Multi-criteria cost-benefit analysis for base isolated buildings

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ABSTRACT: Base isolation has been widely proven to be effective in mitigating the effects of earthquake on buildings. However, common prejudices about actual costs of implementing such a low-damage solution have arguably impaired the widespread of this solution within ordinary constructions, whilst limiting its use mostly to large and important/critical facilities. In fact, the economic comparison between base-isolated buildings vs. their fixed counterparts is usually carried out considering only the structural performance and the initial cost of construction. The actual overall "added value" of the solutions is not properly communicated to non-technical stakeholders.

The present paper provides a proposal for a multi-criteria method able to appreciate the role of a series of additional parameters, beyond structural engineering aspects, that appear to affect the decision-making process.The cost-benefit analysis is developed from the building owner perspective, including initial costs, flexibility of architectural plan and overall downtime in terms of business interruption.

1 INTRODUCTION

Providing a building with base isolation system could lead to different benefical effects when compared to a fixed base one as a) a significant reduction of the accelerations transmitted to the superstructure and b) a reduction in the interstory drift, causing the building to act as a rigid body since most of the base drift is absorbed by the isolators.

This in turns would lead to:

- Significantly reduce if not avoid damage to the structural skeleton, as it would be designed to remain mostly in the elastic range;
- avoid the damage to the non-structural elements, including partitions/infills, ceilings, facades, which can make the building temporarily inagible;
- keep the building operational, since there can be a only minor damage to the contents;
- reduce users' panic, as the perception of the seismic shake is highly reduced, due to the slow movements of the building excited by lower accelerations.

To fully appreciate the benefits of base isolation, it is worth recalling that the traditional seismic design, based on member hierarchy of strength criterion, primarily aims at saving lives; in the meantime, it accepts the chance of having significant level of damages, even not reparable. Thus, the most evident advantage of a base-isolated buildings is the possibility to significantly reduce, or ideally fully eliminate, the damage to all the structural and non-structural parts of the buildings, contents included. This latter aspect is particularly important in the case case of "strategic" buildings, which have to be operational after a strong earthquake, as hospitals, National Protection centres, fire stations, or all those buildings whose contents is often more valuable than the building itself (museums, banks, etc.).

The economical convenience of providing buildings and infrastructures with a seismic isolation protection has been proven in a number of studies, but most of them rely on case studies regarding buildings designed in a traditional way (e.g. no seismic isolation), then simply adding a seismic isolation device (Mayes at al. 2012). The total base isolation system cost counted for about 3% of the total construction cost for two recent built hospitals in New Zealand, namely the Wellington Regional Hospital and the Christchurch Womens' Hospital (Charleson et al. 2012).

The added construction costs of a base isolated building include the cost of a structural floor versus a slab on grade at the basement level (unless the isolators are on top of a basement column), the cost of the isolators, architectural modifications to permit movement of the building and the cost of flexible connectors for mecahnical piping and electrical wiring entering a building.

The application of seismic isolation should however be recommended also to ordinary residential or commercial multi-storey buildings, given the significant socio-economic costs and impacts a major earthquake event can have on the general community.

Considering the different dimensions of the structural grid a building can have, with more span between the columns and lower dimensions of columns and beams, a base isolated building can be an attractive choice to investors, thanks to its fewer architectural contraints and more productive square meters, and opportunity to increase the market value. Moreover, there can be some level of savings even in the construction itself, due to the structural form requiring less seismic force, ductility demands and structural deformations.

Another interesting aspect when considering the economical convenience of an isolated building is about the insurance premium rebate, which is usually provided in Japan (discount rates of up to 30% apply when the building is earthquake resistant, according to the Japanese Performance Designation Standards). At this stage, even in the aftermath of the Canterbury earthquake sequence, no significant premium reductions are officially provided in New Zealand yet, but many companies have initiated the discussion, as it usually happens when a building is retrofitted with a fire or burglar alarm, to account for the benefical reduction in losses (and thus insurance pay-back) associated to damage as well as business interruption.

