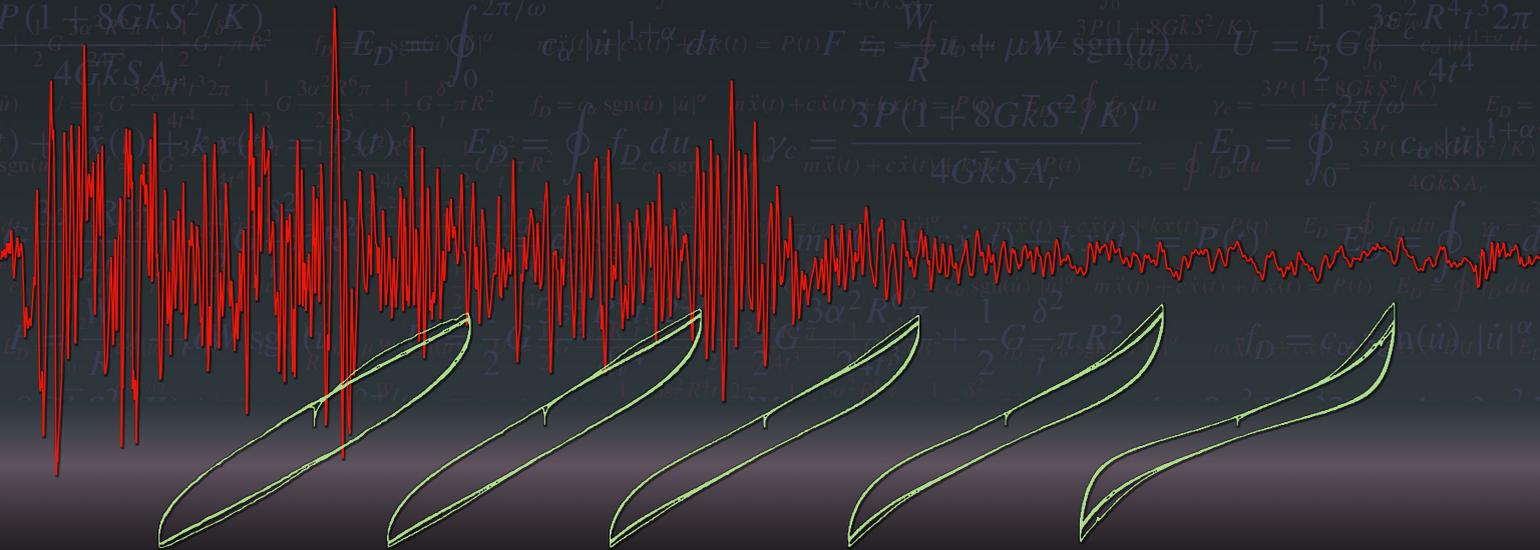


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BASE ISOLATION: DESIGN AND OPTIMIZATION CRITERIA

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BASE ISOLATION: DESIGN AND OPTIMIZATION CRITERIA

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Use of new antiseismic techniques is certainly suitable for buildings of strategic importance and, in general, in the case of very high risk. For ordinary buildings, instead, the cost of base isolation system should be balanced by an equivalent saving in the structure. In this paper the comparison criteria have been first defined, and then a large numerical investigation has been carried out to analyze the effectiveness and the economic suitability of seismic isolation, using elastomeric isolators and sliders, in reinforced concrete buildings.

1. Introduction

The number of seismic isolated buildings is increasing all over the world where the seismic hazard is particularly high. Besides, the very good performance of such buildings, even under very strong earthquakes, encouraged the use of seismic isolation, but a very spread diffusion of this technology has found an obstacle in its cost up to now. In fact, choose of new antiseismic technologies is quite obvious for strategic structures, which should be operational even during and just after a strong earthquake, and for buildings such as schools, banks and public offices in general, which can be very crowded. When the risk is very high or the safety requirements are very strong, such as in the cases mentioned, traditional technologies, based on an increase in structural resistance, cannot guarantee the required level of safety.

For ordinary buildings the safety requirements are lower and their use after strong earthquakes is usually not a matter. So seismic codes allow to design them taking into account their energy dissipation capacity, and structural damages under strong earthquakes are welcome, the safeguard of human life being the only goal to be pursued. Obviously, in ordinary buildings the increase in construction cost due to base isolation does not encourage its use.

Therefore, it is worth to analyze in detail the design criteria and the cost of an isolation system, in the optic of its optimum design. It is worth to remind that seismic isolation is economically more convenient in a long term analysis. In fact any building will be subject during its life time at least to one strong earthquake, which will certainly cause important damages so that heavy repairing works will be needed. Instead, a well designed isolated building will not suffer any important damages even under strong earthquakes and so no repairing works will be needed.

2. Reduction of the seismic actions

As well known seismic isolation is based on the terrific reduction of the energy that the soil transmits to the building, which is pursued by increasing the fundamental period of the structure. With reference to the usual spectrum relations, such as those suggested by the Italian code [MinInfra 2008], the spectral

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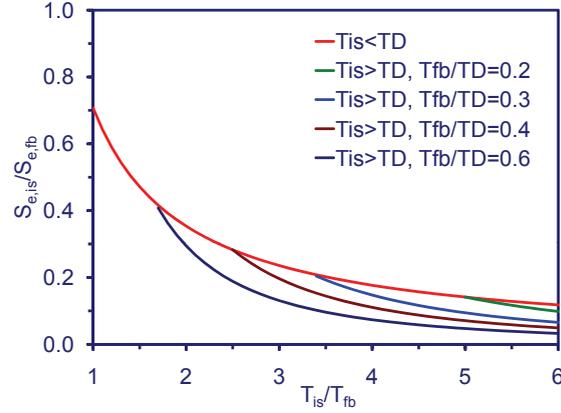


Figure 1. Elastic spectra ratios $S_{e,is}/S_{e,fb}$ ($\eta_{is}/\eta_{fb} = 0.707$).

acceleration reductions related to the use of seismic isolation are plotted in Figure 1 versus the ratio T_{is}/T_{fb} between the fundamental period of the building designed with a base isolation system and the fundamental period of the same building designed without isolation system (fixed base building), for $T_{is} \in [T_C, T_D]$ and $T_{is} \in [T_D, 4.0]$, respectively [Buffarini et al. 2007]:

$$\frac{S_{e,is3}}{S_{e,fb}} = \frac{\eta_{is}}{\eta_{fb}} \cdot \frac{T_{fb}}{T_{is}}, \quad \frac{S_{e,is4}}{S_{e,fb}} = \frac{\eta_{is}}{\eta_{fb}} \cdot \left(\frac{T_D}{T_{fb}}\right) \cdot \left(\frac{T_{fb}}{T_{is}}\right)^2.$$

The first curve ($T_{is} < T_D$, upper line) is unique if we assume $T_{fb} = T_C$ for $T_{fb} < T_C$. For the second relation ($T_{is} > T_D$), different curves relative to different values of T_{fb}/T_D are plotted. These start from the first upper curve at the abscissa for which $T_{is} = T_D$. In the “isolated spectrum” the value of damping $\zeta = 15\%$ ($\eta_{is} = 0.707$) has been considered, while as usual $\zeta = 5\%$ for nonisolated buildings ($\eta_{fb} = 1$).

The design spectrum ratios, corresponding to the ultimate limit state analysis, are plotted in Figure 2, for $q_{fb}/q_{is} = 2.7$, which is usual value for regular frames. These ratios are given by the following relations,

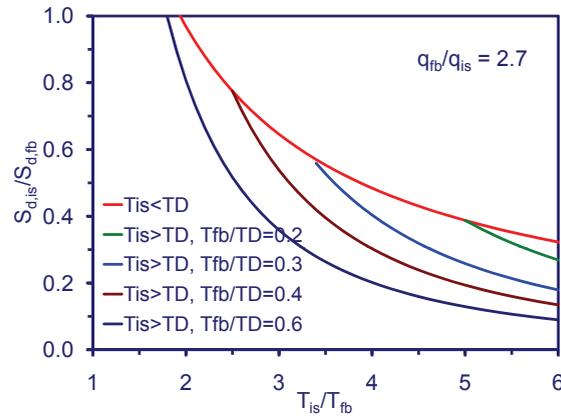


Figure 2. Limit state spectrum ratios $S_{d,is}/S_{d,fb}$ ($\eta_{is}/\eta_{fb} = 0.707$).

valid for $T_{is} \in [T_C, T_D]$ and $T_{is} \in [T_D, 4.0]$, respectively:

$$\frac{S_{d,is3}}{S_{d,fb}} = \eta_{is} \cdot \frac{q_{fb}}{q_{is}} \cdot \frac{T_{fb}}{T_{is}}, \quad \frac{S_{d,is4}}{S_{d,fb}} = \eta_{is} \cdot \frac{q_{fb}}{q_{is}} \cdot \left(\frac{T_{fb}}{T_{is}}\right)^2 \cdot \left(\frac{T_D}{T_{fb}}\right).$$

The economical comparison between isolated and nonisolated buildings depends on the design spectra reduction. It is worth reminding that for a good decoupling of the building motion, with reference to the soil motion, the ratio T_{is}/T_{fb} should be high enough. In the following the minimum value $(T_{is}/T_{fb})_{min} = 3$ has been assumed.

