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LARGE SCALE SEISMIC ISOLATION FOR A POST-EARTHQUAKE RECONSTRUCTION PRESERVING IDENTITY OF SITES

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Abstract

The effects of seismic attacks in oldest parts of hit towns mostly depend on the quality of materials and construction technique even for low and medium intensity earthquakes. The negative consequences of traditional construction approaches appeared in all their evidence in many areas of Central Italy affected by recent seismic sequences of medium intensity (M5-M6) in 2016-17 where entire villages were destroyed. The reconstruction should solve the problem to rebuild with safety but preserving the historical aspect of buildings and landscape. This paper presents a particular application of the known technique of seismic isolation for the reconstruction with integral seismic protection of the worldwide known village of Castelluccio di Norcia in Umbria (Central Italy). The adoption of a seismic isolation system at city scale involves the construction of a large floating platform, having the dimensions of the entire compartment, supported by seismic isolators. In the considered case the platform is stepped due to the site orography, and, above it buildings are built with the aesthetic and constructive characteristics of the collapsed original ones. The solution allows a correct interpretation of the objective to rebuild "as it was, where it was", safeguarding the landscape, prolonging the lifetime, saving the expected cost.

Keywords: seismic isolation, artificial ground, large scale isolation.

1. Introduction

The main events of the seismic sequence of the 2016-17 Central Italy earthquake resulted in the total destruction of some small towns like Arquata del Tronto, Pescara del Tronto, Castelluccio di Norcia, as well as of the large historic center of Amatrice [1]. The buildings that form these agglomerations, generally being spontaneous buildings, are characterized by a high seismic vulnerability [2] due to well-known multiple causes: low quality of the materials and construction methods; lack or absence of earthquake-resistant details; decay of materials and damage associated with the age of the buildings and the attacks suffered over the lifetime; absence or inadequacy or harmfulness of maintenance works.

For the management of the post-earthquake rebuilding, the Legislative Decree 189/2016 provided for an Extraordinary Commissioner carrying out his duties also by means of ordinances. To cope with difficulties that emerged during the first rebuilding phase, the Legislative Decree 76/2020 introduced a significant strengthening of the commissioner powers in derogation from the current legislation. The Extraordinary Commissioner has therefore, among others, the task of identifying urgent and particularly critical interventions and works, also in relation to the rebuilding of historical centers of the hardest hit municipalities, in order to arrange the acceleration measures necessary to ensure their fastest and most effective implementation. In order to achieve an immediate implementation of the interventions and ensure a rapid recovery of the territories damaged by the earthquake, both in terms of relaunching the normal living conditions of the population, and to support the restoration and restart of the economic activities present therein, the ordinances provided for derogating provisions of the regulations in force, with particular regard to the rules of the code of public contracts, taking into account that the

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rebuilding's needs are of such complexity that they cannot be effectively addressed with ordinary procedures.

In particular, the Special Ordinance no. 18/2021 entrusts the rebuilding of the entire village of Castelluccio di Norcia, almost entirely destroyed by the seismic crisis of 2016, to the public management, within a single recovery program that integrates the construction of primary services and the restoration of both public and private buildings, in order to allow the complete rebuilding of the *forma urbis* by restoring the morphology of the soil and the configuration of public and private spaces. The Rebuilding Special Office (USR) of Umbria Region is identified as the implementing body for the execution of the interventions which procedural simplifications have been envisaged. The Ordinance defines the actions and activities that have to be implemented to start the overall rebuilding of Castelluccio's historical center, identifying the works whose rebuilding or restoration takes on a particularly urgent and critical nature in relation to both intrinsic functions and characteristics, and to purposes the rebuilding of the social and economic fabric.

This paper presents the results of a feasibility study [3] [4] that was the base for the reconstruction of the entire town of Castelluccio on a single seismically isolated platform, evaluating the main aspects of technical-economic feasibility: earthquake-resistant performance; construction technologies; compatibility of the urban fabric; cost/benefit analysis.

2. The village of Castelluccio di Norcia

Castelluccio, 1452 m a.s.l., is a fraction of Norcia's Municipality, located between Monte Vettore (2470 m) and Monte Patino (1885 m). Below the town extends the Conca di Castelluccio, a great depression at an altitude between 1250 and 1350 meters, surrounded by particularly high hillsides, which make the area unique and a source of tourist attraction. The area (greater than 17 km^2) includes the so-called "Piani di Castelluccio": Pian Perduto, Pian Grande and Piano Piccolo. The city center, due to its position on the hill overlooking the plateaus on the border between Umbria and the Marches, has a conspicuous symbolic, identity and cultural value for the entire region and, thanks to the flowering's phenomenon of the Pian Grande (Figure 1a), of international fame and recognition.

The history of Castelluccio date back to some centuries prior to 1200, the date of the first mention in the archive and is also linked to the tectonic and seismogenic characteristics of its territory. For seismic events of the past there are certain sources starting from 1703; in more recent times, we recall the several damages resulted from the Valnerina earthquake of September 9, 1979; from the seismic events of 1997; up to the earthquakes of 2016. Currently Castelluccio is almost entirely destroyed (Figure 1b): the seismic shock of 2016 caused the collapse of many buildings and the instability on the portions of the surviving buildings that led to their mandatory demolition and prohibition access to the area. The characteristic and typological image of the area is seriously compromised and altered due to the extensive damage and therefore requires an immediate and accurate rebuilding and restoration.

