Open Journal of Civil Engineering, 2024, 14, 469-485
https://www.scirp.org/journal/ojce
ISSN Online: 2164-3172
ISSN Print: 2164-3164

Assessment of Intangible Losses in Earthquake Engineering

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How to cite this paper: García-Pérez, J., Díaz-López, O. and García-López, E. (2024) Assessment of Intangible Losses in Earthquake Engineering. *Open Journal of Civil Engineering*, **14**, 469-485.
https://doi.org/10.4236/ojce.2024.143026

Received: August 10, 2024
Accepted: September 11, 2024
Published: September 14, 2024

Abstract

In order to find optimum design parameters in earthquake engineering, an objective function is optimized. This function comprises the initial cost of a structure and the cost due to the damage of earthquakes. Intangible losses may be included in the latter, such as how much society is willing to invest to preserve a human life. In this paper, the expression of the objective function is developed in terms of the seismic design coefficient, and the aforementioned intangible loss is calculated from both the individual point of view and that of society. The calculation of the intangible is based on utility curves. Finally, optimum seismic design coefficients are calculated for a firm ground site.

Keywords

Seismic Risk, Optimum Coefficients, Structural Reliability, Intangible Losses, Utility

1. Introduction

The optimization of the total cost of losses caused by earthquakes is normally used to select optimal design parameters in earthquake engineering. This total cost is given by the sum of the initial cost and the damage caused by earthquakes. Among this damage may lie how much society is willing to invest to preserve a life. Some techniques have been developed that allow for obtaining the optimal solution in rational decision making, provided that the relationships between utility on the one hand and benefits, resources and losses on the other are known. In many problems, the magnitude of the benefits, expenditures, and losses are small enough for it to be worth assuming that utility is a linear function of them. But often, when human lives are at risk, the losses tend to be so high that this hypothesis loses validity, and it becomes necessary to define the shapes of the relevant utility functions. The criteria found in the literature to take into account how much society is willing to invest to preserve a life lead to such different results that they lack any reliable criteria. These circumstances are the ones that have mainly motivated this study.

We start by establishing the decision framework in order to compute optimum seismic design coefficients. The objective function to be maximized includes the cost of saving potentially endangered lives. Next we present a model, based on utility curves, for computing the cost to save lives, or more precisely, how much we must invest to preserve a human life.

2. Decision Framework

From the point of view of society, a convenient objective function to be maximized in earthquake engineering in order to find optimum design parameters, equals the expected present value of the benefits derived from the existence of the structure, minus the initial cost and expected present value of losses due to earthquakes. Often the expected present value of benefits is practically independent of the design parameters, thus the objective function can advantageously be taken as the sum of the initial cost plus the expected present value of losses due to earthquakes, and it is the one to be minimized. Among the losses may lie intangibles such as human lives. When this concept is considered, many difficult questions arise regarding the assignment of quantitative values. The formulation presented here deals explicitly with these questions, and the proposed framework can be expected to support the formulation of decision criteria.

2.1. Seismic Hazard at a Site

We can describe the seismic hazard at a site by means of a stochastic process model of the occurrence of seismic events and of the conditional probability density function of seismic intensities. Moreover, this function can be described by a ground motion indicator that shows a high correlation with the peak values of the structural response, such as peak ground accelerations or velocities or the ordinates of the response spectra for the fundamental period of the system of interest. Poisson process or renewal models with a random selection of magnitudes are generally used in order to represent the generation of seismic events in a source. Models of stochastic processes of the occurrence of earthquakes of different intensities at a site near one or more active sources are generated by combining these models with intensity attenuation laws. In the case of the Poisson process model, the seismic hazard remains constant, regardless of the time elapsed since the previous event.

2.2. Expected Present Value of the Losses

The deduction of equations of the expected present value of losses for the case of earthquakes caused by a Poisson process is presented. We begin with the relationship between the initial cost of a structure designed with a coefficient *c*. Based on available results, García-Pérez [1] concludes that it is reasonable to adopt the following expression:

$$p=\begin{cases} C & \text{if } c\le c_0 \\ \left[1+a_2\left(c-c_0\right)^{a_3}\right]C & \text{if } c>c_0 \end{cases} \tag{1}$$

where, if the structure is not designed to resist earthquake, C would be its initial cost and c_0 would be its lateral resistance; a_2 and a_3 are constants.

