Seismic Loss Estimation Including Environmental Losses

D. Arroyo, & A. Teran-Gilmore
Universidad Autónoma Metropolitana, Mexico

M. Ordaz
Instituto de Ingeniería, UNAM, Mexico

SUMMARY:
We introduce the consideration of environmental losses in the seismic design of structures within the framework of cost optimization analysis. We use the equivalent carbon emissions (CO2-e) as a proxy for the environmental cost related to seismic damage. We present a mathematical model to assess the environmental cost in seismic loss estimation and trough some simple examples we illustrate the application of the proposed method. Our results suggest that under certain circumstances the consideration of environmental issues in seismic design of structures may become important, especially as the planning time horizon of the facility increases.

Keywords: Seismic losses, probabilistic seismic hazard analysis

1. INTRODUCTION

Normally the seismic design of structures involves the consideration of the initial cost of the facility and the potential future losses caused by earthquakes. The proper level of performance is computed by minimizing of the total cost (i.e. initial cost plus future losses in present value). This approach has been extensively used in the seismic design of structures (Esteva 1968, Newmark and Rosenblueth, 1971, Liu and Neghabat 1972, Vanmarcke *et al.* 1973). The losses produced by earthquakes may be divided between physical losses (i.e. building and infrastructure damage) and incidental losses (i.e. loss life, injury, economic losses and all other consequences of future earthquakes).

Recently, concerns regarding global environmental conditions are rising worldwide. Global-warming and its potential effects on the earth are produced by a long term accumulation of the so-called greenhouse gases in the high layer of the atmosphere (Nordhaus 1991, Pearce 2003, Asif *et al*. 2007). In addition, it has been established that the construction industry is a major contributor to greenhouse emissions (Buchanan and Honey 1994, Venkatarama Reddy and Jagadish 2003) because of the large amounts of concrete and steel that are consumed.

Normally a carbon tax approach is used to place a value on the social cost of greenhouse gases emissions. The level of carbon tax is obtained from cost benefit analysis or by analysis that directly computes the difference in future damage levels caused by a marginal change from the current level of emissions (Clarkson and Deyes 2002). Currently, there are several controversial issues involved in the estimation of the level of the carbon tax (Ulph and Ulph 1997, Clarkson and Deyes 2002 and Tol 2008). However, there is a consensus that greenhouse gases emissions should be controlled in order to limit the potential impacts of global warming.

We noted that earthquakes may cause environmental losses because each time that certain facility is repaired after a given seismic event new materials are consumed and greenhouse gases emissions are produced. The objective of the paper is to conceptually introduce the consideration of environmental losses in the framework of current earthquake-resistant design methods, for brevity in this paper we describe the method and we present some main results of our analysis a more detailed presentation can be found in Arroyo *et al*. (2012). In view that similar studies have not been developed the paper is focused on some environmental concepts that are not familiar in the current earthquake-resistance design practice.

2. EARHQUAKE LOSS ESTIMATION INCLUDING ENVIRONMENTAL LOSSES

Consider a facility located in certain seismic region. For an earthquake occurring at the time t the present value of the earthquake loss ($D(c)$) is defined as follows:

$$D(c)=L(c)F(a,c)e^{-\gamma t}+L_e(c)F(a,c)e^{-\gamma_e t} \tag{2.1}$$

where $L(c)$ is the total cost of the facility, which is a function of the design load (c), $F(a,c)$ is a function which define the fraction of damage in the facility related to a seismic intensity (a) when the design load is c, $L_e(c)$ is the environmental cost of the facility which is function of the CO2-e emissions, of the level of the carbon tax and design level and γ and γ_e are discount rates for facility and environmental costs, respectively. The first term of equation (2.1) accounts for earthquake losses related to cost of repair and replacement of damage buildings and lifeline components and social costs, while the second term is related to environmental costs (i.e. the social cost of releasing greenhouse gases to the atmosphere as a consequence of the material consumptions during the construction and repair and replacement of damaged components of buildings).