Finally, to proceed to a correct economical comparison, buildings with and without a base isolation device should be compared taking into account the nominal life of the building and the probability of occurrence of a major earthquake during this period, resulting in costs associated to the repairing of the damage, or the demolition and subsequent reconstruction, or the downtime, which is a significant issue, since an office can be forced to relocate and rent another property to continue its activity, and the time required to be fully operational again. As many people all over the world have experienced in the case of a major seismic event and of the need to move out of their houses/offices, the real estate market registers a significant raise in prices, resulting into a great expence for the tenants. This latter aspect has not been tipically investigated, since it is very difficult to provide an estimation of the increase of this type of costs, as too many variables have to be taken into account, e.g. a very urbanized area (as it was in the case of the earthquake in L'Aquila, 2009) versus a more productive infrastructure (earthquake in Emilia, 2012), the availability of vacant areas (and their dimensions), the transport system and so on. In this paper a multi-criteria cost-benefit analysis is proposed to be able to appreciate the role of a series of additional parameters, beyond structural engineering aspects, that appear to affect the decision-making process.

The analysis is developed on four case study buildings from the building owner's perspective, including initial costs, flexibility of architectural plan and overall downtime in terms of business interruption, to help him choose between realising a fixed-base building or an isolated one.

The multi-criteria method has already been applied to similar topics. Giovinazzi and Pampanin (2007) proposed a multi-criteria approach as a valuable tool to select an effective retrofit strategy while accounting for both monetary and non-monetary-based criteria. Caterino et al (2008) evaluated and comared four different alternative seismic strategies using a multi-criteria decision making method.

2 THE CASE STUDY BUILDINGS

Several economic factors affect the choice of realising a base-isolated building or non isolated one. Among these:

- the size of the building, since the cost of the isolation system is percentually lower in larger buildings;
- the shape of the building, in elevation and in plan, because it is quite difficult to design a seismic resistant structure in irregular buildings using “traditional” systems;
- the earthquake intensity, since a low seismic excitation can be absorbed by a traditional building in the elastic range, so no damages should occur;
- the characteristics of the soil, if the building is realised on a soft soil the earthquake spectra results in a wider range in which the acceleration is constant at its maximum value; the natural period of the building could be higher enough and consequently it can show higher displacements.

It is quite difficult to effectively compare a base-isolated building and a corresponding non isolated one. That is because the architectural plan cannot dramatically change, or the economic values of the two buildings could be very different. In the base-isolated buildings, the isolators have been placed on the top of the columns at the underground level. The locations for the columns cannot be assumed to be the same for the isolated and the non-isolated building, since both show better performances for different spaces between the columns: the fixed base buildings have been designed with a mutual distance of 5 m and 4 m, respectively in x and y direction; the isolated buildings have distances of 7.50 m and 6 m; materials with the same mechanical characteristics have been used for the structural elements of both the structures.

All of the buildings are provided with an underground parking; the ground floor is supposed to be used for shops and retails, and the above levels for residential or office use. The evaluation of the initial building cost has been carried out using the New Zealand Rawlinsons guide (2013/14) to compare the possible added costs of the base-isolated building to the ones related to business disruption.

The dimension along the direction Y is assumed to be constant at 12 m. The four case-study buildings are located in Christchurch CBD, they reflect four common typologies planned for the area. The dimensions in the X direction, the gross floor area and the function for each floor are summarized in Table 1. The structural plan and section Y is showed for case building 3 (Fig.1).

Table 1. Summary of the four case-study buildings.

	Dim. X [m]	Height [m]	Floor	Function
Building 1	15	10,8	-1	Parking
			G	Retail
			1	Residential
			2	Residential
	Dim. X [m]	**Height [m]**	**Floor**	**Function**
Building 2	15	18	-1	Parking
			G	Retail
			1	Office
			2	Office
			3	Office
			4	Office

	Dim. X [m]	Height [m]	Floor	Function
			-1	Parking
Building 3	45	10,8	G	Retail
			1	Office
			2	Office
	Dim. X [m]	**Height [m]**	**Floor**	**Function**
			-1	Parking
			G	Retail
Building 4	15	14,4	1	Residential
			2	Residential
			3	Residential

