 3.2, through fieldwork, it was necessary to 'simplify' and progressively organise the immense amount of data that characterises an architectural complex. The study, therefore, envisages a division into the different standing buildings that constitute the complex to determine the relationship between the different structures and unveil their chronological sequence (fig. 8). The analysis then proceeds towards a greater degree of detail through a stratigraphic reading by masonry stratigraphic units (fig. 8) (USM). In this way, the individual building operations that characterise the multi-layered stratification of the elevation are identified; this makes it possible to relate the cracks framework and the interventions made by workers through the centuries with the operations that lead to the progressive transformation of the building and to the damage and disruption that altered their features and structures. Therefore, the historical evolution of the street fronts is charted through the reconstruction of a relative chronology.

3.3.3 Characterisation of traditional and post-seismic building techniques

The documentation of building techniques enables the recording of the specific characteristics of each wall, both in terms of understanding their material, constructional and mechanical characteristics, as well as their historical and archaeological profile. This analysis, therefore, recommends a developmental approach connected to the chronological and typological analysis of masonry within a given territory, which, on the one hand, allows us to connect specific types of building techniques to historical periods of reference and, on the other, offers the opportunity to compare these changes with the social, political, and economic context in which they occur. This approach, if used in earthquake-prone areas, requires important reflections on the evolution of the technological aspect in relation to the technical capabilities and specificity of the patrons and craftsmen who operated in that area, linking the use of specific materials and

Fig. 8. Reading by Standing Building (top) and by USM (bottom) of the street front of Via Pendola. The plastered portion of the street front was not considered in the readings because the absence of stratigraphic data did not allow a clear understanding of how its façade relates to the evidence emerging from the documentation of the deformations of the surrounding buildings.

technical-operative choices to the needs imposed by the dynamics of the emergency or the reconstruction phases (Alberti *et al.* 2019; Arrighetti 2016; Correia *et al.* 2015). In the latter case, there is often the desire to empirically experiment with new solutions, and modifications of varying complexity of traditional techniques of autochthonous or allochthonous derivation, leading to the creation of building cultures aimed at counteracting or mitigating the effects of new seismic events. These are building systems that remain unchanged in specific areas in the short or long term, sometimes losing the function for which they were initially conceived (Arrighetti, Minutoli 2019).

At an operational level, the documentation of construction techniques takes place on the margins of the archaeological reading of the masonry, an operation that enables their stratigraphic and chronological characterization, together with the documentation of the damages and instabilities visible on the building and of the interventions carried out to repair or counteract these problems. The record-

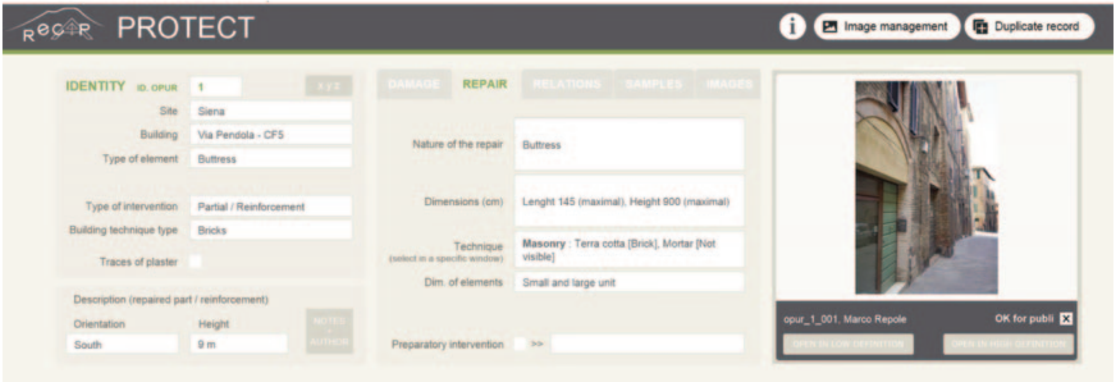

Fig. 9. Image of the user interface in the OPUR database updated by the PROTECT project.

ing of the techniques, damages/instabilities and repairs is carried out by means of a special filing system[14], which enables a precise qualitative and quantitative recording of these elements within the framework of the stratigraphic investigation of the building. The aim is, therefore, to link these interventions to the historical-constructional development of the building and to interpret them from an archaeo-seismological point of view.

