Journal of Cultural Heritage 56 (2022) 167–182

Contents lists available at ScienceDirect

Journal of Cultural Heritage

journal homepage: www.elsevier.com/locate/culher

Original article

Urban morphology parameters towards multi-risk scenarios for squares in the historical centers: Analyses and definition of square typologies and application to the Italian context

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ARTICLE INFO

Article history:
Received 10 January 2022
Accepted 22 June 2022
Available online 12 July 2022

Keywords:
Historical built environment
Urban morphology
Multi-risk
Resilience
Squares
Built environment typologies

ABSTRACT

The historical built environment (HBE) in urban areas is prone to disasters, which threaten both people and the historical built heritage itself. In such a scenario, risks depend on the combination between different possible (multi-) hazards (including climate change-related ones), the vulnerability and exposure of HBE users, and the physical (morphology-, typology- and construction-related) features of the HBE. In this context, squares are relevant components of the HBE from a meso–scale perspective, which is based on the layout and morphology of open spaces, buildings blocks and their users. Squares host cultural heritage and attract users, both tourists and citizens. Moreover, squares are nodal points for the emergency path network and are crucial and significantly affected during the immediate aftermath of the disaster occurrence (e.g. by debris on the ground in the case of seismic hazard during the evacuation phase). Current approaches for risk assessment and mitigation entail the consideration of each specific square, but this approach is time-consuming, scattered between the different hazards and complex to apply to a multi-risk perspective. Therefore, this work provides a methodology to identify and classify the most relevant physical features of squares in the HBE, which are able to improve or worsen the performance of the HBEs to multi-risks from multi-hazard scenarios. The research is rooted in the existing literature and strengthened by experts' judgement analyses. The proposed methodology synthesizes the considered relevant features of the squares in the HBE into quantitative parameters, which allow to verify the vulnerability to multi-risk of the squares. Such parameters are further organized into classes for the typological assessment of the multi-risk. To test and detail the parameters, the method is tested on a relevant case study, which is the Italian context. Indeed, such a case study is relevant not only for being subject to multi-risks (e.g., seismic, terrorist, heatwave and air pollution), but also because the vast majority of the urban areas are composed by HBEs and hosts cultural heritage sites. Moreover, in this context, squares have not only an environmental, but also a social and economic importance in the HBE and are thus particularly relevant. Then, in the relevant case study of Italy, further detailing and calibration of the defined classes of the relevant parameters, as well as their ranges, are tested on 133 squares, which cover the entire Italian territory. Results demonstrate that the identified classes and ranges of the parameters are suitable for describing historical squares by arranging them into typologies for multi-risks assessment. Although the parameters are here presented for the Italian context, they are of general value and could be tested in other contexts, by calibrating the ranges as illustrated for the specific considered sample. Thus, the outcomes of this work allow moving towards the classification of squares into built environment typologies according to the meso–scale perspective, provide the bases for and promoting the application of expeditious approaches to multi-risk assessment in the HBE.

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https://doi.org/10.1016/j.culher.2022.06.012
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1. Introduction

Urban areas, which host the vast majority of the world population [1], are increasingly prone to disasters [2,3]. Furthermore, projections for the next future state that urban population will be increasingly growing, exacerbating the pressure on cities [4]. Land consumption and the growing pressure on the infrastructure system [5], together with Urban Heat Island effect (UHI) [6], pose serious threats to users' safety and wellbeing, already menaced by climate change-related challenges [7]. In this panorama, critical conditions for both the users and the built environment (BE) are particularly exacerbated in the historical built environment (HBE). Indeed, the historical built environment is defined as a built environment that was built in the past and often retains an historical value [8]. The HBE is usually characterized by the presence of cultural, architectural and artistic heritage [9], as well as by specific morphology, typology and construction technologies [10]. As such, the HBE is complex with respect to the following factors [11–14]:

(i) hazard (including single-hazard and concurrent/successive multi-hazards), which is defined as "a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation. (…) Hazards may be natural, anthropogenic or socionatural in origin" [15];
(ii) vulnerability (including physical vulnerability of the cultural heritage and compound, narrow and tangled urban form), which is defined as "the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards" [15];
(iii) exposure (including the HBE intended uses and their attractiveness for visitors and citizens), which is defined as "the situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas" [15].

These terms (e.g., hazard, vulnerability and exposure) allow framing the risk related to disasters. Indeed, according to UNDRR [16], a disaster is "A serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to (…) human, material, economic and environmental losses and impacts" [17], and entails the effect of hazard on specific vulnerability and exposure conditions. Disasters can be classified according to the timing of their consequences [18,19]. Therefore, according to the definitions by the UNDRR, a disaster is different from a hazard, as it entails an intrinsic risk due to its effect on a vulnerable environment, where something/someone is exposed to it. Moreover, the term risk is related to the potential effect of a disaster, considering the hazard, the vulnerability and exposure. Thus, also the term hazard is different from risk, as hazard is one component of risk. Disasters can emerge gradually over time and take a long time to produce the emergency, leading to SLOD (Slow-Onset Disasters), such as strong air pollution and more frequent and intense heatwaves. Else, they can be unexpected and rapid events, i.e. SUOD (SUdden-Onset Disasters), such as earthquakes and terrorists' attacks [19], where the effects of the disaster suddenly appear, thus leading to the rapid development of emergency conditions. Nowadays, the frequency and intensity of some of the above-mentioned disasters is increasing due to the combination of exacerbating hazard, vulnerability and exposure factors, especially while referring to HBEs [2,3].

Therefore, this work aims at proposing effective parameters related to HBE features, which are useful to evaluate HBE vulnerability to multi-risks.

In the following subsections, the background of the research (Section 1.1) and the identified gaps (Section 1.2) are illustrated, while delineating the detail of this research. The remainder of the article is structured as follows: in Section 2, the research aim is presented; Section 3 illustrates the research methodology, which is further detailed in the dedicated subsections related to the selection of the morpho-typological parameters (3.1) and the data gathering (3.2). Results are presented in Section 4, which illustrates the identified parameters for multi-risk scenarios (4.1), their application and testing in the case study of Italian historical urban settlements (4.2) and the definition and discussion of the square typologies for multi-risks (4.3). Finally, conclusions are drawn (Section 5).

1.1. Multi-risks in the built cultural heritage: background

The combination and concurrence of such multiple cascading SLODs or SUODs imply facing multi-risk scenarios in the HBE [20,21]. In this context, it is worth noting that the features of the HBE at the macro-, meso– and micro-scales are able to influence the effects of single and multiple hazards on the physical elements as well as on the hosted users of the HBEs [22]. Indeed, at the macro-, meso– and micro-scale, the HBE possesses physical features (morphology-, typology- and constructions-related), that are able to influence the overall urban resilience, which is defined as the ability of the urban system to resist and adapt to change and hazards [15]. According to existing categorizations for the above-mentioned scales [22], the macro-scale is related to the urban dimension, the micro-scale is concerned with buildings and their components, while the meso–scale deals with the layout of building blocks, streets' structure and network, open spaces pattern and distribution, at the neighborhood scale. Meso-scale analyses are particularly suitable for considering interactions among users and a significant part of the surrounding HBE (i.e. the basic buildings and open spaces network where users "behave" before, during and after the disaster) [23,24]. Indeed, meso–scale analyses allow an expeditious approach, i.e., a rapid assessment based on the identification of synthetic indicators [25,26], but still considering the critical, punctual conditions of the HBE that can influence the risk scenarios [11,13].

By tapping on meso–scale analyses, the square is the fundamental component of the HBE, and is the most relevant Open Space (OS) to consider [27]. Indeed, squares in the HBE often host relevant cultural heritage points-of-interest and sites, and at the same time they are condensers of users' activities and events [27]: as such, they are attractors of risks and exposure, and are thus of primary importance to investigate during and after SLODs- and SUODs-related emergencies [28]. The role of squares in the HBE as places where social life happens [27,29] is highlighted especially in the Mediterranean region and Mediterranean squares are defined as "*the urban element par excellence, which from antiquity has supported public activity — religious, commercial, administrative, leisure, etc.*" [30].