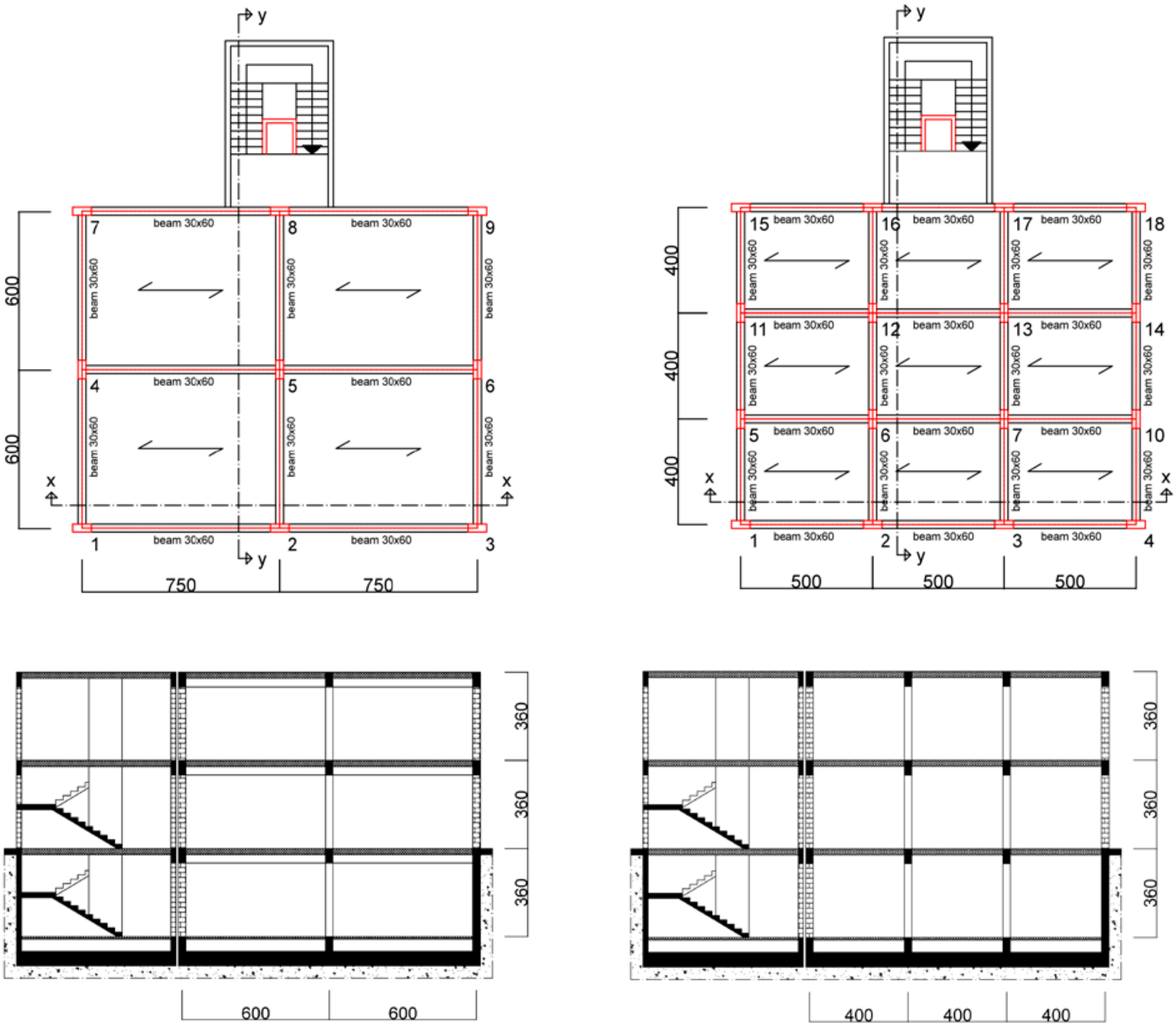


Figure 1. Case building 3: structural plan and section Y, isolated version (left) vs fixed base (right).

3 THE CONSTRUCTION COSTS

The rates are given for the base building cost: since the structures are designed to be built in Christchurch City Centre, the appropriate cost element is chosen within the Rawlinsons guide. The following tables summarize the four buildings considered in the present study:

Table 2. Cost of construction, Building 1.