For a given seismic region and assuming that earthquake occurrences can be modelled through a Poisson process the present value of the expected value of the loss related to the first earthquake during the planning time horizon of the facility can be computed as:

$$E\left[D_1(c)|t_e\right]=\int_0^{\infty}\int_0^{t_e}\left(L(c)F(a,c)e^{-\gamma t}+L_e(c)F(a,c)e^{-\gamma_e t}\right)\frac{1}{\lambda_0}\left|\frac{d\lambda(a)}{da}\right|\lambda_0\,e^{-\lambda_0 t}\,dt\,da \tag{2.2}$$

where $\lambda(a)$ is the seismic hazard curve of the intensity parameter, λ_0 is the rate of exceedance of the minimum value of a considered in the analysis and t_e is the planning time horizon.

Performing the integration in equation (2.2) with respect to time one obtains:

$$E\left[D_1(c)|t_e\right]=L(c)\left(\frac{\lambda_0}{\gamma+\lambda_0}\left(1-e^{-(\gamma+\lambda_0)t_e}\right)+\frac{\eta\,\lambda_0}{\gamma_e+\lambda_0}\left(1-e^{-(\gamma_e+\lambda_0)t_e}\right)\right)\int_0^{\infty}F(a,c)\frac{1}{\lambda_0}\left|\frac{d\lambda(a)}{da}\right|da \tag{2.3}$$

where η is the ratio between $L_e(c)$ and $L(_c)$.

Furthermore, the present value of the expected value of the total loss can be computed by adding the losses for the expected number of seismic events (n_e) during the planning time horizon.

$$E\left[D_T(c)|t_e\right]=L(c)\left(h(\lambda_0,\gamma)+\eta\,h(\lambda_0,\gamma_e)\right)\int_0^{\infty}F(a,c)\frac{1}{\lambda_0}\left|\frac{d\lambda(a)}{da}\right|da \tag{2.4}$$

$$h(l,g)=-\left(\frac{l\left(1-e^{-(l+g)t_e}\right)}{l+g}\right)^{n_e+1}\left(\frac{l+g}{l\,e^{-(l+g)t_e}+g}\right)+\frac{l\left(1-e^{-(l+g)t_e}\right)}{l\,e^{-(l+g)t_e}+g} \tag{2.5}$$

The optimum design level can be obtained by minimization of equation (2.4). For the application of the proposed method several parameters are needed regarding seismic hazard, structural response, seismic losses and environmental losses. In the next section we describe how to set the required parameters for the analysis, especially for those parameters related to environmental losses which are not familiar in the current earthquake-resistance design practice.

3. PARAMETERS FOR THE ANALYSIS

In equation (2.4) the seismic hazard is defined through a hazard curve ($\lambda(a)$) which can be obtained with standard PSHA. For simplicity we use as intensity parameter the spectral acceleration at the first mode period (SA); however other intensity parameters can be used provided that the hazard curve for such parameter is known.

The procedure is not constrained to a specific form of $F(a=\text{SA}, c)$ and many vulnerability functions may be used. For simplicity and based on previous work (Ordaz *et al.* 1989), we used the log-normal function, with parameters m_z and $\sigma_{\ln z}$, shown in equation (3.1) (where $\Phi()$ denotes standard normal function). For the computations we set m_z= 17.1 and $\sigma_{\ln z}$=1.10 according to (Ordaz et al. 1989) to represent an average Mexican earthquake-resistant facility.

$$F(SA,c)=\Phi\left(\frac{1}{\sigma_{\ln z}}\ln\frac{SA}{c\,m_z}\right)=\Phi\left(\frac{1}{\sigma_{\ln z}}\ln\frac{z}{m_z}\right) \tag{3.1}$$

We considered that the initial cost of the facility increases with c, therefore we use the model proposed by Jara and Rosenblueth (1988), which is shown in equation (3.2), in order to estimate $L(c)$.

$$L(c)=\begin{cases}K_0 & \mathit{If}\ c\le c_r\\ K_0+\varepsilon K_0\,(c-c_r)^a & \mathit{otherwise}\end{cases} \tag{3.2}$$

where K_0 is a fixed cost regardless of the design load and c_r is the design load for a facility designed without earthquake resistant design considerations. For the computations we set c_r=0.05, ε=2.4 and a=1.1 according to Jara and Rosenblueth (1988). In addition, we set the discount rate of the facility cost equal to 0.05.