Once identified, the post-seismic techniques are catalogued in a digital database called OPUR (Outil Pour Unité de Réparation / Repair Units Tool), developed as part of the RECAP programme (Reconstruire après un tremblement de terre. Expériences antiques et innovations à Pompéi / Rebuilding after an earthquake: ancient experiments and innovations in Pompeii)[15] by a team of researchers from the École Normale Supérieure - Université PSL, Paris[16]. The database, originally set up for the documentation of post-earthquake repair techniques identified at the archaeological site of Pompeii (Dessales, Tricoche 2018; Dessales 2022), was later tested and is now being updated by the PROTECT project (fig. 9).

14 With regard to the sheets used for recording damage/instabilities and repairs, see the publication of a project carried out in Florence (Arrighetti 2019).

15 Project ANR-14-CE31-0005, 2015-2019, coordinated by the AOROC department (UMR 8546, ENS-CNRS-EPHE, Université PSL), associating the IPGP (Institut de Physique du Globe de Paris, UMR 7154), the INRIA (Institut national de de recherche en informatique et en automatique, Paris – Rocquencourt, UMR 8548) and the Jean Bérard Centre (USR 3133, CNRS – EFR), in collaboration with labex TransferS, ISTerre (UMR 5275), the University of Padua, the University of Naples Federico II and Pompeii Archaeological Park: see http://recap.huma-num.fr.

16 The OPUR database was created in Filemaker 13 by Agnès Tricoche, under the supervision of Hélène Dessales, with contributions from Guilhem Chapelin (CNRS, CJB) and Julien Cavero (ENS, labex TransferS) for its design.

3.4. The integration of the analyses: the "stratified instability maps"

As seen above, the application of point cloud survey enables an accurate three-dimensional recording of structures, by providing a characterization and documentation of certain types of instabilities and monitoring the structural problems present in the material structure of the buildings. When this type of data is integrated with the vast amount of information obtained from archaeoseismological readings, a process is set in motion that leads to a profound knowledge of the artefact under examination. The result is the characterisation of the construction and mechanical history of the building, and also of its seismic history. But how can all this information be summarised in a visual representation? The objective should be not only to periodise the construction and destruction phases visible on the buildings and develop their structural analysis but also to integrate these data in order to suggest a periodised characterization of the instabilities that have occurred over time and are still occurring, by relating the results obtained to the historical and seismological documentation of a certain area. Using the data in our possession and the documentation produced by different types of analyses, this process resulted in the elaboration of "stratified instability maps", i.e. images that combine the archaeological reading of the building with its main instabilities, represented by the cracking and deformation pattern (fig. 10). Unlike classical archaeological or structural readings, however, in these representations, attention is also paid to "when" the instability occurred and its relationship with the stratigraphy present on the monument. To achieve this, the deformation pattern obtained through the Elevation Maps was represented by lines with elevation differences of 2 cm[17] and superimposed onto the archaeological reading by Masonry Stratigraphic Units (USM). In this way, some of the deformation curves were clearly interwoven with the building's stratigraphy and stratigraphic interfaces, highlighting the relationship between these two key readings of the monument[18]. The result is, therefore, a periodised reading of the material components of the architecture, which provides essential data for technicians, both in terms of the chronological aspect (when the instability was triggered or transformed), the interpretative aspect (what caused the instability to form), and the operational aspect (the instability is still occurring or some elements have established a new static equilibrium). Therefore, the "stratified instability maps"

[17] After a series of tests, a 2 cm elevation difference between lines was chosen because it was the most effective both in representing the deformations accurately on a geometric level and in achieving good readability when superimposed and integrated with the archaeological analysis.

[18] This paper represents the first practical step towards the long term methodological objective of the project PROTECT, namely the development of a visual aid capable of representing the interpretation of the deformations using the methods of the archaeological reading of the building. This will create an operational process that will allow us to propose quantifiable stratigraphic relationships between these two elements.

