Optimal strategies for seismic risk reduction

B. Palazzo, L. Petti & G. Albano

Department of Civil Engineering,
Salerno University, Italy

Abstract

The present paper deals with the problem of an analytical definition of optimal strategies for seismic risk management. The problem of optimal financial resource allocation into an assigned area, such as Towns, Countries or Regions is examined. Optimal policies are evaluated by a cost-benefit analysis or a multiple criteria decision making methodology. After setting a probabilistic model based on poor data for risk assessment, the paper investigates the financial resources required to perform established risk reduction objectives, according to some assigned criteria. The investigation has been carried out using both Operation Research methods and Montecarlo analysis by using statistical data which can be easily obtained from the national data base. Finally, the paper illustrates an application of the investigated methodologies to Salerno’s Provincial area.

1 Introduction

Seismic risk management is included within the broader framework of land areas risk management with regards to natural events, or those due to human activity. For some time it has been evident that in a risk society, disasters should not be considered as events which are outside the social structure, but rather as social phenomena with respect to which human activity can play a fundamental role of prediction and prevention. According to recent socio-economic studies [13], the magnitude of disasters is to be found in the inadequacy of the social system to address them: the inability to forecast and mitigate the risks, the lack of perception as well as the increment in vulnerability.
Effective policies for the prevention of seismic risk require adequate methodologies for economic analysis and forecasting of a multidisciplinary character which are able to model not only the direct effects on buildings, infrastructures, people etc, but the indirect effects as well, which require more complex evaluation. In recent years, several important research contributions have been made which have permitted a characterization of prediction models of the hazard and seismic vulnerability in urban and regional areas with respect to the direct risk to buildings. On the other hand, systematic studies on the seismic risk management strategies are still limited in number.

In this field, the choice of the risk level considered acceptable for a given area involves delicate evaluations of socio-economic aspects which are not always quantifiable (Intangible Quantities). To this end, one should recall the contribution by Grandori [8] on the concept of the marginal cost of a saved life compared with regards to different risks which a society must address. This study which also discusses these delicate themes, investigates some methodologies for the optimal mitigation policy identification on the basis of some criteria and methodologies of the economic theory of utility and in particular, the concept of marginal utility. Such methodologies - in consideration of the number and the type of optimization criteria selectable and of the risk examined - are understood to be in assistance of the decision – maker and not as a substitute of the same. The advantage of the proposed approach consists in the capability of damage scenarios forecasting as a function of mitigation policies for an established optimum criteria in an area. This allows one to instantaneously measure the effects of any considered policy.

2 Optimal risk management formulation

The problem of identifying an optimal policy of risk management, for an assigned area, requires the delineation of opportune retrofit strategies for the purpose of optimally modifying the seismic vulnerability of a complex system, since it is not possible to take direct action with respect to the hazard. The formulation of the problem of risk reduction may be expressed as the maximization of a function of risk reduction of multiple variables (the losses and resources invested), which are not continuous, (the strategies delineated corresponding to the resources invested are discrete variables) under defined restrictions (the resources to be invested are limited).

The considered factors which contribute to reaching the objective are: the financial resources allowed and the direct socio-economic effects of these investments.

To define a prevention policy over an area, the following options of a decision-making process can be performed:
1) Identification of the minimum financial resources necessary for the reduction of the risk to an assigned level, through a cost-effectiveness analysis;
2) Identification of the best retrofit strategy in the area for the purpose of minimizing the risk for an assigned level of financial resources, through a cost-benefit analysis;
3) Identification of the financial resources, of the retrofit strategies for an area and of the optimal level of the residual risk, and therefore choice of the optimal policy in accordance with the adopted criteria.

With the first two options, the decision-maker may proceed knowing the optimal relationships between resources invested and related reduction of the risk. Instead, through the last option, the decision-maker will have an aid available for the evaluation of the optimal policy which permits the identification of the optimal level of the residual risk and of the optimal resources, as well as the retrofit strategies for the area, once the selection criteria have been set. In particular, in this study, two criteria for the definition of the optimal policy are examined: 1) maximization of the net benefit produced (cost-benefit analysis), 2) maximum increase of utility for the entire society (multi-criteria analysis).

3 Optimal allocation of financial resources

The considered Risk Management methodology involves the following steps to optimally allocate financial resources:

- *structural typological level* - the identification of the optimal retrofit strategies to be taken on the different structural typologies in the given area;
- *municipal level* - the identification of the optimal economic distribution of the resources to reduce the vulnerability in a municipality as a function of the exposed structural typologies and of the retrofit actions;
- *regional or provincial level* - the identification of the optimal distribution of the economic resources for the different municipal areas in order to reduce the risk at an assigned level.