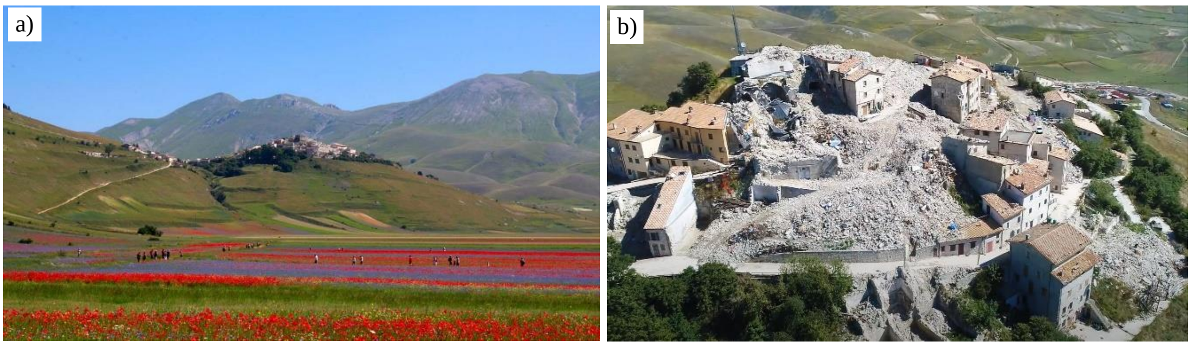

Figure 1. Castelluccio di Norcia: a) flowering phenomenon of Pian Grande; b) post-earthquake conditions.

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3. Target of the rebuilding

The reconstruction works aims not only to provide the community with the ability to cope with a future calamitous event, but most of all to create a resilient village capable of transforming a critical issue into an opportunity for territorial development and progress research. It is evident that in the recovery's context of small historic villages a more resilient system is, and must be in general, an urban system of higher quality (landscape, environmental, social, construction) which aims at respecting and enhancing local identities, with the regeneration of the affected areas through new unitary revitalization visions, territorial's reactivation and anthropic balances, as well as the rebuilding not only of the buildings, but of the communities, reducing the risk of isolation of these places.

The rebuilding of Castelluccio's center has the ambition to constitute an important design model not only for the safety of the inhabitants and of the many tourists who visit every year the site, but also for the research and innovation sector from an anti-seismic perspective, through the creation of a system of spaces and paths that will make the infrastructure accessible and open to insiders and the entire scientific community interested in advanced processes and methods for post-seismic rebuilding [5].

The examination of places and works has highlighted a strong mutual interference between the buildings undergoing rebuilding and the public spaces, both for the direct sharing of containment structures of the foundational land and for the proximity of the location, which makes it strictly necessary to coordinate the construction site, imposing a specific implementation sequence.

Based on the objectives contained in the board resolution of 24/05/2021 and the general principles laid down in Art.1 of the Special Ordinance no.18/2021, confirmed with the approval of the Implementation Plan (Resolution of the Municipal Council of Norcia no.1 of 03/14/2022), the public priority and preparatory interventions have been identified for public and private rebuilding, essential to fulfil the urban planning and primary services for the overall rebuilding of Castelluccio village and to provide it with the necessary functional autonomy. These works, calibrated on the basis of the site characteristics and the area conditions of the built center, are designed to prepare and offer the essential elements for the reconstruction of living conditions for individual citizens and the community. It is important to highlight the complexity of the rebuilding action aimed at restoring functionality, in addition to preserving and restoring the identity of the places, through the safeguarding and rebuilding of the peculiar and representative elements of the architectural-landscape heritage, as well as of the cultural symbolic values.

The priority public works, included in Annex n.1 of the Special Ordinance no.18/2021, relevant and urgent for the correct organization of territory protection and urban context, consist of: restoration of the main and secondary roads of the inhabited nucleus; terracing of the inhabited nucleus necessary for the consolidation and restoration of the morphology, as well as for the foundations themselves of the aggregates and religious buildings; underground utilities of the inhabited nucleus; construction of public areas; construction of underground parking lots, pedestrian and safety paths. To complete the implementation of the priority public interventions, necessary for the recovery of village livability and its socio-cultural values, it was also considered essential to regenerate, or rebuild, the entire building heritage due to its structural peculiarities of setting the buildings one above the other and in direct correlation with the roads and containment works, in order to coordinate and convey a quick and organized rebuilding with the full regeneration of this territory's iconographic symbol.

Along with the public interventions priority, therefore, the repair and rebuilding of the aggregates, private buildings and places of worship will have to be carried out, through a single recovery program that includes the restoration of public buildings and private residential fabric, simultaneously with the restoration of related infrastructures and underground services. The need to recover Castelluccio di Norcia village as soon as possible with a single program obviously cannot ignore the coordination and the organized action of the total rebuilding of the built complex and its public services, which, due to the center characteristics and to their complexity and identity value, must necessarily be carried out jointly to obtain a quick and synergistic implementation with the restoration of the *forma urbis*.