In order to set the environmental parameters (η and γ_e) in equation (2.4) we proceed as follows. As has been stated the Global-warming and its potential effects on the earth are produced by a long term accumulation of the so-called greenhouse gases in the high layer of the atmosphere. In the construction industry the main greenhouse gases are carbon dioxide (CO2), carbon monoxide (CO), sulfur dioxide (SO2) and nitrous oxide (NO) (Jönsson *et al.* 1998). CO2 emissions occur both as process emission from cement production and from use of fossil fuels, on the other hand, the other gases are mainly related to energy consumption. In order to quantify greenhouse emissions, for a given process, all gases are transformed to an equivalent carbon dioxide emission (i.e. CO2-e). Normally, the estimation of CO2-e emissions related to a certain process is obtained through life-cycle-analysis (LCA) (US EPA/600, 2006). LCA is a technique to assess the environmental aspects and potentials impacts associated with a product, process or service, further details can be found elsewhere (US EPA/600, 2006).

In table 1 we present CO2-e emission factors for some construction materials which were reported in several references. Significant scatter in the reported values were observed, this uncertainty is related to several factors. CO2-e emission factors are dependent on the system boundaries (i.e. the selection of the parts of the production process to be considered in LCA). For instance, some analysts may include greenhouse emissions generated during the production of the envelope of some product while other analysts could disregard this part of the production process. The system boundaries should be set based on the objective of the analysis and on the information required by the users of LCA. The uncertainty observed in table 1 is also produced by differences in production process in different countries and differences in natural resources between countries. For instance, some country may have efficient production process for electricity while other countries may use an inefficient production process that may lead to large greenhouse emissions. Furthermore, more greenhouse gases emissions may be produced in countries which lack of raw materials as a consequence of the emissions related to transportation of raw materials from other countries. For the applications presented herein we assessed the uncertainty in CO2-e emission factors by a sensitivity analysis as will be described later.

Table 1. CO2-e intensities for several construction materials

Material	Reference	Kg CO_2-e /ton
Concrete	Buchanan and Honey (1994)	76
	Penttala (1997)	147
	Gonzalez and García (2006)	19
	Gustavsson and Sathre (2006)	11
	Asif *et al.* (2007)	123
	Flower and Sanjayan (2007)	120
	Yan *et al.* (2010)	170
	Zabalza *et al.* (2011)	179
	Monahan and Powell (2011)	174
Steel	Buchanan and Honey (1994)	1070
	Gustavsson and Sathre (2006)	35
	Gonzalez and García (2006)	516
	Yan *et al.* (2010)	377
	Monahan and Powell (2011)	3809
Glass	Penttala (1997)	2100
	Gonzalez and García (2006)	257
	Asif *et al.* (2007)	568
	Yan *et al.* (2010)	1858
Plasterboard	Gustavsson and Sathre (2006)	82
	Gonzalez and García (2006)	99
	Asif *et al.* (2007)	265
Ceramic brick	Gonzalez and García (2006)	40
	Monahan and Powell (2011)	519
	Zabalza *et al.* (2011)	271
Wood	Buchanan and Honey (1994)	44
	Penttala (1997)	124
	Gustavsson and Sathre (2006)	14
	Hacker *et al*. (2008)	400
	Zabalza *et al.* (2011)	300
	Asif *et al.* (2007)	116

With the factors shown in table 1 we estimate the quantity of CO2-e emitted during the construction and repair of a facility and we use the carbon tax as a measure of the potential environmental impact of those emissions. In order to set the value of the carbon tax we compiled several studies available in the literature. Nowadays, a large number of studies concerning the cost to carbon emissions can be found, however, based on the results of Tol (2005) we decided to include a majority of peer-reviewed studies because this type of studies have lower estimates and smaller variability (see Tol, 2005 for further details). In figure 1 we summarize the reported carbon tax values, as a function of time. In many cases several values were reported by a given study in those cases we included all reported values. We present the results in US$, 2000 prices, for the computations involved in figure 1 we assume an inflation rate of 0.03 per year.