Now let $\kappa=\kappa(z)=-\mathrm{d}\lambda/\mathrm{dz}$ be the density of occurrence of earthquakes with intensity *z*, $\lambda=\lambda(z)$ the exceedance rate of *z*, and L_z the loss due to an earthquake of intensity *z* at the instant in which it occurs. If we assume that the structure is restored to its original condition as a result of every earthquake, and that the structure was built at the instant $t=0$, then the expected present value of the loss due to the first earthquake with intensity between *z* and $z+\mathrm{dz}$ is equal to:

$$\nu_{z1}\mathrm{dz}=L_z\kappa\mathrm{dz}\int_0^\infty \mathrm{e}^{-(\gamma+\kappa dz)t}\mathrm{d}t=L_z\kappa\mathrm{dz}/\left(\gamma+\kappa\mathrm{dz}\right) \tag{2}$$

that of the second earthquake with intensity in this interval, $\nu_{z2}\mathrm{dz}$, will be $\nu_{z1}\mathrm{dz}$ times $\kappa\mathrm{dz}/\left(\gamma+\kappa\mathrm{dz}\right)$, and so on. therefore, the contribution of all earthquakes with intensity in $\left(z,z+\mathrm{dz}\right)$ will be

$$\mathrm{d}\nu_z=L_z\sum_{n=1}^{\infty}\left[k\mathrm{dz}/\left(\gamma+\kappa\mathrm{dz}\right)\right]^n=L_z\left(\kappa/\gamma\right)\mathrm{dz} \tag{3}$$

(see [2]). It follows from this that the expected present value of losses due to all earthquakes in a structure built in $t=0$ is equal to

$$\nu=\left(1/\gamma\right)\int_0^{z_m}L_z\kappa\mathrm{dz} \tag{4}$$

where z_m is the maximum intensity that can occur at the site of interest.

We will take L_z comprised of the following three terms, the first of which represents the direct material damage suffered by the building itself, when struck by an earthquake of intensity *z*. We will write this term in the form $L_z=p\xi\left(z,c\right)$. The function ξ must be increasing with *z*, decreasing with increasing *c* and such that $\lim_{z\to0}\xi=0$ and $\lim_{z\to\infty}\xi=1$. Moreover, it must tend very quickly to zero when *z* tends to zero, since we know that earthquakes of very low intensity do not cause any damage. The second term quantifies the loss of contents of the buildings that suffer damage. It should be insignificant when ξ is small, since the content of the buildings practically does not suffer any damage, and it should tend to be much higher than the first term when it approaches one, since it is about buildings that suffer collapse. The third term takes into account the losses of human life considering whether the structure collapses or not. This is made through a vulnerability function relating the intensity of earthquakes to the loss of human life inside the buildings, $f(z/c)$, and how much society is willing to invest to preserve an anonymous life ($\bar{L}$). The vulnerability function shown in **Figure 1** is taken from [3], which corresponds to a five-story building, with a fundamental vibration period of 1.06 s. This function is shown for the following cases: day time (solid line), commuting time (dotted line) and nighttime (dashed line). Based on these considerations, we will take $L_z = p\xi(z,c)\left[1+\alpha_4\xi(z,c)\right]+\bar{L}f(z/c)$ where α_4 is a factor significantly greater than one.

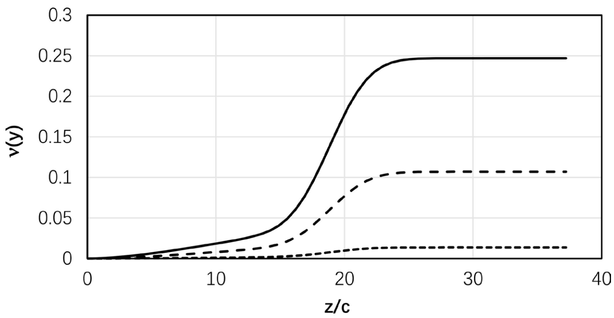

Figure 1. Vulnerability functions of loss of human lives.