Additionally, the Mediterranean region is one of the most relevant and significant case-study areas worldwide with respect to multi-risks [31], considering the frequency and intensity of disasters and considering the vulnerability and exposure that characterize such a peculiar historical and densely populated region [32,33]. In fact, the majority of the Mediterranean building stock is historical, with many protected historic buildings and cultural heritage sites and squares, and most often inadequate to provide safe and comfortable conditions to risks [9,34]. These issues particularly affect the squares in close proximity of such vulnerable built heritage, e.g., debris could prevent an effective response to the seismic hazard.

In greater detail, the hazards affecting Mediterranean HBEs derive from both climate change and geo-morphological characteristics, in addition to the exposure given by the high population density [35].

With respect to SLODs, heatwaves (HW) and UHI are increasingly growing, where UHI implies higher temperatures (up to +10 °C) in cities than in surrounding suburbs [6]. Mediterranean HBEs are also particularly sensitive to air pollution (AP), due to the high density of population and the related pollution-provoking anthropic activities, such as traffic [36]. UHI and Urban Pollution Island (UPI), which is a similar concept to UHI but related to the presence of increased pollution particles in cities than in the rural atmosphere [37], are linked and urban form has a significant role in determining both of them [38]. Compact urban areas (as typical for most of the Mediterranean HBEs) aggravate both UHI and UPI [39] and density was demonstrated to be the most relevant predictor, together with urban land cover in the suburbs of sprawling urban areas [40], thus identifying typology and morphology as relevant determinants of the vulnerability of a square or an open space. Many studies demonstrated the relevance of the ratio between height and width (e.g., for urban canyons) in determining thermal stress or pollution dispersion [41,42]. Pollution, in addition to being harmful to people wellbeing and health is also deleterious for the built heritage, as it causes deterioration by means of atmospheric corrosion, soiling and degradation [43,44]. Also construction features, such as the finishing of urban surfaces, are able to affect thermal stress and air quality, as there are specific materials that can mitigate extreme temperatures [45,46].

With respect to SUODs, many of the Mediterranean HBEs are subject to elevated seismic (S) risk [47] and are characterized by the high fragility of the building stock due to the prevalence of un-reinforced masonry structures and monuments, which are more vulnerable to collapse during seismic shocks [48,49]. Users' safety in the immediate aftermath of the disaster and during the evacuation process is affected by (i) the peculiar configuration of the meso–scale components, thus the squares as the most significant and relevant component due to their role in the emergency network and in the HBE in general, and by (ii) the post-earthquake damages of buildings, which entails the presence of debris on the ground of the square and its accesses [11,50]. Moreover, as above-recalled, HBE squares are also rich in historical landmarks that could be vulnerable to the SUOD of terrorist attacks. Indeed, the presence of important cultural heritage points of interest, as well as the high population density and social activities the SUOD case, typology, morphology and construction features have demonstrated their relevance in determining the vulnerability of square/OS. Indeed, depending on the square typology and morphology, debris could block the way out/way in or provide for adequate safe space at the center of the OS [11] or to reach a safe space outside the square [51]. Moreover, construction features determine the amount of debris falling down [25,52].

In the above-illustrated panorama, the knowledge and understanding of such vulnerable components of the Mediterranean HBE, the squares, is crucial for safeguarding people living and visiting such areas, as well as for maintaining and protecting the cultural heritage hosted by the HBE.

Indeed, a deeper knowledge at the meso–scale of the urban physical features of Mediterranean squares in the HBE would allow reducing multi-risks coming from the above-mentioned hazards (both natural and man-made), thus favoring the conservation of their cultural heritage, while safeguarding users and promoting tourism, towards the valorization and environmental, social and economic sustainability of such region.

1.2. Identified gaps and original contribution

Previous studies dealt with the definition of multi-risk assessments models for cultural heritage sites, but there are some gaps that still need to be filled, as briefly reported below. Indeed, Appiotti and colleagues [53] evidenced that risk assessment is generally applied at the urban and territorial scale (macro-scale) rather than on smaller scales (micro- and meso–scales), thus limiting the understanding of the most critical and punctual elements that affect the HBE and its users' safety. Anyway, research moving towards the micro-scale analysis have been recently increased, thus allowing the characterization of single building components of the urban settlements and their typological organization, in view of risk assessment and mitigation actions. Indeed, Sesana and colleagues [12] developed an approach to assess the vulnerability of World Heritage Sites to climate change-related risks on a periodic basis, by means of consultations with local experts and stakeholders. Santos and colleagues [54] conducted an inventory of buildings and urban mesh typologies for the historical city center of Seixal, in Portugal, with the aim of conducting rehabilitation interventions to support risk mitigation. Belpoliti and colleagues [55] performed an expeditious evaluation of the energy performance of buildings in an historical urban settlement by considering three archetype buildings based on geometry, age and material features. The expeditious method allowed them to propose the best retrofit solutions for the entire urban settlement, by focusing on the specific case in a general manner. While the above-mentioned works focused mainly on the building component of the urban settlements, only few studies focused on how such built heritage could affect the surrounding open spaces, which is a critical element with respect to multi-risk management scenarios. Quagliarini and colleagues [11] considered buildings, open spaces and streets of HBE to evaluate risk scenarios for earthquakes, by focusing on the hosted individuals and their behavior.

This work adopts the same approach in considering the squares of the HBE at the meso–scale, but aims at giving a general framework for quantitatively assessing the physical (morphology-, typology- and construction-related) features of the square that are relevant for multi-risks, such as heatwaves, air pollution, terrorism and earthquakes. The understanding of such physical features plays a key role for performing a meaningful classification of Built Environment Typologies for squares (i.e., square typologies), according to their sensitivity to risks and multi-risks [22].

Towards this aim, urban morphology is exploited, which specifically considers the components of the urban form at the neighborhood scale [56] and aids in the analyses of the relations between physical form and spatial structure according to geographical, historical and architectural considerations [57]. Within the discipline of urban morphology, it is useful to introduce urban morphometrics [56], as adopted from morphometrics and taxonomy in life sciences, as a quantitative method for classifying urban forms by means of parameters based on physical features.

With respect to urban morphology, the square is conceived as a nodal outdoor area surrounded by frontiers with specific morphology, typology and construction features, which determine the shape of the outdoor space with its layout, type of buildings or other urban elements facing the square [58]. The parameters for systematizing typologies of squares with respect to their performance towards multi-risks, which are the subject of this work, are the bases for future expeditious approaches, and thus of interest for researchers in the field of urban resilience, urban planners and policymakers. The purpose of this classification is not defining unequivocally the typology of squares as components of the HBE, but implementing the method to provide and classify a list of parameters that allow the expeditious identification of specific square typologies. Every square could be defined with respect to its typology by means of a combination of the given parameters, to allow tracing its performance during disasters. The characterization of the parameters is the preliminary step towards the assessment of the performance of the square to multi-risks, as the site that plays a key role during emergency phases and influences the behavior of the users [11]. The performance of the square, nodal point of the OS, influences the overall safety conditions of the HBE [59].

In order to identify and test such parameters, a relevant and significant sample of squares is considered among the Mediterranean region. Given the baricentric position and the richness in cultural heritage and historical urban settlements; given the high sensitivity to multi-risks due to historical and geomorphological features, the entire Italian territory is considered as a relevant case study. The depiction of the Italian context is achieved due to the consideration of at least one city for each Italian province, with a sample of 133 urban areas. For each of these cities, the analysis is focused on squares, defined as nodal “unroofed ground space in the city (either natural or human-made)” [22].

The original contribution of this work, in addition to considering the specific Italian context at the meso–scale towards urban resilience, is to tap on the multi-risk approach, deemed as fundamental to address risks, as cascading disasters could affect the management of the risks. Therefore, an overall panorama about all the parameters affecting multi-risks in the HBE and the identification of the mentioned parameters for the Italian context is proposed in this contribution.