3. Cost of fixed base buildings in seismic area

Preliminary considerations. The economic suitability of seismic isolation depends on several factors, among these [Clemente and Buffarini 2008]:

- the earthquake intensity: for very low seismic input also a traditional building could be able to absorb the seismic actions in the elastic range and no damages should occur during the design earthquake;
- the soil characteristics: as well known, earthquake spectra on soft soils present a wider range in which the acceleration is constant at its maximum value; as a result the period of the isolated building should be higher enough and consequently the displacement will get higher;
- the shape of the building both in plan and elevation: design a seismic resistant structure in irregular buildings could be quite hard with traditional systems;
- the size of the building: the percentage cost of the isolation system is lowered in higher and larger buildings.

It is clear that it is impossible to find out general results that can be valid for all the structures. So, in order to point out the main aspects of the comparison, consider the building in Figure 3. It is a five plus one underground level building, having size in plan equal to $L_x = 17.50$ m and $L_y = 12.00$ m (Figure 4). Due to its very regular shape it is not difficult to design a traditional seismic resistant structure.

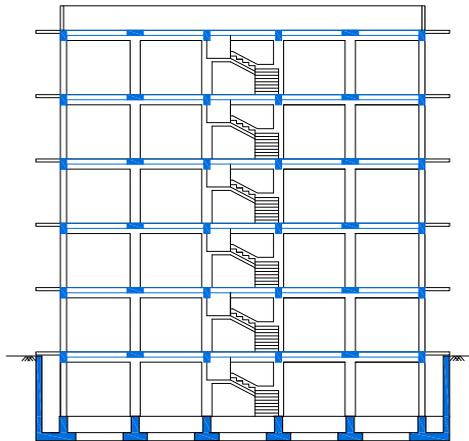


Figure 3. Longitudinal vertical section of the building.

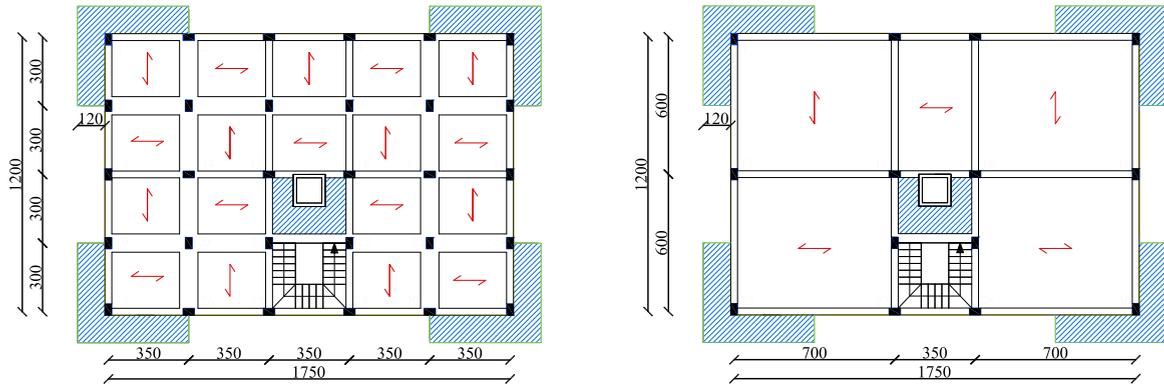


Figure 4. The two structural solutions: $i_x = 3.5$, $i_y = 3.0$ m (left), and $i_x = 7.0 - 3.5 - 7.0$, $i_y = 6.0$ m (right).

An effective comparison between a base-isolated building and the corresponding traditional one is quite hard. It is important to state that the architectural results should be very similar, otherwise the economic values of the two buildings could be very different. This preliminary consideration resulted in choosing the same solution for the underground level, where the isolators have been placed at the top of the pillars and the same sustaining concrete wall in both cases has been considered around the structure (Figure 3).

For the same reason, the same locations for the pillars have been assumed. Of course, the pillars of the isolated building will have cross-sections and reinforcing steel area different from the nonisolated one. Two different solutions have been considered for the number of pillars, and therefore for the space between the pillars:

- (a) $i_x = 3.5$ and $i_y = 3.0$ m, which should be the best solution for the fixed base building (Figure 4, left);
- (b) $i_x = 7.0 - 3.5 - 7.0$ and $i_y = 6.0$ m, which should be a better solution for the base-isolated building (the central span contains the stairs and the elevator, Figure 4, right).

In all the cases the same materials have been used for all the structural elements:

- the concrete has a characteristic compression strength $R_{ck} = 30 \text{ N/mm}^2$; the compression design strength at the ultimate limit state is $f_{cd} = 14 \text{ N/mm}^2$;
- the steel of the reinforcing bars has a tensile characteristic strength $f_{yk} = 450 \text{ N/mm}^2$; the tensile design strength at the ultimate limit state is $f_{yd} = 390 \text{ N/mm}^2$.

The decks have always a thickness equal to 25 cm (20 + 5). The buildings have been designed following the same design criteria both for the concrete sections and for the reinforcing steel area, both for the superstructure and the foundation. The structural analysis and the design have been carried out according to the Italian seismic code [MinInfra 2008; MinInfra 2009]. The structure is subject to the usual permanent loads (self weight and other permanent loads) and to the typical variable loads of the residential buildings (2.0 kN/m^2).

The seismic analysis has been performed by means of the response spectrum analysis. The fixed base building (denoted by a subscript “fb”) has been designed considering several values of the spectrum amplitude at T_{fb} , ranging up to 1.50 g. In practice, with the purpose of evaluating the internal forces, the analysis has been performed by referring to a structure with pillars and beams having the same concrete cross-sections constant at all the levels (30 × 50 cm) and imposing a spectral amplitude, independent of the actual fundamental period of the building. Due to the rules assumed for the design of the pillars and beams, which will be specified later, this turns to have no significant influence on the results.

The set of cross-sections. On the basis of the resulting internal forces, the effective concrete cross-section of each structural element has been designed. A selected set of cross-sections has been chosen for the beams. In more detail, the following concrete cross-sections have been considered:

$$A_c = b_t \times H \text{ (cm)} \quad 30 \times 40 \quad 30 \times 50 \quad 30 \times 60 \quad 40 \times 60 \quad 40 \times 70 \quad 40 \times 80$$

Some internal beams have the same height as the floor (25 cm); these beams have always the same width of 80 cm. For each concrete cross-section, we have considered all the values of bending reinforcing steel area in the allowable range $[A_{s,min}, A_{s,max}]$, where

$$A_{s,min} = 0.26 \cdot b_t \cdot d \cdot \frac{f_{ctm}}{f_{yk}} \geq 0.0013 \cdot b_t \cdot d, \quad A_{s,max} = 0.04 \cdot A_c$$

($d = H - 4$ cm, $f_{ctm} = 2.6$ MPa, $f_{yk} = 450$ MPa), with a step equal to the area of a bar of 10 mm diameter. Stirrups of diameter 8 mm have been considered with a space ranging from 5 to 25 cm. Each span has been divided into three parts, the central half span and the side quarter spans, in which the reinforced steel area has been kept constant (Figure 5, left).

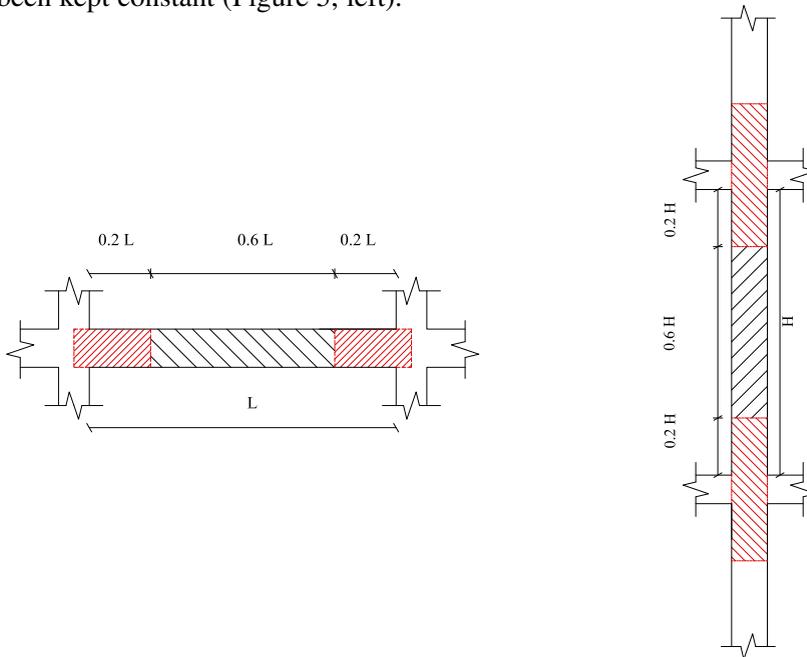


Figure 5. Parts of a beam (left) and a pillar (right) in which the steel reinforcement has been kept constant.