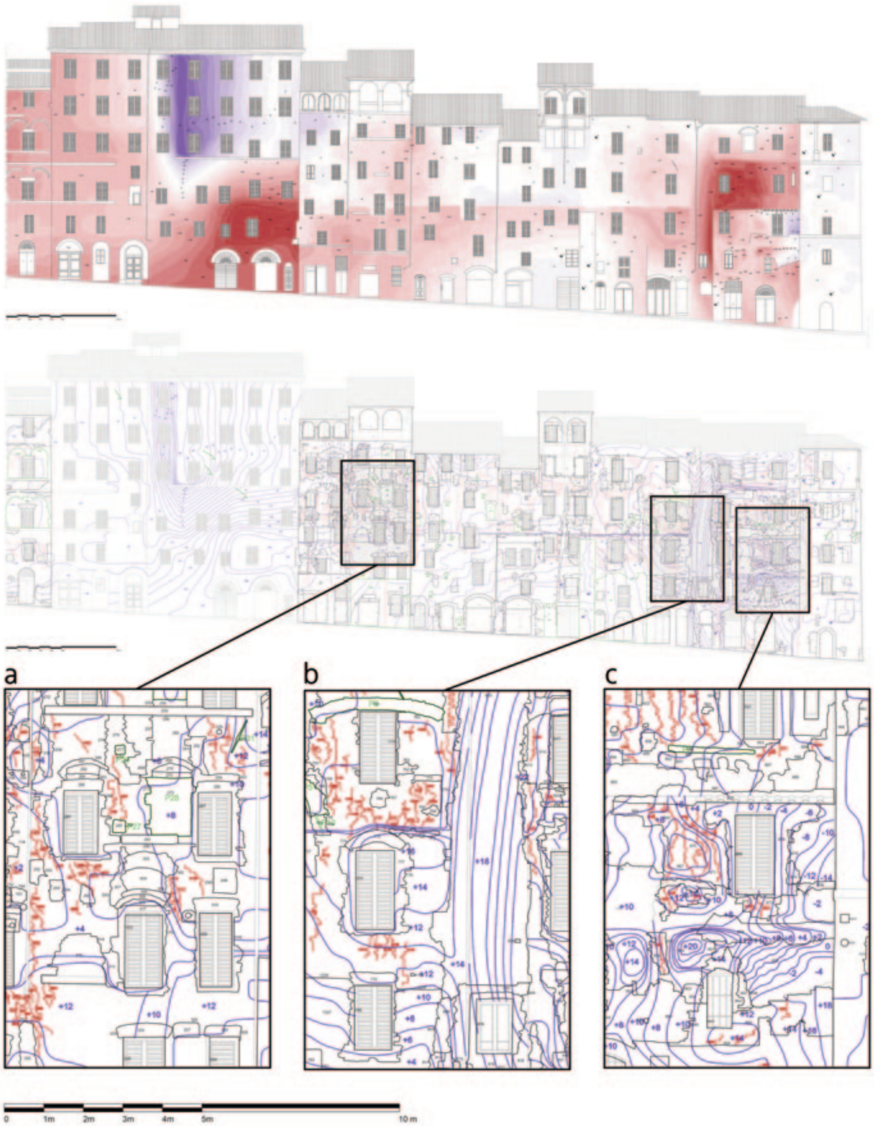

Fig. 10. The image shows the differences in the level of legibility of the deformation pattern between the restitution through colours and lines (top) and that based on lines alone (middle) of the street front of Via Pendola. To further understand how it is possible to quantify and integrate the deformation data with the archaeological data, the bottom image shows details of the interactions between stratigraphy (in black), deformation framework (in blue), crack framework (in red) and post-seismic building techniques (in green). In particular, it is possible to appreciate the clear deformation that the isohypses undergo when they cross the stratigraphic interfaces of the infilling of the openings (a, b) or in the connecting masonry between two buildings erected in different periods (b). Furthermore, in figures b and c some cracks are clearly cut by the construction of new masonry or new openings within the buildings.

constitute a palimpsest comprising different types of information (historical-archaeological, architectural, structural) that are closely linked to each other, and become significant elements of the knowledge base used both for historical and archaeological interventions and technical and planning choices.