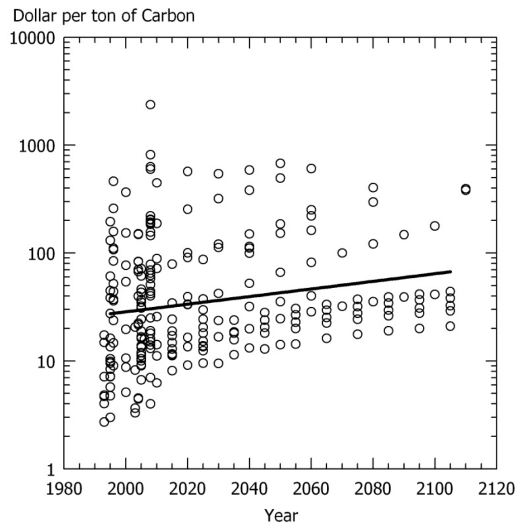

Figure 1. Carbon tax as function of time (reported values are in US$, 2000 prices)

The values of carbon tax span 3 orders in magnitude as has been observed before (Watkiss and Downing, 2008). As has been stated, there are several controversial issues regarding the estimation of the value of carbon tax (see for instance, Ulph and Ulph 1997, Clarkson and Deyes 2002 and Tol 2008, Watkiss and Downing, 2008) which lead to the large uncertainty observed in figure 1. Some factors that produce this uncertainty are:

a) Some studies have used the cost-benefit approach to set the value of carbon tax while other studies have used the marginal damage approach (i.e. the value is set by assessing the difference in future damage levels caused by a marginal change from the current level of emissions) (Clarkson and Deyes 2002).

b) It has been identified that developing countries are more vulnerable to global warming than developed countries because there are more climate-sensitive activities in their economies (Clarkson and Deyes 2002, Pearce 2003, Tol 2005). Therefore, some studies have used the equity weighting approach to aggregate the valuation of impacts of global-warming in a geographical zone (the weighting factors for the impact of the global-warming depends on the income of the region). On the other hand, some studies have disregarded this issue in the aggregation of the impacts of global warming (i.e the weighting factors are equal to unity for all region) (Pearce 2003).

c) The value of carbon tax may be dependent on the strategy undertaken by nations to control greenhouse gases emissions (Nordhaus and Yang 1996). In the cooperative policy approach the global environmental concerns are treated cooperatively through several nations while in the non-cooperative policy approach individual nations undertake policies that are in their self-interest disregarding the effect of their actions in other nations. Nordhaus and Yang (1996) reported large values of carbon tax when a cooperative approach is used in the cost-benefit analysis.

d) The current understanding of the regional details of the impact of climate change is incomplete and current climate change models use rough spatial and temporal resolutions (Tol 2005). Despite the value of carbon tax is controversial and very uncertain, we considered that it is useful to assess the environmental cost of seismic damage provided the current state of knowledge on the understanding of the effects of climate change. In the applications presented in the article we considered the uncertainty in the value of carbon tax through a sensitivity analysis that will be described later.

Finally, for the application of the proposed method the value of γ_e is needed. As can be observed in figure 1, the value of carbon tax will tend to increase with time because the damage related to greenhouse gases emissions is function of the cumulated stock, therefore a ton of CO2-e emitted in the future may have a higher associated damage than a ton of CO2-e released now (Nordhaus 1991, Richards 1997, Clarkson and Deyes 2002 and Pearce 2003). Therefore, γ_e should attain negative values and we set its value by fitting an exponential curve to data in figure 1, this model is plotted with continuous line in figure 1. We obtain a value of γ_e equal to -0.008. Although significant uncertainty is observed in figure 1 we considered that variation of the carbon tax with time can be reasonable modelled with an exponential function for the planning time horizon of standard facilities. Also, in the presented applications the uncertainty in the value of γ_e will be addressed through a sensitivity analysis.

4. APPLICATIONS

In order to keep the focus in the objective of the article we present applications of the proposed method involving an actual seismic hazard scenario and considering that the seismic response of a facility can be correctly described by a SDOF system. In this paper, we do not intend to provide accurate estimates of design load considering environmental losses. The important issue with the presented applications is to identify under which circumstances the inclusion of environmental analysis in the seismic design of structures is worthwhile. Nevertheless, the presented method is general enough to be used with more sophisticated structural models for particular applications.

We considered 2 five-story facilities located in the City of Acapulco on hard-rock conditions (NEHRP B class). Acapulco is a medium-sized (ca. 1 million people) Pacific coastal city located in the middle of a seismic gap where an Mw 7.5–8.2 earthquake is expected in the near future. Both facilities are moment-resistant framed buildings, one building is a reinforced concrete building while the other is a steel building. Both buildings have the same dimensions in plan (24 by 24 meter plan), the same story-height (4.5 meters) and 3 bays in each one of its principal directions. For the steel building we considered a roof system, which will be considered a rigid diaphragm, composed of a composite steel-reinforced concrete slab that is connected to the top flanges of the beams through shear tabs, while for the reinforced concrete building we considered a concrete slab with a thickness of 12 centimeters. The buildings were designed according to the Acapulco City Building Code.