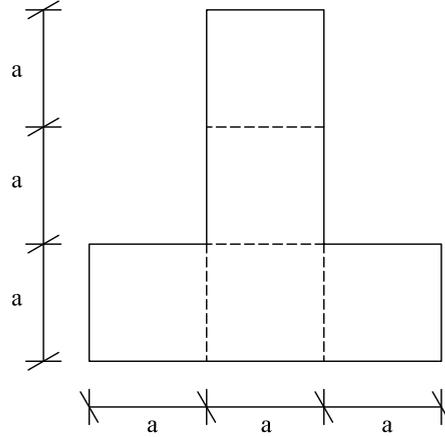


Figure 6. Cross-section of foundation beams.

For the pillars a certain (high) number of cross-sections have been considered having the same concrete cross-sections of the beams and with reinforced steel area varying in the range $[A_{s,\min}, A_{s,\max}]$, where

$$A_{s,\min} = 0.10 \cdot \frac{N_{Ed}}{f_{yd}} \geq 0.003 \cdot A_c, \quad A_{s,\max} = 0.04 \cdot A_{rnc}$$

(N_{Ed} = design axial force, $f_{yd} = 390$ MPa) by a step equal to the area of a 14 mm diameter bar. Stirrups of diameter 8 mm have been considered with a space ranging from 5 to 25 cm. Pillars have constant steel area along their height between two consecutive decks. Instead, their height has been divided into three parts, the central half and the side quarter, for the deployment of the steel stirrups, which are obviously less spaced near the joints (Figure 5, right).

The foundation beams have T cross-sections (Figure 6), composed by five equal squares of size a , ranging from 30 to 50 cm, and steel area increasing by a step equal to the area of a 14 mm diameter bar. In this case, stirrups of diameter 10 mm have been considered with a distance ranging from 5 to 25 cm. Also for the foundation beams, each span has been divided into three parts, the central half span and the side quarter spans, in which the reinforced steel area has been kept constant.

The cost analysis has been carried out by referring to the official prize list of the Molise region in Italy [Molise 2005].

Cost analysis of a fixed base building. As already said, with the purpose of evaluating the internal forces only one model has been considered, in which all the pillars and the beams have the same constant concrete cross-section in the entire building. First of all the internal forces due to the vertical loads have been calculated both for their maximum values (ultimate limit state) and for the values of them, which are supposed to act contemporarily to seismic actions (as usual, the variable actions are reduced with reference to their maximum value). Then the response spectrum analysis has been performed by referring to a design spectral amplitude S_d deduced from the elastic spectral amplitude S_e by means of a structural factor $q_{fb} = 4.1$, which is typical for concrete buildings with regular frame structure.

Then for the significant sections of all the beams (end-span and half-span sections) the internal forces (shear and bending moment) have been evaluated as a function of the spectral amplitude S_e . For example,

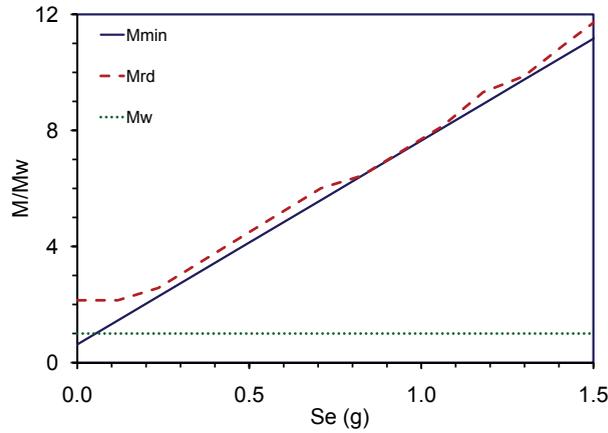


Figure 7. Minimum bending moment (M_{min}), resistant bending moment (M_{rd}) and bending moment due to vertical loads (M_w) versus S_e for the end-section of a beam.

in Figure 7 a typical diagram of the bending moment versus S_e is plotted for a end-span section (continuous line). The bending moment at $S_e = 0$ is relative to the vertical loads acting contemporarily to seismic actions. The horizontal dotted line represents the bending moment due to the maximum vertical loads. The values of the bending moment have been compared with the ultimate resistant moments of the previously defined set of cross-sections and the cross-sections of minimum cost have been chosen. The same procedure of the beams has been used for the foundations.

Analogously, for the end sections of all the pillars, the $M-N$ values have been evaluated as a function of the spectral amplitude S_e and have been compared with the $M-N$ domains of the defined cross-sections; see the left part of Figure 8. The right part of Figure 8 plots the cost per unit length versus S_e , both for a beam and a pillar.

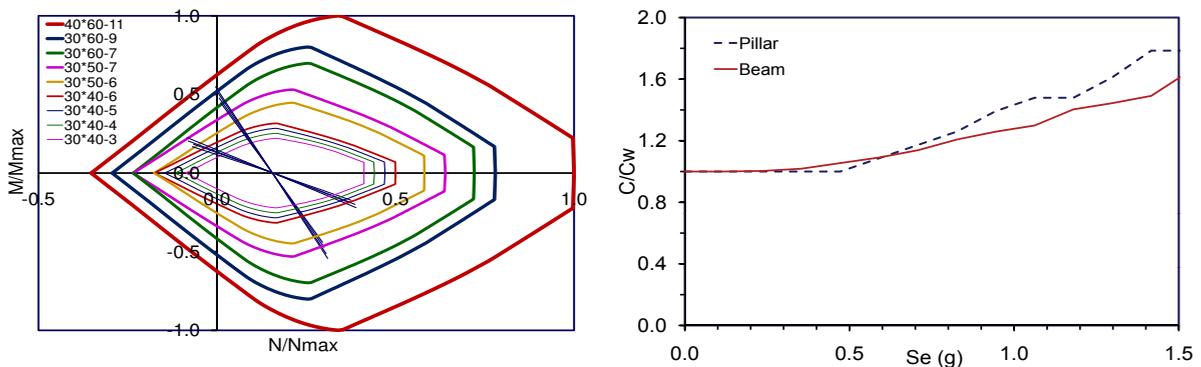


Figure 8. Left: $M-N$ pairs in a pillar cross-section and domain of the cross-sections selected (individualized by “ $b \times H$ -number of $\phi 14$ bars”; the values are normalized with reference to the maximum N and M of the larger domain in the figure). Right: cost of pillar and beam, both normalized with reference to the cost for nonseismic design.

After this step the cross-section of beam and pillar can be very different at the same deck and also along the same span. So a suitable homogenization should be done. The final cross-sections have been selected under the following conditions:

- the pillars at each level have the same concrete cross-section but can have different reinforcement steel area; obviously, from one level to the other also the concrete cross-sections can be different;
- the beams of each deck have the same concrete cross-section but can have different reinforcement steel area; from one deck to the other also concrete cross-sections can be different;
- as already said, some internal beams have the same height of the floor and their cross-section is 80×25 ;
- the foundation beams have the same concrete cross-section but can have different reinforcement steel area.

With this assumption, in order to perform an economic comparison, the seismic analysis carried out on the building having a unique constant cross-section for beams and pillars can be supposed to be sufficiently approximated. Table 1 summarizes the concrete cross-sections of pillars and beams for the fixed base building, for both pillar locations a and b . Note that for $S_e = 1.50g$ the cross-sections of the pillars at the lower levels, for case b , are out of the defined set.

The total cost has finally been evaluated by the summation of the local costs. In Figure 9 the cost of the structure of the building is plotted versus S_e , with reference to the two solution adopted for the pillar spacing (cases a and b). The contributions of the superstructure and the foundation are distinguished. As already pointed out, the solution b is not suitable for the fixed base building in areas of high seismicity.

Level	$S_e =$ case =	0.50g		1.00g		1.50g	
		a	b	a	b	a	b
5		30×40	30×50	30×40	30×60	30×50	—
4		30×40	30×50	30×50	30×60	30×60	—
3		30×40	30×50	30×50	40×70	30×60	—
2		30×40	30×60	30×50	40×80	40×70	—
1		30×40	30×60	30×60	40×80	40×80	—
Foundation		30×40	40×60	30×60	40×90	40×80	—

Deck	$S_e =$ case =	0.50g		1.00g		1.50g	
		a	b	a	b	a	b
5		30×40	30×40	30×40	30×50	30×40	—
4		30×40	30×50	30×40	40×70	30×50	—
3		30×40	30×60	30×40	40×70	30×60	—
2		30×40	30×60	30×50	40×70	30×60	—
1		30×40	30×60	30×50	40×70	40×70	—
Foundation		30×40	30×60	30×50	40×70	40×70	—

Table 1. Fixed base building: pillar cross-sections (top) and beam cross-sections (bottom) for some values of the spectral amplitude, in the pillar locations a and b .

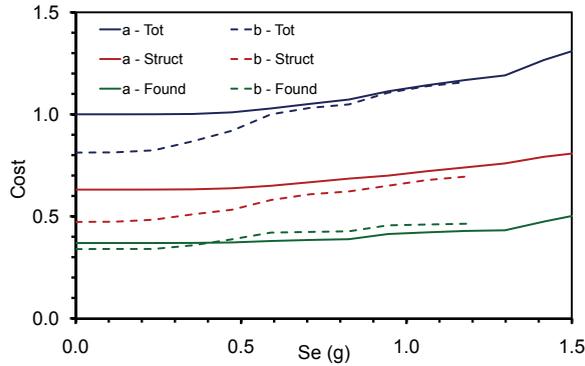


Figure 9. Fixed base building *a* and *b*: cost of the building versus S_e (note that for high values of the seismic input the solution *b* cannot be realized). The values are normalized with referenced to the total cost of the building in absence of seismic actions.