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The Implementation Plan identified the urban core to be rebuilt in the pre-existing volumetric and architectural configuration, according to the provisions of Ordinance no. 110/2020 and the Special Ordinance no. 18/2021. The goals that the Commissioner action intends to pursue in the rebuilding of the inhabited centers damaged or destroyed by the seismic events are the city rebirth, understood as the social and economic fabric underlying the urban's agglomeration life, and the rebuilding speed, understood as effectiveness and efficiency of physical rebuilding processes of buildings and urban spaces. In order to ensure compliance with these principles, the rebuilding of the *forma urbis* configuration with a unitary intervention, through the public rebuilding of public and private buildings coordinated with morphology's restoration of the soil and the configuration of both public and private spaces, represents an innovative solution.

The portion of Castelluccio that will be treated with the "artificial ground" solution is the one represented by the historic center; this, in fact, is also the only possible isolation solution due to the excessive buildings' proximity: the construction of a single terraced platform including the entire historic portion of Castelluccio avoids possible lengthening of the construction times deriving from working with independent construction sites relating to individual aggregates, furthermore avoids the criticalities and further interferences connected with the construction of support works and terracing.

4. Artificial ground for seismic isolation

The term "artificial ground" defines a solution that provides for the seismic isolation of large platforms above which different constructions are built [6] [7]. Referring to the post-seismic reconstruction proposals based on the application of "artificial ground" previously formulated [5] [8] and to the realizations referred to in the aforementioned works, a collaboration activity was started between the Department of Civil and Environmental Engineering of University of Perugia, the USR of Umbria Region, and the Municipality of Norcia aimed at defining a seismic isolation system on a large platform for the reconstruction of Castelluccio.

The use of artificial ground for post-earthquake reconstruction can only be planned in cases in which the destruction of a portion or an entire inhabited center is complete, and therefore a total reconstruction of the entire village or neighborhood should be provided. Within the historic center of Castelluccio, an area of approximately 6000 m^2 was identified to be rebuilt on an isolated platform. The area (Figure 2a) has an irregular in-plan shape with overall dimensions of 90 x 80 m and is characterized by average slopes equal to 25% in the NS direction and 15% in the EW direction. Before the seismic events of 2016, the area included 18 masonry aggregates of 1, 2 and 3 stories, which covered about 4150 m^2 of ground area, with 59 residential units with a total floor area of about 12880 m^2 and a volume of about 38650 m^3. Among the buildings there are the Oratory Church of the Sacramento, completely destroyed, and the Church of Santa Maria dell'Assunta, of which only a portion of the apse remains.

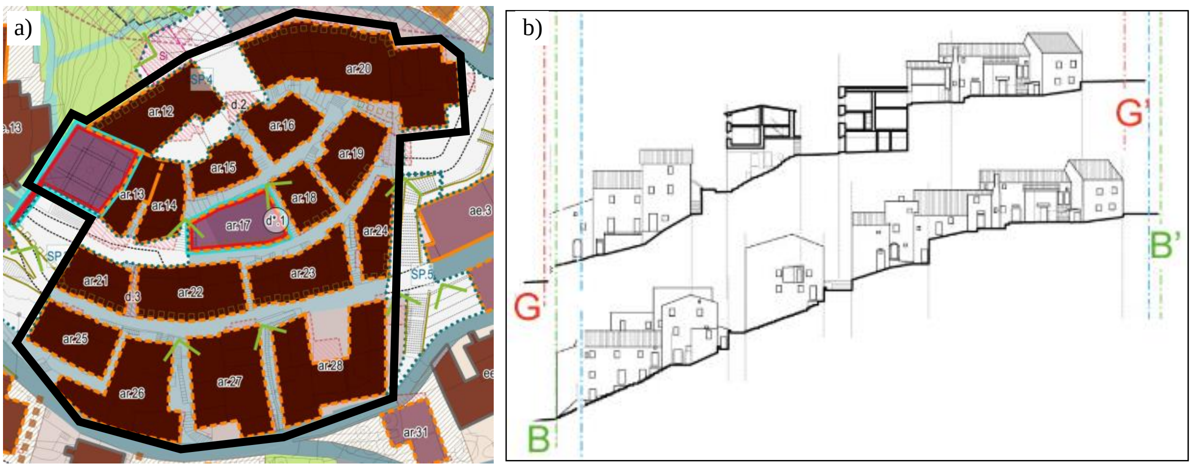

Figure 2. a) Implementation Plan for reconstruction (cultural heritage building in red color) and perimeter of the seismically isolated area (black color); b) typical development of buildings along the streets.

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The total mass of the buildings involved in the project is equal to approximately 17300 t (assuming a unit mass of 1.3 t/m^2 for masonry buildings). Since the building land area is 4150 m^2, the unit mass of buildings to be isolated is 4.10 t/m^2. To this contribution must be added the mass related to the "remaining" area, required for the restoration of the urban aspect, that is estimated equal to 11500 t: the unit mass of the "remaining" area to be insulated, equal to 2120 m^2, is equal to 5,40 t/m^2.

