Proceedings of International Structural Engineering and Construction
Holistic Overview of Structural Design and Construction
*Edited by* Vacanas, Y., Danezis, C., Singh, A., and Yazdani, S.

ISSN: 2644-108X

# SEISMIC ISOLATION OF WHOLE CITY QUARTERS FOR AN EFFECTIVE AND PRESERVATIVE RECONSTRUCTION

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The post-earthquake reconstruction should solve the problem to rebuild with safety but preserving the historical aspect of buildings and landscapes. This paper proposes a particular application of seismic isolation for the reconstruction of entire urban quarter or entire small centers with integral seismic protection. This involves the construction of large floating slabs having the size of entire compartments supported by seismic isolators and/or dampers, above which to construct buildings that can present the aesthetic and constructive characteristics of the collapsed traditional ones. The solution is suited for the reconstruction of villages or quarters collapsed or damaged. Buildings of any type (masonry, stone, r/c, steel, wood) and of different characteristics also significantly irregular can be freely built above slabs and all of them will be fully protected from the consequences of future expected quakes. Paper illustrates a case study related to a quarter of a historic town in Central Italy.

*Keywords*: Ground isolation, Preservation, Urban texture, Post-seismic rebuilding.

## 1 INTRODUCTION

On the occasion of the last severe events that hit Italy – L'Aquila earthquake in 2009 and the Central Italy earthquake in 2016-2017 - serious and extensive damage occurred in the historic inhabited centers of the affected areas, in many cases with the almost total destruction of entire centers or districts (EERI 2009, Mazzoni *et al.* 2018).

In general, the historical relevance, associated with the set of buildings that constitute them and their urban structure, is accompanied by a significance that is also social. Indeed, the population recognizes the urban structure as a whole as a fundamental element of its own aggregation and compactness and as an identifying sign of its own identity. A usual problem that relates to the principles that must guide reconstruction arises again: in particular, the question that is re-proposed concerns the opportunity to reconstruct "where it was, as it was" or if it is more appropriate to reconstruct with different structural configurations or even reconstruct in different sites, delocalizing the old inhabited centers.

After the last earthquake sequence of Central Italy in 2016-17, the authors advanced the proposal to rebuild "where it was, as it was", even with traditional construction techniques, such as unreinforced or stone masonry, building entire inhabited center of limited extension, or entire urban sections, in the case of towns of more significant extension, on seismically isolated platforms (Martelli *et al.* 1999, Zhou *et al.* 2004). The main aspects of the technical-economic feasibility are examined: compatibility of the optimal urban texture; construction technologies; seismic-resistant performance of the solution; cost / benefit analysis.

## 2 FEASIBILITY OF THE SOLUTION

For the identification of a favorable site for the feasibility of reconstruction on a seismically isolated platform, the situations of some inhabited centers severely damaged in the 2016-17 seismic events were evaluated considering: land morphology, number of inhabitants, size of the intervention area, level of available information, level of damage, number of buildings of historical and cultural importance present.

Within the historic center of Amatrice, an area of approximately 19,000 sqm, characterized by an average slope of 5.00% and by the presence of 1100 inhabitants, was identified as a study case. The area (Figure 1) is irregular in shape with dimensions of approximately 230 x 100 m and is identified by the main roads that cross the historic center.

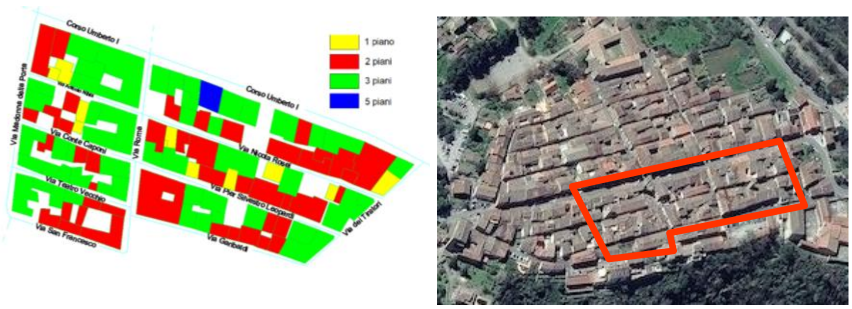


Figure 1. Layout of the case study urban sector before the 2016 seismic events.

