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To compute or not to compute?

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HIGHLIGHTS

- A fast method to assess monetary advantage of seismic retrofitting is proposed.
- The study focuses on existing structures.
- Just one subtraction and one multiplication in many a real case are sufficient.

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ABSTRACT

In a previous paper "to retrofit or not to retrofit?" (Nuti and Vanzi, 2003) a straightforward procedure able to forecast the economic return of seismic structural upgrading was presented. More recently, the authors realized that the final mathematical results can be much simplified so as to allow back-of-an-envelope computation. The title of this paper tries to highlight precisely this aspect, namely that for many a regular seismic structural upgrading cases, nearly no computation is needed (apart from one subtraction and one multiplication) to assess their economic convenience. These findings are presented and discussed in this paper, together with a state of the art on the cost-studies available in literature and technical codes. The mathematical formulation leading to the proposed approximation is suitably explained, underlining its applicability field and comparing it with the rigorous solution. Also a table and a formula are furnished that alternatively allows to calculate the maximum estimation errors, in order to obtain an upper and lower bound for the maximum amount of money which should be allocated for seismic structural upgrading.

Finally an application example is described, dealing with retrofitting of reinforced concrete viaducts, a widespread bridge typology in Italy. The adopted upgrading solution

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consists of a concrete jacket at the base of some piers, particularly suitable in order to increase their ductility.

1. Introduction and scope

Over recent years, the economic impact of natural hazards and disasters received much attention. The reliable estimation of the economic, as well as human, losses incurred by an earthquake is a need for the development of seismic risk scenarios, which are now widely accepted as an essential tool for seismic risk management (Fiore et al., 2018a; Fiorentino et al., 2018; Nuti et al., 2009; Vanzi et al., 2015). In Countries such as Japan and California the monetary damage caused by past earthquakes, such as Great Hanshin earthquake in 1995 or Northridge one in 1994 (Nuti and Vanzi, 2003) was estimated as some points per cent of the gross domestic product (GDP).

In this context the economic impacts deriving by earthquakes received interest in the research community just in the last years (Aon Benfield, 2013; Braga et al., 2014; Grossi and Kunreuther, 2005; Nuti and Vanzi, 2003; Nuti et al., 2004; Paudel et al., 2015; Rose, 2004; Yang et al., 2009).

Cost studies on earthquake retrofitting were carried out by Smyth et al. (2004) for Turkey and Kappos et al. (2007) for Thessaloniki, Greece. Smyth et al. (2004) proposed a cost-benefit analysis for a common and vulnerable building type in Turkey and extended the results probabilistically. Kappos et al. (2007), using the databases collected after the 1999 Athens earthquake, developed cost analyses for the Ana Liosia site. In a successive study Kappos and Dimitrakopoulos (2008) proposed the estimation of the reduction of structural vulnerability by retrofitting. The application of the methodology was given for reinforced concrete buildings in Thessaloniki, Greece. It is a complex study, including both benefit-costs and life-cycle analyses. However all the proposed analyses require a starting database on urban built stock in order to compare the computation and the real costs.

In some cases the economic impact deriving by earthquakes is more important than the structural damages. For instance, this occurs in industrial buildings and industrial plants (Demartino et al., 2017a, 2017b, 2018; Fiore et al., 2018b). On the same topic the paper (Nuti and Vanzi, 2003) was aimed at assessing the monetary return of seismic structural upgrading for an existing structure.

As to technical codes, notable cost studies are the ones reported in FEMA (1988), Neddermann (2007), INCERC (2000), ATC (1996), and FHWA (2006). FEMA (1988) provides both a methodology for estimating seismic retrofit costs and an extensive database of retrofit costs. Retrofit costs are expressed in function of three main parameters: i) the building characteristics; ii) the building seismicity that is the level of seismic hazard exposure; iii) the performance objective that is the building anticipated performance in a seismic event. However retrofit measures are strictly connected with data from the US and therefore are only partially applicable to other geographic regions. Such databases for costs related to building retrofit or rehabilitation, exist also in Germany. More precisely Neddermann (2007) employs the so-called “construction element method” as a subdivision procedure for the estimation of costs. Similarly in Romania INCERC (2000) contains devices of costs for retrofit measures, always based on existing databases. ATC (1996) contains documentation on cost studies as well. Also in the FHWA (2006) seismic retrofitting manual for highway structures, cost considerations are furnished. For example if the cost of the seismic retrofitting approaches about 75 percent of the cost of a new bridge, bridge replacement should be considered.