Even if here the case of Italy is taken into account, the method that is here employed is of general applicability to other contexts. The identified parameters for defining square typologies can be easily modelled for further simulation analyses, and are thus the first theoretical step towards multi-risk assessment in urban areas, which is the aim of the BE S2ECURE Italian National project [58,59], of which this work is part.

2. Research aim

Based on the above considerations, the research question we want to respond to is: are there suitable morpho-typology parameters that allow describing the attitude of squares in the HBE towards multi-risks, to support the application of a rapid multi-risk assessment?

Thus, this article aims at systematizing the physical features (morphology-, typology- and construction-related) relevant towards multi-risks, by focusing on squares in the HBE, which are prone to risks, in that they are vulnerable, subject to hazards and high exposure. In so doing, the traditional approach to risk assessment for open spaces, which considers specifically each individual space at a time to assess its vulnerability, is surpassed. Instead, we set the bases for a novel, expeditious meso–scale approach, by identifying quantitative parameters based on physical features. Indeed, the complexity of the BE in historical multi-hazard-prone areas, calls for the definition of suitable parameters to identify squares typologies that are most vulnerable in the HBE. Thus, the identification and classification of specific parameters aids in the summary of the key characteristics that may have a mitigating or exacerbating effect on the HBE response to multi-risks from multi-hazard scenarios. The article identifies quantitative parameters, tests and further details them by applying them on a significant sample of historical squares in the relevant Italian context. The focus of this work is characterizing squares as crucial components of the HBE subject to risks, not the elaboration of a risk assessment method.

3. Methodology

The proposed methodological approach relies on a thorough knowledge of the multi-risk analysis with respect to the factors determining risks and the physical characteristic of the HBE affecting them. The method employed for delineating the proposed methodological approach is based on successive steps (Fig. 1).

The first step consists in the identification of HBE physical features that are correlated to SUODs/SLODs factors. The choice of the most relevant features is based on an extensive literature review developed in the previous BE S^{2}ECURE Italian National project and on the use of groups of experts [28,58,59]. After selecting the relevant features, quantitative parameters to describe each of the identified feature are defined, with the aim of providing quantitative measures for the representation of the physical form of the square typologies. According to this purpose, and as a second step, the specific case study of the Italian context is considered, and a sample of 133 squares covering Italian historical towns is considered. It is worth evidencing that the case study is not aimed at investigating square typologies in historical cities in Italy. Instead, the purpose of the case study is to identify general criteria that allow describing in an exhaustive but still synthetic manner the most relevant features for multi-risks evaluation of HBE squares. A descriptive statistical analysis is carried out with respect to the said parameters, considering the broad sample of Italian historical squares by means of a database, in order to test and further detail their ranges. The following subsections will provide an in-depth illustration of the method employed to carry out each step.

3.1. Selection of morpho-typological parameters in a multi-risk perspective

According to the state-of-the-art overview (as by [28,59] and by the introduction of this article), the correlation between risks factors and physical characteristics of a generic HBE square is discussed by combining considerations about SUODs/SLODs assessment and the morphological characterization of the square. Physical characteristics of the HBE influencing risks have been collected in previous steps of the research due to their demonstrated crucial role during all the phases of disasters [58,60,61]. Moreover, a quick survey form has been implemented to collect the risk-related features of the squares according to the multi-risk approach [28]. The form is composed of five sections representing different specific fields of the square features, namely morpho-typological, geometry and space, construction, functional and environmental characteristics. These characteristics deal with both the elements of the frontier of the square (e.g. buildings facing the square, or rather the built fronts as recalled above) and elements contained within the square [58].

Even if such features affect differently the risk definition of SUODs and SLODs, it is possible to detect some significant parameters that are simultaneously relevant for more than one, up to all the four risks (seismic, terrorism, heat waves and air pollution) [60].

Among the parameters contained in the survey form, those referring to morphological and spatial features are selected based on the purpose of the square typology definition towards multi-risks, in terms of physical features. Fig. 1 shows the considered features by organizing them into typology-, morphology- (as characteristics of geometry and space) and construction-related categories. Additionally, Fig. 1 points out the relationship of the features with risk factors (H-hazard, V-vulnerability and E-exposure, as defined in the introduction section) and the SUODs/SLODs risks considered in this work, including relevant literature references and the results of the experts' judgment criteria for their selection. The experts' groups are composed of eight building engineers with a recognized extensive experience in the specific field of resilience strategies in HBE prone to risks [62]. Experts identified the relevant parameters by assigning a “relevance score” to each of them, and elaborated the correspondence between the parameters and the risk factors (H, V, E). It is worth noting that the resulting “total count of the relevance” for each feature is not assigned by assessing the risk level, but to identifying the most crucial components of the

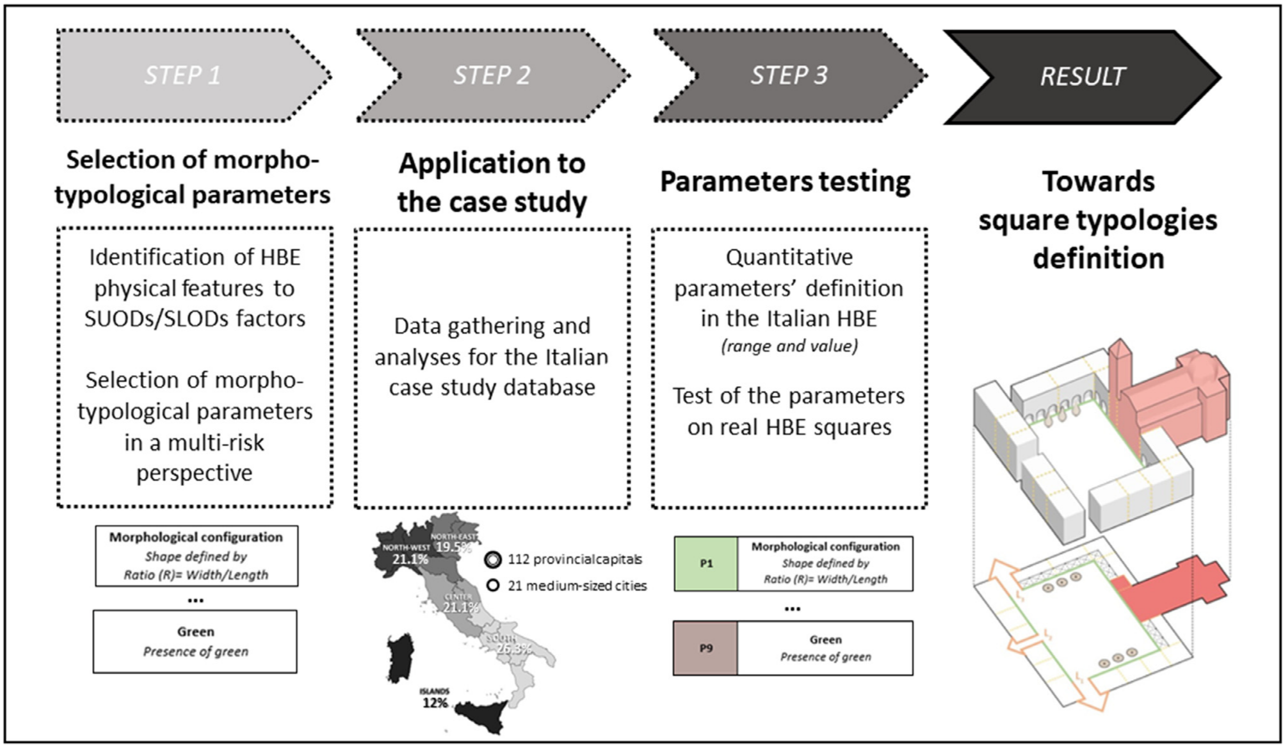


Fig. 1. Diagram of the applied methodological steps.

squares in the HBE that influence risk. Indeed, such characterization is conducted on the basis of quantitative parameters that have a significant influence in the definition of risks. Therefore, the higher the "total count of the relevance", the higher the impact of the square feature on the multi-risk characterization. As such, the total count of the relevance is comprised between 1 and 4, where the maximum of 4 is obtained when the parameter is relevant for all the four considered hazards and thus particularly relevant for the multi-risk analysis.