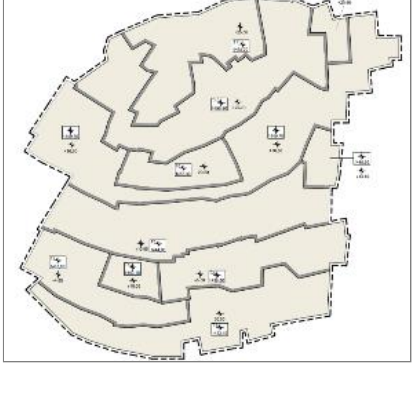
The fundamental aspects that are the subject of the evaluation of the technical feasibility of the project are the following [5] [8] [9]: (1) definition of the heights of buildings and plates; (2) optimization of excavations; (3) consolidations and terracing; (4) foundation and substructure; (5) isolation system; (6) isolated plate; (7) basements for elevation compensation; (8) plants and sub-services; (9) restoration of the urban fabric.

5. Isolated stepped platforms

The trend of the altitudes, with very significant slopes, represents one of the most problematic and characterizing aspects of the project. Figure 2b shows, as an example, the development of the elevations along one of the transversal streets of the village. In order to achieve a reconstruction spatially equivalent to the pre-earthquake situation, the aspect of the elevations must be considered as a priority. The base quotas and the elevation development of the buildings must be maintained or restored, both for the principle of restitution "where it was" and for avoiding incompatibility in the solutions of continuity between the isolated portion and the fixed base boundary. The isolated plate, which acts as the foundation of the buildings, is stepped and organized on a limited number of staggered elevations defined in order to satisfy two criteria: (i) to envelop the base quotas of buildings with a lowering from 0.70 m (minimum) to 4.00 m (maximum); (ii) to limit the elevation differences of the steps below 6.00 m. The resulting stepped plate has 11 reference elevations (Figure 3a) which cover the maximum difference in height of 25 m between the lowest and the highest area.

Below the plate, the isolation interface and the foundation structure are provided. Figure 3b shows a constructive section of the solution. The base quotas of the excavation follow the same trend of the plate but are deepened by 1.50 m to cover the height of the isolation system and foundation structures. Similarly, the vertical retaining walls are set back by about 0.80 m with respect to the vertical faces of the stepped isolated plate. Ultimately, there is an increase in excavation volume of approximately 8000 m^3 compared to that of a conventional fixed-base solutions.

A total number of 301 devices is provided for the seismic isolation of the plate. Their positioning derives from: (i) the arrangement at a distance of about 5-6 m, compatible with the vertical bearing capacity of the isolated plate, (ii) the modulation on the shapes of the horizontal shelves, (iii) the optimization of the dynamic response. The isolated plate has a height of 0.70 m which derives from a pre-dimensioning based on the assumption of a permanent load of 40 kN/m^2 and an accidental load of 8 kN/m^2, derived from the estimates of the provided superstructure (buildings and fillings). In order to satisfy the strength check, a total reinforcement percentage equal to 0.8% is assumed.

a)

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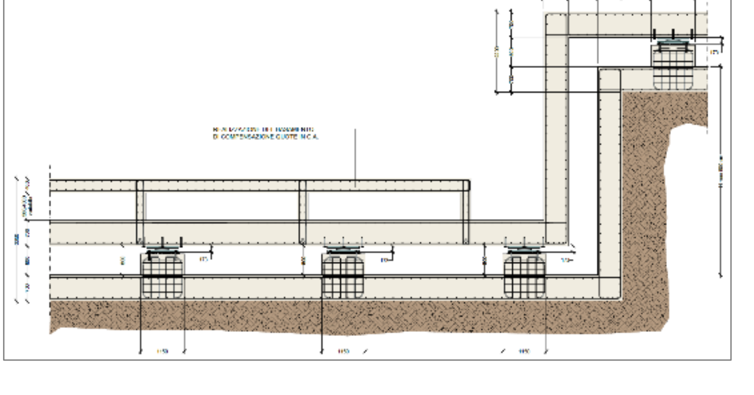

Figure 3. a) elevations of the stepped isolated plate; b) section of the isolated plate and sub-structures.

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The isolators are arranged on pedestals having a section of 1.15×1.15 m set on a foundation consisting of a grid of 0.70 m thick r.c. beams. The space between the lower edge of the isolated plate and the upper edge of the foundation is limited to a height of 0.80 m, allowing for inspection operations also using self-moving automated systems.

The equipment serving the buildings are installed in the space between the foundation and the isolated plate and are collected in the tunnels created in correspondence with the roads. The plants network include: water supply, sewer, electricity, optical fiber and telephone, gas. As regards the water (white/black) leaving the houses, pipes for the collection of the down pipes coming from each house are provided to converge to the lowest point of the plate where there will be flexible pipes descending towards the "fixed" ground below the isolated compartment.

The urban fabric is reconstituted in a way that substantially corresponds to that pre-existing at the 2016 seismic event (Figure 4a) according to the concept "where it was, how it was", except for minor variations provided by the urban Recovery Plan.

Above the isolated plate, both the road network and the buildings will be reconstituted. The correct positioning in elevation is got through rigid r.c. boxed bases (Figure 3b), located under the buildings and roads, which ensure the compensation of the differences between the quotas of the isolated plate and those of roads and buildings. These volumes do not have a functional definition but could be used as basements or for public use. The achievement of the design road quotas can be locally obtained through the filling of landfill material.