4. The base-isolated building

The same buildings (cases *a* and *b*) have been designed with base isolation (subscript “is”), for several values of the spectrum amplitude at T_{is} , ranging up to $0.30g$, which is certainly higher than the maximum suitable value to design structures in the elastic range. In this case, too, the seismic analysis has been performed by referring to a structure with pillars and beams having the same concrete cross-sections constant at all the levels (30×50 cm) and imposing spectral amplitude, independent of the actual fundamental period of the building.

Level	$S_e = 0.50g$		$1.00g$		$1.50g$	
	case = <i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>
5	30×40	30×40	30×40	30×50	30×40	30×50
4	30×40	30×40	30×40	30×50	30×40	30×50
3	30×40	30×40	30×40	30×50	30×50	30×60
2	30×40	30×50	30×40	30×60	30×50	40×70
1	30×40	30×60	30×50	40×60	30×50	40×80
Foundation	80×80	80×80	80×80	80×80	80×80	80×80

Deck	$S_e = 0.50g$		$1.00g$		$1.50g$	
	case = <i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>
5	30×40	30×50	30×40	30×50	30×40	30×50
4	30×40	30×50	30×40	30×60	30×40	30×60
3	30×40	30×50	30×40	30×60	30×40	40×70
2	30×40	30×50	30×40	30×60	30×40	40×70
1	30×40	30×50	30×40	30×60	30×50	40×70
0	30×40	30×50	30×40	30×60	30×50	40×70

Table 2. Base isolated building: pillar cross-sections (top) and beam cross-sections (bottom) for some values of the spectral amplitude, in the pillar locations *a* and *b*.

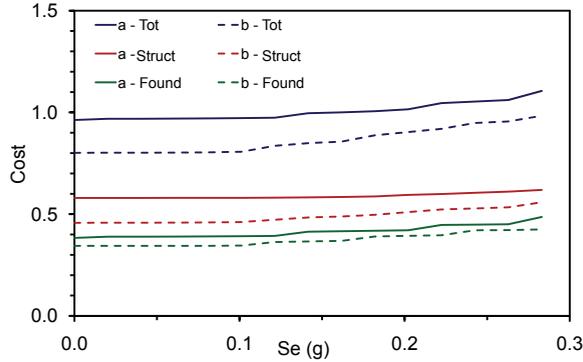


Figure 10. Base isolated building *a* and *b*: cost of the building versus $S_{e, is}$.

The isolation system was placed at the top of the underground level. The same procedure explained before for the fixed base building was used, first evaluating the internal forces due to the vertical loads for their maximum values (ultimate limit state) and for the values of them, which are supposed to act contemporarily to the seismic actions. Then the response spectrum analysis was carried out by referring to a design spectrum having constant amplitude and reducing the resulting internal forces due to seismic action by means of a structural factor $q_{is} = 1.5$, the maximum value compatible with regular frames structures. Then for each significant section (end-span sections of pillars, end-span and half-span sections of the beams) the internal forces due to the seismic actions were evaluated as functions of the spectral amplitude $S_{e, is}$.

Table 2 summarizes the concrete cross-sections of pillars and beams. The costs of the structure of the building are plotted versus $S_{e, is}$ in Figure 10, for the cases *a* and *b*. As one can see, the increase of the cost is apparent at two values of the spectral amplitude ($S_{e, is} \approx 0.1 g$ and $S_{e, is} \approx 0.2 g$). It seems obvious to consider one of these as limit value $S_{e, is, d}$ for the superstructure and to design the isolation systems in order to guarantee the corresponding period T_{is} . In the following $S_{e, is, d} = 0.2 g$ has been assumed, which turned to be more suitable from the economical point of view. It is worth observing that this value is relative to the studied building and will change for different buildings.

5. The isolation system

The sets of elastomeric isolators and sliders. For the elastomeric isolators, too, a selected set of types was defined. They were designed according to the ISO recommendations [ISO 2007]. For each value of the diameter D_e , all possible values of the thickness t_i of the rubber layers have been considered. Note that for usual buildings the maximum values of t_i are the most suitable, due to the low value of the vertical load V . So for each pair $D-t_i$, and for each number of rubber layers n_g , the total rubber thickness can be deduced:

$$t_e = n_g \cdot t_i.$$

By setting the shear strain γ_s to the maximum allowable value $\gamma_{s, lim}$,

$$\gamma_s = \frac{d_2}{t_e} = \gamma_{s, lim},$$

and by taking $\gamma_{s,\text{lim}} = 2.0$, according to the Italian code [MinInfra 2009], we deduce the maximum horizontal displacement under seismic action:

$$d_2 = 2 \cdot t_e.$$

If we fix a maximum value for the bending rotation α (usually very low in buildings), the corresponding shear strain γ_α can be deduced:

$$\gamma_\alpha = \frac{3}{8} \cdot \alpha \cdot \frac{D_e^2}{t_i t_e}$$

and then the maximum value of the shear strain due to vertical load:

$$\gamma_c = \gamma_{t,\text{lim}} - (\gamma_s + \gamma_\alpha),$$

where we take $\gamma_{t,\text{lim}} = 5.0$ according to [MinInfra 2009]. The corresponding vertical load

$$V_c = S_1 \cdot G_{\text{din}} \cdot A_r \cdot \frac{\gamma_c}{1.5}$$

is to be compared with the critical load

$$V_{\text{cr}} = S_1 \cdot G_{\text{din}} \cdot A_r \cdot \frac{D_e}{t_e}$$

and the vertical load corresponding to the maximum stress in the steel plates:

$$V_{\text{lam}} = f_{yk} \cdot \frac{A_r \cdot t_s}{1.3 \cdot 2t_i}.$$

The maximum load for the chosen isolator, compatible with the displacement d_2 , is

$$V = \min(V_c, V_{\text{cr}}, V_{\text{lam}}).$$

In the following investigation isolators with damping factor $\zeta = 15\%$ have been used. Besides $G_{\text{din}} = 0.8 \text{ MPa}$ has preferably been used. When $G_{\text{din}} = 0.4 \text{ MPa}$ it is specified in the tables. Figure 11 plots K_e and V against d_2 for some isolators. The characteristics of some isolators used in the following are

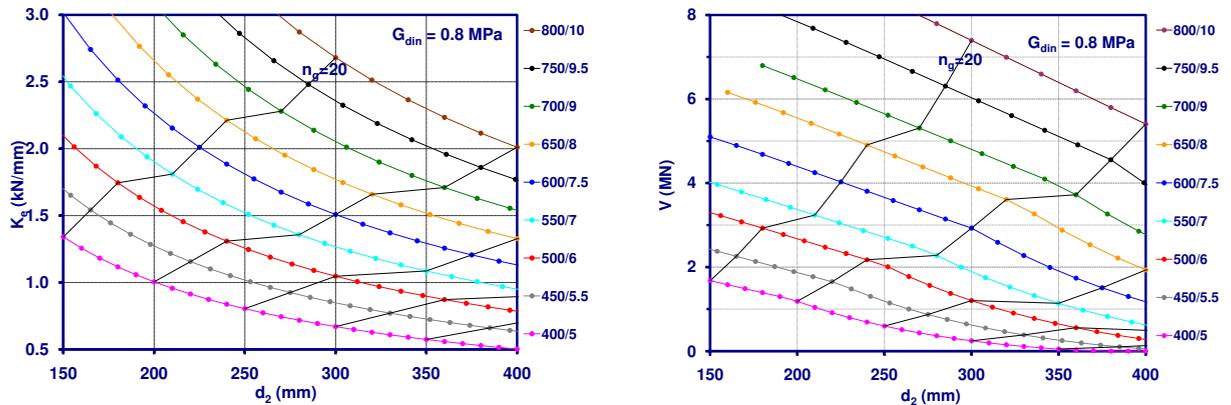


Figure 11. Elastomeric isolators: K_e versus d_2 (left) and V versus d_2 (right).

Elastomeric isolators	G (MPa)	D (mm)	t_i (mm)	t_e (mm)	t_s (mm)
400/5/25	0.8	400	5	125	2
500/6/24	0.8	500	6	144	2
600/7.5/21	0.8	600	7.5	157.5	3
700/9/16	0.8	700	9	144	3

Table 3. Characteristics of some isolation devices used in the investigation.

reported in Table 3. According to a proposal consistent with the official prize list used, the cost per unit volume of the elastomeric isolators has been assumed equal to 570 or 850 times the cost of the concrete (in €/m³), if the total volume of the device is higher or lower than 50 dm³, respectively.

The sliders are individualized by the maximum vertical load and the maximum horizontal displacement in any direction. The costs suggested by the Italian producers have been used.