The obtained most significant parameters can be adopted for the definition of square typologies, as they represent physical features of the OS, and, at the same time, they influence the HBE response to SUODs/SLODs. The parameters identified in Table 1 scoring the upper half of the total count of the relevance (i.e., those scoring 3 and 4) have been aggregated into the final nine main parameters for the square typologies definition (Table 1). Some parameters, which did not emerge as relevant from the analysis, were still identified by means of a second round of judgement of the same experts and added to the final considered parameters. In greater detail, **Structural Type** (SA/SU) characterizes the built fronts with respect to both the geometrical configuration of the square frontier (i.e. isolated building (SU) or continuous built front (SA)) and the structural response especially to the seismic risk. Moreover, the presence of **Special buildings** (such as municipal buildings, educational ones and similar) and also monuments and churches, provides a crucial information about the type of buildings facing the square, both with respect to structural and functions-related aspects that strongly influence the exposure to risks. A short description of the parameters is provided in Fig. 2, also according to the related references shown in Table 1.

On the other hand, some parameters that were first selected for the total count of the relevance are not included in the final selection of parameters, according to the same second round of expert judgement. Although fixed obstacles, pavement/surface condition and the presence of water can be listed in the relevant features scheme of Table 1, they include a broad variety of components and thus do not allow providing a typologically univocal characterization of the square for the purpose of this expeditious assessment. Indeed, even if some of these excluded parameters are quantifiable, such as "pavement finishing" with respect to albedo and thus potential in mitigating heatwave [91], the enormous variety of materials and the difficulty to gather this information by means of expeditious assessment motivated the exclusion. For example, high-albedo materials are not always detectable, as, especially in the HBE, they are colored as traditional materials, e.g., cool-colored materials [92,93]. Similarly, "Urban furniture and obstacles" include a wide variety of possible systems that conflict with an expeditious assessment, and they can be similarly managed for their assessment in the proposed methodology.

Each parameter in Fig. 2 is quantified to allow the collection of the relevant data from real world cases, by using both Boolean and non-Boolean values, and then arrange them into classes for the typological representation of the squares. Such data are also required for the in-depth analysis of the capability of parameters to describe the square, also pursuing a statistic-based representation of squares' features.

Moreover, the parameters are recalled in a specific order (from 1 to 9), by following a dimensional criterion. Indeed, the parameters related to macro dimensions of the square are investigated first, and then smaller-scale parameters characterizing the content of the square (the frontier first, and then the OS) are described. This order facilitates the definition of the typologies, as the parameters are considered in sequence, starting from those for the higher scale (macro), down to the small scale (micro).

3.2. Data gathering and analyses for the construction of the morpho-typological database of Italian squares

In order to practically define the square typologies by means of quantitative assessment of their physical features [56], a significant and relevant case study is selected. As illustrated in the introduction section, the Italian context of historical urban settlements is

Table 1
Summary of the main features from literature, specifying the relation with the risks factors (H-hazard, V-Vulnerability, E- exposure), SUODs (Seismic-S, Terrorism-T) and SLODs (Heat Wave-HW, Air Pollution-AP) risks and the results of the survey to the experts [28,42,48,50,51,58,60,61,63–90].

FEATURE	S		T		HW		AP		TOTAL COUNT OF THE RELEVANCE
TYPOLOGY FEATURES									
Morpho-typology	V	[58,60,63,64]	V	[51,58,60]	V	[58,61,65]	V	[58,61]	**4**
Dimension of OS	V	[58,60,63,64,66]	V	[51,58,60]	V/E	[58,61,65]	V/E	[58,61]	**4**
H_{max} built front	V	[58,60,66,67]			V	[58,61,65]	V	[58,61]	**3**
H_{min} built front					V	[58,61,65]	V	[58,61]	2
MORPHOLOGY FEATURES: CHARACTERISTICS OF GEOMETRY AND SPACE									
Structural Type (SA/SU)	V	[67–72]							1
Accesses	V	[63,66,73–75]	H/V	[51,76]	V	[61]	V	[61]	**4**
Special buildings	V/E	[48,71]	V	[51,76,77]					2
Porches	V	[50]	V	[51]	V	[61]	V	[61]	**4**
Water / Green area	V/E	[74,78]	E	[51]	V	[61,79,80]	V	[61]	**4**
Slope	V	[50,64,74]	V	[51]	V	[81]	V	[42]	**4**
Canopy					V	[61,82]	V	[42,61]	2
Fountain			V	[51]	V	[61,83]			2
Dehors			V	[51]					1
Monuments / Archaeological sites	V/E	[48,84]	V	[51,76]					2
Underground cavities / Underground park	V	[64,85,86]	V	[76]					2
CONSTRUCTION FEATURES									
Homogeneity of built environment age	V	[28]							1
Homogeneity of construction techniques	V	[75]			V	[61]	V	[61]	**3**
Façade finishing					V	[45,61,87]	V	[61]	2
Urban furniture /obstacles	V	[50,64,88]	H/V/E	[51,76,89]	V	[61]	V	[61]	**4**
Pavement materials	V	[64,88,90]			V	[45,61,87]			2
Pavement lying	V	[64,88,90]			V	[61]	V	[61]	**3**
Pavement finishing	V	[64,88,90]			V	[61,87]	V	[61]	**3**

considered towards this purpose, due to its relevance and significance, still aiming at defining a general methodology.

A quantitative definition of the above-described parameters allows for the collection of the relevant data from the case study context and the implementation of the database.

Therefore, the procedure for the creation of the database of squares from the Italian context is addressed in this section. The data gathering process is performed on the basis of empirical observations and measurements of the selected morpho-typological parameters by means of web-based investigations. A combination of Google Earth [94], Maps and Street View by Google Maps [95] are employed to extrapolate all the features of the considered squares. The database is implemented in MS Excel [96], and the descriptive statistics are conducted by means of STATA 10 tool [97].

In order to select a significant sample of HBEs for the relevant case study of the Italian context, the main cities of Italy are taken into account. All the 112 provincial capitals of all the Italian Regions, plus further 21 medium-sized cities (i.e., over 20,000 inhabitants) are considered. The 21 towns have been included, even if they are not provincial capitals, to enrich the sample of squares with representative situations that are widespread in medium sized and small urban contexts. The database is thus composed by 133 Italian squares. The whole database adopted for the statistical analysis is reported in the supplementary material.

4. Results and discussions

4.1. Parameters for multi-risk scenarios

The quantitative parameters resulting from literature and experts' judgement analyses are illustrated in this section. As above recalled, squares are first classified according to their typology and morphology configuration, whether they are compact or elongated.

Given the great variety of shapes, it is worth further simplifying their geometry features to be included in the analysis, with the aim of providing the geometrical description unambiguously towards a clear typological characterization. A polygon is defined "convex" if and only if for any pair of points A and B in *P* (Polygon) the line segment between A and B lies entirely in *P*. Else, polygons that are not convex are defined "concave" (Fig. 3). After a first screening of the database, 43 squares have been excluded from the database for the calculation of the ranges of the parameters, as they presented peculiar characteristics with respect to their morphology. Indeed, concave squares present a high spatial com-

	SQUARE TYPOLOGIES PARAMETERS	By relevance	By expert judgment	Features (Fig. 1)
P1	**Morphological configuration** *Proportion between the width and length of the square*	X		*Morpho-typology*
P2	**Dimensions** *Width/length of the OS and height of the buildings' front*	X		*Dimension of OS, Hmax*
P3	**Structural type** *Geometrical configuration of the square frontier (i.e. isolated building (SU) or continuous built front (SA)) affecting the structural response*		X	*Structural Type (SA/SU)*
P4	**Accesses** *Number and dimensions of the accesses, i.e., square's permeability*	X		*Accesses*
P5	**Special buildings** *Type of buildings facing the square: presence of peculiar buildings, e.g, municipal or educational buildings, monuments and churches, relevant both with respect to structural and functions-related aspects*		X	*Special buildings, monuments, arch. sites*
P6	**Homogeneity of construction technique** *Type of constructions (e.g. masonry, concrete, steel) belonging the square frontiers*	X		*Homogeneity of construction techniques*
P7	**Porches** *Presence of porches in the square on the frontiers*	X		*Porches*
P8	**Slope** *Presence of slopes in the square*	X		*Slope*
P9	**Green** *Presence of green areas trees, bushes or grass within the square*	X		*Water / Green area*

Fig. 2. The nine parameters defining the square typologies by merging results of the counting of the relevance of the parameters of Table 1 and of the experts' judgement.

