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An application of a cost-based programming model for the management of seismic vulnerability of the historic center of San Giorgio a Cremano (Italy)

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Abstract

Within historic city centers, custodians of a timeless cultural heritage, lies an often-overlooked reality: the seismic vulnerability of buildings. These ancient structures are often constructed with techniques and materials that do not meet modern seismic safety standards. In the outlined framework, the contribution aims to address the issue of managing the seismic vulnerability of urban and historical fabrics, implementing a tool capable of coordinating and optimizing resources, whether public or private. This is achieved through the application of a cost-based programming model for the management of seismic vulnerability in the historic center of San Giorgio a Cremano (Italy). Operational areas of relevance for the present study include the conservation of architectural-urban heritage, the management of territorial planning processes and urban redevelopment, and the implementation of economic assessment and programming tools to support decision-making processes.

Keywords: Seismic vulnerability; Cost-based programming model; Historic centers; Decision-making processes.

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1. Introduction

The social capital of the city manifests through both urban and human dimensions. Urban capital (information, organization, integration, interdependence, self-building capacity) constitutes the form of cities and, as such, the context in which human capital is shaped. Human capital represents the value term of urban form. The function of human capital value encompasses multiple aspects, among which safety regarding a possible seismic event plays a primary role, particularly in the formation of strategies for preserving historic buildings.

Among the key aspects of the revitalization of historic centers, safety is increasingly crucial, given the weight of present dramatic evidence and the “rigidity” of historical building heritage and its structural inadequacy to transformations. This drastically selects the entities exercising demand for properties for residential, commercial, recreational, and even public uses (administration, education, etc.).

Seismic risk is influenced by specific factors such as hazard, exposure, and vulnerability. Among these factors, seismic vulnerability is the only element that can be targeted to mitigate seismic risk. This entails implementing coordinated measures at the urban level, with the evaluation of their economic feasibility often serving as a guide for the formulation of risk reduction policies tailored to the socioeconomic and political context involved. Ancient urban fabrics exhibit much higher seismic risk due to various specific factors such as construction typology, general deterioration of masonry due to impromptu and inadequate renovation interventions, high building density, and specific urban development principles, the effects of which are challenging to mitigate (Giuffrida et al., 2019 and 2020; Manganelli et al., 2018 and 2022; Forte et al., 2021; Del Giudice et al., 2014a, 2014b, 2016a, 2016b 2021, 2023).

Small urban centers are often characterized by territorial and socioeconomic aspects that increase their exposure to seismic risk, such as limited or restricted internal and/or external accessibility (Carbonara, 2012), a general demographic and socioeconomic decline resulting from the prevalence of elderly individuals and/or residents with low income (Barreca et al., 2017; Curto and Fregonara, 2019).

In the outlined framework and with reference to an urban area in the historic center of San Giorgio a Cremano (Italy), the work develops a detailed analysis and a set of evaluations aimed at identifying the economic feasibility conditions for establishing the seismic emergency limit, combining the technical aspects of seismic vulnerability assessment with the economic aspects of intervention cost evaluation. Operational areas of relevance for the present study include the conservation of architectural-urban heritage, the management of territorial planning processes and urban redevelopment, and the implementation of economic assessment and programming tools to support decision-making processes.

2. Materials and Methods

Seismic vulnerability mitigation refers to the set of actions and strategies aimed at minimizing the harmful effects of an earthquake on a specific area or structures. These actions may include structural reinforcement interventions, improvement of building regulations, targeted territorial planning to reduce exposure to seismic risk, and raising awareness among the population about safe behaviors to adopt during an earthquake. In other words, the goal of seismic vulnerability mitigation is to make communities and structures more resilient to the effects of earthquakes.