Despite their scarcity, such studies represent a first attempt to establish a relationship between benefit and cost of a retrofit measure, that may influence the application of such a measure in earthquake-prone areas and address to the choice of an adequate seismic retrofit system and strategy.

Nevertheless the dilemma faced by the designer of retrofitting - how to compromise money spent in upgrading related works and risk of failure during the remaining life of the structure - is still an open task. This is a very frequent problem in earthquake-prone areas and is traditionally solved mainly by engineering judgment. In fact, as above outlined, the cost effectiveness of a retrofit strategy should be rigorously evaluated by a cost-benefit analysis. The following variables should be estimated: the restoration cost for the damaged structures, the retrofit cost, and the economic loss due to social cost. The cost avoided could so be calculated as the difference between the economic loss without and with retrofit, while the economic benefit could be determined as the cost avoided minus the cost of retrofit. The economic analysis should be carried out for all the possible probabilistic earthquake scenarios. Thus the reason why the models proposed in the scientific literature are not often used in practical applications is probably represented by their set-up complexity, due to the many parameters of difficult and questionable evaluation involved.

In this framework, the authors have been keeping on searching still simpler ways to assess monetary advantage of seismic structural retrofitting of existing structures. In detail, the proposed study is aimed at making the first formulation from Nuti and Vanzi (2003) simpler and simpler, and at reducing the governing variables into the lowest possible number. Thus a careful mathematical simplification of the final formulas proposed by Nuti and Vanzi (2003) is herein presented, allowing the designer to assess the economic suitability of the retrofitting investment with one subtraction and one multiplication in many a real case. A discussion about its validity field and the application to a significant case study are finally presented.

2. Summary of previous findings

In this section a summary of previous findings from Nuti and Vanzi (2003) is presented, in order to frame and make the discussion that follows more understandable. The questions around which the above paper was centered can be synthesized: given an existing structure built in an earthquake-prone area, is it economically justified to spend money in seismic upgrading? Would not it be better to do nothing and simply live (for a limited time, the economic life of the structure) together with the risk of failure? The above questions convey the necessity to strike a balance between the economic resources deployed in seismic retrofitting and the expected cost of structural failure, which is obviously dependent, among other variables, on the length of risk exposure.

It is intuitive that the answer to the above queries is conditioned by the length of risk exposure (quantified via L, the economic life of the structure), the rate of interest of borrowed money (i), the risk of failure for the structure in its current state and how it decreases after retrofitting (quantified via λ and Λ, the mean annual rates of failure before and after upgrading), and finally what the costs of failure and upgrading are (C and S).

The first step of the procedure proposed by Nuti and Vanzi (2003) is consisted in computing the following quantities.

$$\begin{cases} R_l = \dfrac{S_l}{C_l} = \text{costs ratio} \\ i_{\lambda_l} = \dfrac{\exp[L(i+\lambda_l)]-1}{\exp[L(i+\lambda_l)]} \\ i_{\Lambda_l} = \dfrac{\exp[L(i+\Lambda_l)]-1}{\exp[L(i+\Lambda_l)]} \\ f_l = \dfrac{\lambda_l}{\lambda_l+i} i_{\lambda_l} \\ F_l = \dfrac{\Lambda_l}{\Lambda_l+i} i_{\Lambda_l} \end{cases} \tag{1}$$

where the suffix l indicates the limit state under consideration; C_l is the cost to restore the structure to its previous functionality level if the limit state l is exceeded; S_l is the cost to upgrade the structure; $i = \ln(1 + i^*)$ is the inflation-free logarithmic interest rate; $i^* = (i_f - f)/(1+f)$ is the inflation-free money interest rate for the owner of the structure, i_f is the money interest rate for the owner of the structure, and f is the inflation rate. After upgrading, the mean rate of collapses changes from λ_l to Λ_l.

The second step was checking if $R_l < f_l - F_l$. If it was satisfied, fast upgrading was suggested; otherwise the indication was to not do anything (this includes only economic considerations). The value of R_l, $R_l = f_l - F_l$, was then defined as $R_{l\_\max}$.

$$R_{l\_\max}\text{: } \left\{R_{l\_\max} = f_l - F_l\right\} \tag{2}$$

The quantity $R_{l\_\max}$ is of interest because it is the maximum amount of money that should be spent upon upgrading a structure whose current state is defined by (λ, C), with a retrofitting defined by (Λ, S), if one borrows money at an interest rate equal to i and the structure has an economic life equal to L. For instance, if $R_{l\_\max}$ from Eq. (2) is equal to, say, 0.4, then one should not spend more than 40% of the expected cost of failure in the upgrading activities.