FLOOR #	AREA [m²]	FUNCTION	NZ$/m²	COST OF CONSTRUCTION NZ$	Base isolators # of columns	Base isolators NZ$/col	Base isolators Tot NZ$
-1	180	Parking	1.875	337.500	9	15.000	135.000
G	180	Shops	2.500	450.000			
1	180	Residential	1.930	347.400			
2	180	Residential	1.930	347.400			
Volume [m³]	**2.592**	**TOTAL [NZ$]**		**1.617.300**			
NZ$/m³	**624**						

Table 3. Cost of construction, Building 2.

FLOOR #	AREA [m²]	FUNCTION	NZ$/m²	COST OF CONSTRUCTION NZ$	Base isolators # of columns	Base isolators NZ$/col	Base isolators Tot NZ$
-1	180	Parking	1.875	337.500	9	15.000	135.000
G	180	Shops	2.500	450.000			
1	180	Office	2.075	373.500			
2	180	Office	2.075	373.500			
3	180	Office	2.075	373.500			
4	180	Office	2.075	373.500			
Volume [m³]	**3.888**	**TOTAL [NZ$]**		**2.416.500**			
NZ$/m³	**622**						

Table 4. Cost of construction, Building 3.

FLOOR #	AREA [m²]	FUNCTION	NZ$/m²	COST OF CONSTRUCTION NZ$	Base isolators # of columns	Base isolators NZ$/col	Base isolators Tot NZ$
-1	540	Parking	1.875	337.500	21	15.000	315.000
G	540	Shops	2.500	450.000			
1	540	Office	2.075	1.120.500			
2	540	Office	2.075	1.120.500			
Volume [m³]	**7.776**	**TOTAL [NZ$]**		**4.918.500**			
NZ$/m³	**633**						

Table 5. Cost of construction, Building 4.

				COST OF CONSTRUCTION			
					Base isolators		
FLOOR #	AREA [m²]	FUNCTION	NZ$/m²	NZ$	# of columns	NZ$/col	Tot NZ$
-1	180	Parking	1.875	337.500			
G	180	Shops	2.500	450.000			
1	180	Residential	1.930	347.400	9	15.000	135.000
2	180	Residential	1.930	347.400			
3	180	Residential	1.930	347.400			
Volume [m³]		**3.240**	**TOTAL [NZ$]**	**1.964.700**			
NZ$/m³		**606**					

4 THE MULTI-CRITERIA DECISION MAKING METHOD

Multi-Criteria Decision Making (MCDM) methods are decision-support procedures used in many fields allowing the evaluation and comparison of a set of alternatives when many evaluation criteria are involved. Ranking the alternative solutions leads to the identification of the optimal solution, which better performs in respect to all relevant goals. In the case study, the Decision Maker (DM) is hesitant about using or not a base isolation strategy to be realised under the building, and his decision depends on many different and indipendent criteria.

4.1 Definition of the evaluation criteria

Criteria can be generally defined as different points of view from which the same solution can be evaluated. According to Thermou and Elnashai (2002), criteria can be grouped into two categories: economical/social and technical criteria. Only the criteria that may have a significant influence on the final decision should be considered. Since the DM is assumed to be the owner, non technical and willing to build for renting, the following criteria have been selected.

Table 6. Evaluation criteria.

Group	Symbol	Description
	C1	Initial building cost
	C2	Insurance premium rebate
Economical/Social	**C3**	Repair/Rebuild cost
	C4	Downtime cost
	C5	Added value
	C6	Skilled labour
Technical	**C7**	Flexibility of the architectural plan
	C8	Construction time

