A Direct-Indirect Cost Decision Making Assessment Methodology for Seismic Isolation on Bridges

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Making decisions of when to intervene on bridges taking into consideration more than owner costs is a growing field of interest in earthquake engineering. In particular, bridges can be considered critical links in highway networks because of their seismic vulnerability in terms of direct and indirect losses. This paper aims at defining a general criteria capable of taking into account both these costs in a simplified and efficient formulation. Indirect losses generally neglected elsewhere, are taken into consideration by applying a formulation that assesses investment efficiency. The presented formulation follows the one proposed for buildings by L. Kantorovich, 1975. Direct costs are computed from a Performance Based Earthquake Engineering (PBEE) methodology by the Pacific Earthquake Engineering Research (PEER) center. The problem considers two competitive objectives (maximizing economic efficiency and minimizing costs) in a multi-objective structural optimization procedure. The formulation has been applied to a case study aimed at strengthening a benchmark bridge. The optimum investment has been assessed between several isolated configurations.

Key Words: Multi-objective optimization; decision making; direct costs; indirect costs; bridge; isolation.

Introduction

Allocation of resources within an infrastructure network is becoming an increasingly prevalent problem. Many methodologies have been recently developed (such as Liu and Frangopol, 2006 and Orcesi and Cremona 2010) with the aim to include network maintenance management. In this regards, economic impacts should be defined in terms of structural damage and costs associated with traffic flow. In particular, these losses, should include both direct and indirect costs (Brookshire et al., 1997). Direct costs are those incurred by the infrastructure owner, such as material and labor costs due to undertake an action (i.e. deck replacement and rehabilitation). Indirect cost are those incurred by users such as travel time and vehicle operating costs. In particular, indirect costs depend not only on structures but also on network conditions. In addition, indirect losses to the surrounding region include time delays that induce interruption of goods and services to those businesses affected by earthquakes.

In this work, a general criteria is performed in order to take into account different dimensions of the problem in an efficient formulation. Direct costs are computed directly from a Performance Based Earthquake Engineering (PBEE) methodology (Cornell and Krawinkler, 2000, Krawinkler et al. 2006) by the Pacific Earthquake Engineering Research (PEER) center. Decision variables are generated as output from the PBEE framework and consist of repairtime and costs. These results will be used in order to assess the investment efficiency introducing a criterion to help decision makers estimating indirect costs, generally neglected

elsewhere. In this paper, they are estimated assuming economic efficiency as the main parameter taken from the formulation proposed for buildings by L. Kantorovich, the Nobel Laureate in Economics in 1975. This procedure is capable of estimating efficiency of investments (defining the optimum) by optimizing investment distribution among part of structural elements and thus controlling construction and repair costs. It applies outputs from a PBEE analysis in terms of cost and time adopting economic efficiency concept, currently applied in various field as the most common objective for public sector problems. In an engineering sense, economic efficiency aims at cost minimization to achieve a particular design. As the formulation has been built up, the problem can be shifted to solving “in the best way possible” two contradictory objectives: maximizing economic efficiency and minimizing costs. In this regards, application of the proposed procedure is highly useful for a decision maker in order to investigate several scenarios affecting the bridge. In particular, the paper shows an application of such efficiency criteria in defining “the optimum investment” between different isolated strengthening configurations.

Background

Bridge failure prevention during a seismic event is a significant target in earthquake engineering in order to avoid serious economic losses and high costs for rehabilitation. Past earthquakes all over the world showed how damage occurs primarily in piers (Basozc et al. 1997). Therefore, bridge strengthening procedures should be mainly focused on assessing pier connection behaviors. In this regards, seismic isolation is conceivably one of the most promising methods especially in post-earthquake rehabilitation (Makris and Zhang 2004 and Troy et al. 2011), giving the possibility to control demands imposed by earthquakes. Although many seismic isolated buildings have been constructed in countries with significant seismic hazards, such as Japan, China, Taiwan, United States and Italy during last decades, isolation applications in bridge arena are not so dispread. Nevertheless, many steps have been recently moved in seismic isolation design procedure for new bridge constructions and comprehensive retrofit guidelines for existing bridges, especially in California. In particular, this paper aims at assessing seismic strengthening with isolation moving from previous analytical studies, such as Kelly (1997) and Forcellini and Kelly (2014). Moreover, new code approaches are based on performance-based design by monitoring responses to recent earthquakes. In particular, costs resulted from major earthquakes can be split into direct losses (repair of infrastructure, replacement of damaged contents) and indirect losses (business disruptions, relocations expenses, supply chain interruption), as shown in Brookshire et al. (1997).