For the steel building we use a box shape section for the columns and a W shape section for the beams. For the stories 1-3 we used a 28” x 28” x 1” section and a W27” x 114 section for the columns and beams, respectively, while for the stories 4-5 we used a 24” x 24” x 1” section and a W18x106 section for the columns and beams, respectively. In all stories we used a W12x65 section for the secondary beams in the roof system. For the concrete building we use rectangular sections for columns and beams. In the stories 1-3 we used 80 cm x 80 cm columns and 45 cm x 80 cm beams while for the stories 4-5 we used 65 x 65 cm columns and 30cm x 70 cm beams. Also, we used a 25 cm x 50 cm section for the secondary beams in all stories. The first mode periods for the steel and reinforced concrete buildings are 0.77 and 0.69 seconds, respectively.

For the analysis, we considered the SA seismic hazard curves shown in figure 2 those curves were computed through standard probabilistic seismic hazard analysis (PSHA) for the City of Acapulco based on seismicity information of sources located in the Pacific coast of Mexico.

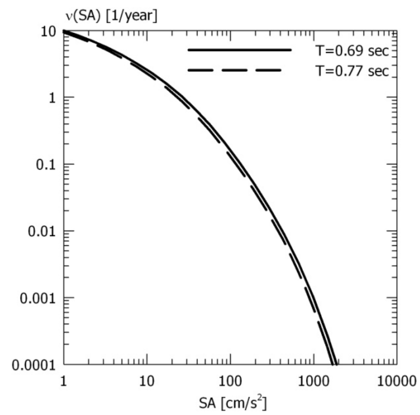

Figure 2. SA hazard curves for *T*=0.69 sec and 0.77 sec

In order to assess the CO2-e emissions we set the LCA boundaries according to the following considerations:

a) We suppose that main contributors to CO2-e emissions are materials in the structural system and in the non-structural components. Therefore for the analysis we considered concrete, steel, glass, partition walls, roof ceilings and tiles. We assume a standard architectural distribution of partition walls for a typical apartment building.
b) For simplicity, we disregard the CO2-e emissions related to the foundation of the buildings and to the mechanical and electrical systems. Also, we disregard the CO2-e emissions related to construction activities because their small contribution to CO2-e emissions.
c) For the computation of CO2-e emissions we used the factors reported in table 1 and we assumed that future replacement materials were identical to those being replaced and their CO2-e emission factors are at current levels without allowance for future improvements in manufactory techniques.

Therefore, we computed CO2-e emissions as the product between the weight of the different materials in the building and the factors shown in table 1. In view of the variability in the CO2-e emission factors and based on the objective of the article we perform a sensitivity analysis considering 3 different levels of CO2-e emissions factors. We analyzed 3 scenarios related to: a) the largest CO2-e emissions factors, b) the smallest CO2-e emissions factors and c) the average CO2-e emissions factors for each material (herein after the 3 analysis will be referred as LI, SI and AI, respectively). It is important to state that none of these analyses can be considered as a realistic scenario, because of the dependence of intensity emission index on the technological development and on the available raw natural resources of a given country. We do not expect significant effect of such unrealistic scenarios in the sensitivity analysis. However, for practical applications a better choice may be select CO2-e emissions factors that can be considered as representative of the country where the building is located. For the steel building we estimated the initial CO2-e emissions equal to 1941 tons, 34 tons and 649 tons for the LI, SI and AI cases, respectively. While for the concrete building we estimated 458 tons, 34 tons and 286 tons for the LI, SI and AI cases, respectively. Large CO2-e emissions are related to the steel building due to the large intensity emission factor for steel, in both buildings the structural system contributes with roughly 90% of CO2-e emissions.