Obviously, the total initial cost to be beared for the realization of an isolated building vs a fixed base one has to be taken into account to compare the options (criterion C1). But, in a multi-criteria approach, the deferred expenses to be incurred during the economic life of the building are not only limited to the initial once. Therefore, since insurance companies could grant significant benefits in terms of insurance premium rebate, this aspect has to be considered (criterion C2). The time span necessary to realize an intervention of restoration or a total rebuild, is of course another important aspects to take into account (criterion C3). The downtime, resulting into a disruption of normal building activities, is a very important aspect to keep in mind when running such a MCDM method, yet it is often neglected (Criterion C4). It is appropriate to take into account, by means of a specific criterion (C5), that the perception of safety and the possibility of not having any disruption in the activities by the tenants can be converted into an added rental appeal. The technical criterium related to the common belief of a more complicate structural design and realisation has to be considered, since the DM has no technical background (C6). In the same manner, he can approve a different structural design approach to his building, if this can translate into a more flexible architectural plan which can help him rent the spaces, given the increased span between the columns in the isolated version of the buildings (C7). Last but not least, the construction time (C8) is another important aspect to take into account, since a shorter time translates into an increase of earnings by the DM.

4.2 **Weighting the evaluation criteria**

A quantitative evaluation of the relative importance (weight) of each criterion to the final decision is needed. The weights will amplify or de-amplify the evaluations of the alternatives in order to reflect how much each criterion is important relatively to the others in the choice of the best solution. Therefore this step, necessarily involving the DM's choices, requires special attention.

The approach used herein to compute weights w_i of the criteria C_i (i = 1, 2, ..., 8) is proposed by Saaty (1980) and is based on pairwise comparisons of criteria and eigenvalues theory. It requires the DM expressing his opinion about a pairwise comparison at a time. In particular, with reference to two generic criteria C_j and C_k (j, k = 1, 2, ..., 8), the DM has to define the relative importance of C_j in respect of C_k choosing among 17 possibilities. Each choice is a linguistic phrase, such as those reported in the second column of Table 7.

Table 7. Scale of relative importance.

Intensity of Importance	**Definition**
1	Equal importance
3	Moderate importance of one to another
5	Essential or strong importance
7	Demonstrated importance
9	Extreme importance
2,4,6,8	Intermediate values between the two adjacent
Reciprocal of above	If criterion j compared to k gives one of the above, then k, when compared to j, gives its reciprocal

The value of a_{jk} can be considered as a rough estimate of the w_j/w_k ratio. Therefore, a_{jk} is equal to 1 when criteria C_j and C_k are judged to be equally important; greater than 1, if C_j is considered to be more important than C_k ($a_{jk} \in \{2, ..., 9\}$); lower than 1, if C_j is considered to be less important than C_k ($a_{jk} \in \{1/9, ..., 1/2\}$). In the last row of Table 7 is underlined that two criteria have to be compared once only since it should be assumed $a_{kj} = 1/a_{jk}$. After defining all the a_{jk} values, they can be assembled into the matrix A, which results to be a symmetric square matrix of order n (n = 8 herein because 8 is the number of compared criteria). For the case under consideration, 28 comparisons between criteria in terms of relative importance have been performed, simulating a likely behavior of the DM, and the A matrix given in Figure 2 was obtained.

	C1	C2	C3	C4	C5	C6	C7	C8
C1	1	5	1	1	1	6	1/3	4
C2	1/5	1	1/7	1/4	1/2	1/3	1/5	1/4
C3	1	7	1	1	1/2	5	1/2	1
C4	1	4	1	1	1	5	1	1
C5	1	2	2	1	1	6	1	2
C6	1/6	3	1/5	1/5	1/6	1	1/6	1/5
C7	3	5	2	1	1	6	1	1/3
C8	1/4	4	1	1	1/2	5	3	1

Figure 2. Matrix A.

After having completed the A matrix, it is necessary to carry out a consistency measurement of the DM's judgements. If the comparisons among criteria are made in a consistent manner, each a_{jk} value is exactly equal to the ratio w_j / w_k between the weights of criteria C_j and C_k, respectively. If this happens (ideal case), the A matrix has rank equal to 1 and its principal right eigenvalue l = n = 8. It is possible to demonstrate that the vector W of relative weights w_1, w_2, ..., w_8 is the principal right eigenvector.