Since $R_{l\_\max}(i, L, \lambda, \Lambda)$, Eq. (2) is not easy to visualize, in the previous study (Nuti and Vanzi, 2003) the level curves of $R_{l\_\max}(\lambda, \Lambda)$ for selected values of i and L were derived. One such diagram is shown in Fig. 1. Although $R_{l\_\max}$ in Eq. (2) can be easily computed by a personal computer or, for selected cases, graphs similar to Fig. 1 could be used, it is not suited for hand calculation. In the following it will be shown how, making some algebraic simplification to Eq. (2), in many a case $R_{l\_\max}$ can be computed by the simple expression $(\lambda - \Lambda)L$ or, if Λ is rather smaller than λ (the retrofitting is effective), as λL.

3. Simplified assessment of the economic convenience of retrofitting

The expanded form of Eq. (2) is

$$R_{\max} = \frac{S_{\max}}{C} = \left\{\frac{\lambda}{\lambda+i}\cdot\frac{\exp[L(i+\lambda)]-1}{\exp[L(i+\lambda)]}\right\} - \left\{\frac{\Lambda}{\Lambda+i}\cdot\frac{\exp[L(i+\Lambda)]-1}{\exp[L(i+\Lambda)]}\right\} \tag{3}$$

Each of the two terms within braces at the right-hand side can be expressed in series. For the former:

$$\frac{\lambda}{\lambda+i}\cdot\frac{\exp[L(\lambda+i)]-1}{\exp[L(\lambda+i)]} = \lambda\sum_{k=1}^{\infty}\left[\frac{L^k(\lambda+i)^{k-1}}{k!}(-1)^{k-1}\right] \tag{4}$$

A similar expression holds for the latter, substituting Λ for λ. The first order approximation of Eq. (3) is then

$$R_{\max} = \frac{S_{\max}}{C} \approx R^{I}_{\max} = (\lambda - \Lambda)L \tag{5}$$

Further, if Λ may be disregarded with respect to λ, Eq. (5) may be rewritten as

$$R_{\max} = \frac{S_{\max}}{C} \approx R^{I\_\text{appr}}_{\max} = \lambda L \tag{6}$$

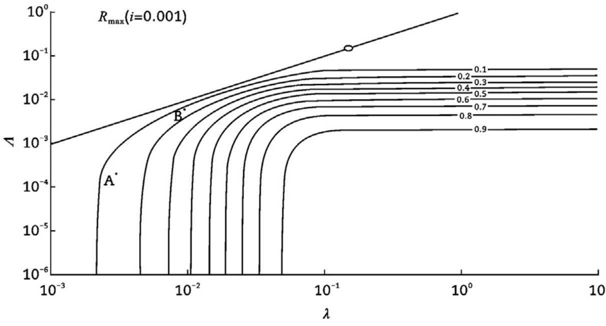

Fig. 1 – Level curves of $R_{l\_\max}(i,\lambda_l,\Lambda_l)$ for $i = 0.001$ and $L = 50$ years.

Eqs. (5) and (6) are definitely simple expressions for $R_{\max}$ and are certainly suitable for back-of-an-envelope computations (provided that the value of λ is known). With regard to their applicability, as a general rule, the smaller the values of i, L, λ and Λ the better the approximation of Eq. (5) to the real value of $R_{\max}$; and, of course, the smaller the value of Λ with respect to λ, the better is the approximation of Eq. (6). The user of Eqs. (5) and (6) should also be aware that the approximations are on the unsafe side, i.e., they tend to overestimate the value of $R_{\max}$.

In order to be more precise on when the approximations can be used, while retaining simplicity, the errors of both Eqs. (5) and (6) with respect to the real value of $R_{\max}$ were studied for selected values of i and L

$$\begin{cases} \Delta^{I} = \dfrac{R^{I}_{\max} - R_{\max}}{R_{\max}} \\ \Delta^{I\text{–appr}} = \dfrac{R^{I\text{–appr}}_{\max} - R_{\max}}{R_{\max}} \end{cases} \tag{7}$$

For example, for $i = 0.001$ and $L = 50$ years, the results shown in Figs. 2 and 3 were obtained.