Design of the isolation system. The isolation system is designed on the basis of the period T_{is} . This is chosen in order to have the maximum allowable acceleration $S_{e,is} = S_{e,is,d}$ ($= 0.2g$) in the building. Obviously the choice of T_{is} , for which $S_{e,is} = S_{e,is,d}$ depends on the shape and amplitude of the elastic spectrum. In the analysis the usual shape for the spectrum has been considered, characterized by the following relationships in the ranges of interest:

$$\begin{aligned}
 T_B \leq T < T_C & \quad S_e(T) = a_g \cdot S \cdot \eta \cdot F_0, \\
 T_C \leq T < T_D & \quad S_e(T) = a_g \cdot S \cdot \eta \cdot F_0 \cdot T_C / T, \\
 T_D \leq T & \quad S_e(T) = a_g \cdot S \cdot \eta \cdot F_0 \cdot T_C T_D / T^2.
 \end{aligned}$$

The following average values of the periods have been assumed as a function of the soil characteristics:

Hard soil (HS)	$T_B = 0.15$	$T_C = 0.40$	$T_D = 2.50$	(sec),
Medium soil (MS)	$T_B = 0.15$	$T_C = 0.50$	$T_D = 2.50$	(sec),
Soft soil (SS)	$T_B = 0.15$	$T_C = 0.80$	$T_D = 2.50$	(sec).

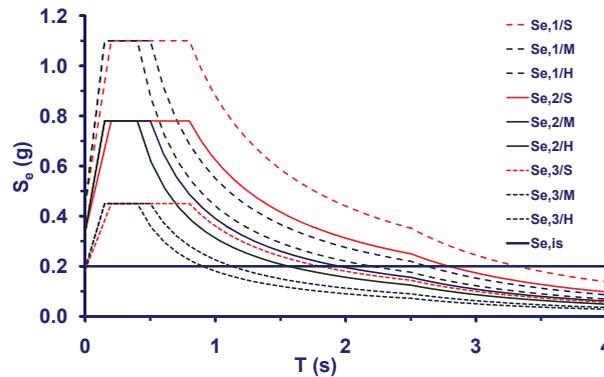


Figure 12. Choice of T_{is} for the different spectra.

With the hypothesis $T_B < T_{fb} < T_C$, three values of the spectral amplitude in the interval $[T_B, T_C]$ have been considered:

$$S_{e,1} = 1.10g, \quad S_{e,2} = 0.78g, \quad S_{e,3} = 0.45g.$$

In the resulting spectra, plotted in Figure 12, the chosen value $S_{e, is, d} = 0.2g$ is obtained at different periods. When the period turned out lower than 2.0 s, it was increased up to this value in order guarantee a suitable decoupling between the soil and the structure vibrations. Obviously, in these cases, the spectral value at $T = 2.0$ s, which is lower than $0.2g$, was used for the design. Finally the assumed periods were:

Hard soil (HS)	$T_{is,1} = 2.0$	$T_{is,2} = 2.0$	$T_{is,3} = 2.16$	(sec),
Medium soil (MS)	$T_{is,1} = 2.0$	$T_{is,2} = 2.0$	$T_{is,3} = 2.60$	(sec),
Soft soil (SS)	$T_{is,1} = 2.0$	$T_{is,2} = 2.8$	$T_{is,3} = 3.32$	(sec).

For any T_{is} found, the total stiffness $K_{e, tot}$ can be evaluated, the total mass of the superstructure being known with sufficient accuracy.

The design of the seismic isolation system was performed according to the usual suggestions. The devices were put under each pillar, at least 8 of them are elastomeric isolators, which have been mainly deployed under the perimeter pillars. Only one type of elastomeric isolator and one type of sliding device have been used.

Several deployments have been considered, which comply with the previous requirements and for which the dynamic behavior is optimum. This is very simple for the building considered and in the case of only one type of elastomeric isolator. Finally, four deployments have been selected, as shown in Figure 13.

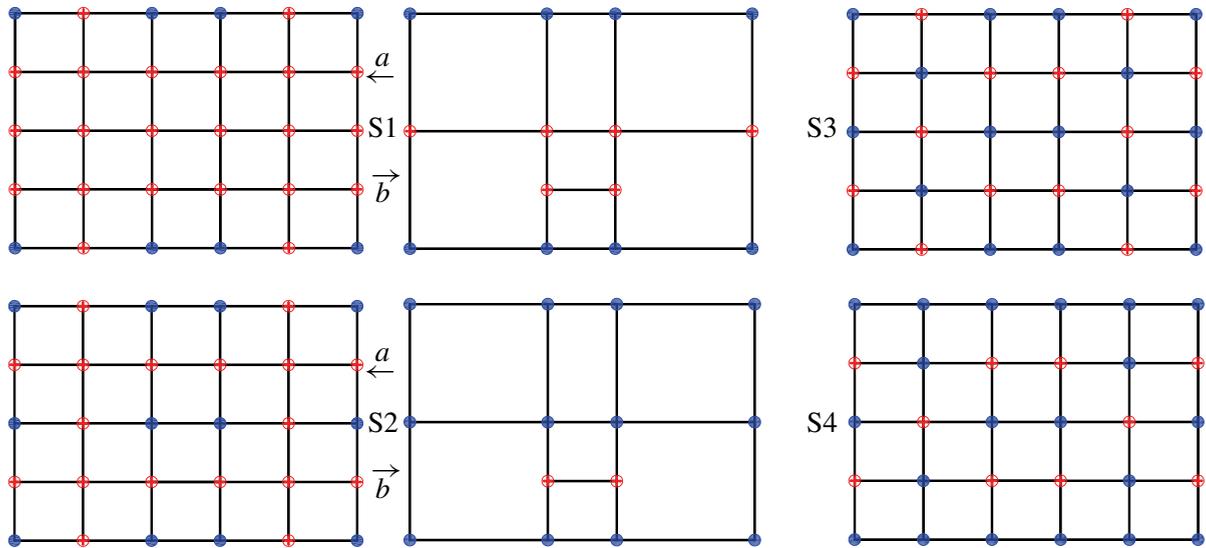


Figure 13. Different deployments of the elastomeric (filled circles) and sliding devices. Note that S3 and S4 are not possible for case b .

Deployment / Case	Elastomeric		Sliders	
	No.	$D/t_i/n_g$	No.	V/d_2
S1 / a	8	700/9/16	22	1500/300
S1 / b	8	650/8/22	6	3000/350
S2 / a	12	600/7.5/21	12	1500/300
S2 / b	18	750/9.5/19*	2	3000/350
S3 / a	16	500/6/24	12	1500/300
S4 / a	14	650/8/19*	12	1500/300

Table 4. Isolation systems for $S_{e,1} = 1.10g$ and medium soil. Asterisks mark the cases where $G = 0.4$ MPa.

For each of them, the following steps were taken:

1. The stiffness K_e of the single device was deduced, by dividing $K_{e,tot}$ for the total number of elastomeric isolators.
2. The building being very regular, a first but good approximation to the value of the design displacement can be deduced on the basis of the spectral displacement and of the rotational stiffness of the isolation system, which influences the displacement due to the additional eccentricity (5% of the corresponding length of the building).
3. With K_e and the value of the design displacement, the isolator to be used can be chosen in the previously defined set, and then the vertical load can be verified.

The characteristics of the elastomeric isolators and the sliding devices corresponding to the selected deployments are summarized in Table 4. The comparison between the different solutions is performed on the basis of economical considerations.

		Fixed Base			Base Isolated
		$S_{e,3} = 0.45g$	$S_{e,2} = 0.78g$	$S_{e,1} = 1.10g$	$S_{e,is} = 0.20g$
case a	Excavation	0.088	0.088	0.091	0.088
	Foundations	0.236	0.248	0.277	0.278
	Structure	0.555	0.590	0.632	0.544
	Total	0.879	0.926	1.000	0.910
case b	Excavation	0.094	0.098	0.101	0.094
	Foundations	0.242	0.273	0.300	0.248
	Structure	0.462	0.537	0.594	0.469
	Total	0.799	0.907	0.995	0.812

Table 5. Cost comparison for the structures of a fixed base building (for three typical values of the spectral amplitude) and of a seismic isolated building, for medium soil.

Soil	case =	$S_{e,3} = 0.45 g$		$S_{e,2} = 0.78 g$		$S_{e,1} = 1.10 g$	
		a	b	a	b	a	b
	Fixed Base	0.88	0.80	0.93	0.91	1.00	0.99
	Base Isolated	0.91	0.81	0.91	0.81	0.91	0.81
Hard	isolation system	0.12	0.07	0.14	0.08	0.17	0.13
	total BI	1.03	0.88	1.05	0.89	1.18	0.94
	BI/FB	1.17	1.10	1.13	0.97	1.08	0.94
Medium	isolation system	0.10	0.07	0.20	0.13	0.24	0.21
	total BI	1.01	0.88	1.11	0.94	1.15	1.02
	BI/FB	1.15	1.11	1.20	1.04	1.15	1.02
Soft	isolation system	0.20	0.13	0.42	0.43	-	-
	Total BI	1.11	0.94	1.33	1.24	-	-
	BI/FB	1.26	1.15	1.44	1.34	-	-

Table 6. Comparison between the costs of the structures of the fixed base building and the seismic isolated building.

6. Cost evaluation

The top half of Table 5 compares the costs of the fixed base building for the three values of the spectral amplitude with those of the isolated building (without the cost of the isolation system) for case a . The values have been normalized with reference to the total cost of the fixed base building in high seismicity area. As you can see the construction cost of the isolated building is lower than the cost of the fixed base building for high level seismicity area, while the difference is negligible in the other cases. In more details the superstructure of the isolated building is always cheaper and almost equal to the cost of a fixed base superstructure in low seismicity area. The cost of the substructure of the isolated building is always higher and very close to the cost of the substructure of the fixed base building in the high seismicity area.