For the purpose of evaluating the technical feasibility of the seismic isolation solution (Mezzi and Petrella 2013, Comodini and Mezzi 2011, Mezzi *et al.* 2011) the following aspects are considered (Figure 2): (a) excavation and definition of elevations; (b) foundation and substructure; (c) isolation system; (d) isolated plate; (e) plants and sub-services; (f) works to adjust elevations; (g) restoration of the urban texture.

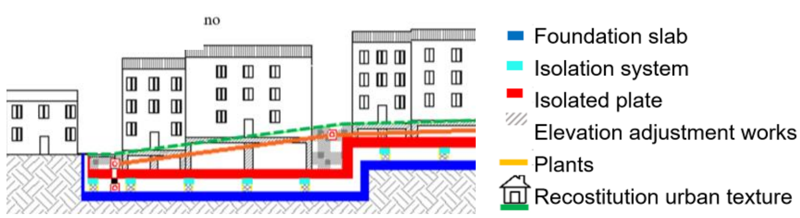


Figure 2. Layout of the provided works.

The total mass of the buildings involved in the intervention, assuming a unit mass of 1.5 t/sqm (for masonry buildings), is equal to about 50,000 t. The overall area of buildings is 12780 sqm, so the unit load to be insulated is equal to 39 kN/sqm.

To carry out a reconstruction equivalent to the pre-earthquake situation, one of the main aspects to be treated is elevation. Buildings' elevations are maintained, to avoid inconsistencies at the edge areas between the isolated sector and the fixed context. The isolated plate must be configured in large steps corresponding to a limited number of staggered elevations at which to group the largest number of buildings. In the case study, four reference elevations were adopted that break the maximum elevation difference of 8.50 m between the south-west area and the north-east area. It results in an overall volume of excavation of about 150,000 cu.m.

A shallow foundation is hypothesized, made of a 0.90 m thick r.c. plate. Above the plate, there are short columns (1.20 x 1.20 m) supporting the seismic isolators at their top. The height between the upper surface of the foundation and the lower surface of the isolated plate (Figure 3a) is equal to 1.60 m, the space is used for inspection, maintenance operations and for positioning underground systems (i.e., heat pumps for geothermal plants, surface water disposal systems, wiring for "smart city" hi-tech systems). The isolated plate has a height of 1 m and has the same stepped development of the excavation (Figure 3b). The isolators are arranged in a square mesh of 6.50 m sides (Figure 4a), compatible with the load-bearing capacity of the isolated plate with respect to vertical loads. For the whole sector, it results in a total number of devices equal to 560.

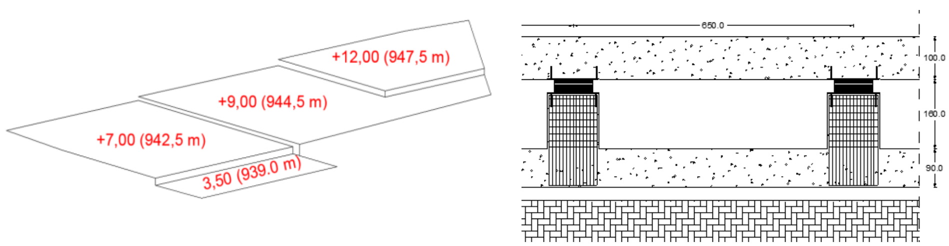


Figure 3. Elevations of the isolated plate and scheme of sub-structure, isolation system, isolated plate.

For the correct functioning of the work, the infrastructures necessary for the residential life of the sector have to be considered. Such infrastructures, integral with the isolated sector must be connected to a base network integral with the "fixed" ground, in fact it is not economically compatible the location of services and infrastructures intended only to the isolated quarter, however of modest dimensions compared to those of the entire inhabited center to which it belongs. The connections between the isolated and the fixed portion will be made with flexible systems compatible with the design displacements corresponding to the Maximum Considered Earthquake (Collapse Limit State - SLC, for Italian code). This is part of the concept of "zero damage" building, which characterizes the philosophy of the project. In fact, in the case of a severe seismic event, not only the buildings are free of damage, but the entire urban sector keeps its operation unchanged.

The thickness of a non-structural layer above the isolated plate to be allocated to the plants is evaluated considering the type of present plant networks (Figure 4b): water supply network, sewerage network, electricity network, optical fiber and telephone, gas network.