From the preceding figures, and the similar ones for different values of i and L, not shown here, it is clear that the applicability of Eqs. (5) and (6) strongly depends on the values of i and L since the errors may be either acceptable or not. The applicability of the approximations is summarized in Table 1, where the values 10, 50, 100 and 200 years for L and the values 0.001, 0.01, 0.02 and 0.03 for the inflation-free interest rate i are considered. The four i values are respectively representative of debts for Euro area governments at 2 years ($i \approx 0.001$), for USA and Japan at 2 years and Euro area at 10 years ($i \approx 0.01$), for USA and Japan at 10 years and Euro and Japan companies ($i \approx 0.02$), and finally for USA companies ($i \approx 0.03$) (Nuti and Vanzi, 2003).

Table 1 shows the maximum errors Δ^{I} with the assumption that $\lambda \le 10^{-2}$; it can also be used to estimate the errors $\Delta^{I\text{–appr}}$ provided that $\Lambda \le 2 \times 10^{-5}$. The no symbol indicates that the approximations should not be used. Also notice that the values in Table 1 can be approximated by

$$\Delta^{I} \approx \Delta^{I\text{–appr}} \approx L(0.4 + 75i) \tag{8}$$

As an example, assume $i = 0.01$, $L = 50$ years, $\lambda = 8 \times 10^{-3}$, $\Lambda = 5 \times 10^{-6}$. The correct value of $R_{\max}$, Eq. (3), is 0.26; the value of $R^{I}_{\max}$, Eq. (6), is 0.39. From Table 1 it results that the maximum error is about 0.6 (0.58 if Eq. (8) is adopted), leading to a minimum value for R equal to 0.39/(1 + 0.6) = 0.24. The real value of $R_{\max}$ will be in the interval [0.24, 0.39] (and it is 0.26 as already noticed).

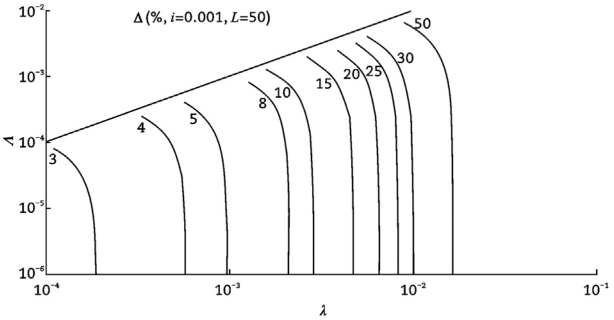

Fig. 2 – Level curves of $\Delta^{I}(i, L, \lambda_l, \Lambda_l)$ in points per cent for $i = 0.001$ and $L = 50$ years.

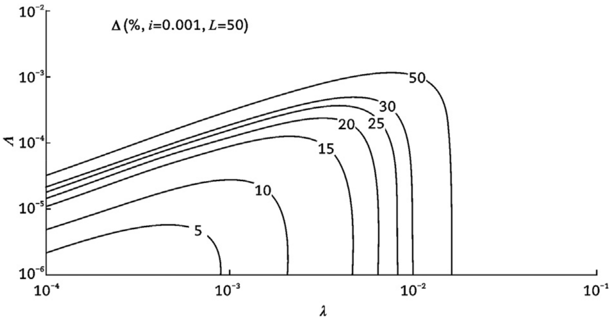

Fig. 3 – Level curves of $\Delta^{I\text{–appr}}(i, L, \lambda_l, \Lambda_l)$ in points per cent for $i = 0.001$ and $L = 50$ years.

Since $\Lambda \le 2 \times 10^{-5}$, the same computation could be made adopting $R^{I\text{–appr}}_{\max}$ in Eq. (6), which in this case results equal to 0.40; again this is an upper bound for $R_{\max}$, with the lower bound given by 0.40/(1 + 0.6) = 0.25. As shown, the computation can be very easily made by hand.

Notice that in this case the value of $R_{\max}$ is rather close to the lower bound of the intervals; this happens because the value of λ of the example ($\lambda = 8 \times 10^{-3}$) is close to the value $\lambda = 10^{-2}$ with which Table 1 has been built.

4. Application

Nowadays, the assessment and retrofitting of existing infrastructures like bridges is becoming of paramount importance. The structural security of bridges requires periodic monitoring, maintenance, and restoration (Lavorato and Nuti, 2010, 2015; Lavorato et al., 2017). Accurate knowledge of the behavior of bridges is becoming crucial as an increasing number of existing bridges is required to remain in service beyond their theoretical service life.