2.1. The city of San Giorgio a Cremano

San Giorgio a Cremano is an Italian municipality with a population of 42,435 inhabitants in the metropolitan city of Naples in Campania, the third Italian municipality by population density after Casavatore and Portici (both in the same metropolitan city of Naples). It covers an area of 4.11 square kilometers and is located 56 meters above sea level. Its numerous 18th-century Vesuvian villas are an integral part of the so-called "Golden Mile," the stretch of road passing through the city of San Giorgio to Torre Annunziata. Situated between the slopes of Mount Vesuvius and the sea, it is now an integral part of the urban agglomeration of the city of Naples.

2.2. Seismic vulnerability mitigation and the cost-based programming model

The seismic vulnerability analysis of historic centers can be carried out in three phases: knowledge, assessment, and design (Carocci, 2012 and 2013). The knowledge phase concerns the main evolutionary stages of the historic center, as well as the identification of elements that can have significant effects on the seismic behavior of the urban fabric, such as building resistance factors and vulnerability factors related to possible overturning of interfering facades. In this regard, the aim is to identify possible points of constructional discontinuity and relationships of contiguity between buildings with different geometric and structural characteristics. In the assessment phase, a judgment must be formulated on the quality of the urban fabric and anticipate the possible expected damages corresponding to the identified criticalities. The economic evaluation of interventions aimed at reducing the vulnerability of buildings and the entire historic center represents conclusively the design phase.

The cost-based programming model can measure the probability of facade overturning under the dynamic action of the ground, with an acceleration coefficient α_{0b} and α_{0v} depending on whether the basic (less favorable) or varied (more favorable) configuration is considered. The coefficient measures the ground acceleration at which the facade overturns, and therefore its magnitude is inversely proportional to the resistance to overturning of the structure.

The assessment of the seismic vulnerability of buildings, understood as susceptibility to damage following the occurrence of a seismic event, unfolds in two consecutive phases: 1. identification of parameters of geometric, constructional, and structural nature deemed significant for predicting seismic damage; 2. definition of a vulnerability indicator correlated with seismic acceleration and expressed as a function of the aforementioned parameters.

The quantitative correlation between the various parameters influencing seismic vulnerability allows obtaining a measure of the level of acceleration required to achieve assigned damage levels and is therefore suitable for evaluating, by comparison with the expected accelerations in San Giorgio a Cremano, the degree of safety defined above.

2.3. Criteria for seismic damage prediction

The identification of parameters necessary for qualifying seismic vulnerability requires the preliminary formulation of assumptions to underpin the anticipation of damage and subsequent construction of the mechanical model to be used for safety assessment. In this regard, some general considerations are possible.

Considering that each of the fronts of the involved blocks can be affected by seismic action orthogonally or parallel to its mean plane, seismic damages will essentially consist of initiating out-of-plane overturning kinematics of the most vulnerable portions of the facade walls, or damage due to shear of these walls (Giuffrida et al., 2019 and 2020).

Out-of-plane overturning damage to exposed walls typically exhibits some recurring characteristics:

- the most vulnerable wall portions are generally those at the top (wall copings or top floors);
- total overturning of exposed fronts is very rare, requiring the concurrence of several circumstances usually not all verified (lack of tapering, non-restraining frames, absence of seismic measures, etc.);
- rarely does the overturning of exposed walls, even limited to only the top portions, involve the entire extent (width) of a facade.

Damage due to shear of exposed walls can generally be hypothesized:

- for the terminal portions of each exposed front;
- for intermediate portions characterized by geometric or positional peculiarities (wall spurs, projecting portions, etc.).

For both forms of damage - out-of-plane and in-plane - it is then evident how the presence, extent, and configuration of the disturbances present on the exposed walls can introduce further points of weakness.

Simultaneously, for the Municipality of San Giorgio a Cremano, the Emergency Limit Condition (ELC) has been considered, a measure introduced by the Italian Government aimed at ensuring the functioning of the emergency management system in the post-earthquake phase. By definition, the ELC represents the limit condition in which, after the seismic event, the urban settlement loses all its functions (including residence) and retains only the exercise of most strategic functions for emergency management, their accessibility, and connection with the territory.