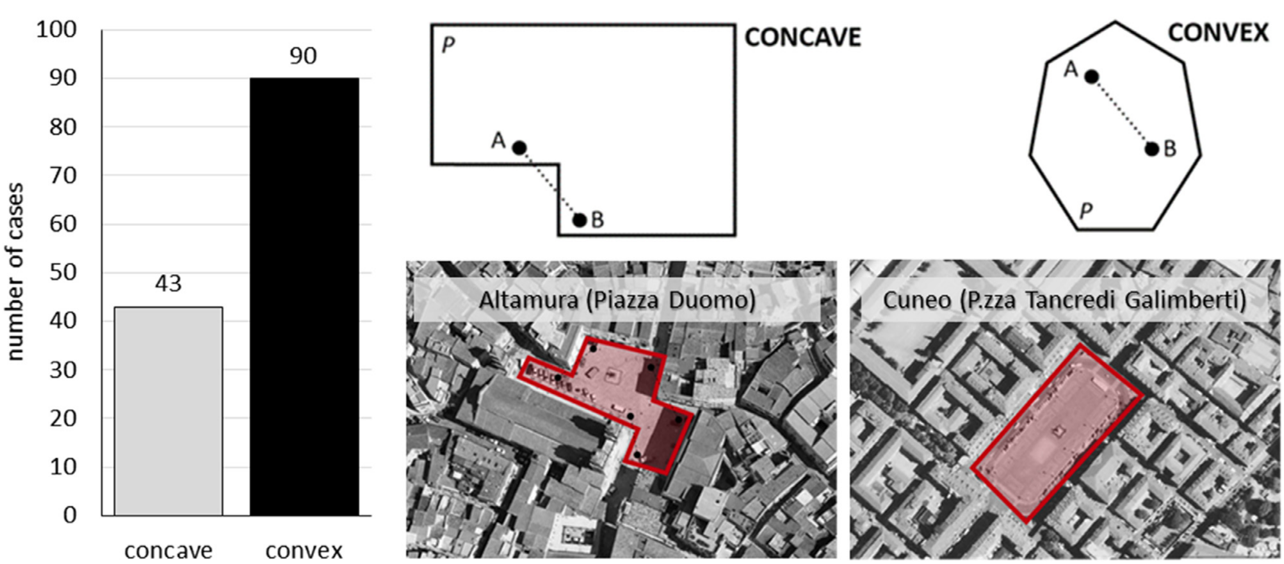


Fig. 3. Examples of concave and convex squares and frequency in the Italian sample of cases.

Acronym	Parameter	Acronym of the Option	Values	u. of m.	Need further quantitative analyses
P1	**Morphological configuration** *Shape defined by Ratio (R)= Width/Length*	a	Compact	[-]	Yes, ordinal / Define the ranges of each category
		b	Elongated	[-]	
		c	Very elongated	[-]	
P2	**Dimensions** *Relation between Maximum height (Hmax) and Width of the shorter side (W)*	d	True, $H_{max} > w$	[m]	No, boolean
		e	False, $H_{max} \leq w$	[m]	
P3	**Structural type** *Number of continuous built fronts*	f, g	Numerical (0 to 4);	[#]	Yes, ordinal/ Define the most common range
P4	**Permeability** *Characteristics of accesses*	h	$\Sigma\ \alpha_i > x°$; $\lambda > y$	[°],[-]	Yes, ordinal / Define the ranges of each category
		i	$\Sigma\ \alpha_i \leq x°$; $\lambda \leq y$	[°],[-]	
P5	**Special buildings** *Presence of special buildings*	l, m	True/False	[boolean]	No, boolean
P6	**Homogeneity of construction technique** *Presence of construction techniques*	n, o	True/False	[boolean]	No, boolean
P7	**Porches** *Presence of porches*	p, q	True (porches at least on 1 side of the frontier); False	[boolean]	No, boolean
P8	**Slope** *Presence of slope*	r, s	True/False	[boolean]	No, boolean
P9	**Green** *Presence of green*	t, u	True/False	[boolean]	No, boolean

Fig. 4. Quantitative description of the identified parameters.

plexity, and moreover they can be considered as the sum of convex shapes. Thus, according to this geometric assumption, only convex squares have been included in the database for the statistical analysis. This criterion has been adopted for sake of generalizability, and further research could include also concave shapes for further developments. This choice is also motivated by the results on the 133 samples: the 32% (43 squares) of Italian squares is concave, while the 68% (90 squares) is convex.

The parameters described in the methodology section are below illustrated with respect to their quantitative evaluation (Fig. 4), by organizing them into relevant classes so as to move towards the typological description of the squares among the multi-risks scenarios. They are all either Boolean or ordinal. The range of variability of the parameters is calculated solely for ordinal parameters, which are thus calibrated on the sample of 90 squares of Italian HBE (see Section 4.2). Indeed, Boolean parameters could either assume the value of false, i.e., 0 or true, i.e., 1 and thus their range does not need to be defined. Ordinal parameters are P1 to P4; Boolean parameters instead are P5 to P9 (Fig. 4).

- **P1 - Morphological configuration** (ordinal)**:** it is the ratio between the square length (L) and width (w). This ratio provides a quantitative value to distinguish the main types of square that have been previously identified in qualitative terms [58].
- **P2 – Dimensions** (boolean): it is expressed in terms of maximum height (H_{max}) of the frontiers and width (w) of the

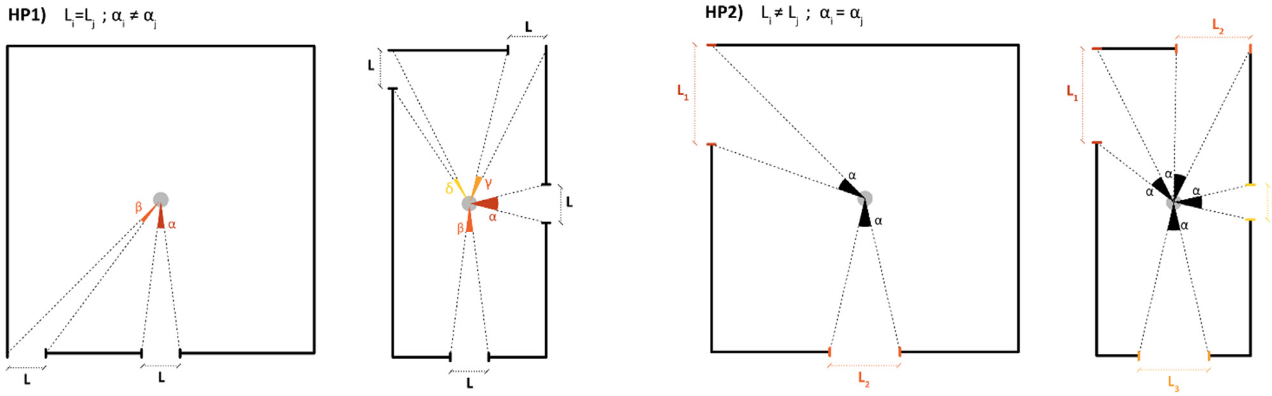
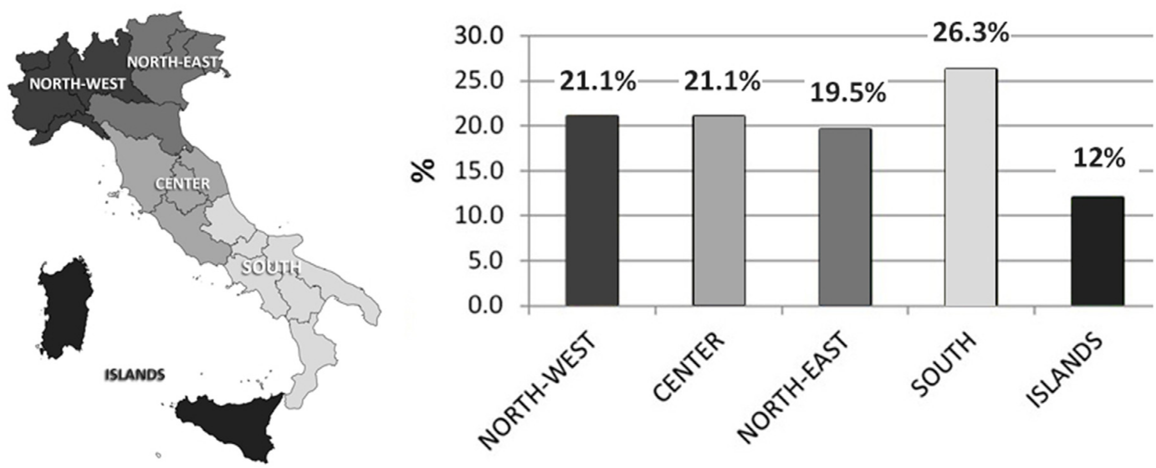


