De León, David
Cost-Benefit Ratios for Risk Mitigation on Structures in Mexico
Instituto Politécnico Nacional
Distrito Federal, México

Available in: http://www.redalyc.org/articulo.oa?id=61411302
Cost-Benefit Ratios for Risk Mitigation on Structures in Mexico

David De León

Universidad Autónoma del Estado de México, Facultad de Ingeniería.
Ciudad Universitaria, Toluca.
México

Tel. (722)2140855 ext. 259, Fax (722)2140855 ext. 110
correo electrónico: david_de_leon0585@yahoo.com.mx

Recibido el 2 de octubre de 2006; aceptado el 25 de abril de 2007.

1. Abstract

Risk aspects of planning and design of engineering works in Mexico are usually considered into the mitigation and development plans only in a subjective and qualitative form. This practice does not produce the minimum costs in the long term. In order to optimally allocate limited funds used for mitigation purposes, a careful, systematic and objective estimation of the failure consequences as well as the underlying risk is required.

Also, mitigation policies for several regions in Mexico and different hazard types are not risk-consistent.

In this paper a criterion to calculate cost/benefit ratios in terms of the expected number of fatalities, the expected losses and the investment made on structural safety is proposed. The criterion may be used to appraise the risk on engineering works and to compare the consistency of risk mitigation expenditures made by national highway agencies with the cost/benefit involved on the increment of structural safety for buildings. These concepts may be considered to generate an effective risk management for optimal policies for life and property protection. This formulation is applied to the specific case of buildings under seismic exposure in Mexico City and expected life-cycle cost functions are developed for typical costs and practices.

Key words: cost-benefit relationship, risk mitigation, building on seismic zone.
4. Formulation

The expected life-cycle cost $E[C_L]$ is composed by the initial cost $C_i$ and the expected damage costs $E[C_D]$:

$$E[C_L] = C_i + E[C_D]$$ (1)

The expected damage costs include the components of damage cost: expected repair $E[C_r]$, injury $E[C_{inj}]$ and fatality $E[C_{fat}]$ costs and each one depends on the probabilities of repair and failure of the structure.

These component costs of damage are defined:

$$E[C_r] = C_r (PVF) P_f$$ (2)

where:
- $C_r$ = average repair cost, which includes the business interruption loss, $C_{bi}$,
- $PVF$ = present value function [1, 2].

$$PVF = \sum_{n=1}^{\infty} \left[ \sum_{k=1}^{n} \frac{\Gamma(k,\gamma L)}{\Gamma(k,\nu L)} (\nu/\gamma)^k \right] (\nu L)^n / n! \exp(-\nu L)$$ (3)

where
- $\nu$ = mean occurrence rate of earthquakes that may damage the structure.
- $\gamma$ = net annual discount rate, and $L$ = structure life.

And $P_f$ = probability of repair, defined in a simplified way, as a factor of the failure probability $P_f$.

Similarly, the business interruption cost, is expressed in terms of the loss of revenue due to the repairs or reconstruction works after the earthquake, assumed to last $T$ years.

$$C_{bi} = L_r (T)$$ (4)

where:
- $L_r$ = loss of revenues per year.

The expected cost of injuries is proposed to be:

$$E[C_{inj}] = C_{inj} (N_{inj}) P_f$$ (5)

$C_{inj}$ = average injury cost for an individual

$N_{inj}$ = average number of injuries on a typical building in Mexico City given an earthquake with a mean occurrence rate $\nu$.

5. Number of expected fatalities

The expected number of fatalities if a failure occurs, $E[N_f]$, is estimated from a curve previously developed for typical buildings that collapsed due to earthquakes in Mexico, in terms of their plan areas, given an earthquake with a mean occurrence rate $\nu$. See Fig. 2.

$$E[N_f] = C_{fat} (N_{fat}) P_f$$ (6)

In the next sections, all the figures are estimated for typical costs in Mexico.

A typical geometry of a structure, a 7 stories regular framed building (Figure 3), located on the soft soil of Mexico City is selected to analyze its critical frame under seismic loads. Statistics of its maximum response, at critical joint level, are obtained from the frame analyses subjected to Poissonian earthquakes (with mean occurrence rate $\nu$) as scaled from the seismic hazard curve for Mexico City [3]. Figure 1 shows the annual cumulative distribution of maximum accelerations.

For the expected cost related to loss of human lives, the cost corresponding to a life loss, $C_{L_t}$, and the expected number of fatalities, $N_f$, are considered. The cost associated with a life loss may be estimated in terms of the human capital approach, which consists in the calculation of the contribution lost, due to the death of an individual, to the Gross Domestic Product during his expected remaining life. The details of this calculation are explained in previous works [3, 4].

$$E[C_L] = C_{L_t} (N_f) P_f$$ (6)

Fig. 1. Cumulative distribution of annual maximum soil accelerations in Mexico City.
6. Reduction on fatalities and losses

