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

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 sismic zone.

2. Resumen (Relaciones costo-beneficio para mitigación del riesgo en estructuras en México)

Los aspectos de riesgo en la planeación y diseño de obras de ingeniería en México se consideran para mitigación y desarrollo solamente de una manera subjetiva y cualitativa. Esta práctica no produce los costos mínimos en el largo plazo. Para distribuir de manera óptima fondos limitados utilizados con fines de mitigación, se requiere una estimación cuidadosa, sistemática y objetiva del riesgo subyacente y de las consecuencias de falla.

También, las políticas de mitigación aplicadas a diversas regiones de México y para diferentes tipos de peligro no son consistentes en riesgo.

En el presente artículo se propone un criterio para calcular relaciones costo/beneficio en términos del número esperado de fatalidades, las pérdidas esperadas y la inversión realizada en seguridad estructural. El criterio puede utilizarse para evaluar el riesgo en obras de ingeniería y para comparar la consistencia de gastos realizados por agencias nacionales para mitigación de riesgo en carreteras con el costo/beneficio involucrado en el incremento de seguridad estructural en edificios. Estos conceptos pueden ser considerados para generar una administración efectiva de riesgo para políticas óptimas de protección de la vida y la propiedad.

Esta formulación se aplica al caso de edificios bajo exposición sísmica en la ciudad de México.

Palabras clave: relación costo-beneficio, mitigación de riesgo, edificio en zona sísmica.

3. Introduction

For infrastructure works, or facilities where the affected population is significant, life-cycle studies that explicitly take into account the inherent uncertainties due to the occurrence of natural hazards and their consequences on human life and property, are widely justified and recommendable.

Two examples of such works are buildings located on a high seismic zone and infrastructure, like bridges and breakwaters, exposed to wind and storm hazard.

4. Formulation

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

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

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:

$$E[C_r] = C_r\,(PVF)P_r \qquad (2)$$

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

$$PVF = \sum_{n=1}^{\infty} \left[\sum_{k=1}^{n} \Gamma(k,\gamma L)/\Gamma(k,\upsilon L)(\upsilon/\gamma)^k \right]$$

$$(\upsilon L)^n / n!\exp(-\upsilon L) \qquad (3)$$

where
υ = mean occurrence rate of earthquakes that may damage the structure.
γ = net annual discount rate, and L = structure life.

And P_r = 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.

$$C_{bi} = L_R(T) \qquad (4)$$

where:
L_R = loss of revenues per year.

The expected cost of injuries is proposed to be:

$$E[C_{inj}] = C_{1I}(N_{in})P_f \qquad (5)$$

C_{1I} = average injury cost for an individual
N_{in} = average number of injuries on a typical building in Mexico City given an earthquake with a mean occurrence rate v.
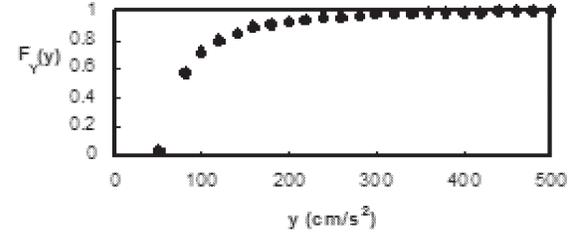

Fig. 1. Cumulative distribution of annual maximum soil accelerations in Mexico City.

For the expected cost related to loss of human lives, the co corresponding to a life loss, C_{1L}, and the expected number fatalities, N_D are considered. The cost associated with a li loss may be estimated in terms of the human capital approac which consists in the calculation of the contribution lost, du to the death of an individual, to the Gross Domestic Produ during his expected remaining life. The details of th calculation are explained in previous works [3, 4].

$$E[C_L] = C_{1L}\,(N_D)P_f \qquad ($$

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

A typical geometry of a structure, a 7 stories regular fram building (Figure 3), located on the soft soil of Mexico City selected to analyze its critical frame under seismic load Statistics of its maximum response, at critical joint level, a obtained from the frame analyses subjected to Poissonia earthquakes (with mean occurrence rate v) as scaled from th seismic hazard curve for Mexico City [3]. Figure 1 shows th annual cumulative distribution of maximum acceleration