2.4. Vulnerability index

Following the identification of the most vulnerable portions of the exposed fronts, based on the qualitative criteria mentioned earlier, it is possible to evaluate for individual walls a numerical indicator related to the level of acceleration capable of triggering elementary overturning kinematics (out-of-plane). This indicator is defined, consistently with the conceptual framework of the Italian Technical Standards for Constructions (NTC, 2018), as the motion triggering multiplier for overturning (α_0) of the wall, taking into account:

- presence and extent of tapering;
- direction of floor joist layout (parallel or orthogonal to the wall);
- presence of floor tie beams;
- effectiveness of anchorage with orthogonal walls.

By calculating the motion-triggering multipliers, the dependence of the chosen indicator on a limited number of significant geometric and typological parameters is recognized for San Giorgio a Cremano, which are as follows:

- $S1$= wall thickness at ground level;
- H = total wall height;
- L = distance between shear walls;
- N = total number of floors;
- p = number of floors without tie beams (counted from the top);
- k = direction of frame layout (k=1: floor parallel to the facade; k=3: floor perpendicular to the facade);
- r = anchorage with shear walls (r=0 for absence of anchorage), where:

$$r = 0.01 \cdot (9 - L) \cdot \left[\frac{(p+1)^2}{k}\right] \tag{1}$$

The expression of r is valid only for L<9 mt., beyond which the substantial ineffectiveness of the anchorage is revealed, thus r=0 can be assumed.

The motion-triggering multiplier assumes different expressions for the base configuration and the varied one.

The first is characterized by the simultaneous occurrence of two circumstances: absence of tie beams ($N=p$); floors laid parallel to the facade ($k=1$). The second by the absence of one or both of the aforementioned circumstances, thus ($N>p$) and/or ($k=3$). For both, the contribution of anchorage with shear walls acts in the same way (i.e., with an additive term).

The expression for the basic configuration follows ($N=p$, k=1):

$$\alpha_0 \approx (1 + r) \cdot \left(\frac{S1}{H}\right) \tag{2}$$

The equation for the varied configuration ($N>p$, k=3) is characterized by the r parameter defined as equation (1):

$$\alpha_0 \approx (1 + r) \cdot 0.3 \cdot \left(\frac{S1}{H}\right)^{\left(1 - \frac{n}{100}\right)} \tag{3}$$

also considering that:

$$\begin{cases} n = 72, if\ N = p \\ n = 83 - 21p + 13(p + 1)\left(\frac{k-1}{2}\right), if\ N > p \end{cases} \tag{4}$$

It is recognized that the motion-triggering multiplier α_0 for overturning, of each segment of exposed wall between two shear walls, predominantly depends on the ratio between the thickness of the wall segment at ground level and its total height ($S1/H$), both easily obtainable from external visual inspection.

The acceleration coefficient is calculated for each facade unit (UF). These are delimited by two orthogonal walls, which are considered to have independent dynamic behavior compared to others within the same unit or adjacent.

It is possible to consider two additional supplementary metrics to identify facade units, namely blocks and architectural units (AU).

Within the evaluation/programming process, attention will be focused on the vulnerability of each AU. This is based on characterizing each UF in terms of geometric and constructional characteristics useful for calculating the two acceleration coefficients. The information base used to calculate and select interventions includes the identification of UF in the real estate complexes to which they belong (block and architectural unit); facade units per aggregate; number of facades for each building; above-ground floor numbers; gross surface area of facades; heights of different floors; average height of each floor; construction system; wall type; orientation of the floor structure relative to the direction of the facade; projecting elements; tie beams, assumed necessary if the width of the front facade exceeds 6.50 mt and the number of floors is greater than 1; presence of tie beams; and presence of lesions.

The tendency for facade overturning has been calculated according to (a) a cautious pessimistic scenario indicated as the base configuration quantified by coefficient α_{b0}, and (b) an optimistic scenario indicated as the modified configuration quantified by coefficient α_{v0}.