4. Results

When working in large, socially and politically complex situations with low economic impact, it is often necessary to achieve significant qualitative and quantitative results in a short time. The method applied in Via Pendola and Via Fontebranda was created to this end, namely, to document a 100-metre street front with an evident and complex stratification, measure accurately the time and resources needed to carry out the overall work and assess the type of data returned.

The first consideration that emerges from this experiment focuses on the time required for the work. In approximately 20 days of work, a three-person team, consisting of two archaeologists and one surveyor, mapped the complete geometry of the street front and also finalized the archaeological, material, and constructional reading of it. Crack and deformation patterns, stratigraphy, and traditional and post-seismic construction techniques were documented, using digital tools. In addition, the quality of the data produced by the survey was verified by comparing the results achieved with different acquisition systems. A second consideration concerns the selection of the activities required for the archaeological analysis of the street front in relation to its documentation, which is useful for an initial historical-constructive restitution of the façades. The work carried out on the street fronts did not involve an analysis entirely in keeping with the modus operandi generally adopted by archaeologists working on historical buildings[19]. The unique aims that guide this type of research require a rethinking of the tools to be used so that they are as suited as possible to the task ahead. One can, therefore, speak in this case of an ‘expeditious archaeoseismological analysis’: among the tools in the archaeologist’s armoury, those that achieve the necessary degree of thoroughness and details are selected, favouring the steps that are truly useful to the cognitive process, according to the characterising elements of each case study. This inevitably produces a streamlining of the workflow and timescale. The reading by masonry stratigraphic units is thus used to satisfy the conditions that archaeoseismology demands in order to fulfil its aims. The observed building phases are then documented by means of the filing systems considered most ef-

[19] The statement ‘modus operandi generally adopted by archaeologists working on historical buildings’ refers to an approach to interpreting historical buildings based on the levels of analysis structured in the manual that currently serves as a reference for archaeologists of architecture: Brogiolo, Cagnana 2012.

fective for the ensuing interpretations. For example, it may be considered redundant to proceed with the compilation of individual USM sheets similarly, it may be considered superfluous to outline construction activities and phases. This has led to a significant reduction in the time needed for the documentation on paper during fieldwork and its subsequent digitization into specific databases. Furthermore, the decision not to outline the construction phases, which are important for a diachronic reading of the evolution of the artefact, was taken because, in our opinion, it appeared redundant for the reading of the deformation and cracking patterns which already arranged in a relative chronology through their comparison with the USMs. Analyses of this kind would not only fail to provide elements of particular relevance to the archaeoseismological investigation but would also greatly increase the time required to complete the research.

A third consideration concerns the results obtained from this type of analysis. The comparison of the analysis of the crack and deformation palimpsest with the stratigraphy on the masonry allowed for numerous considerations. In some specific areas of the alley, close relationships were identified between stratigraphic interfaces and deformation that characterized the building over time. Figure 10 clearly shows us some examples, where the deformation lines change with reference to the cuts and reconstructions made following the construction of the masonry (fig. 10, numbers a and c), and where some cracks are stratigraphically older than some masonry that has been built above them (fig. 10, numbers b and c). In this way, the deformation and the crack frameworks enter the archaeological analysis of the masonry walls and become an essential element in the interpretation and periodization of the stratigraphy.

This is therefore the first step in testing an expeditious operative procedure born from the dialogue between humanistic and scientific disciplines. The procedure is qualitatively and quantitively rich in data, and positively aids the complex task of recreating the construction and mechanical history of buildings while assessing the preservation of the architecture in historic town centres.