Fig. 5. Permeability (P4): distance from the barycenter of the square to accesses, considering the subtended angle.



Descriptive statistics		P1 [-]	P3 [-]	P4_$\sum\alpha_i$ [rad]	P4_$\sum\alpha_i$ [°]	P4_λ
Minimum		0.14	0.00	0.10	6	0.04
Percentile	25th	0.36	4.00	0.34	22	0.09
	50th (Median)	0.57	4.00	0.57	34	0.11
	75th	0.70	4.00	0.78	50	0.17
Maximum		1.00	4.00	1.87	107	0.35
Mode		0.67	4.00	0.60	39	0.11
Mean		0.55	3.67	0.63	38	0.13
St. Deviation		0.22	0.79	0.40	23.6	0.06

Fig. 6. Geographical location and distribution of the squares in the different areas of Italy (above); and descriptive statistics of the sample (below).

shorter side of the square. It means that there is at least one building/front that is higher than the shorter side of the square.

- **P3 - Structural type** (ordinal)**:** it is referred to the structural arrangement of the built fronts as Structural Aggregates (SA), meaning that it is not possible to distinguish separate buildings on the front, as they are aggregates with buildings sharing at least one side. This structural type characterizes the majority of historical urban settlements in the Italian context.
- **P4 – Permeability** (ordinal)**:** it is referred to the “quality” of the accesses on the frontiers of the square. The access can be described by different parameters that influence the whole evacuation process: the total number of accesses, the width of each access, its position in the square, the distance between accesses. Some studies [98] outline that the evacuation time is influenced by the exit width (i.e. in case of a single exit), the distance between the exits and the distance to the exits (i.e. in case of two or more exits).

For the purpose of the identification of the square typologies, we focus on the features providing the morphological characterization of the access system, such as the layout of the accesses with respect to the perimeter of the square. A novel characterization of the accesses has been carried out considering the permeability in geometrical terms (Fig. 5). Given the barycenter of the square, permeability is represented by the sum of the subtended

Acronym	Parameter	Acronym of the Option	Values	u. of m.
P1	**Morphological configuration** *Shape defined by Ratio (R)= Width/Length*	a	Compact (1 ≥ R ≥ 0.70)	[-]
		b	Elongated (0.70 > R > 0.36)	[-]
		c	Very elongated (R ≤ 0.36)	[-]
P3	**Structural type** *Number of continuous fronts*	f, g	up to 3 fronts (No) or all fronts (Yes)	[boolean]
P4	**Permeability** *Characteristics of accesses*	h	Σ αi > 34° ; λ>0.11	[°],[-]
		i	Σ αi ≤ 34° ; λ ≤ 0.11	[°],[-]
P5	**Special buildings** *Presence of special buildings*	l, m	Yes/no	[boolean]
P6	**Homogeneity of construction technique** *Presence of construction techniques*	n, o	Yes/no	[boolean]
P7	**Porches** *Presence of porches*	p, q	yes (porches at least on 1 side of the frontier); no	[boolean]
P8	**Slope** *Presence of slope*	r, s	Yes/no	[boolean]
P9	**Green** *Presence of green*	t, u	Yes/no	[boolean]

Fig. 7. The calibrated parameters, based on the descriptive statistics of the HBE squares of the sample.

angle ($\Sigma\alpha_i$) [rad]. It is worth clarifying that the measure of the angle varies depending on the different positions of the accesses: HP1) accesses with same width (L_i) will have different angle depending on whether they are set in the middle or in a corner of square's side; HP2) accesses with same angle will have different width depending on their position on the frontier. Hence, $\Sigma\alpha_i$ is related: (1) to the variation of L_i depending on the overall dimension and morphology of the square; and (2) to the maximum degree of the angle (360°) thus taking into account all the frontiers.

The $\Sigma\alpha_i$ is more adequate to represent the permeability of not extremely elongated elements, as the measurement of the subtended angles would be more prone to errors. Therefore, for elongated spaces another coefficient has been tailored, coefficient λ which is given by the ratio between the sum of the width of the accesses (ΣL_i) [m] and the perimeter (2P) of the square [m].

- **P5 - Special buildings** (Boolean)**:** it refers to the presence of buildings that stand out from the surrounding context and constitute emerging elements for the specific function or the architectural value.
- **P6 – Homogeneity of construction techniques** (Boolean)**:** it refers to buildings facing the square that are characterized by masonry as prevalent structural type.
- **P7 – Porches** (Boolean)**:** it refers to the presence of porches on the OS frontiers, evaluated as 1 if at least one side of the square has porches.
- **P8 – Slope** (Boolean)**:** it refers to the presence of a slope over 8%, which is the maximum slope for paths accessible to everyone (while 5% is recommended [99]), according to Italian regulations.
- **P9 – Greenery** (Boolean)**:** it refers to the presence of greenery (trees, bushes, grass).

4.2. Parameters in the Italian historical urban settlements

After identifying the quantitative parameters, the calibration of the ranges is conducted. To this aim, ordinal parameters have been calculated for the sample, and have been arranged in a spreadsheet to allow descriptive statistical analysis (see Supplementary materials).

After the above set of parameters is defined, and the database built, descriptive statistical analyses are conducted on the 90 historical squares, which are equally distributed among Italian regions (Fig. 6).

The descriptive statistics related to the quantitative definition of the parameters are reported in Fig. 6. The percentile distribution, the maximum, the mode, the mean and standard deviation