According to data and analysis by Esteva *et al.* [4] and Ordaz *et al.* [5] [6], given an earthquake characterized by *z*, the expected value of the loss due to material damage to the building itself at the time of the earthquake is proportional to the 1.6 power to the ratio $\zeta = z/c$ of the intensity to the design coefficient on the interval $1 \le \zeta \le 7$. According to the empirical data and the considerations made, the following expressions are taken for $\xi(z,c)=\xi(\zeta):\xi(\zeta)=0.025\zeta^6-0.015\zeta^9$ if $\zeta \le 1$ and $\xi(\zeta)=\left(0.188+\zeta^{1.8}\right)/\left(117.8+\zeta^{1.8}\right)$ if $\zeta > 1$ (see **Figure 2**). By substituting in Equation (4), we get:

$$\nu = \frac{1}{\gamma}\int_0^{z_m}\kappa(z)\left[p\xi(z/c)\left(1+\alpha_4\xi(z/c)\right)+\bar{L}f(z/c)\right]\mathrm{d}z \tag{5}$$

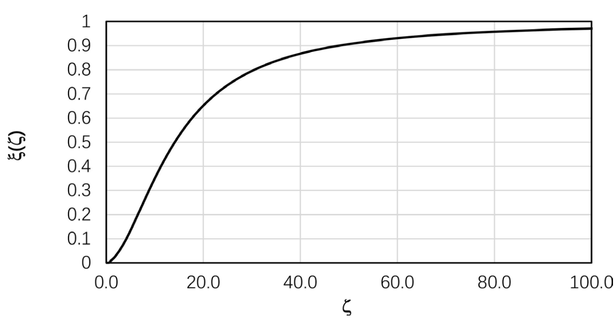

Figure 2. Variation of ζ.

According to Cornell and Vanmarcke [7], we will take the exceedance rate of the magnitudes of the earthquakes produced in a tectonic province as:

$$\lambda(M)=\alpha_5\left(\mathrm{e}^{-\beta_1 M}-\mathrm{e}^{\beta_1 M_m}\right) \tag{6}$$

where M means magnitude, M_m is the maximum value of M that can be generated in the province, and α_5, and β_1 are constants. On the other hand, most attenuation formulas provide the peak ground acceleration, velocity, and displacement, as well as the ordinates of the response spectra for a given period and degree of damping, at long distances from the origin, as z equal to a function of the focal coordinates and those of the site of interest multiplied by $\exp(\beta' M)$ where β' is a constant. By combining this expression with Equation (6), we obtain:

$$\lambda(z)=\alpha_6\left(z^{-\alpha_7}-z_m^{-\alpha_7}\right) \tag{7}$$

where α_6 and α_7 are constants. The expression for λ is valid when the earth's crustal material behaves linearly between the source and the site of interest, and the distance between it and the source is large compared to the dimensions of the rupture area. Then we can write

$$\kappa(z)=\alpha_6\alpha_7 z^{-\alpha_7-1} \tag{8}$$

By substituting in Equation (5), it turns out $\nu=\frac{\alpha_6\alpha_7}{\gamma}\int_0^{z_m}\frac{\left[p\xi(z/c)\left(1+\alpha_4\xi(z/c)\right)+\bar{L}f(z/c)\right]}{z^{\alpha_7+1}}\mathrm{d}z$, which with the change of variable $\zeta=z/c$ becomes

$$\nu=\frac{\alpha_6\alpha_7}{\gamma c^{\alpha_7}}\int_0^{\zeta_m}\frac{\left[p\xi(\zeta)\left(1+\alpha_4\xi(\zeta)\right)+\bar{L}f(\zeta)\right]}{\zeta^{\alpha_7+1}}\mathrm{d}\zeta \tag{9}$$

where $\zeta_m=z_m/c$.

2.3. Optimum Seismic Design Coefficients

In order to calculate the optimum coefficients, we need to minimize the expected present value of the total cost, given by the sum of the initial cost, Equation (1), and the expected present value of losses, Equation (9).

3. Intangible Losses

As we have seen, to optimize reliability, we must quantify the value that society is willing to invest to preserve a human life. In the area of earthquake engineering, we can find some works that deal with this topic. Among them are those based on utility curves. Rosenblueth [8] [9] establishes a lower limit to the social value of an anonymous life. García-Pérez [10] reviews the human capital approach and computes, how much society is willing to invest to preserve a life, as the expected present value of the person's contribution to gross domestic product. García-Pérez and García-López [11] [12] consider the problem from the individual and social point of view and discuss the ethical concepts on which the method used is based.

Since we base our proposals on this work on the willingness approach, we begin by describing it. The impacts caused by the loss of a life, both individually and in the social case, are discussed next. Finally, the equations for calculating the amount that society is willing to invest to preserve a human life are presented.

3.1. Willingness Criteria

The willingness approach, either to accept or to pay, seems to respond to the question of how much the persons involved value their lives. Posed in this manner, the question does not find a useful answer, but it points to the possibility of inferring the value that each person gives to his own life, when he/she tries to face a certain increase in risk in exchange for an economic payment. In economic theory, it is said that life is considered a substitute good; that is, consumption is sacrificed to have more years of life or vice versa. Howard [13] studies both types of the willingness approach to accept or to pay, and we briefly review them below in order to extend them when we have small risks, which is the case of earthquakes that we are interested in.