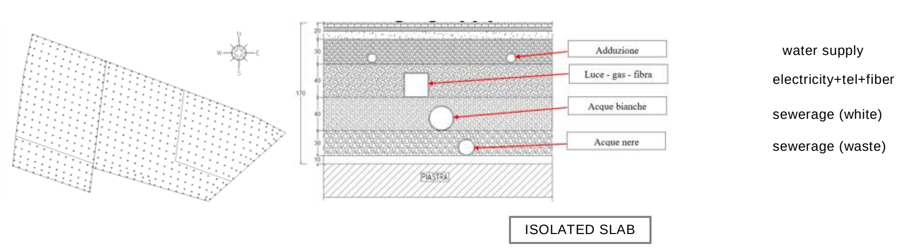


Figure 4. Layout of isolating devices (left) and plant arrangement (right).

The urban texture is re-formed in the same way that pre-existing to the 2016-17 seismic events according to the concept: "where it was, as it was". Once the topographical surface of the land was defined, a three-dimensional model was built reproducing the correct in plan and 3D positioning of the original buildings (Figure 5). The empty space that remains between the upper surface of the isolated plate and the surface of the ground (net of the 1.70 m layer dedicated to the systems) is compensated with filling material where there are no buildings and with rigid boxed r.c. structures below the buildings that could be used as basements.

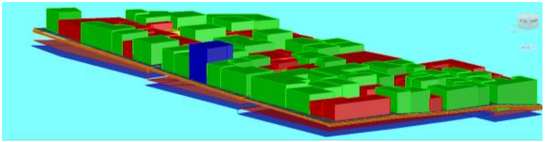

Figure 5. 3D virtual view of the restored urban texture.

## 3 SEISMIC ISOLATION SYSTEM AND RESPONSE

For the design of the isolating system, the acceleration elastic response spectra corresponding to enhanced levels of the Maximum Design Earthquake or Life Safety Limit State SLV (PGA = 0,366 g and Tr = 1068 yrs) and Maximum Considered Earthquake or Collapse Limit State SLC (PGA = 0,433 g and Tr = 2193 yrs) are adopted (NTC 2018).

The overall isolated seismic mass is $M_{iso}$ = 150000 t. The unit load acting on the isolated plate is $Q = P_{tot} / A_{plate}$ = 77,45 kN/sqm. The use of elastomeric devices with equivalent damping equal 10% and a target period of oscillation of the isolated system in the interval 2.50 - 3.00 s is assumed. Market devices having the following characteristics have been adopted: diameter $D_g$ = 1000 mm; total height H = 406 mm; total elastomer thickness $t_e$ = 210 mm; height of elastomer and steel sheets h = 326 mm; effective lateral stiffness $K_d$ = 1500 kN/m; vertical stiffness $K_v$ = 1772000 kN/m; max displacement at SLC design level $s_{disp}$ = 400 mm; maximum vertical load in seismic conditions V = 5385 kN; maximum vertical load in static conditions $F_z$ = 20320 kN. Using these an overall stiffness of the isolating system $K_{iso}$ = 840000 kN/m results.

Building and roads were considered in terms of loads acting on the isolated plate. Four variants (I, II, III, IV) of the arrangement of the buildings were considered according to a concept of "flexible" re-construction to demonstrate the flexibility of the adopted seismic protection strategy at urban level. Aiming at optimizing the response of the sector by mitigating the torsional effects, a system of magneto-rheological (MR) dampers has been conceived, which through a "smart" regulation of their stiffness, allows to control the response achieving an instantaneous re-centering between mass and stiffness centers. A complex of 12 suitably arranged dampers, with reaction force up to 400 kN and a corresponding stiffness of 1000 kN/m is assumed. The periods of oscillation and the participating masses in longitudinal (Ux) and transversal (Uy) directions for the two major translational modes are reported in Table 1.

Table 1. Modal analysis: period and percent participating mass.

| | **Mode 1** | | | **Mode 2** | | |
|---|---|---|---|---|---|---|
| **Variant** | **Period (s)** | **Ux (%)** | **Uy(%)** | **Period (s)** | **Ux (%)** | **Uy(%)** |
| I | 2,71 | 98,0 | 0,1 | 2,70 | 0,1 | 99,0 |
| II | 2,60 | 0,0 | 99,0 | 2,50 | 98,0 | 0,1 |
| III | 2,59 | 97,0 | 0,2 | 2,58 | 0,2 | 98,0 |
| IV | 2,69 | 0,0 | 99,0 | 2,69 | 99,0 | 0,0 |

Table 2 shows the maximum values, at both SLC and SLV design levels, of axial force N and shear force Tx and Ty, acting on the isolators, as well as the maximum device displacements at

SLC design level in longitudinal (X) and transverse (Y) directions. The maximum displacement values (367 mm) are compatible with the devices adopted and the checks carried out according to EN 15129 (2009), not reported for the sake of brevity, give a positive result. No isolator has tensile stresses. The substructure checked with the stresses at SLV design level requires columns of dimensions 1.20 x 1.20 m with reinforcement percentages lower than 1.00%. In the examined situation the effects of wind (Ubertini *et al.* 2017) are not relevant.