Passing to case b , the cost of the fixed base building in the high seismicity area is almost the same of case a , while the cost of the isolated building is much lower, also than the fixed base building in medium seismicity area and very similar to the cost of the building in low seismicity area; see the bottom half of Table 5.

In order to conclude the comparison, the costs of the isolation system have been added to those of the isolated structures. The results are summarized in Table 6 for the three areas and for both case a and b . It is worth noting that the cost of the foundation structure is influenced by the seismic acceleration S_e , but this influence is very low on the structural total cost. The results confirm that solution a is more suitable for fixed base buildings while solution b is more suitable for isolated buildings. Actually, case b appears to be more convenient also for the fixed base building but it is worth pointing out that beams and pillars have very large cross-sections in this case. In areas with low intensity seismicity, the cost of the traditional building is low enough and use of seismic isolation could be expensive. Finally, the use of seismic isolation requires more care in the case of soft soil in high seismicity area also from the economical point of view. In fact, it is very hard to find a suitable solution.

Note that use of different number of pillars turns in different values of usable surface in the building. So taking into account the architectural and functionality requirements and economic value of the usable surface, it appears obvious to chose the solution a for a fixed base building and the solution b for the base-isolated one. The comparison between these two cases gives negligible differences for all seismic intensities. So we can conclude that use of base isolation does not determine a significant increase in cost.

7. Other investigations

The previous analysis refers to the case of a very regular building, for which it is not difficult and not expensive to realize a traditional structure without seismic isolation. As already said the numerical results are just relative to the case analyzed and cannot be generalized, especially to buildings with less regular geometrical characteristics.

Therefore it is interesting to analyze what happens for different cases. The next few subsections show the results of numerical investigations carried out on a broad selection of cases: buildings having different height, irregular buildings, and structures with particular functions. The soft soil case will not be considered for irregular and special buildings, given what was said about the use of seismic isolation in the presence of soft soil.

Influence of the height. Two buildings with the same plan as the previous one have been considered but having 3+1 and 7+1 levels; for convenience we call them “squat” and “tall”.

Squat buildings. In Figure 14 the total costs of the fixed base and the base-isolated buildings having 3+1 levels are shown. In this case the base-isolated building has been designed for a spectral amplitude $S_{e, is} = 0.23 g$. The minimum value of the period T_{is} has been fixed equal to 1.5 s, compatible with the period of the superstructure.

Table 7 summarizes the total costs. It is apparent that the increase of the cost of the foundation due to the isolation system is not balanced by the reduction of the cost in elevation. Use of seismic isolation determines the increases of the total cost not lower than 10%. The influence of seismic isolation on the total cost becomes very important for low intensity seismicity.

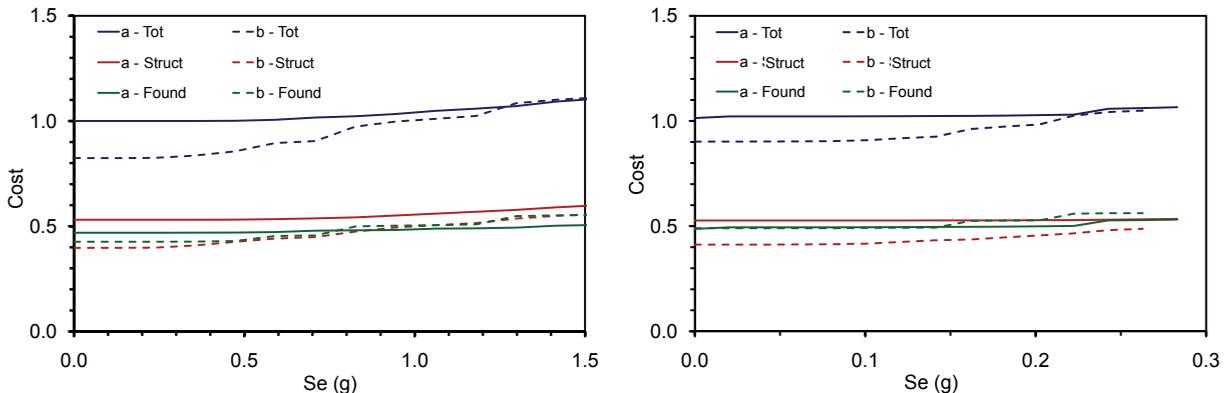


Figure 14. Squat building (3+1 levels): total cost of the building versus S_e , in the case of fixed base (left) and base isolation (right).

Soil	case =	$S_{e,3} = 0.45 g$		$S_{e,2} = 0.78 g$		$S_{e,1} = 1.10 g$	
		a	b	a	b	a	b
	Fixed Base	0.95	0.81	0.97	0.90	1.00	0.96
	Base Isolated	0.98	0.94	0.99	0.94	0.99	0.94
Hard	Isolation system	0.15	0.08	0.18	0.09	0.20	0.12
	Total BI	1.14	1.01	1.16	1.02	1.19	1.06
	BI/FB	1.19	1.24	1.20	1.14	1.19	1.10
Medium	Isolation system	0.16	0.09	0.22	0.12	0.25	0.18
	Total BI	1.15	1.03	1.20	1.06	1.24	1.11
	BI/FB	1.21	1.26	1.24	1.18	1.24	1.15
Soft	Isolation system	0.20	0.15	0.44	0.48	—	—
	Total BI	1.19	1.08	1.43	1.42	—	—
	BI/FB	1.25	1.33	1.47	1.58	—	—

Table 7. Squat building (3+1 levels): Comparison between the costs of the structures of the fixed base building and the seismic isolated building.

Tall buildings. In Figure 15 the total costs of the fixed base and the base-isolated buildings having 7+1 levels are shown. In this case the base-isolated building has been designed for a spectral amplitude $S_{e,is} = 0.20g$. The minimum value of the period T_{is} has been fixed equal to 2.5 s, compatible with the period of the superstructure, which is in this case out of the range of constant spectral acceleration.

Table 8 summarizes the total costs. The cost reduction of the building structure is very low in case a , and significant in case b . But also in this last case this reduction is not sufficient to balance the cost of the seismic isolation except that in the high seismicity area. This is due to the increasing of the period of the superstructures with reference to the 5+1 levels building, which happens not to be at the plateau but in the decreasing zone of the spectrum, and to the consequent increase in the period of the isolated structure, with turns in higher displacements and so in higher cost of the isolation system. We see that,

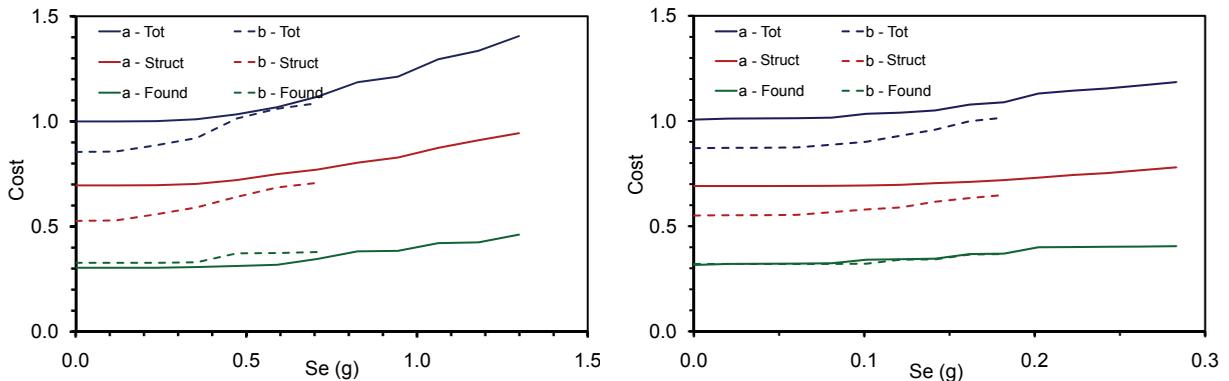


Figure 15. Tall building (7+1 levels): total cost of the building versus S_e , in the case of fixed base (left) and base isolation (right).

Soil	case =	$S_{e,3} = 0.45 g$		$S_{e,2} = 0.78 g$		$S_{e,1} = 1.10 g$	
		a	b	a	b	a	b
	Fixed Base	0.91	0.82	0.94	0.92	1.00	0.98
	Base Isolated	0.97	0.87	0.97	0.87	0.97	0.87
Hard	Isolation system	0.11	0.06	0.16	0.10	0.20	0.11
	Total BI	1.07	0.93	1.12	0.97	1.16	0.98
	BI/FB	1.18	1.14	1.20	1.06	1.16	1.00
Medium	Isolation system	0.13	0.10	0.20	0.15	0.28	0.21
	Total BI	1.09	0.97	1.16	1.02	1.25	1.07
	BI/FB	1.20	1.19	1.24	1.11	1.25	1.10
Soft	Isolation system	0.21	0.12	0.39	0.24	—	—
	Total BI	1.17	0.99	1.36	1.11	—	—
	BI/FB	1.29	1.22	1.45	1.20	—	—

Table 8. Tall building (7+1 levels): comparison between the costs of the structures of the fixed base building and the seismic isolated building.

as always, the use of seismic isolation leads to a significant cost increase for buildings in low seismicity area.