3.1.1. Willingness to Accept

Howard [13] describes the following situation: consider the case of a person who takes a short-term risk of losing his/her life in a single event in exchange for compensation. Suppose we offer a black pill to this person, warning him/her that if he/she takes it, he/she has a probability F of dying in a very short time and without pain. We ask the person how much money he/she would be willing to accept in order to swallow the pill. He/she answers that for the quantity E.

Now, let us consider a person of age x whose utility curve is known and who has neither life insurance nor assigns value to the legacy that he/she could leave for the benefit of their loved ones. Then, we ask him/her which economic compensation he/she would require to be willing to assume a specific risk of losing his/her life. Let $U\left(W\left(x\right)\right)$ be the utility associated with the expected present value of his/her future income, and E the compensation he/she would require to start an activity with probability F of dying. This sum should not be less than that which would lead to a situation of indifference between its current state and the state with the risk and compensation discussed, that is, the one that satisfies the equality: $U\left(W\left(x\right)\right)=\left(1-F\right)U\left(W\left(x\right)+E\right)$. Whatever the expression given by $U\left(W\left(x\right)\right)$ is, we can assign values to E and find the corresponding F. Once E and F are determined, the value of how much we are willing to invest to save a human life that governs in this circumstance is obtained as $L\left(x\right)=E/F$.

3.1.2. Willingness to Pay

Let us now ask ourselves about the answer to the problem of the white pill. How much the person would be willing to pay to take the pill that eliminates the probability F that the person had to die in the short term. The statement of the problem is the same as in the willingness to accept, thus we can write $\left(1-F\right)U\left(W\left(x\right)\right)=U\left(W\left(x\right)-E\right)$, and $L\left(x\right)=E/F$ is still valid.

3.1.3. Willingness Approach for Small Risks

In the case of small risks, the two approaches mentioned are practically indistinct. Therefore, the limit of how much we are willing to invest to save a life, denoted by $L(x)$ when F tends to zero, and if we include the personal impact I_p, is given by the following expression [8].

$$L(x) = \left(U + I_p\right)/U' \tag{10}$$

where the prime denotes derivative with respect to W, we also see that when F tends to 1, $L(x)$ tends to $W(x)$.

To invest to preserve a human life are presented.

3.2. Impacts

The magnitude of the impact, whether the risk is taken voluntarily or involuntarily, depends appreciably on the precise nature of the dangerous activity through which the risk is incurred, that is, on the immediate cause of death. A disproportionate aversion prevails towards some activities in many parts of the world; such as the case of nuclear power generators or air travel. There is relative indifference towards others, as happens with automobile accidents. The decision-maker should tend to eliminate these differences, of somewhat irrational origin, by making his intentions explicit, but it will be difficult to ignore them completely.

For our purposes, the fact that we present an explicit treatment of what concerns the utility curves makes it desirable that we include only the non-economic concepts that the utility curves do not account for under the heading of impacts. The opposition between personal and social impact remains within this convention. Both impacts are conditioned by our congenital aversion to death and by considerations about the rule utilitarianism. The personal impact concerns the anguish felt by the person who is going to die or who dies, and the pain felt by those closest to them. The impact on the victim and the impact on those closest to them should be considered as the personal impact.

It is usually considered that the personal and social impacts produced by a death, which originates from knowingly and voluntarily carrying out an activity that involves risk, are less than when the cause of death is the unavoidable performance of some activity or there is no awareness of the risk involved. We call the deaths of the first type, deaths due to voluntary risk, and those of the second type, deaths due to involuntary risk. As far as social impact is concerned, we are practically interested only in deaths due to involuntary risk. However, we are interested in the personal impacts of deaths from both types of risk.

The subject of impacts deserves an in-depth study. It is particularly sensitive from an ideological point of view. It is worth remembering that the meaning we give here to the concept of impact excludes economic losses for the victim, their relatives and society, and also excludes the loss of utility for the victim who is being deprived of the joy of living and other non-economic sources of his potential happiness. What it includes is strictly non-economic and a consequence of our congenital aversion to death. Hence, the personal impact I_p is taken the same for all people and proportional to the number of victims. The social impact I_s, however, is the result of the familiarity that society has had with the victims, and the profusion with which deaths are reported.