Another important element, not related to the structural aspects and seismic protection, is given by the infrastructural nature and the urban dimension of the work, and is represented by the possibility of making a part of it visible and open to visitors with the creation of a multifunctional space accessible from the outside (Figure 4b) designed by prof. arch. Paolo Verducci. Accessibility to the infrastructure is guaranteed by an annular path (also designed for maintenance and monitoring) and through the creation of multi-purpose vaulted hypogeal spaces. On a strictly functional level, it is envisaged a museum use aimed at illustrating the main characteristics of the seismic isolation intervention and telling the millennial history of the territories of the plateau of Castelluccio di Norcia. The architectural form of the rooms is characterized by a double arch structural system resting on a reticular mesh of seismic isolators. The area, to be checked in the subsequent design phases, is approximately 650 m^2.

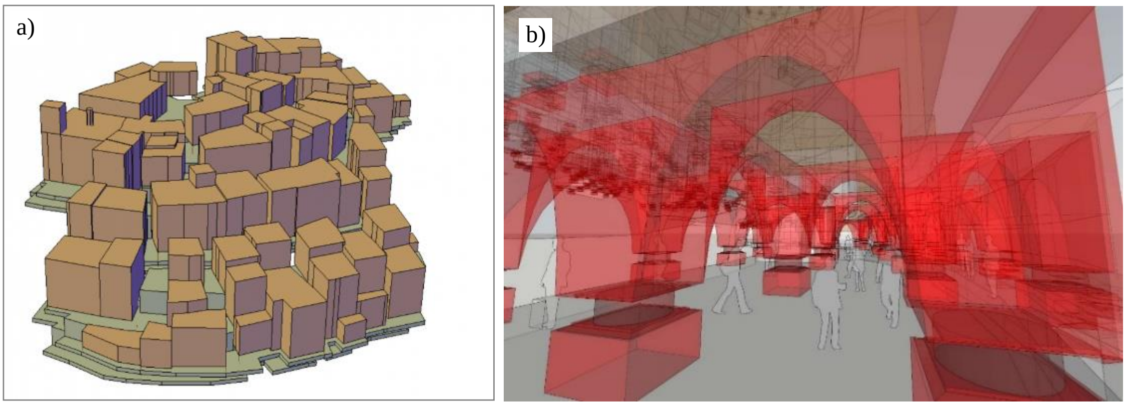

Figure 4. a) 3D simulation of rebuilt compartment; b) representations of the polyfunctional underground space.

6. Characteristics and design of isolation system

Given the importance of the project, the design has been carried out ensuring to the isolated system a performance level higher than the standard one, considering that this can be achieved without significant cost increases. It has been considered a reference period V_r = 200 years. The corresponding design seismic action is identified by a return period T_r = 2475 years.

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On the basis of the available information, the subsoil category is B (semi-rigid soil) and the topographical condition is T3 (slope >15%). Ultimately, the elastic acceleration spectrum for the collapse limit state (SLC) is characterized by the following values of the seismic parameters:

- bedrock acceleration a_g = 0.441 g;
- amplification coefficient F_O = 2.45;
- characteristic period T_C* = 0.497 s;
- soil amplification coefficient S = 1.20;
- horizontal ground acceleration PGA = 0.529 g.

The total isolated seismic mass given by platform shelves and walls, buildings, volumes of non-built areas, is approximately equal to M_{iso}=45000 t. The average load acting on the isolated plate is Q=70 kN/m^2.

The use of curved surface sliding devices with a coefficient of friction μ equal to 2.5% is assumed. This type of device is characterized by a bi-linear force-displacement behavior. The effective stiffness is equal to the sum of two contributions

$$K = N(1/R + \mu/d) \tag{1}$$

where
N is the axial load,
R is the radius of curvature,
μ is the coefficient of friction,
d is the maximum displacement.
Since the stiffness is proportional to the axial load and therefore to the mass that determines it, the isolation system is characterized by a substantial coincidence of the centers of mass and stiffness and therefore by the absence of significant torsional effects. Actually, this condition is not fully attained because also the friction coefficient is dependent on the axial load. The eccentricity between the centers of mass and the stiffness is anyhow reduced to values lower than 0.2% of the platform dimensions.

From the preliminary assessments carried out with the aim of an oscillation period of the isolated system in the interval 2.50 - 3.50 s, the adoption of market devices with the following characteristics appears appropriate:
D_g = 880 mm, diameter;
H = 173 mm, total height;
N_{Ed} = 6000 kN, maximum vertical load in the presence of horizontal displacements;
K_d = 591 kN / m, effective lateral stiffness for mean axial force;
K_v = 10000000 kN / m, vertical stiffness;
d_E = 350 mm, maximum displacement (collapse limit state).

In order to optimize the response of the isolated compartment by mitigating the torsion effects, the possible additional installation of dissipating devices, strategically located and working in parallel and synergistically with the isolator system, has been hypothesized. The adoption of magneto-rheological (MR) dissipating devices is hypothesized which, through an intelligent system for regulating their stiffness, allow to control the response with instantaneous re-centering.

For the purposes of evaluating the seismic response of the system, a numerical model was built in which the stepped plate is reproduced with two-dimensional elements and the devices with linear elements. The superstructure (constructions and infrastructures) was considered in terms of loads acting on the plate with the values previously reported. Linear dynamic analyses were carried out to determine the response of the isolated platform and to carry out checks on the isolators.