This optimal financial allocation resources can be established by using both deterministic or probabilistic approach.

3.1 Selected retrofit strategies to building vulnerability reduction

evaluated. In this analysis, the economic resources are evaluated by the unitary cost of investment \( C_u \), which expresses the retrofit cost per unitary volume of construction. Instead, the effects are measured from the decrease \( \Delta I_v \) in the index of the average vulnerability \( I_v \) [1] for each considered structural typology.

### Table 1. Unit costs of basic retrofit actions (EURO).

<table>
<thead>
<tr>
<th>BASIC RETROFIT ACTIONS</th>
<th>UNIT COSTS C(_u) BY TYPOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>A</td>
<td>toothing and clamping</td>
</tr>
<tr>
<td>B</td>
<td>reinforced concrete slab on one side of wall and injections</td>
</tr>
<tr>
<td>C</td>
<td>reinforced concrete slab on two sides of a wall</td>
</tr>
<tr>
<td>D</td>
<td>injections in the walls</td>
</tr>
<tr>
<td>E</td>
<td>vertical steel tie rod</td>
</tr>
<tr>
<td>F</td>
<td>horizontal steel tie rod</td>
</tr>
<tr>
<td>G</td>
<td>concrete floor slab</td>
</tr>
<tr>
<td>H</td>
<td>labs Retrofitting</td>
</tr>
<tr>
<td>I</td>
<td>retrofitting of vaults</td>
</tr>
<tr>
<td>M</td>
<td>wooden floors retrofitting</td>
</tr>
<tr>
<td>N</td>
<td>steel floors retrofitting</td>
</tr>
<tr>
<td>O</td>
<td>enforcement of vaults</td>
</tr>
<tr>
<td>P</td>
<td>enforcement of r.c. floors</td>
</tr>
<tr>
<td>Q</td>
<td>roof Retrofitting</td>
</tr>
<tr>
<td>R</td>
<td>enforcement of wooden roof</td>
</tr>
<tr>
<td>S</td>
<td>enforcement of r.c. roof</td>
</tr>
<tr>
<td>T</td>
<td>enforcement of r.c. roof</td>
</tr>
</tbody>
</table>

Table 1 illustrates the unit cost of basic retrofit actions according to the costs analysis in [7]. In particular, the unitary cost \( C_u \) is obtained considering the average room extension for each structural typologies \( T \) for the Campania Region in southern Italy.

### Table 2. Retrofit Strategies.

- **C1** Horizontal tie rod
- **C2** Horizontal tie rod + toothing and clamping
- **C3** Reinforced concrete slab on one side of a wall and injections + horizontal tie rod
- **C4** Reinforced concrete slab on two sides of a wall
- **C5** Slabs retrofitting + floor + wall connections + roof retrofitting
- **C6** Reinforced concrete slab on two sides of a wall + slabs retrofitting + roof retrofitting
- **C7** Floors retrofitting + reinforcement of roof
- **C8** Vertical tie rod + floors retrofitting + reinforcement of roof
- **C9** Reinforced concrete slab on two sides of a wall + floors retrofitting + reinforcement of roof
- **C10** Reinforced concrete slab on two sides of a wall + floor + wall connections + concrete floors slabs + reinforcement of roof
For each construction typology $T$ the retrofit strategies, obtained from the combination of basic retrofit actions which provide the greatest benefit, are then examined (table 2). For these retrofit strategies, the benefit for assigned hazard $I$ MCS and typology $T$ is evaluated by considering the average decrease of the expected economic damage $\Delta D_{T,I}$ shown in [5].

3.2.1 Optimal resource distribution in municipal areas – deterministic approach

With respect to the exposed construction typologies, the costs and benefits for each retrofit strategy are evaluated, taking into account the risk assessment [11].

The maximum financial resource necessary to the Municipality is given by the total of the costs associated with the retrofit strategies which provide the greatest benefit for each construction type. Now, it is necessary to identify the optimal retrofit strategy pattern to achieve the best risk reduction by fixing a financial resource less than the maximum one. This problem may be solved with the optimal non-linear allocation of discrete limited resources method. The optimization procedure is non-linear inasmuch as the benefit, consistent with utility theory, is not proportional to the resources used. In addition, the economic resource available is a discrete variable in relation to the considered retrofit strategies.