In this paper, both these categories of costs have been investigated. On the first hand, direct costs can be split into two categories: costs directly connected with structural damage and costs for bridge rehabilitation. The first category strongly depends on structural characteristics and operational state of the bridge after seismic events. The second category takes into account time for structural repair and restoration (defined as recovery work). In this paper, both these two categories of direct costs are considered as explained in the next sections. On the second hand, indirect costs depend on many assumptions principally connected to network state and its characteristics. They generally can be split into two categories: costs associated with temporal prolongation of travel and those associated with loss of connectivity (Adey et al 2004). Indirect costs associated with prolongation of travel are important especially when a network is highly redundant. They consist of different types, such as additional travel time, vehicle operation costs and increased risk of accidents. Indirect costs associated with connectivity loss are more important when a network has low redundancy and consist of loss of

economic activity that occurs when is not possible to use the network. This work aims at presenting a first attempt to consider both these two indirect costs in a unique category as described in the following section.

A Complete Direct-Indirect Cost Decision Making Modeling for Isolation Strengthening

This paper applies a cost estimation formulation taken from that proposed for buildings by L.Kantorovich, 1975, included in the guidelines published by the USSR Academy of Sciences (Keylis-Borok et al. 1962) and developed by other researchers (Perelmuter, 2000, Sakharov, 2004 and Bogdanova et al., 2012). Efficiency (E) can be defined probabilistically from the original formulation by considering a general Intensity Measure (IM) and using traditional assumption that earthquakes can be described with Poisson flows of events.

$$E(IM) = -I_{inv}(I) + f(I) \cdot \left[P_0(I) - P_m(I) - (1 + \alpha \cdot P_0(I)) \cdot \sum_{i=1}^n (D(I) - Ins(I)) \cdot L_I \right] \quad (1)$$

Where

I_{inv} is the annualized investment of a generic aseismic strengthening of the structure.

f is the ratio which takes into account the discounting of receipts and expenses from common structure functionality.

P_m the annual insurance payment and Ins is the insurance coverage caused by the insurance event.

P_0 is the annual income of the owner expected from the structure operation.

α is an index that takes into account the economic loss connected with stop time for recovery work after the earthquake.

D is the damage caused by the earthquake.

L_I is region shake-ability which is equal to the average number of earthquakes with intensity (I) per year.

This paper aims at assessing repair procedures by applying isolation technique. Therefore, insurance contributes ($P_m(I)$ and $Ins(I)$) can be neglected. The first term (I_{inv}), representing costs for anti-seismic strengthening, is generally small, if compared with other terms. In the next, it has been neglected. Therefore, the above formula becomes:

$$E(IM) = f(I) \cdot \left[P_0 - (1 + \alpha \cdot P_0) \cdot \sum_{i=1}^n (D(I) \cdot L_I) \right] \quad (2)$$

The term:

$$\sum_{i=1}^n D(I) \cdot L_I$$

represents direct costs connected to bridge damage and can be named with $D_D(I)$.