Table 2. Maximum isolators forces and displacements at the design levels.

| Variant | $N_{max}$ (kN) | $N_{min}$(kN) | $T_x$(kN) | $T_y$(kN) | $S_{max,x}$ (mm) | $S_{max,y}$ (mm) |
|---|---|---|---|---|---|---|
| SLV | 4794 | 25 | 387 | 416 | - | - |
| SLC | 4819 | 12 | 481 | 519 | 352 (I) | 367 (II) |

## 4 COSTS AND BENEFITS OF THE GROUND ISOLATION

The costs necessary for the restoration of the case study sector are evaluated, both in terms of reconstruction (direct costs) and emergency management (indirect costs). The former is evaluated in accordance with the orders of the Commissioner for reconstruction, considering a unit cost, including the various foreseen increases, of 1690 €/sqm for a total surface area of approximately 33000 sqm, to which are added the costs related to the non-residential reconstruction, reaching an estimate of direct costs equal to 70 M€. With regard to indirect costs, the following aspects must be considered: (a) relocation of the inhabitants; (b) activities downtime; (c) first emergency costs; (d) cost of public and cultural infrastructure. An amount of indirect costs has been cautiously assumed approximately double that of direct costs. The amount of 210 M€ of estimated costs has been validated considering the incidence (5-6%) of the area within the total funding provided by the government for the entire Lazio region (3.7 G€).

To integrate the sector with a "ground-isolation" system, total cost of 11.9 M€ was estimated on the basis of a quick calculation of the hypothesized solution: this represents an additional cost to the one already provided for the superstructures. Therefore, the economic incidence of isolation system of the sector is almost equal to 17% of direct costs and 5-6% of total costs.

It should also be considered that an extreme seismic event involves further costs connected to the social, cultural and management consequences, such as: depopulation, resettlement, and social reintegration criticalities, deficit in production activities, remuneration of investments, debt of the state. Last but not least, the direct consequences on people (victims, wounded) must be taken into consideration. All these aspects are not evaluated in the present work, but they assume a decisive importance in the choices and strategies for managing extreme events.

To define the criteria of opportunity in the context of an optimal reconstruction strategy, it is suitable and necessary to move from the economic estimates to an assessment based on performances. The design strategy of the conventional reconstruction, according to the current regulations, would provide for the achievement of the Life Safety (SLV) capacity for a seismic intensity having an exceeding probability of 10% over the next 50 years. If this limit state is reached and exceeded, the costs of restoring the affected area would be substantially the same as those of the event occurred in the recent past and for which reconstruction is taking place, but also minor consequence should be expected for events of lower intensity. An expected cost can be calculated as in Eq. (1):

$$C_{exp} = \sum_{i=1}^{m} p_{n,i} \cdot C_{pot,i} \tag{1}$$

to be sustained in the next *n* years can be evaluated (Comodini *et al.* 2017) being:
$p_{n,\,i}$ = probability of reaching the consequences of the event with the *i-th* consequences level,
$C_{pot,i}$ = economic consequences corresponding to the *i-th* consequences level.

It results that the consequences expected in the next 50 years for the urban section in question, if affected by a conventional reconstruction, amounts to about € 30 million. This cost is about three times higher than the higher cost associated with seismic isolation.

On the other hand, the expected cost for the sector with ground isolation is practically null, indeed, as illustrated in this work, a seismic event having an intensity even higher than that corresponding to the design level (SLV), such those recorded in 2016, would not produce significant damage to the sector that would remain in an operational status. Moreover, there is the reduction of consequences that cannot be strictly evaluated economically: almost total cancellation of consequences on people and socio-cultural consequences.

## 5 CONCLUSIONS

Reconstructing entire urban centers or sectors destroyed by earthquakes using the seismic isolation of the entire sectors according to the technology defined “ground isolation” is feasible. The objective of reconstructing “as it was, where it was” can be fully implemented, applying techniques equal to the traditional ones and obtaining “quasi-zero damage” construction. The economic evaluations show the cost/benefits convenience of the strategy. Relevant not economic benefits related to the absence of all the social, cultural, and management consequences, as well as the absence of consequences on people, should be added.

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