2.5. Cost-based programming model

Once the acceleration coefficient is calculated and therefore the degree of vulnerability of each UF determined, logical and research functions associate it with safety measures, starting from the most common ones, up to the most consistent or invasive ones, such as the installation of tie beams, filling of superficial lesions, integration of masonry damaged by through lesions, introduction of reinforced masonry, fixation of protruding and towing elements, and external and internal finishing works related to walls and ceilings, articulated into a total of 36 actions in a price list. The elementary costs associated with interventions on each facade unit are then aggregated to calculate the total cost of each hypothesis related to the ELC.

Each hypothesis related to the ELC is defined by varying the intensity of interventions and/or their extent. The intensity depends on the degree of completeness of interventions with the same extent. The extent is the number of UF involved with the same degree of safety completeness. The result is two cost functions, one intensive and one extensive. Therefore, we can conclude that the cost of the ELC is calculated by combining an intensive function and an extensive function.

Combining the five degrees of completeness with the five degrees of safety, 25 different hypothetical strategies with increasing costs have been defined. The extensive cost function refers to the number of UF included in the ELC, according to their degree of vulnerability measured based on the previously defined acceleration coefficient. The UF are grouped according to the five thresholds $k_{60\%}$, $k_{70\%}$, ..., $k_{100\%}$, delineating five corresponding sub-ranges of the acceleration coefficient associated with each UF: $k_{60\%}$ defines the subrange of facades whose acceleration coefficient is lower than the minimum (α_{min}) corresponding to the maximum level of vulnerability and the minimum number of UF included in the ELC; vice versa for $k_{100\%}$, which corresponds to the maximum number of facades included in the ELC. Intermediate levels are defined by progressively adding one quarter of the range ($\alpha_{max} - \alpha_{min}$) to α_{min}, thus: $k_{70\%} = \alpha_{min} + (\alpha_{max} - \alpha_{min}) \cdot 0.25$; $k_{80\%} = \alpha_{min} + (\alpha_{max} - \alpha_{min}) \cdot 0.50$; $k_{90\%} = \alpha_{min} + (\alpha_{max} - \alpha_{min}) \cdot 0.75$.

Depending on the degree of vulnerability of each of the 209 facade units analyzed (of which 204 need to be protected), the model identifies the interventions necessary to protect them. It should be noted that interventions are not activated automatically and unequivocally, but based on the type of strategy the decision-maker chooses. The interventions to be applied are decided based on the degree of completeness.

The completeness of interventions is described in Table1. This table shows the types of works included in each of the five strategies depending on needs, interested party (public or private), degree of safety, and invasiveness:

- degree of completeness 1 includes only works that can be considered necessary, of public interest, of minimum safety, and non-invasive;
- degree of completeness 2 includes necessary works, of minimal public interest, of safety, of maximum safety for 70% of the total amount of UF, and non-invasive works;
- degree of completeness 3 includes necessary works, of public interest and private interest for 50% of the total amount of UF, of minimum and maximum safety, non-invasive and invasive;
- degree of completeness 4 includes necessary and unnecessary works for 30% outside the total amount of UF, of public and private interest, of minimum and maximum safety, non-invasive and invasive;

- degree of completeness 5 includes all works.

Table 1. Degree of completeness for building works

Type of Building Work	Completeness Degree				
	1	**2**	**3**	**4**	**5**
Necessary	1	1	1	1	1
Unnecessary				0.3	1
Public	1	1	1	1	1
Private			0.5	1	1
Minimum Security	1	1	1	1	1
Maximum Security		0.7	1	1	1
Not Invasive	1	1	1	1	1
Invasive		1	1	1	1

3. Results

With reference to the vulnerabilities observed in the historic center of San Giorgio a Cremano, improving seismic response is pursued through targeted interventions aimed at: controlling thrusts on roofs and reducing the thrusts of vaulted elements; improving connections between walls and horizontal structures with particular attention to restraining facade walls. These indications allow for defining the priorities of public intervention within the historic center - promoting a coordinated management of economic resources - and identifying incentive mechanisms to be implemented for the realization of private interventions.