Considering the seismic event, indirect costs for returning structural functionality can be connected with P_0 , by introducing an adimensional coefficient :

$$P_0(I) = -\gamma Ic(I) \quad (3)$$

Finally, introducing C_0 as initial cost of the bridge, new adimensional quantities can be defined:

$$e = \frac{E}{C_0}, \quad i = \frac{Ic}{C_0}, \quad d = \frac{D_D}{C_0}; \quad (4)$$

Therefore, (2) can be written in this form:

$$e = f \cdot [-\gamma \cdot i - d - \alpha \cdot i \cdot d] \quad (5)$$

Three categories of costs can be identified in (5): direct (damage) costs (d), indirect costs (γi) and a third term ($\alpha i d$). This term depends on α (and thus on recovery time), direct (damage) costs (d) and indirect costs (i). In the next, it has been considered representative of costs for bridge closure. Expression (5) defines that economic efficiency depends on the sum of three non positive contributes. Therefore, an increase in any of these category of costs lead to a decrease in efficiency. In this regards, the new goal is to solve “in the best way possible” the problem with two contradictory objectives: to maximize economic efficiency and to minimize costs. This problem can be solved with a multi-objective structural optimization procedure in the Pareto sense (for more details on the history and methodology, see Sawaragi et al. 1985, Collette and Siarry, 2002, DeWeck, 2004, Cheng and Truman, 2010). Moreover, all categories of costs have been concentrated into a single parameter (economic efficiency). Therefore, it was possible to perform a bi-objective optimization instead of a multi-dimensional analysis that could be very time consuming. In this regards, application of economic efficiency is highly useful for a decision maker in order to find the optimum investment between different configurations in earthquake strengthening.

Cost Efficiency Optimization

In order to apply the general results from the previous section, the terms in equation (5) have been correlated with variables deduced from a Performance Based Earthquake Engineering (PBEE) methodology, by the Pacific Earthquake Engineering Research (PEER) center. In particular, PEER framework (Mackie et al., 2010), aims at assessing structural performances in terms of probability of exceeding threshold values of socio-economic decision variables (DVs) in seismic hazard environment. The methodology is fundamentally based on application of the total probability theorem to disaggregate the problem into several intermediate probabilistic models that involve intermediate variables, such as repair items or quantities (Qs), damage measures (DMs), engineering demand parameters (EDPs) and seismic hazard intensity measures (IMs).

This study uses decision variables generated as output from PBEE framework, by considering repair cost ratio (RCR):

$$RCR = \frac{RepairCosts}{ReplacementCosts} \quad (6)$$

and repair time (RT), necessary for all the operations involved in repair work and measured in terms of crew working days (CWD).

In particular, several assumptions were introduced in the previous formulation (5) in order to take into considerations PBEE results.

First of all, indirect costs are difficult to be defined and in this paper they are considered dependent on repair time (RT) resulted from PBEE analysis, by introducing an adimensional parameter η :

$$i = \eta \cdot RT \quad (7)$$

Moreover, direct costs connected with damage “ d ” can be correlated with total repair cost ratio (RCR) resulted from PBEE analysis by introducing an adimensional parameter β :

$$d = \beta \cdot RCR \quad (8)$$

Finally, parameter α represents time for recovery work. Therefore, it has been considered dependent on repair time (RT), by introducing an adimensional parameter k :

$$\alpha = k \cdot RT \quad (9)$$

Therefore, expression (8) becomes:

$$e = f \cdot [-\eta \cdot RT - \beta \cdot RCR - \beta \cdot k \cdot RCR \cdot RT] \quad (10)$$

This paper aims at showing an application of a cost efficiency optimization procedure able to find the optimum investment between different strengthening configurations.

In the next section, the presented methodology has been applied to a case study consisting of a benchmark bridge that should be repaired after a seismic event. The cost – efficiency optimization procedure is applied to study “the best strengthening method” between bridge isolated configurations with a bi-objective structural optimization procedure in the Pareto sense. In particular, any point (set of design variables) in the design space defines a possible design for the structure. If design objective functions satisfy the given constraints, it is called an admissible design. Therefore, “the best solution” can be found if there exists no feasible vector which would decrease some objective functions without causing a simultaneous increase in at least one objective function (for more details, see Pareto, 1906 and Rafiq, 2000).

Case Study

The case study presented in this section aims at assessing “the best strengthening method” among bridge alternative configurations.