Irregular buildings. According to the Italian code, the structural factor used for design fixed base buildings must be reduced by 0.8 if the building is irregular in plan and/or in elevation. In the following both cases of irregularity are considered.

Buildings irregular in plan. The irregularity in plan has been simulated by increasing the mass of half of the decks at each floor and reducing that of the other part, keeping the total mass constant. The distribution of the stiffness has been kept symmetric as in the normal building.

In more detail, the structural configuration of the building in Figure 16 is the same of the previous building, both in plan and in elevation, while vertical loads and masses have been modified in order to move the center of gravity in the longitudinal direction of 5% of the maximum size. In Figure 17 the total cost of the fixed base and base-isolated buildings irregular in plan are plotted. Table 9 summarizes the total costs. Use of seismic isolation is always convenient for case b .

Buildings irregular in elevation. The building analyzed is in Figure 18. Only one part of the structure has 7+1 levels, the other just 4+1, the change of size being at the fifth level above the ground.

In Figure 19 the total cost of the fixed base and base-isolated buildings irregular in elevation are plotted. Table 10 summarizes the total costs. In this case the considerations already discussed with reference to tall buildings are still valid. The cost reduction of the building structure is not sufficient to balance the cost of the seismic isolation system except that in the high seismicity area because of the value of the period of the superstructure and because of the consequent increase in the period of the isolated structure, and so of the displacements.

The differences are always low, so we can conclude that seismic isolation is very suitable for irregular buildings.

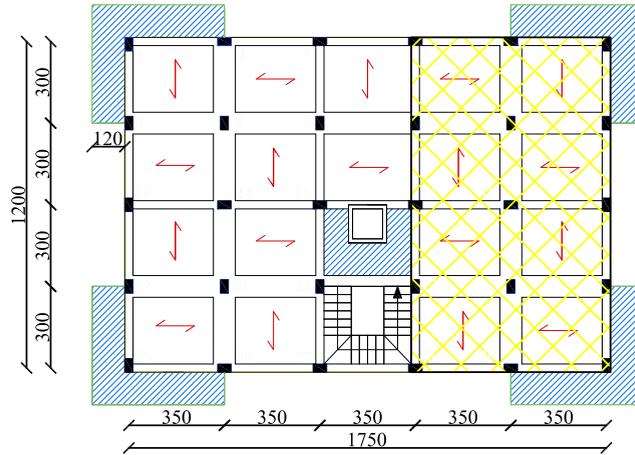


Figure 16. Building irregular in plan.

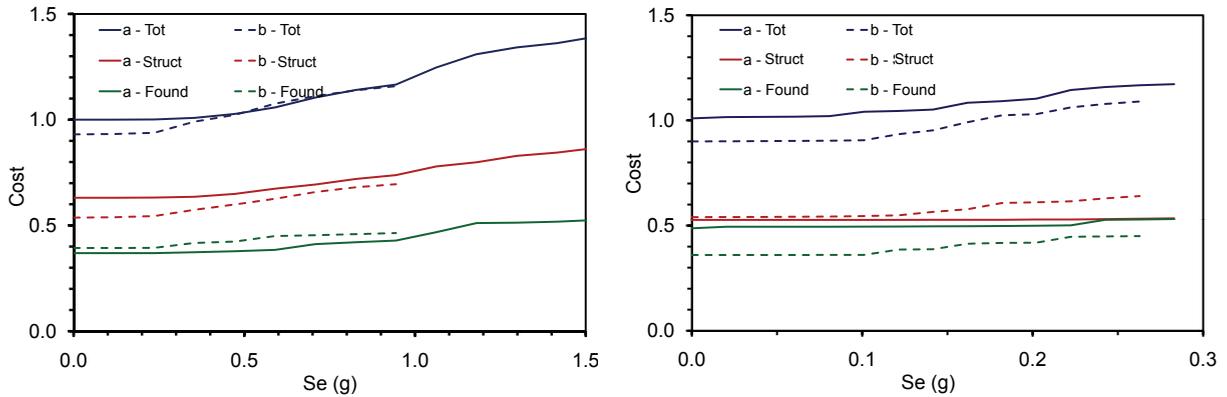


Figure 17. Building irregular in plan: cost of the building versus S_e , in the case of fixed base (left) and base isolation (right).

Soil	case =	$S_{e,3} = 0.45 g$		$S_{e,2} = 0.78 g$		$S_{e,1} = 1.10 g$	
		a	b	a	b	a	b
Fixed Base		0.81	0.80	0.89	0.88	1.00	1.00
	Base Isolated	0.81	0.71	0.83	0.75	0.87	0.81
Hard	Isolation system	0.12	0.06	0.15	0.08	0.19	0.11
	Total BI	0.92	0.78	0.98	0.83	1.06	0.93
	BI/FB	1.14	0.96	1.10	0.93	1.06	0.93
Medium	Isolation system	0.15	0.08	0.21	0.12	0.28	0.18
	Total BI	0.96	0.79	1.04	0.87	1.15	0.99
	BI/FB	1.18	0.98	1.17	0.97	1.15	0.99

Table 9. Building irregular in plan: comparison between the costs of the structures of the fixed base building and the seismic isolated building.

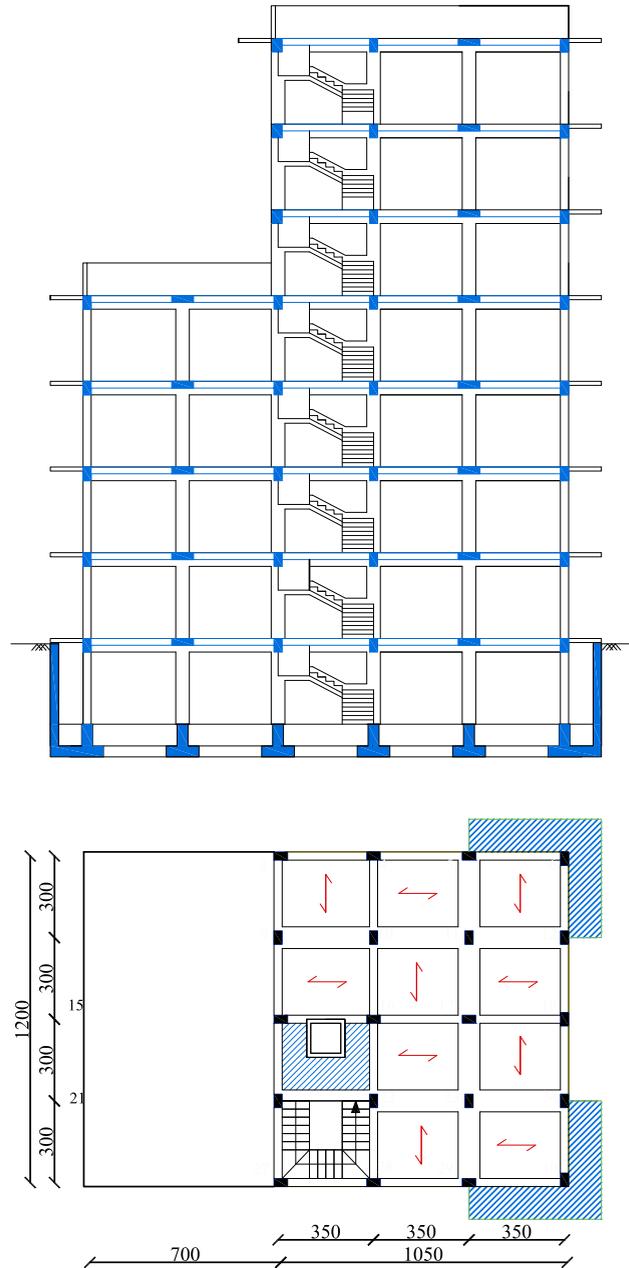


Figure 18. Building irregular in elevation: plan of the taller part and vertical section.

Special-use buildings. The buildings discussed in preceding sections are all characterized by “normal” size and designed for residential use. The structure in Figure 20 is a school building, having size in plan equal to 31.5×18.0 m, and height of 3+1 levels of 4.00 m. The structural system is very easy, with distances between the pillars of 7.0, 7.0, 3.5, 7.0, 7.0 m in longitudinal direction and 6.0, 6.0, 6.0 m

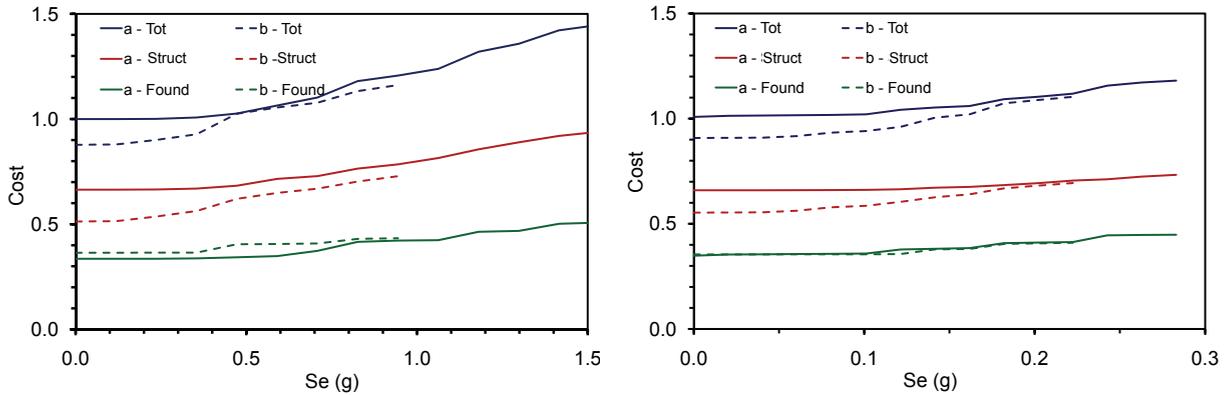


Figure 19. Building irregular in elevation: cost of the building versus S_e , in the case of fixed base (left) and base isolation (right).