The two main translational modes have oscillation period values equal 3.16 s with nearly unitary participation mass rates. The maximum values of displacement and axial force on the isolators at the collapse limit state (SLC) are equal to 335 mm and 4201 kN, respectively, both compatible with the performance of the hypothesized devices. The maximum horizontal force value is 360 kN. None of the isolators exhibit tensile axial force. The 1.15×1.15 m section pillars of the substructure meet the SLV checks with reinforcement percentages less than 1.00%.

As regards the other categories of loads, in the examined situation the effects of the wind are not relevant [10], while the deformations associated with thermal variations are evaluated in the order of 10 mm in consideration of the thermally insulated conditions of the substructure. The effects of temperature and shrinkage under construction can be mitigated and compensated by means of suitable technological and constructive solutions.

7. Response to earthquakes recorded at site

In order to analyze the actual seismic response of the isolated compartment, nonlinear dynamic analyses were carried out using as input the accelerograms recorded in the destructive seismic event of October 30, 2016. The values of the peak accelerations for the three components corresponding to the X (EW), Y (NS) and Z (VERT) directions of the model are equal to 0.420 g, 0.634 g, and 0.801 g, respectively. The elastic acceleration response spectra of the two horizontal components of the event are greater than the SLV site spectrum provided by code. In the field of the fundamental periods of ordinary masonry and r/c structures (between 0.1 s and 0.5 s), the values of the spectral accelerations double those of the SLC site spectrum, reaching values of 2.00 g. On the contrary, in the range of oscillation periods typical of seismically isolated systems (> 3.00 s), the spectral accelerations of the records are lower than those predicted by the standard spectrum, with values of around 0.10-0.15 g. Therefore, considering the event of October 30, 2016, the reduction in the response spectral accelerations of the isolated base systems compared to the fixed base ones is about 15 times.

The nonlinear behavior of the isolators was reproduced in the nonlinear numerical model by means of an elastic-plastic law characterized by the following parameters:
K_1 = 60 MN / m, stiffness of the initial elastic branch;
F_1 = 60 kN, force at the elastic limit;
d_1 = 1 mm, displacement at the elastic limit;
K_2 = 386 kN / m, stiffness of the plastic branch, considering the average axial load.
The values derive from the geometric and physical characteristics of the hypothesized devices:
R = 3700 mm, radius of curvature;
μ = 4%, coefficient of friction (taking into account actual vertical loads).

To evaluate the seismic response of the superstructures, the numerical model was integrated with linear elements constrained to the plate and characterized by periods of oscillation typical of the real buildings (0.10 - 0.40 s). The response was calculated for both the isolated and fixed base condition by applying the recorded accelerograms of October 30, 2016. The maximum displacement of the isolators is 274 mm, lower than those resulting from linear analyses with site spectra. The maximum accelerations evaluated on building above the isolated plate vary from 0.15 g and 0.20 g, that is the seismic isolation determines a reduction in acceleration at the base of the buildings varying between 2.4 and 3.6 times that of the fixed base condition.

Figure 5 shows, for the elements simulating superstructures with different number of floors, the following parameters; the fundamental period of oscillation, T_{FB}; the maximum values of the two components of the top displacements with respect to the base, in the two conditions of base isolation, $\delta_{x,BI}$ and $\delta_{y,BI}$, and fixed base, $\delta_{x,FB}$ and $\delta_{y,FB}$. The isolated solution determines a reduction in displacements, compared to the fixed base solution, varying from 3 to 13 times (8 times on average), with an average interstory drift approximately equal to 0.1%. The displacement values calculated for the fixed base condition exceed the limits of the linear behavior of the structures, but also those of the plastic range, with a ductility demand overwhelming that available for the typical constructions: they therefore identify conditions of severe collapse of the superstructures, like those actually occurred on the occasion of the actual event.

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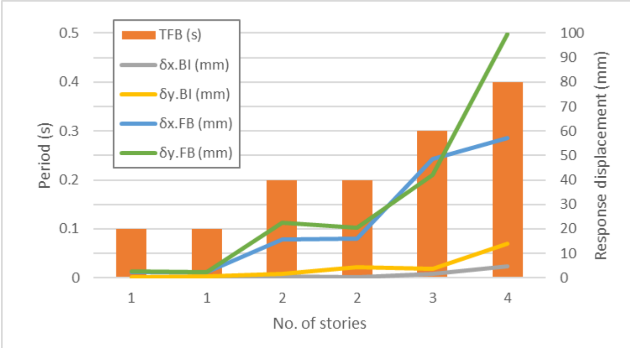

Figure 5. Lateral displacement of buildings in BI and FB scenarios.

Figure 6 shows, for the fixed base and isolated configurations, respectively, the acceleration diagrams at the base and at the top of the element reproducing a superstructure characterized by an oscillation period equal to 0.20 s, in the most significant time window. In the case of isolated plate, the amplifications of the accelerations from the base to the top are very low, going from values equal to about 0.10 g at the base up to values of about 0.20 g at the top. On the other hand, in case of fixed base systems acceleration values go from about 0.5 g at the base to 2.0 g at the top. The isolated solution therefore determines a reduction of floor accelerations by about 10 times. The resulting displacement and acceleration values of the buildings in the isolated solution are even below the limits corresponding to the operational limit state of the constructions.