Fig. 1: Illustrative example of the algorithm of dynamic programming based on Bellman's Optimal Principal
The solution to this problem may be identified applying the fundamental principle of dynamic programming by Richard Bellmann [3] who observed that a distribution policy of the resource is optimal if each sub-policy of which it is constituted is also optimal. Therefore for an assigned economic resource the maximum benefit to the individual construction types is evaluated taking into account their exposure and as a function of the defined shares of said financial resources. Thus the optimal distribution for only two types are evaluated as a function of the shares of the useable resource. Subsequently, the optimal distribution between the sum of these types and a further type is evaluated again as a function of the shares of usable resource. This last step is repeatedly performed until the construction types examined are completed. In correspondence with the maximum benefit obtained at the end of the process the required financial resource is evaluated and thusly its optimal division is obtained backwards from the steps taken. An example of the algorithm is shown in Figure 1.

To this end, the function \( \Delta R \), average decrease of the Seismic Risk for an assigned window of time, is defined as follows:

\[
\Delta R = \sum_{k=1}^{m} E(T_k) \sum_{I=1}^{I} p_I(t) \Delta D_{T,I}
\]

where \( E(T_k) \) is the exposure of the construction typology \( T_k \), \( p_I \) is the seismic hazard of the site and, finally, \( \Delta D_{T,I} \) is the reduction of vulnerability through the effect of the adopted retrofit strategies and for intensity \( I \) MCS. Example is shown in fig. 1, where optimal financial resources for the Municipality of Buccino (SA) are estimated.

3.2.2 Optimal resource distribution in municipal areas – probabilistic approach

An estimate based on the statistics of the effects of the strategies previously identified may be also conducted through a numerical simulation according to the Montecarlo simulation method. To this end, the data on the effects caused by the 1980 Campania Earthquake were examined. The data on the damage to constructions were taken from the CNR - GNDT report and taken from a sample of 41 municipalities which were representative of the entire area affected by the 1980 event, both in terms of volume damaged as well as in terms of repair costs. The statistical analysis of the sample with reference to the type classification previously reported has been described by [10].

It is possible to perform the following types of analyses on the sample:

a) Identification of the vulnerability functions for the assets exposed in municipal areas through the probabilistic interpretation of the data starting from the frequency matrix of the damage applied to the types exposed [10];
b) Estimate of the socio-economic losses expected in a given municipality or area according to a risk assessment model [11];
c) Simulation of loss scenarios.

The risk probability curves for each Municipality in the Province of Salerno have been produced both with and without retrofit strategies. In the analysis the damage decrease produced by a retrofit strategy is assumed to be independent from the initial damage probability description.

Results show that retrofit strategies involve a modification of the probability damage curves according to the results obtained by other studies [4]. For the municipality of Buccino (Sa), the comparison between the benefits evaluated according to the Optimal Deterministic Allocation method and the ones obtained by the Montecarlo approach as a function of the invested resources is shown in Figure 2. As may be noted, the difference between the curves is limited: having considered average parameters for vulnerability, the optimal deterministic allocation method leads to higher values. For each of the curves note the flattening of the risk reduction function with the increase in the resources invested.

Fig 2: Risk reduction - strategy cost relationship Million EURO.

3.3 Optimal financial resources allocation in large areas

For the purpose of identifying an optimal distribution of resources among more than one municipality belonging to a large area, a methodology similar to that adopted to optimize the resources on each municipal area may be used. In particular, assuming the risk of the entire area equal to the sum of the risks belonging to each individual municipality, it is possible to define now the profit function at the area as the sum of the municipality profit functions.
Therefore, the method of optimal allocation of the resources among the different municipality areas is illustrated with the same structure as that shown above.

4 The identification of optimal policies over large areas

The optimal mitigation policy of seismic risk over extensive areas consists in the selection of the municipal strategies which permit the optimization of risk reduction in the area. An optimization procedure corresponds with the maximum increase of socio-economic benefits in accordance with the adopted criteria. In particular in the following, two criteria are considered.

4.1 Cost - Benefit Analysis

An effectiveness evaluation which takes into account only the monetary effects is a cost-benefit evaluation (Risk - Cost - Benefit Optimization). The method compares the economic effects, due to the retrofit strategies, as a variation with respect to the state of non-action. The costs represent all the negative effects in monetary terms (negative flows) while the benefits all the positive effects (positive flows). According to this approach, for each alternative prevention policy $s$, the following net benefit $BA$ is evaluated:

$$BA_s = \sum_{t=1}^{n} \frac{\Delta D_s(t) - Cr_s(t)}{(1+r)^t} - C_s$$  \hspace{1cm} (2)

where $n$ is the number of years in which the prevention policy has an effect, $r$ is the interest rate, $\Delta D_s(t)$ the missed economic damage per year $t$, $C_s$ the economic cost of the strategy and, finally, $Cr_s(t)$ is the residual economic damage evaluated as:

$$Cr_s(t) = \sum_{I=VI}^{X} p(I,t)D_s(I)$$  \hspace{1cm} (3)

with $p(I,t)$ the local seismic hazard and $D_s(I)$ the expected damage for a seismic event of intensity $I$ having applied the prevention policy. The policy which permits obtaining the maximum net benefit $BA$ is the optimal one, and the sum of the optimal municipal strategies completely defines the optimal area policy. It should be noted that in this analysis the indirect and induced damages are not included.