5. Conclusions

To conclude, the documentation of instabilities in buildings using the methods and technologies outlined in this contribution should form the basis of any vulnerability analysis, where the application of invasive diagnostic tools is often impractical. It enables the detection of structural issues in a building promptly and accurately, which in turn allows rapid intervention to secure it. Furthermore, this technique can also be used to monitor the development of instabilities over time, thus assessing the effectiveness of repair and prevention measures. In particular, when implemented in the medieval town centre of Siena, the methodology has produced results that enabled the detection and the documentation of instabilities and restorations, both ancient and modern. This type of documentation offers two positive outcomes: firstly, it improves the knowledge base; by linking the stratigraphy to damages and instabilities, it offers a first appraisal of the effects of earthquakes on buildings, facilitating the interpretation or providing preliminary data that can be later compared to the written sources. Secondly, it provides a clear understanding of the state of preservation of the structures under investigation, especially in view of the planning of suitable interventions in seismic risk prevention, with a ranking of priorities that varies for each building. A practical example of the usefulness of this information is its application when planning the interventions and the analyses for the evaluation of CLE (Condizione Limite di Emergenza / Boundary Condition for Emergency). In Italy, CLE analysis involves the implementation of an operational practice which includes the assessment of the structural condition of buildings in view of the prioritisation of interventions for each property located in a historic town centre or urban area. This data is essential for targeted knowledge aimed at mitigating the effects of one or more earthquakes on historic centres and for the subsequent correct planning of urban intervention and organizational measures related to the state of emergency in the wake of a seismic event[20]. The experimental protocol proposed in this paper has highlighted some considerations arising from the application of the archaeoseismological method to a medieval town centre, especially when integrated with an accurate and comprehensive topographic survey aimed at recording, identifying, and periodizing the instabilities that have occurred over time. This process of documentation and analysis should be implemented and applied to other contexts of interest and the results obtained during these future investigations compared with those discussed here. The ultimate goal is to consolidate the role of archaeology as a tool to support the evaluations for the design of interventions and planning in areas at seismic risk.

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The research presented here, under the scientific direction of Andrea Arrighetti, is the result of the collective work of the authors, whose relative para-

[20] The Department of Architecture (DIDA) of the University of Florence, in collaboration with A. Arrighetti as archaeology consultant, has applied this methodology to the historic centre of Poppi and the results have recently been published (Pancani 2017).

graphs are reported below. Marco Repole wrote paragraphs 3.2, 3.3.1 and 3.4; Andrea Arrighetti wrote the other paragraphs of the article.

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Abstract

The archaeoseismological study of medieval town centres located in seismic areas offers the opportunity to gain information on the effects that previous earthquakes had on its buildings and also provides evidence of the social, economic, and political dynamics that followed these events. These processes are rarely documented in the written sources and are often forgotten. Nevertheless, they remain imprinted in the architecture, which, in turn, often becomes the sole witness of a town's seismic past, the comprehension and understanding of which is constantly evolving. The project PROTECT, financed by the European Union's Horizon 2020 Research and Innovation Program, is part of this line of research. The aim is to apply archaeoseismological analysis to the historic town centre of Siena (Tuscany), in order to acquire an in-depth knowledge of the chosen area of study from the perspective of seismic prevention. The final objective is to create an operational protocol for the archaeoseismological reading of the medieval centre of Siena or at least a portion of it, and to export this model to other Italian or European sites, with a view to understanding, safeguarding, and preserving historic heritage from seismic risk.

Keywords: archaeoseismology, architecture, Siena, building techniques, 3D survey.

Lo studio archeosismologico dei centri urbani medievali situati in aree sismiche offre l'opportunità di ottenere informazioni sugli effetti che i terremoti hanno avuto sugli edifici e fornisce prove delle dinamiche sociali, economiche e politiche seguite a questi eventi. Questi processi sono raramente documentati nelle fonti scritte e spesso vengono dimenticati. Tuttavia, rimangono impressi nell'architettura che, di conseguenza, diventa spesso l'unico testimone del passato sismico di una città, la cui comprensione è in continua evoluzione. Il progetto PROTECT, finanziato dal programma Horizon 2020 dell'Unione Europea, si inserisce in questa linea di ricerca e intende applicare l'analisi archeosismologica al centro storico di Siena (Toscana), per acquisire una conoscenza approfondita dell'area di studio prescelta dal punto di vista della prevenzione sismica. L'obiettivo finale è quello di creare un protocollo operativo per la lettura archeosismologica del centro medievale di Siena, o almeno di una sua porzione, e di esportare questo modello in altri siti italiani o europei, nell'ottica della comprensione, della salvaguardia e della conservazione del patrimonio storico sottoposto a rischio sismico.

***Parole chiave:** archeosismologia, architettura, Siena, tecniche costruttive, survey 3D.*

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