We compute the environmental cost as the product between the CO2-e emissions and the carbon tax. As has been stated the level of carbon tax has a very large uncertainty estimations of carbon tax level span 3 orders in magnitude (see figure 1). Some authors have recommended values between US$224 /ton-CO2 and $US50 /ton-CO2 for sensitivity analysis (Clarkson and Deyes, 2002), nevertheless other authors have proposed that is unlikely that the cost carbon emissions exceed US$50 /ton-CO2 (Tol 2005). However, in a more recent work Anthoff et al. (2008) obtained an expected value of US$173

/ton-CO2. For the application presented herein we decided to perform a sensitivity analysis with carbon tax values of 10, 20, 50, 70 and 224 US$ / ton-CO2.

For the concrete building we obtained η values ranging between 0.0003 and 0.077 for the most optimistic and the worst scenarios, while for the steel building we obtained η values between 0.0003 and 0.3293 for the most optimistic and the worst scenarios. We considered that the value of 0.3293 seems too large and therefore we decided to exclude it from our analysis. Hence, we set η = 0.0005, 0.01, 0.05 and 0.10 in order to perform the sensitivity analysis, we considered that such range will include most practical applications.

There is few information about γ_e parameter in the literature, however there is a consensus that γ_e should attain negative values because the damage related to greenhouse gases emissions is function of the cumulated stock, therefore a ton of CO2-e emitted in the future may have a higher associated damage than a ton of CO2-e released now (Nordhaus 1991, Richards 1997, Clarkson and Deyes 2002 and Pearce 2003). As stated before, we set the mean value of γ_e to -0.008. Also, we compute the standard deviation of γ_e (Drapper and Smith 1981) and we found a value of 0.005 for this parameter. Therefore, we set γ_e = -0.003, -0.008 and -0.013 in the sensitivity analysis.

We performed the analysis according to equation (2.4), with the values of of η and γ_e described before and the SA hazard curves in figure 2 and vulnerability function in equation (3.1). For a given η, γ_e and t_e combination we computed the optimal design level (c_{opt}), in view that very similar results were obtained with the 2 hazard curves we decided to only present results associated with the SA hazard curve for T=0.77 seconds. The results are summarized in figure 3. In figure 3, we plot with continuous line the optimal design level related to standard analysis (S) (i.e. disregarding the environmental losses) and with dotted line, dashed line and dotted-dashed line the optimal design levels for γ_e values of -0.003, -0.008 and -0.013, respectively.

For small t_e values the effect of environmental losses in c_{opt} is marginal, however as t_e increases the effect of environmental losses becomes important. The value of t_e that divides the zone where the environmental losses is important from the zone where the environmental losses can be disregarded depends on η. For η=0.005, 0.01, 0.03 and 0.10 the environmental losses tend to be important for t_e values of 300, 200, 100 and 50 years, respectively. Considering that for standard facilities the largest t_e values are of the order of 200 years (with a discount rate of 0.05 the present value of USD$1 in 200 years is USD$ 1E-5) the increment in c_{opt} with respect to the case without environmental losses is in the range between 5%, for η=0.01 and γ_e =-0.003, and 76% for η=0.1 and γ_e =-0.013.

Based on the results presented herein we conclude that the consideration of environmental losses in standard earthquake resistant design is warranted particularly as t_e increases and for η values larger of 0.01.

There is a large uncertainty related to environmental losses especially for the value of carbon tax used in the analysis, therefore this uncertainty should be properly accounted, specially, when the proposed method is used to provide best estimates of the design level considering environmental losses. The uncertainty on η parameter in the probabilistic analysis can be included through several techniques (see for instance, Helton 2004), nevertheless, normally in current PSHA practice the logic tree approach has been used to model such type of uncertainty.

Our results suggest that in some cases the consideration of environmental losses may lead to a significant increment in the design load. In such cases, there are several design strategies that may be used to control environmental losses in the framework of earthquake-resistant design such as: a) to increase the design load of earthquake-resistant facilities in order to limit the future CO2-e emissions related to repair of future damages, b) to use materials with smaller CO2-e emission factors, and c) to diminish the seismic vulnerability functions through the development of innovative structural systems.