5. Number of expected fatalities

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

After curve-fitting data about the number of fatalities versu plan area of buildings from past earthquakes in Mexico, th following expression was obtained [3, 5]:

$$N_D = 45.48 + 5.53174\,(A\,/\,1000)^2 \qquad (7$$
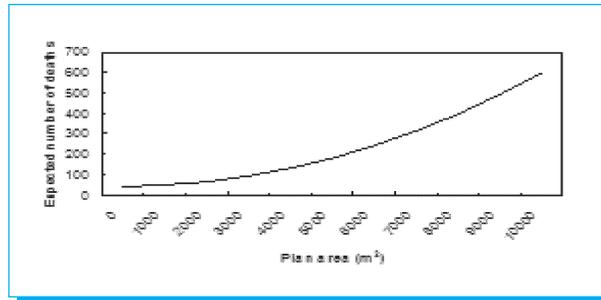
Fig. 2. Expected number of fatalities given the collapse of reinforced concrete buildings in Mexico City as a function of their plan area.

6. Reduction on fatalities and losses

The expected number of fatalities may be expressed:

$$E[N_D] = E \left\langle N_D \mid Failure \right\rangle P_f \qquad (8)$$

where: $E \left\langle N_D \mid Failure \right\rangle P_f$

is the expected number of fatalities given the building failure. The failure probability *Pf* 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.

$$CB_1 = (C_{i2} - C_{i1}) / (E[N_D]_1 - E[N_D]_2) \qquad (9)$$

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

$$CB_2 = (C_{i2} - C_{i1}) / (E[C_L]_1 - E[C_L]_2) \qquad (10)$$

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 m². See Figure 3 for the plan and elevation views.
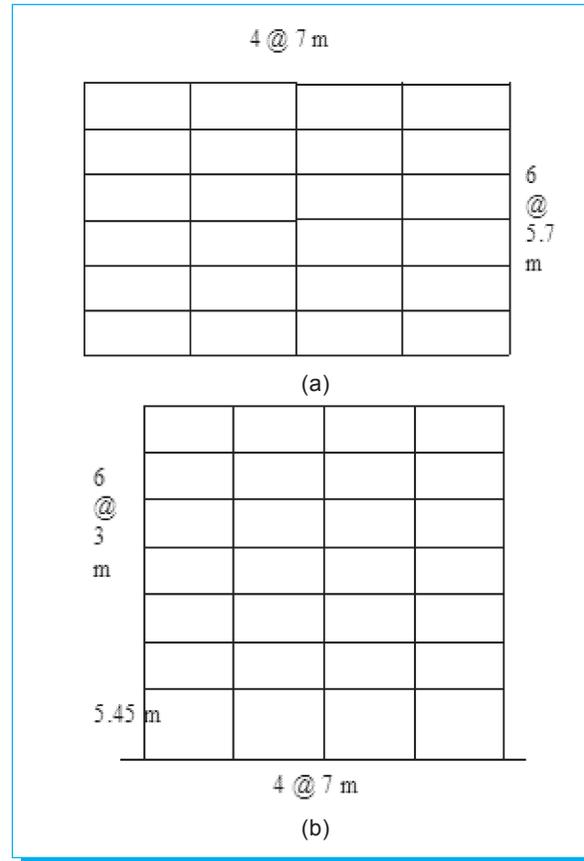
Fig. 3. (a) Plan and (b) elevation of a typical reinforced concrete building in Mexico City.

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 $\nu = 0.142$/yr.

The following costs are all in US million.

$C_{i1} = 0.4$
$C_{i2} = 0.55$
$C_r = 3.24$
$C_{1L} = 8.29$

In addition, the following data are used:

$\gamma = 8\%$
$L = 50$ years
$T = 2$ years

$N_{in} = 0$
$p_{f1} = 0.00875$
$p_{f2} = 0.003$

With the above figures, the expected number of deaths and total loss are:

$$E[N_D]_1 = 297.5*0.00875 = 26 \qquad (11)$$

$$E[N_D]_2 = 297.5*0.003 = 0.89 \qquad (12)$$

And the cost-benefit ratio for fatality prevention is:

$$CB_1 = 0.081 \qquad (13)$$

Also,

$$E[C_L]_1 = 0.65 \qquad (14)$$

$$E[C_L]_2 = 0.45 \qquad (15)$$

And the cost-benefit ratio for losses prevention is:

$$CB_2 = 0.75 \qquad (16)$$

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 th[e] annual discount rate and it is calculated from the followin[g] cost/benefit expression:

$$[R/C_D] = [1 - e^{-i*T^*}]* \ i/\{e^{-i*T^*} - [1 + i*(L - T^*)]*e^{-i*L} \qquad (1[7)$$

where: R is the restoration cost and T^* the time to restore th[e] structure.