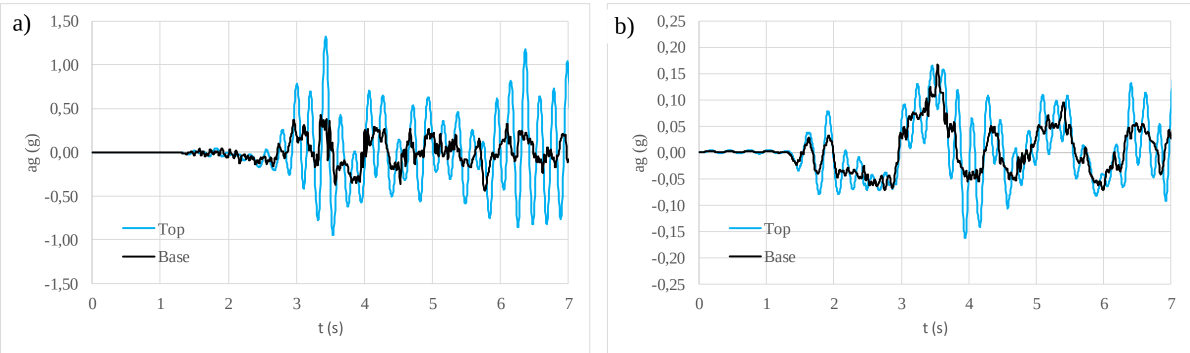

Figure 6. Accelerations at the base and at the top of buildings: a) FB solution; b) BI solution.

8. Cost and benefits of the isolated solution

Aiming at performing economic comparisons, the direct and indirect costs related to the reconstruction of the superstructures as well as the additional costs associated with the adoption of the isolated solution have been analyzed, evaluating the expected consequences over time horizons of 10, 50 and 100 years have been carried out.

First of all, the cost necessary for the restoration of the considered sector has been assessed, concerning both the reconstruction (direct costs) and the emergency and post-event management (indirect costs). The former were assessed in accordance with the ordinances of the Commissioner for reconstruction, considering a unit cost, including the various envisaged increases, of 1740 €/m^2 for a total area of approximately 13000 m^2. Adding the costs related to non-residential reconstruction (public, cultural, social infrastructures), estimated by the Commissioner at 14 M€, it results an estimate of direct costs of 37 M€. To validate the assumed costs, the funding provided by the government for the entire Umbria region and equal to 3.7 G€ were taken into consideration. It was therefore estimated, proportionally, that resources of 80-120 M€ (including indirect costs) are allocated to the area affected by the intervention in question.

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To integrate the sector with a "artificial ground" system, a total cost, additional to that already foreseen for the superstructures, equal to 5 M€ was estimated on the basis of a prompt calculation of the works and related costs: 0.50 M€ for excavation; 0.60 M€ for substructure and foundation; 0.70 M€ for the devices; 2.70 M€ for the stepped isolated plate; 0.20 M€ for the basements; 0.20 M€ for the repost. Therefore, the economic impact of the sector isolation system is equal to about 14% of the direct costs and 5-6% of the total costs.

It is also necessary to consider that an extreme seismic event entails further costs connected to the social, cultural and organizational consequences, such as the depopulation, the critical issues of resettlement and social reintegration, the deficit in production activities, the compensation of investments, the state debt. Moreover, last but not least, the direct consequences on human beings (dead and injured) must be taken into consideration. All these aspects are not evaluated in this work but assume a decisive importance in the choices and strategies for managing extreme events.

To define the convenience criteria in the context of an optimal reconstruction strategy, it is appropriate and necessary to move from economic estimates to performance evaluations [11] [12]. The conventional reconstruction project strategy, in line with current codes, would provide for the achievement of the life safety limit state for a seismic intensity with an exceeding probability of 10% in 50 years. Exceeding this limit state would result in costs substantially of the same order as those of the event that occurred and for which the reconstruction is carried out, but lower damage is to be expected even for events of lesser intensity.

Once L levels of consequences have been defined, it is possible to estimate the expected cost in N years, C_{EXP}, as

$$C_{EXP}^{(N)} = \left[\sum_{l=1}^{L-1} C_{EG,l} \cdot \left(P_l^{(N)} - P_{l+1}^{(N)}\right) + C_{EG,L} \cdot P_L^{(N)}\right] \quad (2)$$

with

$$P_l^{(N)} = 1 - e^{N/T_{R,l}} \cong 1 - \left(1 - \frac{1}{T_{R,l}}\right)^N \quad (3)$$

equal to the probability of occurrence, in N years, of an event of seismic intensity for which l-th level consequences are reached, where
L is the number of considered scenarios;
$T_{R,l}$ is the return period of the seismic intensity corresponding to the l-th scenario;
$C_{EG,l}$ = total costs corresponding to the l-th level of consequences.