Seismic retrofitting is the modification of existing structures that are vulnerable to seismic events, to make them more resistant to earthquakes (Greco et al., 2014; Marano et al., 2015). The protection strategy consists in assessing the seismic vulnerability of an existing structure and in recognizing its inherent capacity to resist to earthquakes. Increasing the local capacity of structural elements is one possible solution to improve the seismic behavior of existing bridges that would be exposed to serious damage under a

Table 1 – Maximum errors Δ^{I} and $\Delta^{I\text{–appr}}$ in points per cent (λ is assumed $\le 10^{-2}$).

L (year)	$i \approx 0.001$	$i \approx 0.01$	$i \approx 0.02$	$i \approx 0.03$
10	5	10	15	20
50	25	60	90	no
100	50	no	no	no
200	no	no	no	no

Fig. 4 – 'Lenze Pezze di Valle' viaduct.

seismic event (Imperatore et al., 2012; Lavorato et al., 2015; Zhou et al., 2015).

In this framework a continuous deck bridge, representing a widespread typology (Fiore et al., 2012; Fiore and Marano, 2017; Quaranta et al., 2014), is selected as a case study: the reinforced concrete viaduct 'Lenze Pezze di Valle' (Fig. 4). A safety assessment before and after retrofitting was carried out on this bridge (Nuti and Vanzi, 2003). Fig. 5 shows the structural scheme of the viaduct. The bridge includes eight piers plus abutments, with heights varying between 18 and 27 m. Slabs are simply supported so that the structural scheme is isostatic. The two extreme piers are single columns with the same height (18 m) and cross-section (rectangular and hollow, 3.0 m × 2.5 m × 0.4 m); the remaining piers are portal frames and are much more ductile than the extreme ones, which are weak in bending. The cross-section of the extreme piers is reported in Fig. 5; the material is reinforced concrete with f_{ck} equal to 30 MPa and with steel rebars classified in Italy as Feb38k ($f_{yk} = 380$ MPa), for a total area equal to 150 cm^2.

The safety assessment of the extreme piers, which govern the overall structural fragility, was carried out (Nuti and Vanzi, 2003) by applying the structural reliability methods. For the mean annual rate of failure λ_u of the bridge in its present state, a value equal to 3.2×10^{-3} was derived in the same study as a result of the combination of seismic hazard and structural fragility.

The assumed upgrading consisted of a concrete jacket at the base, with thickness equal to 0.20 m and with 100 cm^2 steel rebars.

Reinforced concrete jacketing is an efficient, rapid, economic and simple seismic upgrading solution that allows to

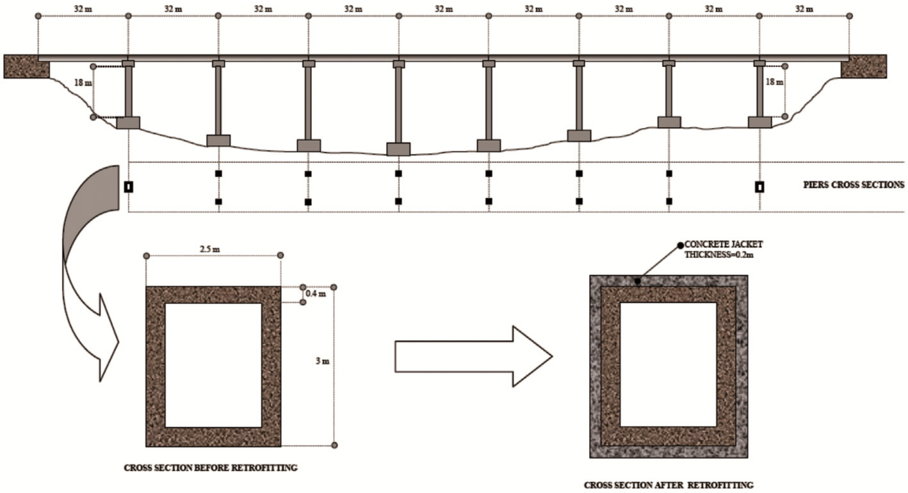

Fig. 5 – Structural scheme of the 'Lenze Pezze di Valle' viaduct.

obtain confinement and increases the ductility of the pier. It is a strengthening method that requires sectional increase of the damaged element and is realized through additional concrete layers and reinforcement. This technique not only simply limits the repair intervention in the critical parts of the piers, but also reuses the original element as much as possible, to reduce costs and environmental impact. The retrofit process can be summarized in five main steps: i) damaged concrete and rebar parts removal; ii) concrete core repair with resin injections; iii) rebar damaged parts substitution using new material; iv) damaged concrete cover restoration; v) confinement with reinforced-concrete jacket. The steps i) to iv) are obviously executed only when necessary, depending on the actual conservation state of the pier. Enlarging the cross section of concrete jacketing can further increase lateral stiffness, strength and ductility.