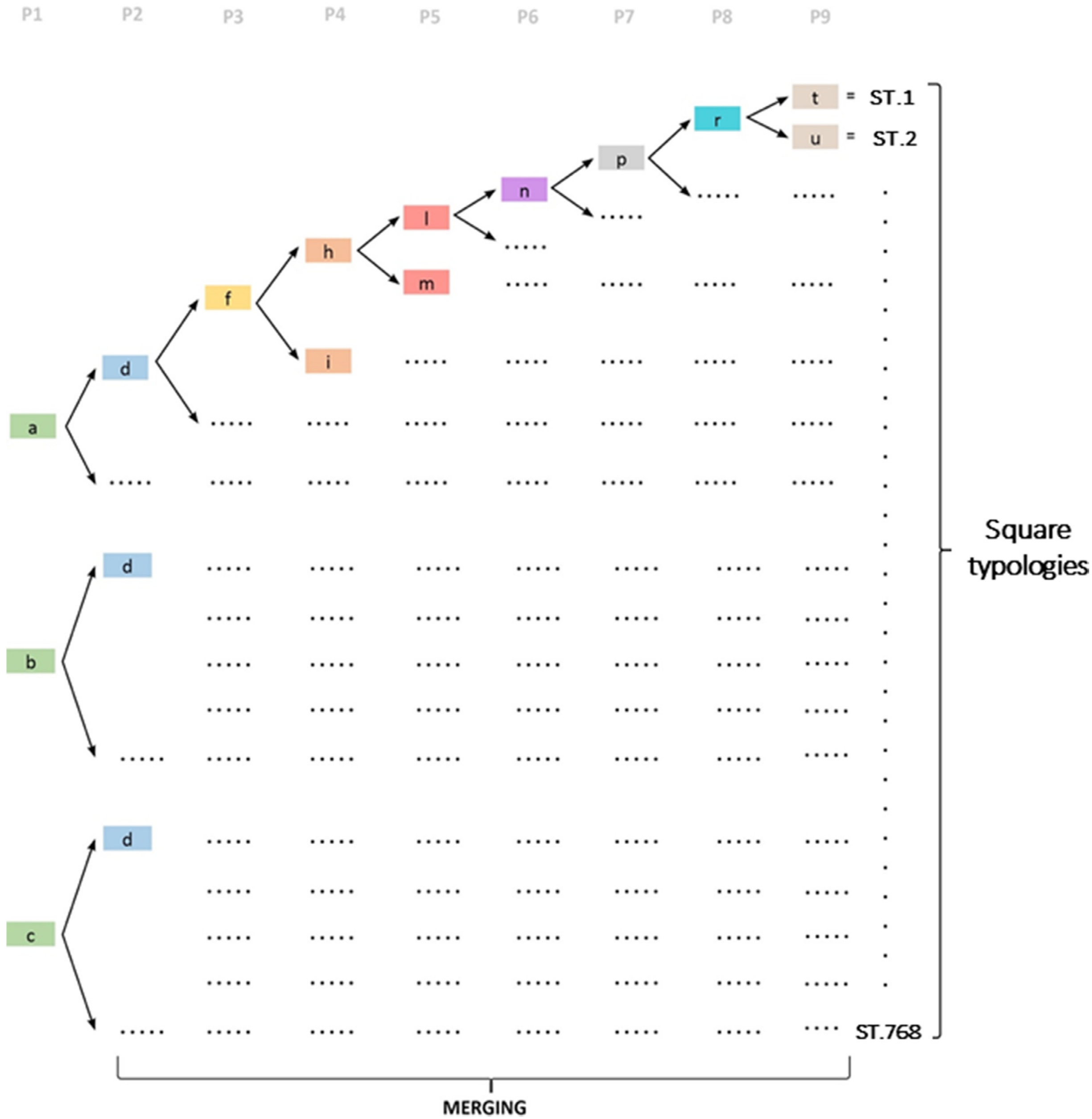


Fig. 8. Permutations to achieve the square typologies, as a combination of values of the parameters: 3×2^8=768.

are illustrated, in order to provide useful information on the distribution of the considered sample for each parameter. In greater detail, the percentile distribution, comprising the 25%, the 50% and the 75% allows observing the score under which a percentage of the sample falls. E.g., for the 70% of the sample, P1 is lower than 0.7. Both the mean and the mode give information about the average values: the mean is the arithmetic average of the values for each parameter, while the mode is the most frequent value in the dataset for each parameter. Finally, standard deviation is the dispersion of a set of values: when it is low, it means that the values in the dataset are close to the mean.

The mean P1 is equal to 0.55, thus the majority of the squares is rectangular-shaped, and the most are comprised between 0.36 and 0.70. With respect to permeability, the mean sum of the subtended angles from the center of the squares to the accesses is 0.63 [rad], equal to 36°, and the majority of the sample is comprised between 20° and 45°.

Based on the descriptive statistics, in order to perform an in-depth analysis of the ranges and their definitions towards typologies definitions, further observations can be made for some parameters.

In order to calibrate P1 values to quantitatively define the shapes of the squares, the sample is further investigated. An analysis of the dimensional ratio (R=w/L) of the 90 samples of convex squares is carried out starting from the ideal shapes of quadrangular-based (R=1) and rectangular-based (R=0.5) square typologies. Then, an intermediate shape class is also included, so as to further detail the geometry. The percentile values of P1 from the sample squares have been considered, and support the definition of three categories pertaining to P1. Such shapes are: (a) the compact shape, close to a quadrangle, with a P1 comprised between 0.7 and 1 (respectively the 75th and 99th percentiles); (b) the elongated shape, which is rectangular, with P1 comprised between 0.36 and 0.7 (respectively the 25th and 75th percentile);

Parameter	Representation needed
P1	PLAN
P2	SECTION
P3	PLAN
P4	PLAN
P5	PLAN, SECTION
P6	PLAN, SECTION
P7	PLAN, SECTION
P8	PLAN, SECTION
P9	PLAN, SECTION

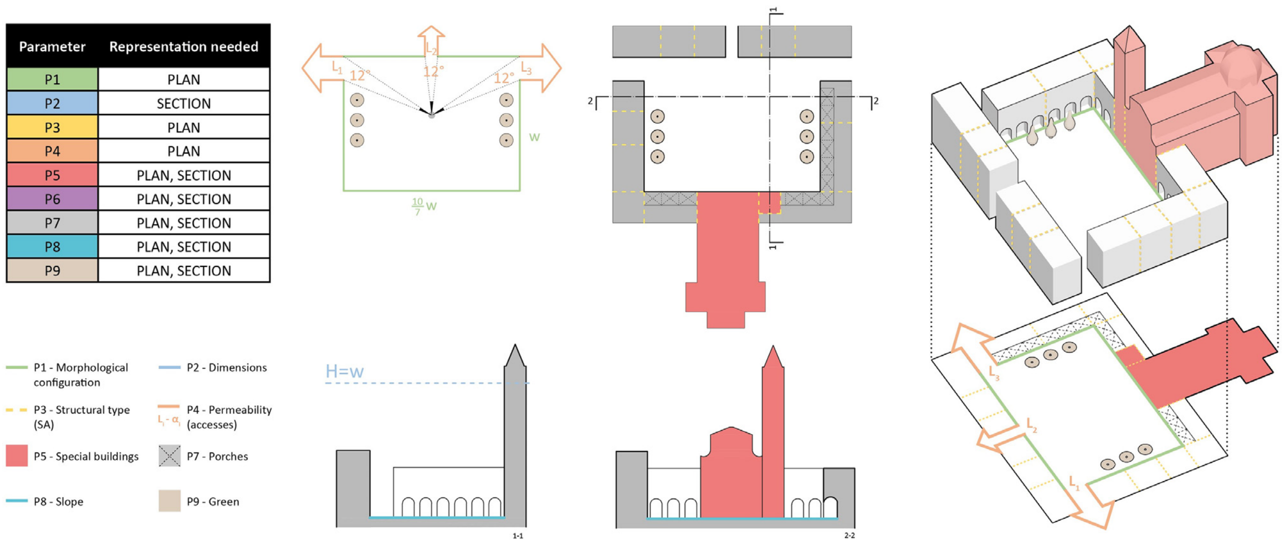


Fig. 9. Square typologies representation for disclosing each parameter.

and (c) the very elongated shape, with P1 lower than 0.36, which corresponds to the 25th percentile.

P3, after evaluating that almost all the squares of the sample have all the 4 sides composed by continuous frontiers, and that the percentiles all corresponds to 4, is transformed into a Boolean parameter: when not all fronts are continuous P3=no/0, when all the fronts of the square are continuous, P3=yes/1.

Finally, with respect to P4, both $\Sigma\alpha_i$ and λ are considered: in this case, two categories are made, for sake of simplification, where the median (also corresponding to the 50th percentile) define the boundary between the two categories. Therefore, as from Fig. 6, category (h) corresponds to higher level of permeability, with $\Sigma\alpha_i > 34°$; λ>0.11; and (i) corresponds to lower permeability, with $\Sigma\alpha_i \leq 34°$; $\lambda \leq 0.11$.

Thus, the calibrated parameters are displayed in Fig. 7 according to this experimental-based classification on the assessed Italian sample.