In particular, the original bridge (named MODEL 1) is intended to be representative of prevalent ordinary construction types for California highway. In this regards, some standard dimensions are taken into consideration. The bridge is a 90 m long, 2-span structure, supported on one circular column (1.22 m diameter) 12 m long, 6.70 m above grade (Figure 1). The deck is 11.90 m wide and 1.80 m deep. Each abutment is 25 m long with 30000 kN as total weight. Connections between the abutment consists of roller links with no resistance between deck and abutments. The column has fixed connections with the deck.

Secondly, thanks to the high capabilities of the interface in implementing several support mechanisms at the abutments and at the top of the column, three strengthening configurations have been studied and compared with the original one. Isolation devices are used in place of conventional bridge bearings in order to protect the substructure by restricting the transmission of seismic accelerations and dissipating energy.

In MODEL 2, deck – abutments connections have been realized with elastomeric bearings while column – deck connection is still fixed.

In MODEL 3 column – deck connection consists of elastomeric bearings at the top of the column, while deck and abutments are still free to move (no resistance).

MODEL 4 consists of a double-isolated configuration with elastomeric bearings in correspondence of the each abutments and on the top of the column.

Isolation devices are modelled with linear springs, following literature contributions, such as Kelly (1997) and Forcellini and Kelly (2014). Springs characteristics are described in Table 1.

FEM model (Figure 1) was built with Bridge PBEE (Lu et al. 2011). This interface is built on OpenSees (Mazzoni et al. 2009), that allows high level of advanced capabilities for modeling and analyzing nonlinear responses using a wide range of material models, elements, and solution algorithms. In this regards, the reinforced concrete column is modelled with nonlinear forced-based beam-column elements (nonlinear Beam

Column) and fiber cross section (Figure 2), with 0.2 rad/m as the maximum curvature value at 11900 kN compression axial load. The deck is modelled with separate elastic beam-column (BC) elements (see table 2). The approach ramps make the connection with the longitudinal boundaries. The soil is modeled with eight-node mixed volume pressure elements (bbar brick, Mazzoni et al. 2009). In order to concentrates on structural responses only, the soil was considered with a high stiffness compared to isolator stiffness (Tongaonkar and Jangid, 2003) simulating fixed conditions and consequently soil-structure interaction effects have been neglected. For more details see also as Elgamal et al. (2012).

Table 1

Data for MODELS Stiffness

	Abutment Link [kN/m]	Top of the column link [kN/m]	ISOLATION
MODEL1	0	fixed	No isolation
MODEL2	4000	fixed	On abutment
MODEL3	0	10000	On column
MODEL4	4000	10000	Double isolation

Figure 1. FEM model.

Figure 2. Moment curvature diagram

Table 2

Data for deck characteristics

Cross Area [m ²]	Transversal inertia [m ⁴]	Vertical inertia [m ⁴]	Weight [kN/m]
5.72	2.81	53.9	130.30

Finally, in order to reproduce typical California seismicity, input motions were taken from PEER NGA database (<http://peer.berkeley.edu/nga/>) and consist of 100 selected ground motions with medium characteristics in terms of moment magnitude ($M_w = 5.8-7.2$) and epicentre distance ($R = 0-15$ km; $15-30$ km; $30-60$ km). For more details, see Elgamal et al. 2012 and Forcellini et al. 2012.

PBEE Results

Figure 3 and Figure 4 represent results of PBEE analyses in terms of Total Repair Cost Ratio (RCR) and Repair Time (RT) for the original configuration (MODEL 1) and the three strengthened configurations (MODEL 2-4). Isolation technique is shown to reduce the damage for all PGA range. In this regards, both RCR and RT decreases when isolation devices are applied. In particular, if MODEL 2 and MODEL 3 are compared with MODEL 1, it is shown that saving the column is more effective than protecting the abutments. More details in Elgamal et al. 2012, Forcellini et al. 2012 and Forcellini and Banfi 2013.