By analyzing more in detail the different steps of the repair intervention, starting from the first one i), cracked and nearly detached part of concrete cover are completely removed from the pier base, in the plastic hinge zone (Fig. 6(a)). About 20 mm of concrete around reinforcing bars are removed and the latter accurately cleaned in order to guarantee optimal bond with the repairing material. The quality of the interface between the existing concrete and the repairing material is essential for durability and effectiveness of restoration. In particular, lack of surface roughness makes the interface a preferential plane of rupture: mechanical removal followed by cleaning of substrate from residual particles is important to provide good bond.

Transversal reinforcement is then cut to be able to freely operate on the longitudinal bars. The damaged parts of these are cut and removed (Fig. 6(b)).

Successively concrete core resin injections, step ii), allows to restore cracking concrete and stabilize the bridge pier during the repair and retrofitting intervention.

As to step iii), the remaining parts of rebars are cleaned using a metallic brush to eliminate rust layers and residual concrete. Single new bars are placed and welded to the existing ones (Fig. 6(c)); inner level arm and cover thickness are set equal to the original ones.

For the concrete restoration, step iv), before casting, a wooden platform is placed on the pier base to prevent the dispersion of material and to have a fixed base for the steel formwork (Fig. 6(d)). The intervention is particularly effective if self-compacting concrete is used for restoration (Lavorato and Nuti, 2015). Steel jacket and wooden platform are

Fig. 6 – Some steps of the reinforced concrete jacketing intervention. (a) Damaged concrete removal. (b) Damaged rebar parts cut. (c) Damaged rebar parts substitution. (d) Damaged concrete cover restoration.

removed three days later the casting; the duration of standard curing is 28 days.

Finally, when realizing the reinforced concrete jacket, step v), the added concrete has generally a maximum aggregate dimension of about 2 mm due to the lack of space in the jacket. This is attributable to its diminished thickness associated with the volume occupied by the added steel reinforcement. It is also for this reason that a self-compacting concrete or a high-strength concrete are frequently used.

As a consequence of the jacketing, the mean value of the available ductility of the structure significantly increased and the mean annual rate of failures Λ_u decreased to 1.7×10^{-4}. These values are shown in Fig. 1, point A, implying a value of $R_{u\_\max}$ equal to about 0.15. The calculation of $R_{u\_\max}$ by the approximated Eq. (5) proposed in this study (with $L = 50$ years), leads to a value equal to 0.1515, almost coincident with the rigorous one. Considering this value has been obtained with concrete jacketing only on two piers and, conversely, failure of the bridge would be a major cost, the convenience of retrofitting is ensured.

5. Conclusions

The approximating formulas presented in this study allow a fast estimation of the economic convenience of seismic structural retrofitting. The range of applicability of the formulas is such that it should be useful for many a structure. Also a table and a formula have been provided that could be alternatively used to compute the maxima of the estimation errors so as to have an upper and lower bound for the maximum amount of money which should be allocated for seismic structural upgrading.

The main conclusion of this paper can be so summarized: seismic structural retrofitting of a structure can be economically convenient only if the cost of upgrading S is lower than the cost of failure C multiplied by the structure economic life L and the pre-upgrading mean annual rate of failures λ, i.e., $S < S_{\max} \approx CL\lambda$. For instance, if $C = 10$ million euros, $L = 50$ years, $\lambda = 0.004$ (the return period of failures is 250 years), the retrofitting is efficient and the owner of the structure is a European public institution, a first estimate of $S_{\max}$ results equal to 2 million euros. A better estimate of $S_{\max}$ can be obtained using Table 1 or Eq. (8) which gives the maximum percentage error in the first estimation. Using the latter, the error results as $L(0.4 + 75i) = 50 \times (0.4 + 75 \times 0.001) \approx 24$. The real (non approximated) value of $S_{\max}$ lies within [1.6, 2.0] million euros. The simple proposed formulas may be useful for decision making and may help to introduce speedy economic reasoning in the rational choice between competing designs.

Conflicts of interest

The authors do not have any conflict of interest with other entities or researchers.

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