In reality, a_{jk} deviates from the ratio w_j/w_k, making the eigenvalues change conversely. In particular, the maximum eigenvalue l_{max} results to be greater than n (but close to it) while the other eigenvalues are close to zero. It is reasonable to assume the vector W equal to the eigenvector that corresponds to l_{max}. In other words, W has to satisfy the equation:

$$A \cdot W = l_{max} \cdot W$$

In the case under examination, it results l_{max} = 8.612 and the vector W results to be the following:

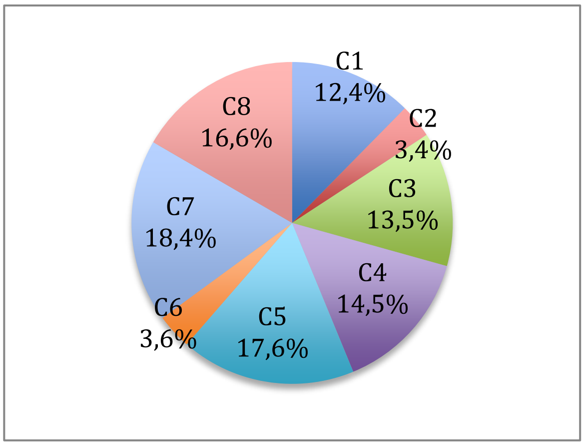
W ={w_i} = {0.320; 0.088; 0.350; 0.374; 0.455; 0.092; 0.476; 0.430}.

Weights w_i can be used to rank the criteria with reference to their relative importance as shown in the following Table:

Table 8. Ranking of criteria according to their weight.

Ranking order	Weights w_i	Criteria	Description
1	0.476	C7	Flexibility of the architectural plan
2	0.455	C5	Added value
3	0.430	C8	Construction time
4	0.374	C4	Downtime cost
5	0.350	C3	Repair/Rebuild cost
6	0.320	C1	Initial building cost
7	0.092	C6	Skilled labour
8	0.088	C2	Insurance premium rebates

The pie chart in Figure 3 represents the shares of importance that the DM has defined via the pairwise comparisons, and the weights have a significant influence on the final solution of the decisional problem and represent the subjective part of the procedure. Since the flexibility of the architectural plan and the added value are recognised as two important aspects a base isolated building can show in respect to a fixed base one, it seems clear that proceeding towards the realisation of an isolated building suits the DM's investment.



C1	Initial building cost
C2	Insurance premium rebate
C3	Repair / Rebuild cost
C4	Downtime cost
C5	Added value
C6	Skilled labour
C7	Flexibility of the architectural plan
C8	Construction time

Figure 3. Shares of relative importance of criteria.

4.3 Comparison among criteria: consistency check

It's necessary to run a consistency measurement of the pairwise comparisons among the criteria to be sure that the final decision is not a result of random prioritization (Shapira and Goldenberg, 2005). In case the check is not positive, a new matrix A has to be done with more coherent values. The Consistency Index (CI) can be computed as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Then, the CI will be normalized by a "Random Consistency Index" (RCI) which can be defined as an average consistency measure function of n (0, 0, 0.58, 1.12, 1.24, 1.32, 1.41, 1.45 for n = 1, 2, …, 9 respectively). In this manner, the Consistency Ratio (CR) is obtained; in general, pairwise comparisons can be defined as consistent enough if CR > 10% when n < 4. In case this results is not obtained, it's necessary to re-examine the judgements until acceptable consistency is achieved. For the case under investigation n = 8, then RCI = 1.41; the A matrix is consistent since it results CR = 6.20% < 10%:

$$CR = \frac{CI}{RCI} = \frac{\lambda_{max} - n}{n - 1} \frac{1}{1.41} = 6.20\%$$

5 DOWNTIME COST EVALUATION AS A RESULT OF LOSS OF EARNING

A survey has been run in the real estate market of Christchurch considering the bonds received in the period January-June 2014. A total of 4722 bonds have been identified; 248 of them are located in Central Christchurch (79 offices, 50 retails, 119 residences). It has been identified the most common dimension for each of the three typologies in the zone, and calculated the average yearly renting to evaluate the downtime cost the DM would face in case his damaged building would not be available for renting. An additional calculation has been done keeping in mind that not the entire floor area is available for renting (column "area"), but only a certain percentage of it depending on its function (column "use"). Then, the results have been put into the Tables 9 to 12 to be easily readable.