Figure 3. Total Repair Cost Ratio (%) – PGA (g): models comparison

Figure 4. Total Repair Time (Crew working Days) – PGA (g): models comparison

C-E Optimization Results

Previous results are used for assessing direct costs and indirect costs by applying formulation (10). Four different scenarios were studied by varying adimensional parameters: β , k and η (see table 3), set up in order to study realistic situations. In particular, direct damage costs parameter β was considered derived (10%) from RCR (see eq. 8). Recovery work parameter k has been set 10%. Finally, indirect cost (i) is the most questionable cost to be calibrated because of its intrinsic uncertainties. It was chosen to consider this kind of costs as 10% ($\eta=0.1$). The discounting receipts and expenses from bridge functionality has been considered constant with $f=1$. Here the details of the four considered scenarios.

Scenario 1 ($\beta = 0.1$, $k = 0$, $\eta = 0$) represents a case where decision maker is interested in taking into consideration damage direct costs only. This can be representative of a small secondary bridge where costs are connected only with structural damage.

Scenario 2 ($\beta = k = 0.1$, $\eta = 0$) considers both categories of direct costs. This case can represent a strategic bridge whose closure can affect network functionality. Indirect costs are here neglected.

Scenario 3 ($\beta = 0.1$, $k = 0$, $\eta = 0.1$) represents a case where indirect costs have to be taken into consideration together with direct damage costs. Recovery work are here neglected.

Scenario 4 ($\beta = k = \eta = 0.1$) takes into account every contributions (direct and indirect costs), representing the case of a high strategic bridge and a decision maker sensitive to all the categories of costs defined before.

Figure 5 compares isolated configurations results for different scenarios. These figures are highly helpful for decision makers to assess “the most efficient” configuration between the four presented. Scenario 1 shows small values of efficiency and a linear correlation. All models seems to have the same level of efficiency. Scenario 2 - 4 show that for values between 10% and 15%, models 3 and 4 are less efficient than model 1 and 2. For high values of RCR (more than 30%), they become more efficient than model 1 and model 2. Scenario 3 shows that results are strongly affected by indirect costs at very low values of RCR (less than 5%). After this value, the efficiency is quite constant with RCR. Scenario 4 shows the importance of each contributions in decreasing the economic efficiency. In particular, it is shown that isolation strengthening is really efficient only at big values of RCR, and in particular, model 3 and model 4 show the best efficient solutions. Model 3 and 4 results seem close each other, meaning that abutment isolation (model 2) is less important than column isolation (model 3), as shown in fig. 3 and 4.

Figure 6 compares four considered scenarios for each four models, showing how decision maker attitude may affect final solutions. These figures underline the importance of taking into account direct costs connected with road closure and indirect costs in the assessment procedure, especially for high values of RCR. This satisfies the principal aim of the paper to investigate other costs apart from those connected directly with damage.

Table 3

Data for SCENARIOS

	β	k	η
SCENARIO1	0.1	0	0
SCENARIO 2	0.1	0.1	0
SCENARIO 3	0.1	0	0.1
SCENARIO 4	0.1	0.1	0.1

Figure 5. SCENARIOS: RCR (%) – E: models comparison.

Figure 6. MODELS: RCR (%) – E: Scenarios comparison

Conclusions

The paper shows a complete direct-indirect cost assessment methodology. A formulation taken from L. Kantorovich allows to include direct costs and indirect costs inside a unique parameter able to assess investments efficiency. As the formulation was built up, the problem has to be shifted to solving “in the best way possible” two contradictory objectives: maximizing economic efficiency and minimizing repair costs. In order to exercise the proposed procedure, a study was performed as to assess the best seismic strengthening solution between several isolated configurations starting from a benchmark bridge.

The paper develops different original contributions. First of all, the proposed formulation allows to consider several categories of costs such as direct costs (connected with damage and road closure) and indirect costs. In particular, the application of the well-known formulation by Kantorovich from building to bridge arena, is also an important contribution. The possibility to reduce all the objectives only by considering repair cost ratio (RCR) and economic efficiency is another important aspect, since it was possible to perform a two-objective procedure instead of a more complicated multi-objective.

This paper should be considered a first attempt to calibrate parameters in order to study a bridge strengthening with isolation. In this regards, the study is based on parameters definitions aimed to make the general Kantorovich formulation consistent with PBEE results. Further work could investigate different assumptions and apply such general methodology with other goals.

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