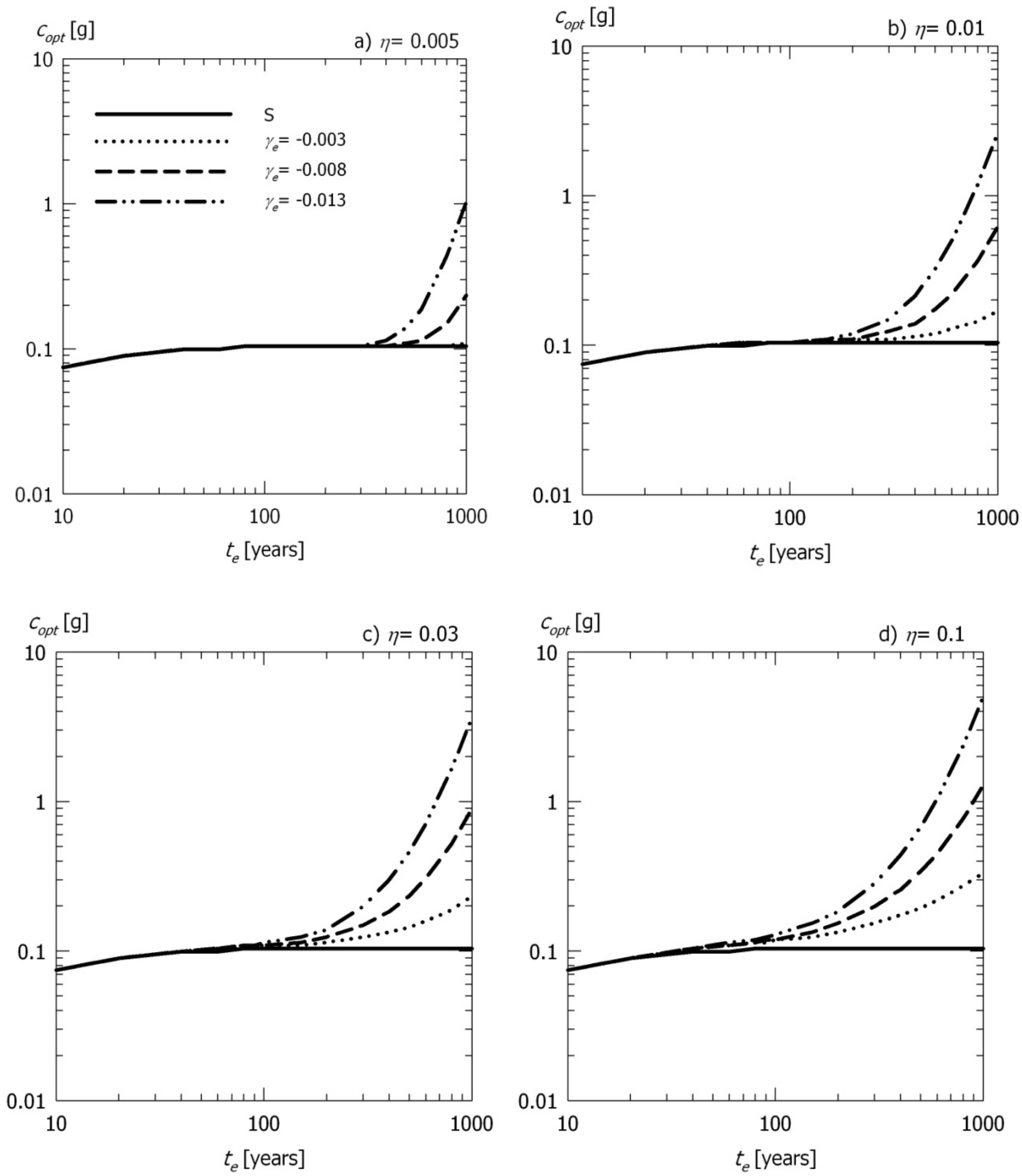

Figure 6. Optimum design level as a function of t_e for SA(T=0.77) hazard curve.

5. CONCLUSIONS

We have presented a probabilistic framework to include environmental losses in earthquake-resistant design of structures. In view that the method requires environmental parameters that are not familiar in the current earthquake-resistance design practice we have included a detailed description of those parameters. Our results shown than in some cases the consideration of environmental losses in the seismic design of structures is warranted, particularly when: a) the environmental cost of a facility is larger than 1% of the cost of the facility and b) when the planning time horizon of a facility increases. In the presented applications we found increments in the design load between 5% and 76% with respect to the design load computed disregarding environmental losses for planning time horizons of the order of 200 years. The uncertainty in the environmental cost is very large, particularly by the uncertainty in the social cost of CO2- emissions and the uncertainty in the CO2-e emission factors, therefore it should be considered in practical situations.