Soil	case =	$S_{e,3} = 0.45 g$		$S_{e,2} = 0.78 g$		$S_{e,1} = 1.10 g$	
		<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>b</i>
Fixed Base		0.84	0.80	0.90	0.88	1.00	1.00
	Base Isolated	0.84	0.73	0.85	0.75	0.87	0.80
Hard	Isolation system	0.11	0.11	0.15	0.11	0.20	0.14
	Total BI	0.95	0.84	1.00	0.86	1.07	0.94
	BI/FB	1.14	1.04	1.11	0.97	1.07	0.94
Medium	Isolation system	0.14	0.11	0.21	0.18	0.39	0.27
	Total BI	0.97	0.84	1.06	0.93	1.26	1.06
	BI/FB	1.16	1.04	1.18	1.05	1.26	1.06

Table 10. Building irregular in elevation: comparison between the costs of the structures of the fixed base building and the seismic isolated building.

in transversal direction. The structure is subject to the usual permanent loads (self weight and other permanent loads) and to the typical variable loads of the school buildings (4.0 kN/m^2). A larger set of cross-sections has been considered. In Figure 21 the total cost of the fixed base and base-isolated special-use buildings are plotted. Table 11 summarizes the total costs. Use of base isolation causes a small increase of the construction cost but this is justified by importance of such buildings, i.e., the seismic risk. Obviously the difference is much lower for taller buildings.

8. Conclusions

In general, the difference between the cost of a building designed with a fixed base and the same building designed with base isolation is very low. Differences are certainly negligible for buildings designed to support very high level earthquakes, but also for low intensity earthquakes the choice of base isolation is obviously justified, especially for irregular and special-use buildings. In this last case, the solution with base isolation could be even less expensive. Besides, we should accounting for the different useful areas

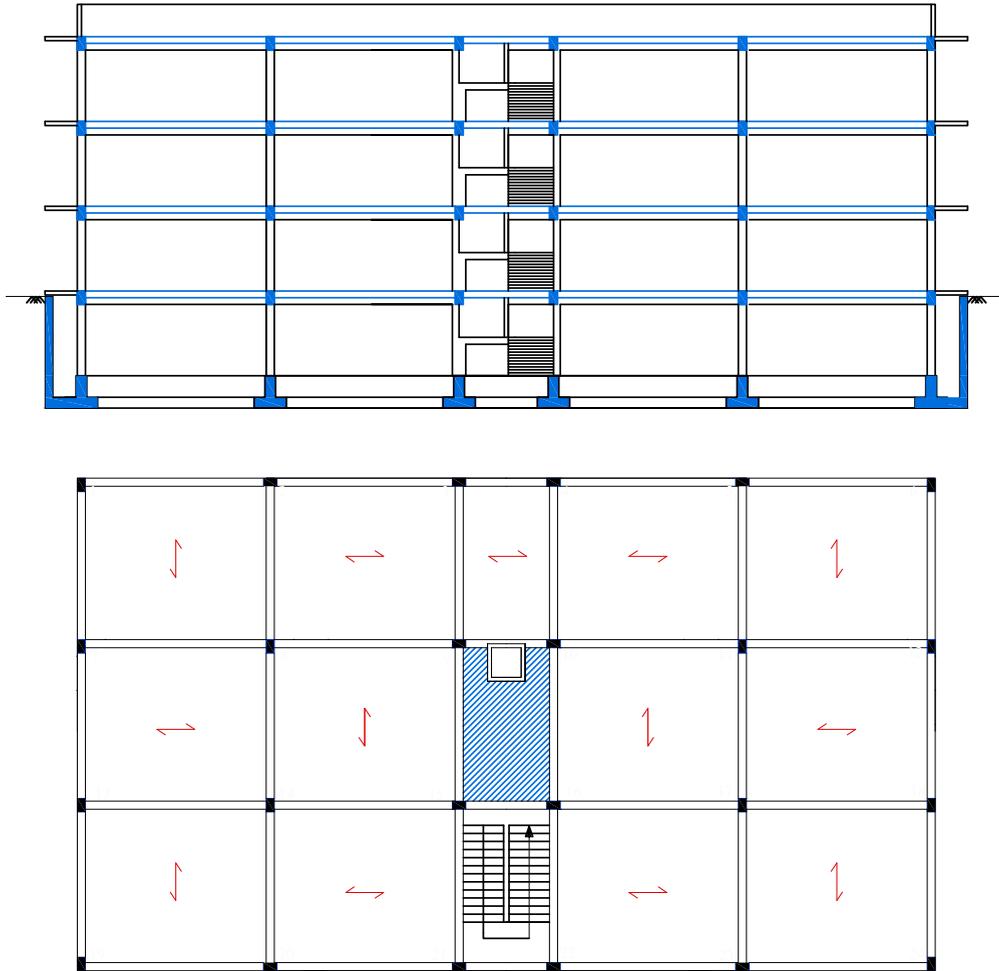


Figure 20. Nonresidential building (3+1 levels).

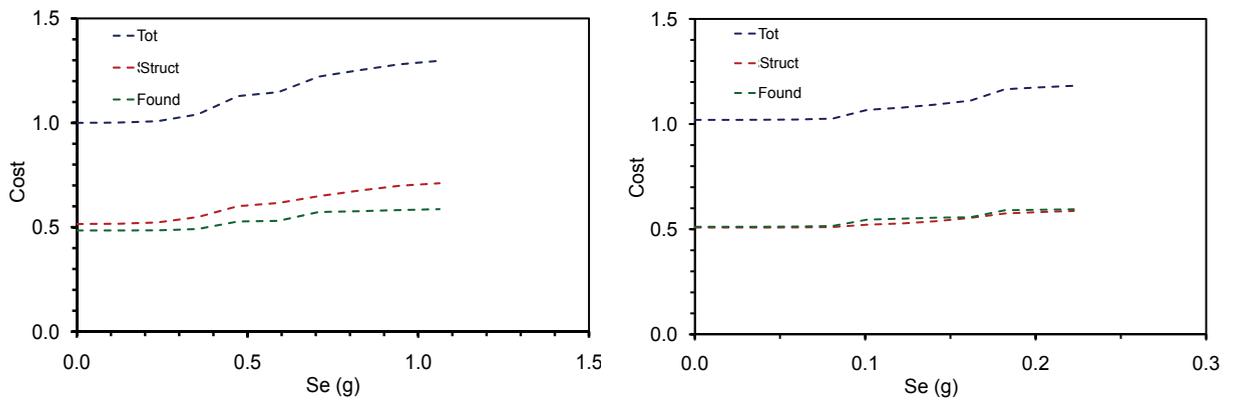


Figure 21. Nonresidential building: cost of the building versus S_e , in the case of fixed base (left) and base isolation (right).

Soil	case =	$S_{e,3} = 0.45 g$	$S_{e,2} = 0.78 g$	$S_{e,1} = 1.10 g$
		b	b	b
	Fixed Base	0.86	0.95	1.00
	Base Isolated	0.79	0.83	0.85
Hard	Isolation system	0.11	0.13	0.16
	Total BI	0.90	0.96	1.01
	BI/FB	1.05	1.01	1.01
Medium	Isolation system	0.12	0.17	0.20
	Total BI	0.91	1.00	1.05
	BI/FB	1.06	1.05	1.05

Table 11. Nonresidential building: comparison between the costs of the structures of the fixed base building and the seismic isolated building.

due to the smaller size of pillars in the solution with base isolation, which translates to a different value of the building. Finally, the use of seismic isolation is certainly suitable if we frame the comparison in the context of the building's life time. In fact, seismic isolated building will not need reparation works, even after strong earthquakes.

The analysis also pointed out that, in order to improve our prevention activities in the seismic field, we should change our way of designing structures in seismic areas. In fact, buildings can be designed to support seismic action in the elastic range up to a certain value of seismic input (for example $S_e = 0.3 g$). Therefore for buildings in low seismicity areas the assumption of a very low structural factor should guarantee their good performance and the absence of important damages. For energy input higher than that value use of new antiseismic technologies should be compulsory, instead of entrusting the safety against collapse to ductility, which will turn into lots of expenses for structural repairing. It is worth recalling that current codes allow the use of the same structural factors in low and high seismicity areas.

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