As it is evident, the base isolation cost counts as a small percentage compared to the total cost of construction. The figure 4 shows the DM will recoup his starting investment in the matter of 10 years or less, considering the total cost of the building, and the added cost for base isolators count for less than one year of rentals of the areas.

Table 9. Yearly earning, Building 1.

COST OF CONSTRUCTION TOTAL [NZ$]	ISOLATORS Cost [NZ$]	ISOLATORS Incidence %	FLOOR	USE %	AREA [m^2]	units per floor	area per unit [m^2]	type of unit	Prices [NZ$/m^2]	yearly earning per floor [NZ$]	total yearly earning [NZ$]
1.617.300	135.000	9,11	**-1**	60	108	-	-	-			150.586
			G	90	162	1	162	retail	540,21	87.514	
			1	80	144	2	72	2 bed	219,00	31.536	
			2	80	144	2	72	2 bed	219,00	31.536	

Table 10. Yearly earning, Building 2.

COST OF CONSTRUCTION TOTAL [NZ$]	ISOLATORS Cost [NZ$]	ISOLATORS Incidence %	FLOOR	USE %	AREA [m^2]	units per floor	area per unit [m^2]	type of unit	Prices [NZ$/m^2]	yearly earning per floor [NZ$]	total yearly earning [NZ$]
2.416.500	135.000	5,92	**-1**	60	108	-	-	-			356.464
			G	90	162	1	162	retail	540,21	87.514	
			1	90	162	1	162	office	375,05	60.758	
			2	90	162	1	162	office	375,05	60.758	
			3	90	162	2	81	office	455,04	73.717	
			4	90	162	2	81	office	455,04	73.717	

Table 11. Yearly earning, Building 3

COST OF CONSTRUCTION TOTAL [NZ$]	ISOLATORS Cost [NZ$]	ISOLATORS Incidence %	FLOOR	USE %	AREA [m^2]	units per floor	area per unit [m^2]	type of unit	Prices [NZ$/m^2]	yearly earning per floor [NZ$]	total yearly earning [NZ$]
4.918.500	315.000	6,84	**-1**	60	324	-	-	-			508.568
			G	90	486	2	243	retail	469,90	228.373	
			1	90	486	1	486	office	248,27	120.660	
			2	90	486	2	243	office	328,26	159.535	

Table 12. Yearly earning, Building 4

COST OF CONSTRUCTION TOTAL [NZ$]	ISOLATORS Cost [NZ$]	ISOLATORS Incidence %	FLOOR	USE %	AREA [m^2]	units per floor	area per unit [m^2]	type of unit	Prices [NZ$/m^2]	yearly earning per floor [NZ$]	total yearly earning [NZ$]
1.964.700	135.000	7,38	**-1**	60	108	-	-	-			177.586
			G	90	162	1	162	retail	540,21	87.514	
			1	80	144	2	72	2 bed	219,00	31.536	
			2	80	144	2	72	2 bed	219,00	31.536	
			3	80	144	2	144	3 bed	187,50	27.000	