REFERENCES

Arroyo, D., Ordaz, M. and Teran-Gilmore A., (2012). Seismic loss estimation and environmetal issues, Subtmitted for publication to Earthquake Spectra.

Asif, M., Muneer, T. and Kelley R., (2007). Life cycle assessment: a case study of a dwelling home in Scotland, Building and Environment 42, 1391–1394.

Clarkson, R., and Deyes K., (2002). Estimating the social cost of carbon emissions, The Public Enquiry Unit, HM Treasury London, Working Paper 140.

Drapper, N.R., and Smith, H., (1981). Applied Regression Analysis, 2nd Edition, Wiley, New York, 709 pp.

Esteva, L., 1968. Bases para la formulación de decisiones en diseño sísmico, Reporte 182, Instituto de Ingeniería UNAM, Mexico (In spanish).

Flower, D. and Sanjayan, J. G., (2007). Green House Gas Emissions due to Concrete Manufacture, Int J LCA 12, 282–288.

Gonzalez, M. J., and García J., (2006). Assessment of the decrease of CO2 emissions in the construction field through the selection of materials: Practical case study of three houses of low environmental impact, Building and Environment 41, 902–909.

Gustavsson, L. and Sathre R., (2006). Variability in energy and carbon dioxide balances of wood and concrete building materials, Building and Environment 41, 940–951.

Hacker, J. N., De Saulles, T. P., Minson, A. J. and Holmes M. J. P., (2008). Embodied and operational carbon dioxide emissions from housing: A case study on the effects of thermal mass and climate change, Energy and Buildings 40, 375–384.

Jara, J. M. and Rosenblueth, E., (1988). Probability distribution of times between characteristic subduction earthquakes. Earthquake Spectra 4, 499–529.

Jönsson, A., Björklund, T. and Tillman, A. M., (1998). LCA of concrete and steel building frames, Int. J. LCA 3(4), 216–224.

Liu, M., and Neghabat F., (1972). A cost optimization model for seismic design of structures, The Bell System Technical Journal 51(10), 2209–2225.

Monahan, J., and Powell, J. C., (2011). An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework, Building and Environment 43, 179–188.

Newmark, N. M., and Rosenblueht, E., (1971). Fundamentals of Earthquake Engineering, Prentice Hall, 660 pp.

Nordhaus, W. D., (1991). A Sketch of the Economics of the Greenhouse Effect, The American Economic Review 81(2), 146–150.

Ordaz, M., Jara, J. M. and Singh, S. K., (1989). Riesgo sísmico y espectros de diseño en el estado de Guerrero, Informe Proyectos 8782-9745, Instituto de Ingeniería UNAM, México, DF (In spanish).

Pearce, D., (2003). The social cost of carbon and its policy implications, Oxford Review of Economic Policy 19(3), 362–384.

Penttala, V., (1997). Concrete and Sustainable Development. ACI Materials Journal 94(5), 409–416.

Richards, K., (1997). The time value of carbon in bottom-up studies, Critical Reviews in Environmental Science and Technology 27, S279–S292.

Tol, R., (2005). The marginal damage costs of carbon dioxide emissions: an assessment of uncertainties, Energy Policy 33, 2064–2074.

Tol, R., (2008). The Social Cost of Carbon: Trends, Outliers and Catastrophes, Economics—the Open-Access, Open-Assessment E-Journal, 2(25): 1–24

US EPA/600, 2006. Life cycle assessment: principles and practice, Report No. EPA/600/R06/060, Cincinnati, Ohio.

Vanmarcke, E., Cornell, C. A., Whitman, R. V. and Reed, J. W., (1973). Methodology for optimum seismic design, in Proceedings, Fifth World Conference on Earthquake Engineering, vol.2, pp. 2521

Venkatarama Reddy, B. V., and Jagadish, K. S.,(2003). Embodied energy of common and alternative building materials and technologies, Energy and Buildings 35, 129–137.

Watkiss, P. and Downing, T. E., (2008). The social cost of carbon: Valuation estimates and their use in UK policy, The Integrated Assessment Journal 8, 85–105.

Yan, H., Shen, Q., Fan, L., Wang, Y. and Zhang, L, (2010). Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong, Building and Environment 45, 949–955.

Zabalza, I., Valero, A., and Aranda, A., (2011). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential, Building and Environment 46, 1133–1140.