4.2 Multiple Criteria Analysis

An effectiveness evaluation which takes into account also the non-monetary effects may be conducted through a multi-criteria or multi-attribute (Multiple...
Criteria Decision Making - MCDM) analysis based on utility theory. It consists of the identification of a multi-objective which aggregates numerous targets (attributes) considering a relative weight of importance to each. To this end, a qualitative utility function of a non-linear monotonic type, in the sense of the marginal utility, is associated to the investment attributes: financial resources and seismic risk. Such utility is measured in a non-dimensional 0-1 scale in correspondence with each attribute. According to Pareto [12] the maximum increase in utility for a society occurs in correspondence with the leveling condition of the marginal utility. If we define \( U(R) \) as the utility of the residual risk and \( U(B) \) the utility of the financial resource invested, these functions present the same marginal utility in correspondence of the optimum economic point. With this premise, and considering figure 3, the result is:

\[
\frac{\Delta U_{12}(R)}{\Delta R_{12}} = \frac{\Delta U_{12}(B)}{\Delta B_{12}} \quad \text{which implies} \quad \frac{\Delta U(R)}{R} \frac{B}{\Delta U(B)} = \frac{\Delta R}{R} \frac{B}{\Delta B} = -K(R) 
\]

\[ (4) \]

![Diagram](image_url)

**Fig. 3:** Qualitative budget and seismic risk utility curves.

In this equation \( K(R) \) represents the percentage variation of risk related to the percentage variation of the budget and is called the elasticity coefficient of the demand curve of the reduction of seismic risk \( R \) to the price variation \( B \) to be paid to obtain it.

It follows that the maximum increase in utility of the reduction of the risk, as a function of the decrease in budget utility, occurs when said coefficient presents a maximum absolute value. This point represents a maximum economic convenience point. Therefore in the case of multi-criteria analysis the optimal policy is defined by the strategies which maximize the elasticity coefficients relative to the considered losses (construction damage, human losses and homeless) or a combination thereof. In this study, unit weights were associated to each of the different attributes: risk to the population (victims and homeless) and to constructions. In figures 4-7 the results of numerical analyses with respect to the areas within the Province of Salerno are shown. In particular, taking into account the hazard of the areas within the Province of Salerno [11], evaluated by means of the Cornell method [6], the
cost comparison between the optimal policies according to the MCDM and to the Risk Cost Benefit Optimization methods is illustrated in Figure 4. Figures 5-7 comparatively show the residual risk maps for the two illustrated criteria.

Fig. 4: Cost of the optimal municipal strategies Million EURO.

Fig. 5: Average expected damage to construction in each municipality.

Fig. 6: Average number of expected victims in each municipality.
Conclusions

In this study an attempt to develop optimal strategies for seismic risk management which utilize optimal allocation of financial resources at the construction typologies, municipal and territorial levels was presented. Such strategies were tested in the areas in the Province of Salerno to estimate the resources to be invested in prevention, measuring the effects on the basis of probabilistic models for prediction of the principal residual risks evaluated by using poor data.

Results were expressed in terms of residual risk maps as a function of the invested resources adopting optimal retrofit strategies. In addition, some optimal policies were explored, having been identified on the basis of some assigned criteria, with the objective of providing a decision-making support. In particular, a cost-benefit procedure and a multi-criteria approach on the basis of microeconomic utility models were developed.

The effects of the optimal prevention policies evaluated on a provincial and municipal scale were illustrated by simulating different scenarios using a geographic information system.

The preliminary results show a greater effectiveness of the multicriteria approach with respect to the cost-benefit analysis. In particular, results have shown that an optimal policy which requires monetary resources to be invested in the entire area of the Province of Salerno varying between 650 and 850 million of EURO, equivalent to 620 - 775 EURO per inhabitant, would permit to reduce the number of expected victims to zero, cut the number of homeless in half and reduce the expected construction damage by 40%.

The discussed strategies, which do not consider the indirect and induced damages, necessitate further investigation in relation to the complexity and importance of the themes which are not consumed only in their economic aspects but also require the analysis of social ones. Lifelines, Highways and infrastructures should be taken into account. While much remains to be accomplished, the obtained results encourage the continuation of this
research, necessarily having a multi-disciplinary character with the objective of offering a coordinated and unitary vision for a rational risk management.

References