4. Individual Value

If we want the situation to represent the problem of earthquake resistant design more closely, we will modify the formulation presented. We choose the willingness to pay approach, and consider first that an event occurs in a short time and that the person has a probability G of losing his/her life. The payment of the person reduces probability G by the amount of probability F. Then we can write the willingness approach for this case as: $(1-G)U(W(x))=(1-G+F)U(W(x)-E)$. We now must say that there is a lower limit of $W(x)$, let us say $W_{\min}(x)$, below which the person cannot survive, therefore: $U(W(x))=0$, if $W(x)<W_{\min}(x)$. Therefore, the person cannot afford to pay more than $W(x)-W_{\min}(x)$, when $G-F<1$. Thus, if G and F approach 1, $L(x)$ tends to $W(x)-W_{\min}(x)$ when $G-F<1$. In the case when $F \le G \ll 1$, which we are interested, Equation (10) is still valid.

There is not a single relation between U and $W(x)$. In fact, at each age, there is a relation between the utility per unit time $u(t)$ of the person, and his/her contribution to the GDP per unit time $w(x)$. Wealth W may be viewed as the present wealth plus the maximum loan the person would get in a fair market. Thus, the relation between U and W depends on how the person intends to return the loan. The loan is expected to be returned together with its interest when it would least affect the person's utility. Therefore, if F is sufficiently small, the person will plan to return the loan when the corresponding expected present value of the decrease in his/her utility is smallest. The value of how much must be invested for saving a life when using the minimum value of u' in the denominator in Equation (10) becomes:

$$L_1(x)=\left(U+I_p\right)\Big/\min_{t\ge x} u'(t) \tag{11}$$

Here, the prime denotes a derivative with respect to $w(t)$. U must be calculated as the expected present value of the utility per unit time, discounting future utilities at the rate γ.

5. Utility Curves

Utility curves must meet certain conditions of rationality. They can be imposed on $u(w(t))$, specify these curves of utility per unit time, and then calculate the expected present value $U(W(x))$. However, we will proceed directly with the expected present values, provided that it is much easier to explain them. These conditions are for $W>W_{\min}$ [14], where $W_{\min}$ is the subsistence value of W.

1) $U(W)=0$ if $W<W_{\min}$. This condition is arbitrarily imposed, and it implies that the utility of a dead person is nil.

2) $U'(W_{\min}) = \infty$. The condition is required since the difference between being dead and alive at a given time makes all the difference between hope and lack thereof.

3) $U''^2(W) < U'(W)U'''(W)$ if $W \geq W_{\min}$. This condition comes from the fact that one expects risk aversion, defined as $-U''(W)/U'(W)$, to be a decreasing function of W. A person, who with a certain wealth is willing to accept certain risks, should be willing to accept the same risks and more with greater wealth.

4) $U''(W) < 0$ if $W \geq W_{\min}$. This means that the utility $U(W)$ is concave. In deterministic circumstances, the function is almost necessarily concave, since the first incomes are used to cover the most pressing needs.

5) $U'(W) > 0$ if $W \geq W_{\min}$. It is often argued that this condition is necessary because if someone does not want to receive an amount of money, he/she can refuse it and economically he/she remains as before. The prime denotes derivative with respect to W.

6) $U < U_{\max} < \infty$. This condition means that the utility has an upper bound and it comes from our limited capacity to experience preference. It is often assigned the unity value.

7) $U(W) > 0$ if $W \geq W_{\min}$. This condition is imposed because it is surely fulfilled for the vast majority of the people we are interested in. Even though the misery of some persons is such that they would prefer to be dead, they still do not take the irreversible step.

The following function was proposed by García-Pérez and García-López [11] based on previous works by Keeney and Raiffa [14] and Howard [13]. Here A, and K, are constants, $U_{\max}$ is the maximum possible utility, assuming that we do not have any economic restriction, and $\delta = (W - W_{\min})/W_{\min}$ is the normalized net wealth. Its shape is shown in **Figure 3**.

$$U(W) = \left(1 - Ae^{-K\delta}\right)U_{\max} \tag{12}$$

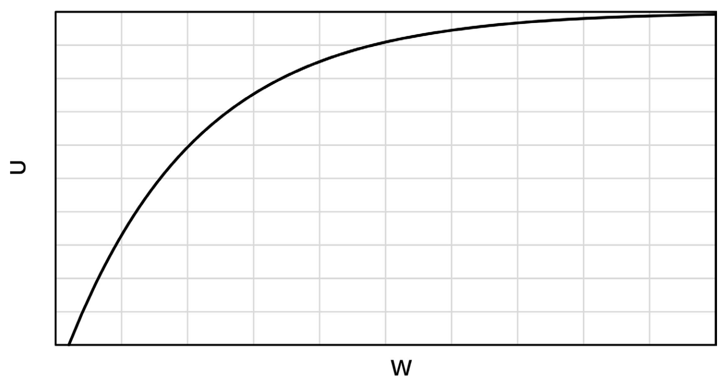

Figure 3. Utility curve.