Fig. 1 shows a mapping of the neighborhood examined and the vulnerability of UFs.

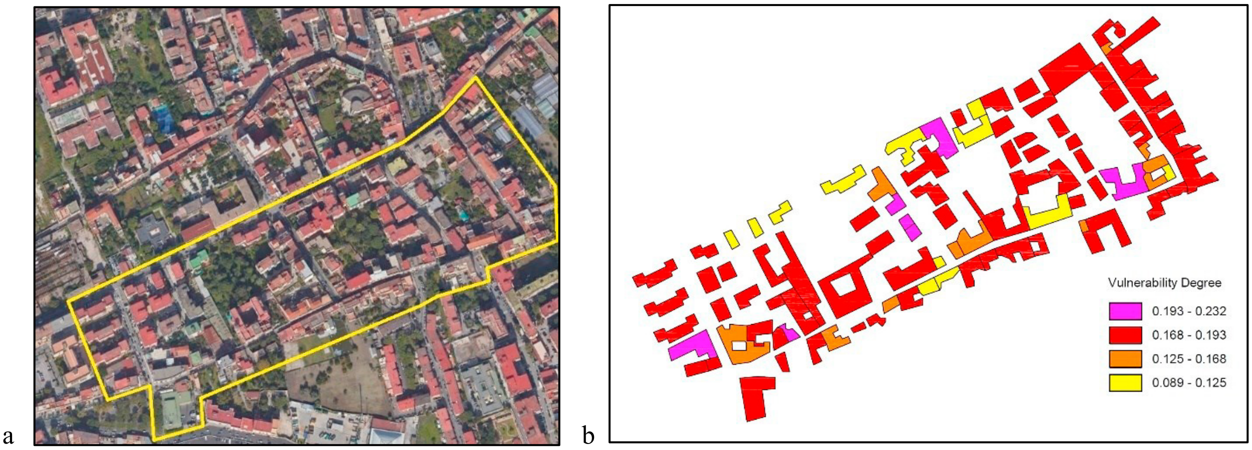

Fig. 1. (a) Map of the neighborhood examinated; (b) Map of Ufs' vulnerability degree

In the case under examination, it was possible to define the various safety levels, which allowed us to calculate the various sub-intervals with their respective affected facades. Considering the minimum and maximum acceleration coefficients, it was possible to exclude the facades that did not require interventions (see Table 2). Once the vulnerability coefficients of each facade were defined, the optimal size of the ELC was selected; to this end, 25 different strategies were configured by varying the types of works and the required safety level; subsequently, they were evaluated in terms of costs, obtaining the results shown in table 3.

Table 2. Safety degree for UFs

Safety Degree		**UF**
$k_{60\%}$	0.121	6
$k_{60\%}$	0.124	15
$k_{60\%}$	0.160	43
$k_{60\%}$	0.195	173
$k_{60\%}$	0.232	204

Table 3. Total cost for each strategy (€ x 10^6)

UF	**Completeness Degree**				
	1	**2**	**3**	**4**	**5**
6	0.06	0.07	0.26	0.33	0.33
15	0.10	0.10	0.40	0.50	0.50
43	0.20	0.22	0.82	1.03	1.03
173	1.10	1.16	4.42	5.54	5.54
204	1.31	1.37	5.23	6.56	6.56

It is possible to observe that, naturally, for the strategies corresponding to completeness level 1, the costs are significantly lower compared to the strategies corresponding to completeness level 5. This is evident because in completeness level 5, all the works necessary to maximize the safety level are included.

It is possible to represent the cost function in discrete terms using a histogram; this is specifically an intensive cost function since the size of the urban fabric area to be secured remains constant; only the works to be carried out and the number of facades for each completeness level vary (see Figure 2).