The optimal restoration time is shown in Figure 4 for sever[al] ratios of restoration to failure costs and several annual discou[nt] rates. The restoration time is represented as a percent of th[e] structure lifetime.

10. Discussion

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

Decisions about the necessary design safety level of th[e] structure may be supported on the cost-benefit ratios in ord[er] 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, th[e] investment on highway safety has also a positive effect.

The difference on the values between CB_1 and CB_3 may b[e] explained because of the different range of human lives [at] risk. Highway, as other infrastructure accidents require mu[ch] more prevention measures than isolated buildings. Howeve[r,] for code making or updating purposes, which involve
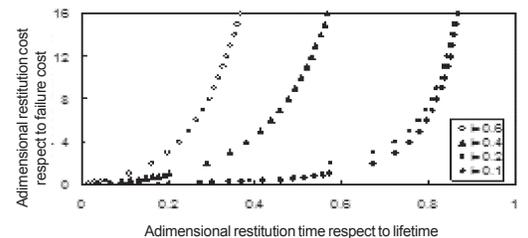

Fig. 4. Optimal restoration times for several discount rates.

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

12. References

[1] Ang, A.H-S. and de Leon, D., 1995, "Optimal Acceptable Risks for Aseismic Design of R/C Buildings", 13th Int'l. *Conf. on Structural Mechanics in Reactor Technology*, Porto Alegre, August.

[2] Ang, A. H-S., and de Leon, D., 1996, "Determination Optimal Target Reliabilities for Design and Upgrading Structures", *Proc. 11th World Conf. on Earthqua Engineering*, Acapulco, Elsevier Sc. Ltd., June.

[3] De León, D., 1996, "Integrating socio-economics in t development of criteria for the aseismic design of reinforc concrete structures", Ph. D. Thesis, Department of Civ and Environmental Engineering, UCI, Irvine, California.

[4] Ang, A. H-S., and De Leon, D., 1997, "Determination Optimal Target Reliabilities for Design and Upgrading Structures", *Structural Safety*, Elsevier Sc. Publ., Vol. 1 No. 1, pp. 91-103.

[5] Ang, H-S., and Lee, J-C., 1999, "Cost-Effectivenes Evaluation of Aseismic Design Criteria", *Trans., SmiR 15*, Seoul, Korea, Vol. X, August.

[6] Colucci, Ríos B. y Rivera Ortiz, Juan, 2005, "Auditorías seguridad en carreteras y su aplicación al sistema de r de carreteras del Caribe y América Latina" 3rd. LACCI *Internacional Latin American and Caribbean Conferen for Engineering and Technology*. Cartagena, Colombia.

[7] De Leon, D., and Ang, A. H-S., 1993, "A Damage Mod for Reinforced Concrete Buildings -- Further Study Wi the 1985 Mexico City Earthquake", *Int'l. Conf. on Stru Safety and Reliability*, ICOSSAR '93, Innsbruck, Augus

[8] Fox, Vicente, 2003, Fox Contigo, entrevista radiofónica d 5 de Julio de 2003, http://www.presidencia.gob.m foxcontigo/index.php?contenido=5725&pagina=8.

[9] *La Jornada*, 2000, http://www.jornada.unam.mx/2000/1 15/048n2soc.html)

[10] Mendoza Díaz A., 2001, "Seguridad Vial en Carretera Mexicanas para un Mejor Desarrollo Sustentable", IMT San Fandila, Querétaro, México.

[11] Secretaría de Salud, 2005. (http://www.salud.gob.m ssa_app/noticias/datos/2005-03-14_1271.html)

[12] Stahl, Bernhard, 1986, "Reliability Engineering and Ris Analysis", Chapter 5 from *Planning and Design of Fixe Offshore Platforms*. Edited by McClelland, B. and Reife M. D. Van Nostrand Reinhold Co. New York.

Magno Congreso Internacional de Computación CIC IPN
2007

del 6 al 8 de noviembre

http://magno-congreso.cic.ipn.mx
magno@cic.ipn.mx , relpub@cic.ipn.mx