The economic consequences must include both the direct costs associated with repairing the damage and the indirect costs. As regards indirect costs, the following aspects must be considered: (a) displacement of the inhabitants; (b) interruption of activities; (c) emergency management. At this stage, an amount of indirect costs has been assumed, expeditiously and precautionary, approximately double that of direct costs. A preliminary estimate of the expected consequences was carried out, with reference to the damage levels provided for by the Commissioner's ordinances (Ord. 19 and subsequent) for private and public reconstruction, i.e. L0, L1, L2, L3-L4. The parametric direct cost of reconstruction, $C_{U,DIR}$, was attributed to each of the four levels in accordance with the aforementioned ordinances and therefore the overall direct costs C_{DIR} results. The direct costs of the public works, $C_{DIR,OP}$, were estimated with the same proportions for all the levels, being known the amount allocated for public works corresponding to the L3-L4 state observed in Castelluccio di Norcia. The total direct cost, $C_{DIR,tot}$, is then given by the sum of the quantities provided for private and public works. Also the total equivalent parametric cost $C_{U,DIR,tot}$ can be computed. Indirect costs, C_{IND}, were estimated with the previous proportions for all the levels, considering for level L3-L4 an amount approximately double that of direct costs. This assumption is congruent with the actual allocations foreseen by the reconstruction plan defined by the Commissioner. Finally, it is possible to obtain the overall C_{EG} costs potentially achievable for each level of damage

$$C_{EG} = C_{DIR,tot} + C_{IND} \quad C_{EG} = C_{DIR,tot} + C_{IND} \quad (4)$$

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The following Table 1 reports the values of the parameter described above considering the reconstruction area equal to 13000 m^2.

Table 1. Direct, indirect, and total costs for the four considered damage levels.

Damage level		L0	L1	L2	L3-L4
$C_{U,DIR}$	(€/m^2)	300	1,000	1,375	1,800
C_{DIR}	(M€)	3,900	13,000	17,875	23,400
$C_{DIR,OP}$	(M€)	2,333	7,778	10,694	14,000
$C_{DIR,tot}$	(M€)	6,233	20,778	28,569	37,400
$C_{U,DIR,tot}$	(€/m^2)	479	1,598	2,197	2,876
C_{IND}	(M€)	390	6,500	26,813	46,800
C_{EG}	(M€)	6,623	27,277	55,381	84,200

The four damage levels have been associated with the performance levels (limit state) provided by the Italian code for the design of buildings, therefore the operational (SLO), damage (SLD), life-safety (SLV) and collapse (SLC) limit states have been considered respectively corresponding to the damage level L0, L1, L2, L3-L4. The return periods $T_{R,l}$ of the seismic intensity corresponding to the limit states for a conventional reference life of 50 years, can be then attributed to each of the damage levels and the exceeding probabilities of the damage level $P_l(10)$, $P_l(30)$, $P_l(100)$ for three significant time horizons of 10, 30, 100 can be computed (Figure 7).

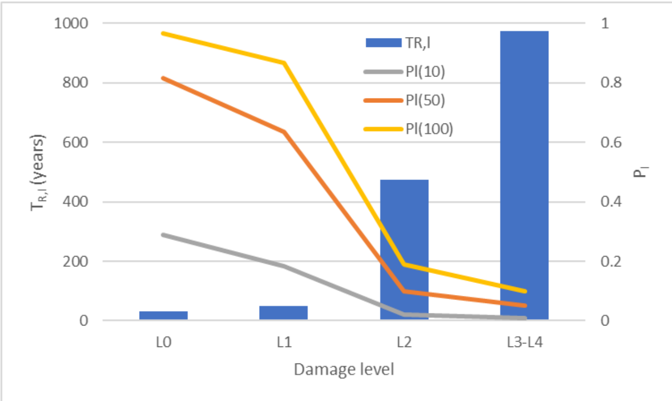

Figure 7. Exceeding probabilities of the damage levels for three significant time horizons of 10, 30, 100 years.

The expected costs probabilistically obtained through the Eq. (1) for the three time horizons considered of 10, 50 and 100 years are equal to 6,563 M€, 22,792 M€ and 32,466 M€, respectively. It is therefore obtained that the expected consequences over the next 50 years for the urban sector in question conventionally rebuilt, are equal to approximately 23 M€. This cost is about 5 times higher than the immediate cost increase associated with seismic isolation and does not take into account the consequences on people. Considering instead a time horizon of 100 years, the total cost associated with the expected consequences would be more than 6 times higher than that associated with seismic isolation.

The expected cost for the sector equipped with "ground isolation" is instead practically absent, in fact, as illustrated in this work, even an extreme seismic event, of an intensity corresponding to or greater than that of SLC, such as the one recorded in 2016, would not produce significant damage on the sector that would remain below the operational limit state. Moreover, in addition to mitigating (canceling) the economic consequences, there would be an almost total reduction of the socio-cultural consequences that are not strictly economically assessable and above all of the consequences on people.

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9. Conclusions

The paper illustrates the study concerning the application of the seismic isolation on a single platform according to the technology defined "ground seismic isolation" or "artificial ground" to the town of Castelluccio di Norcia, practically destroyed in the earthquake of 30 October 2016, for which the reconstruction project is currently being carried out under the guidelines established by the Commissioner for the reconstruction. Due to the dramatic reduction of the seismic response allowed by the isolation technology, the objective of rebuilding "how it was, where it was" can be fully implemented, even applying techniques that can be traced back to traditional ones and by building constructions with "almost zero" expected damage, even for extreme expected earthquakes characterized by return periods of 1000-2000 years. The economic evaluations of the expected costs show that the extra costs associated with the use of the ground isolation technique are 3-6 times lower than the expected costs over the reference life for buildings rebuilt according to conventional criteria. Moreover, there are the enormous benefits associated with the absence of direct consequences on people and social, cultural, organizational consequences, all components whose values cannot be, and are not, evaluated economically.

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