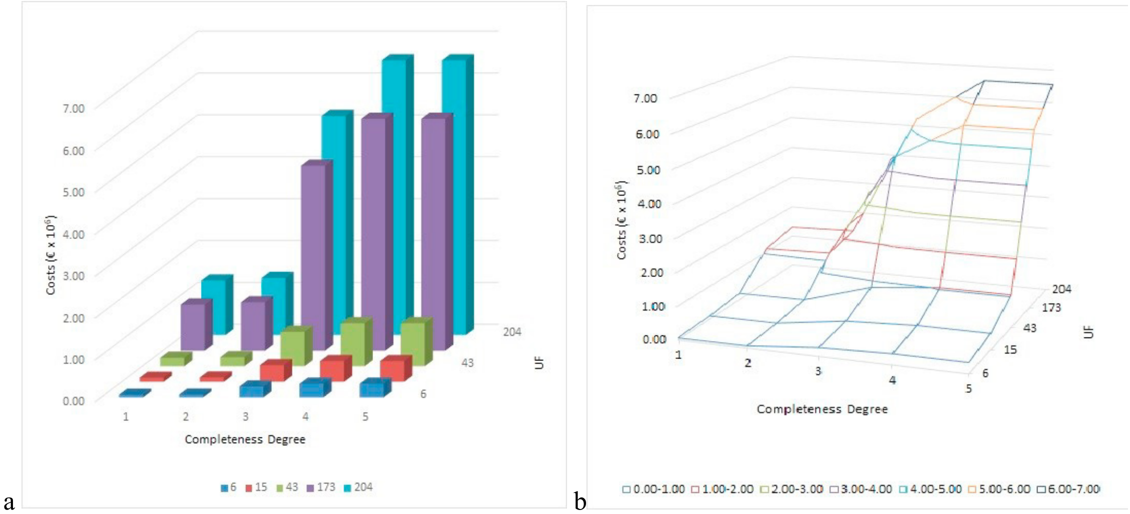

Fig. 2. (a) graph of the total costs of each of the 25 strategies displayed in table 3; (b) Spatial representation of isocost functions with the trade-off between completeness and safety for different cost levels.

The model has outlined a range of possible options regarding how to combine the overall safety level, corresponding to the number of secured buildings (from 6 to 199 UF out of 204), and the budget to cover total costs (from 0.06 to 6.56 million). The various possible monetary amounts contained between these two extremes provide accurate indications of the urban organism's resilience. Assuming the central scenario within the range, 102 facade units can be secured with average design solutions and at a total cost of 2.27 million. In Table 3 and Figure 2a paths along the main diagonal provide a measure of how cost increases with the joint growth of resilience and completeness of interventions, while paths along the isocost curves define the substitution relationship between intervention completeness and the level of resilience achieved at the same budget expenditure. Therefore, we observe that different strategies entail different cost distributions. The intensive cost function is represented by various angles in Figure 2b.

4. Concluding remarks

Within historic city centers, custodians of a timeless cultural heritage, lies a often overlooked reality: the seismic vulnerability of buildings. These ancient structures, bearing centuries of history within their walls, are often constructed with techniques and materials that do not meet modern seismic safety standards. The narrow streets and cobblestone squares not only conceal the charm of the past, but also an imminent risk in the event of an earthquake.

Historic construction, while a symbol of beauty and tradition, exhibits structural flaws that render it particularly vulnerable to seismic movements. The materials used, such as stone and bricks, often fail to effectively dissipate seismic energy, while construction techniques of the time may not ensure sufficient resistance to seismic forces.

Protecting historic city centers from the consequences of earthquakes is not only about preserving architectural heritage, but also about safeguarding human lives and the community as a whole. It is essential to adopt targeted prevention and intervention strategies that take into account the structural and historical peculiarities of each building, in order to minimize damage in the event of a seismic event.

Only through a holistic approach, combining technical knowledge, regulations, and practical experience, will it be possible to ensure the resilience of historic city centers against the threat of earthquakes and thus preserve the cultural and historical legacy they represent for future generations.

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