4.3. Square typologies definition and discussions

The methodology succeeds in identifying parameters that are suitable to describe the case-study context, for supporting the definition of square typologies, by combining the ranges and values for each parameter. The definition of each square typology can be composed starting from one of the three possible morphological configurations of P1 (compact (a), elongated (b) and very elongated (c) shape), and successively applying P2 two options (d, e), P3 two options (f, g) and so on until P9 (t,u) (Fig. 8). Indeed, the parameters were ordered, from P1 to P9, with respect to scale, first defining the more general aspects of the squares and then those related to smaller scale and content features. Thus, we obtain the combinations of parameters that allow identifying the typology of the square. The total number of typologies obtained in this manner by permutation is 768, which are able to identify peculiar features of the squares that are relevant for multi-risk evaluation and are composed by the 9 quantitative parameters. The so-defined typologies thus aid in the comprehension of the HBE, as an expeditious support to evaluate vulnerability and exposure to multi-risks (Fig. 9). Indeed, the huge amount of remotely-acquired digital data to be traditionally processed for defining the vulnerability to multi-risks of HBE squares is significantly reduced. Given the case-study context and the consideration of the relevant parameters, such squares typologies are specifically indicated for identifying their a-priori intrinsic performance towards multi-risk scenarios in the HBE.

In order to test the above defined square typologies and parameters, four squares are randomly selected among historical Italian urban settlements and classified with respect to typologies. Piazza Vittorio Emanuele II (Caldarola), Piazza San Francesco (San Gemini), Piazza del Popolo (San Giovanni in Persiceto) and P.zza della Repubblica (Novara) are assessed with respect to the nine parameters (Fig. 10). Each one of the cases correspond to one square typology: e.g., Caldarola is the square typology (ST) characterized by the following combination of parameters' options $ST_{Caldarola}=b+d+g+h+l+n+p+r+u$.

The implications of the definition of square typologies, based on these parameters, are relevant for many purposes.

Indeed, they facilitate the potential representation of squares of the HBE by means of BIM-based models, towards digitalization and exploitation of information technologies for the conservation and safeguarding of the built cultural heritage. BIM-based models could support the comprehension of the multi-risk performance of square typologies. Indeed, the informative aspects of BIM could aid towards the automation of the calculation and storage of multi-risks analysis, thus highlighting the direct connection between the HBE characteristics and the corresponding risks. This automated process would shorten the computational and representation burden of assessing the sensitivity to multi-risk for a specific square, thus allowing a precise but yet expeditious quantification of multi-risks, which could consequently lead to identify the most sensitive characteristics of the square to risks and consequently prioritize certain mitigation interventions according to the findings of the analyses. To achieve such a result, the first step is to study and develop a method for the square typologies representation in BIM-based models, able to describe properly buildings, infrastructures, and open spaces characteristics related to multi-risk performance. Moreover, considering specific case studies representing square typologies, the complexity and the variety of geometries and features of existing built cultural heritage raise the issue of their representation, both in terms of geometric model and information details. Therefore, it is necessary to plan a tailored workflow from the integrated survey and data acquisition phase to the modeling and implementation phase, able to represent the peculiarity of the multi-risk scenario required.

	PARAMETER	Caldarola	San Gemini	S. G. in Persiceto	Novara
P1	a= compact		X		
	b=elongated	X		X	
	c= very elongated				X
P2	d= $H_{max} > w$	X		X	X
	e= $H_{max} \leq w$		X		
P3	F=not all fronts			X	
	G=all fronts	X	X		X
P4	H= $\Sigma\, \alpha_i > 36°$; $\lambda>0.06$	X	X	X	
	I=$\Sigma\, \alpha_i \leq 36°$; $\lambda \leq 0.06$				X
P5	l	X	X	X	X
	m				
P6	n	X	X		X
	o			X	
P7	p	X		X	X
	q		X		
P8	r	X		X	
	s		X		X
P9	t				
	u	X	X	X	X

Fig. 10. Testing square typologies in the Italian context.

5. Conclusions

In this article, squares of historical urban settlements in the Mediterranean area are considered towards the definition of the relevant parameters, as well as their classes and ranges, towards the identification of square typologies for expeditious multi-risks assessment. Morpho-typological characteristics influencing risks (e.g., SUODs and SLODs) response are first generally analyzed based on literature analysis and experts' judgement, and then applied and verified to a significant and relevant case study, i.e., the Italian context.

Nine parameters are identified, each of them with a quantitatively-defined range of options and possible values, which are calibrated on the case-study context. Results show that the set of parameters and their combination in square typologies could be employed for an expeditious characterization of resilience to multi-risks of squares in the HBE, thus responding to the research question we posed.

The definition of such parameters could be convenient as a preliminary phase to provide representative BIM models for the successive risk-related typological analysis of the Italian squares. Indeed, the opportunity to use the BIM-based models to represent the squares typologies as well as to collect the information for their classification in a multi-risk perspective could be explored in future development of the research. In this view, this study paves the way for following works dealing with the meso–scale of the HBEs, which requires specific considerations to allow for the schematization of complex geometries and risk-related characteristics in BIM-based models.

Moreover, the assessment of the multi-risk parameters, which facilitates the definition of the performance of the square typologies to multi-risks, support the conservation of the built cultural heritage that is hosted in or constitutes the frontier of the square, as well as its safe fruition and sharing with the civil society. Indeed, HBEs are also characterized by significant exposure level, in terms of human lives, due to their attractiveness with respect to tourists. Tourists are assumed to generally be not familiar with the specific HBE they are visiting, both considering layout and site-specific emergency plan and procedures, and then their associated risk is much higher than the one of residents and frequent visitors (e.g. daily users), as demonstrated by previous research [11,100,101]. Thus, promoting the adoption of the parameters towards the expeditious assessment of square typologies performance to multi-risks would aid in: (1) the rapid comprehension of possible conditions influencing risks in the HBEs; and therefore (2) the adoption of effective risk-mitigation strategies (including those focused on emergency management rather than on interventions on buildings). The presented method can be applicable to all the HBEs in the historic city centers, since the parameters could be used (or even adapted) to face risk-related morpho-typological issues for the desired application scenario. However, the current work demonstrates the effectiveness of the method on a relevant case-study database, which is limited to the Italian context. Future research could enlarge the sample dimension of the squares, as well as apply the method and test the parameters in other contexts and different HBEs (e.g. streets in the historic city center rather than squares), to further expand their representativeness.

The research is relevant for policymakers and urban planners, as it facilitates the preliminary analyses of the squares, as nodal components of the HBE in urban areas, towards improved resilience to multi-risk scenarios by means of the identification of square typologies. Indeed, these analyses require in-depth and time-consuming investigations especially in the HBE. Moreover, this work is relevant also for researchers in the field of urban resilience, which could contribute to further studying square typologies, in different geographical locations and contexts, and could start from the proposed parameters and typologies to perform multi-risk scenarios simulations. Finally, the identification of typologies of the HBE that are more prone to specific risks also facilitates macro-scale and micro-scale analyses, as a further benefit of the present work. Indeed, meso–scale results can dialog both with the macro-scale, e.g., by considering the vulnerability to multi-risks of a combination of close-by squares; or either with the micro-scale, e.g., by using it as a base for more detailed simulations and assessments on specific critical elements.

Funding

This work was supported by the MIUR (the Italian Ministry of Education, University, and Research) Project BES^{2}ECURe - (make) Built Environment Safer in Slow and Emergency Conditions through behavioUral assessed/designed Resilient solutions (Grant number: 2017LR75XK).

CRediT authorship contribution statement

Federica Rosso: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Letizia Bernabei:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Gabriele Bernardini:** Conceptualization, Methodology, Validation, Data curation, Writing – review & editing. **Martina Russo:** Conceptualization, Methodology, Writing – review & editing. **Marco Angelosanti:** Conceptualization, Methodology, Writing – review & editing. **Edoardo Currà:** Conceptualization, Methodology, Writing – review & editing, Project administration, Funding acquisition, Supervision. **Enrico Quagliarini:** Conceptualization, Methodology, Writing – review & editing, Project administration, Funding acquisition, Supervision. **Giovanni Mochi:** Conceptualization, Methodology, Writing – review & editing, Project administration, Funding acquisition, Supervision.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.culher.2022.06.012.

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