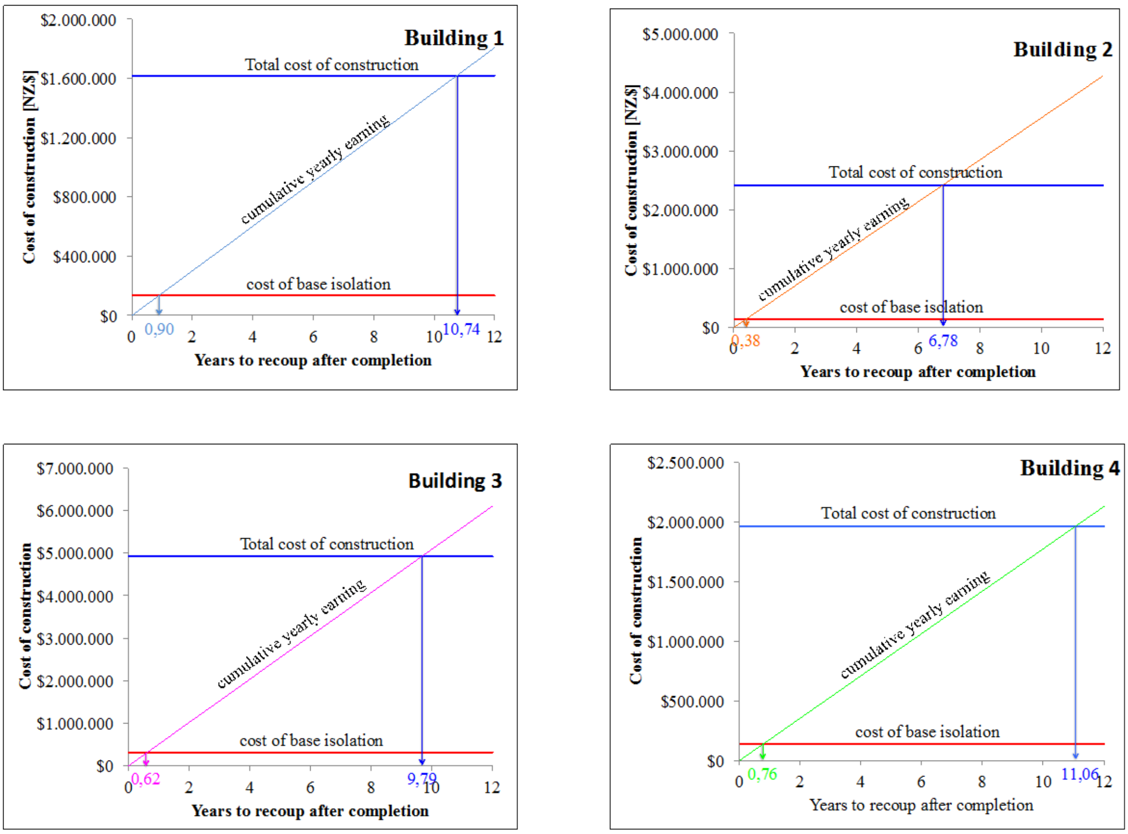


Figure 4. Time to recoup the investment.

6 CONCLUSIONS

The major economic issues in case of a seismic event are related not only to the direct cost of earthquake damage but mainly the business disruption. The paper has examined the cost-benefit analysis for building owners, who would face a huge economic loss in case his building has been damaged and is not fully operational for a certain period of time, resulting into a disruption cost due to a loss of the building function in terms of lost rent. The cost incidence of base isolators depend on the size and shape of the structure, in the case study buildings the variability falls in the interval 6 to 9%, and the DM would recover from the additional cost in a few months.

The results would be far more favourable if many more factors are taken into account, e.g. the physical damage of the building itself, the annual earthquake insurance premium and the loss of market share due to reduced desirability of renting by potential tenants, which can result into decreased rental rates.

In summary, realising a base isolated building is a very cost-effective solution which offers huge benefits in terms of immediate occupation and uninterrupted economic returns for building owners.

7 REFERENCES

Megan Devine, GM Robinson Seismic Ltd, Cost and Benefits of Seismic/Base Isolation, *keynote, CERC Canterbury Earthquakes Royal Commission*, 12 March 2012.

P. Clemente, A. De Stefano, R. Zago, Seismic Isolation in Existing Complex Structures.

P. Clemente, G. Buffarini, Seismic Isolation and Protection Systems, The Journal of the Anti-Seismic Systems International Society (ASSISi).

R.L. Mayes, A.G. Brown & D. Pietra, *Using Seismic Isolation and Energy Disspiation to Create* Earthquake-Resilient Buildings, 2012 NZSEE Conference.

Charleson, A. W. and Allaf, N. J. (April, 2012). *Costs of Base-isolation and Earthquake Insurance in New Zealand*. Paper presented at the New Zealand Society of Earthquake Engineering Conference. Retrieved from http://www.nzsee.org.nz/db/2012/Handbook.pdf

Rawlinsons New Zealand Construction Handbook, 28th edition, 2013/14. Auckland, New Zealand.

http://www.newzealandnow.govt.nz/living-in-nz/housing/renting-a-property

http://www.globalpropertyguide.com/Pacific/New-Zealand/Price-History