The expected number of fatalities may be expressed:

\[ E[N_D] = E \langle N_D | \text{Failure} \rangle P_f \]  \hspace{1cm} (8)

where: \( E \langle N_D | \text{Failure} \rangle P_f \)

is the expected number of fatalities given the building failure. The failure probability \( P_f \) depends on the vulnerability of the structure and might be reduced through an increment on the structural design resistance. Therefore, the cost/benefit ratio of the investment made to increase the resistance versus the number of fatalities avoided may also be assessed.

\[ CB_1 = \frac{(C_2 - C_1)}{(E[N_D]_1 - E[N_D]_2)} \]  \hspace{1cm} (9)

Another cost/benefit ratio is the investment made on resistance versus reduction on total losses.

\[ CB_2 = \frac{(C_2 - C_1)}{(E[C_L]_1 - E[C_L]_2)} \]  \hspace{1cm} (10)

These two ratios may be estimated by assuming alternative designs with additional resistances and by calculating the expected reductions on fatalities and losses as derived from the increased resistance of the structure.

7. Application to a typical building in Mexico

A 7-storeys reinforced concrete building in Mexico is used to estimate the cost-benefit ratios from Eqs. (9) and (10). The floor plan area of the building is 6 750 m\(^2\). See Figure 3 for the plan and elevation views.

In the worst scenario case, it is assumed that there are no injuries but all people inside the building, at the collapse time, die.

The mean occurrence rate of significant earthquakes is \( \nu = 0.142/\text{yr} \).

The following costs are all in US million.

\[ C_1 = 0.4 \]
\[ C_2 = 0.55 \]
\[ C_r = 3.24 \]
\[ C_{ul} = 8.29 \]

In addition, the following data are used:

\[ \gamma = 8\% \]
\[ L = 50 \text{ years} \]
\[ T = 2 \text{ years} \]
With the above figures, the expected number of deaths and total loss are:

\[
E[N_{D}]_1 = 297.5 \times 0.00875 = 26
\]

\[
E[N_{D}]_2 = 297.5 \times 0.003 = 0.89
\]

And the cost-benefit ratio for fatality prevention is:

\[
CB_{1} = 0.081
\]

Also,

\[
E[C_L]_1 = 0.65
\]

\[
E[C_L]_2 = 0.45
\]

And the cost-benefit ratio for losses prevention is:

\[
CB_{2} = 0.75
\]

8. Data of highway investment and fatalities in Mexico

The investment in Mexican highways in 2003 was 470 million USD [6, 8].

The number of fatalities in Mexico, due to transit accidents in 2000, was 35 000(43) = 15 050[9].

The number of fatalities in Mexico, due to transit accidents in 2005, was 14 000[11].

A rough estimation of the economic effectiveness \( CB_{3} \) on the highways safety investment may be obtained as:

\[
CB_{3} = 470/(15050 - 14000) = 0.4285
\]

million USD per fatality avoided.

9. Optimal restoration time for constructed facilities

Other interesting aspect for the risk management of constructed facilities is the decision about when to restore the capacity of a damaged structure in order to maximize the profit or minimize the risk [12]. The optimal restoration time depends on the restoration cost, the profit lost during the restoration and the annual discount rate and it is calculated from the following cost/benefit expression:

\[
[R/C]_d = [1 - e^{-i \tau \gamma}]/i \left[ e^{-i \gamma} - 1 + i (L - T^*) \right] e^{-i \gamma}
\]

where: \( R \) is the restoration cost and \( T^* \) the time to restore the structure.

The optimal restoration time is shown in Figure 4 for several ratios of restoration to failure costs and several annual discount rates. The restoration time is represented as a percent of the structure lifetime.

10. Discussion

The formulation and illustration above presented include, in a systematic and explicit way, the socio-economic aspects underlying the failure of a typical building located on a high seismic risk zone, as Mexico City.

Decisions about the necessary design safety level of the structure may be supported on the cost-benefit ratios in order to keep a balance between safety and costs.

Although it may be argued that the main mitigation measure to reduce traffic accidents, is the promotion on the use of passenger belts and the driving without alcohol, the investment on highway safety has also a positive effect.

The difference on the values between \( CB_{1} \) and \( CB_{3} \) may be explained because of the different range of human lives at risk. Highway, as other infrastructure accidents require much more prevention measures than isolated buildings. However, for code making or updating purposes, which involve
massive number of structures and a high percent of population at risk, the cost of all the consequences involved should be taken into account.

The optimal restoration time is short as the ratio between the restoration and the failure costs is also short. As this costs ratio gets larger, the restoration time gets also larger. For small discount rates (stable economies) the restoration time may be postponed close to the end of the structure lifetime, for optimal results. Larger discount rates require the restoration time to be taken sooner because of the increasing value of money with time.

11. Conclusions and recommendations

A criterion for risk-based assessment including socio-economics has been proposed. The criterion includes cost/benefit ratios which are used to compare the economic effectiveness of investments made on highway and building safety. It is observed that the highway safety receives more investment than the building construction industry.

The formulation intends to contribute on the risk management area and some of the ideas provided may be extended to support government decision-making on the civil protection sector, to optimize resources allocation for mitigation measures and to locate infrastructure for development of industrial areas.

Acknowledgements

Data from the Mexican government is acknowledged and thanked by the author.

12. References