In Equation (12) the value of $U_{\max}$ is irrelevant, but when we work with utility per unit time we must write Equation (12) in the following form.

$$u(w) = \left(1 - a\mathrm{e}^{-k\rho}\right) u_{\max}(x) \tag{13}$$

where $u_{\max}(x)$ is the maximum utility that a person is capable of experiencing depending on his/her age, *a*, κ are constants, and $\rho = (w - w_{\min})/w_{\min}$. It can be calculated by taking into account that a baby and an old person do not experience such an intense sense of well-being as a young adult. We propose the following function based on a modification of a function suggested by Rosenblueth [9].

$$u_{max}(x) = \left(0.29 + 2\sqrt{x/100}\right) \Big/ \left(1 + 4.715(x/100)^2\right) \tag{14}$$

Figure 4 shows a plot of the utility per unit time in terms of age (*x*) and wealth (*w*).

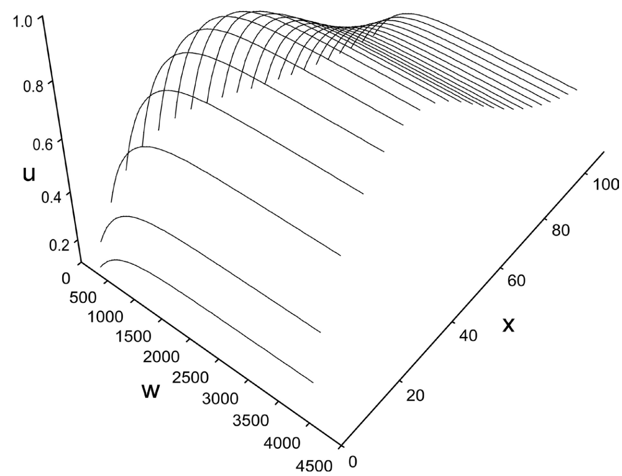

Figure 4. Utility per unit time.

6. Social Value

In this case we consider that the decision maker must stand in the place of each member of society, with a weight factor proportional to the degree of belonging of the member to society. This way, what is established in an explicit or implicit social contract is satisfied, as well as criteria of justice and morality relative to the group in question. The decision maker must also advocate the adoption of a relative morality to larger groups, of which the society he serves is a part, and above all relative moralities, absolute morality, which gives equal weight to all sentient beings. Taking into account the above and the simplicity of the development, we will give equal weight to the happiness of all inhabitants. Furthermore, when we consider the decision maker with equal probability in the place of each inhabitant, the social welfare function becomes the sum of individual utilities.

From the point of view of society, the aim is to make the expected present value of the utilities of its members in their current situation equal, and that corresponding to a second state, in which society invests resources, or receives a benefit in exchange for decreasing or increasing, respectively, the probability that one or more of its members will die. If the possibility that each person has of enjoying the resources of society were independent of the number of inhabitants, the consideration that the decision-maker should proceed as if he had the same probability of occupying the place of each member of society, which would lead to that the value of an anonymous life for society, would be the average (weighted with the degrees of belonging) of the individual values of all the members, increased by the value of the corresponding social impact.

6.1. Social Welfare Function and Utilitarianism

Absolute utilitarianism requires that our decisions maximize the sum of the utilities of all human beings from here to eternity. Since this is not possible in practice, a relativistic utilitarianism is resorted to, where we maximize some quantity that is an increasing function of the utility of each sentient being. Thus, we are looking for a social welfare function that, normatively, has to be maximized. Arrow [15] established a set of axioms regarding the conditions that a social welfare function must meet, which have been widely accepted. Harsanyi [16] shows that the social welfare function necessarily results in a linear combination of the utilities of those who make up society.

It would be impractical to quantify how much society is willing to invest in preserving human life by using all the ethical formulas found in the literature, among other reasons, because the necessary information is lacking in the problems that we are interested in. We will choose to proceed according to a utilitarian morality, however, giving weight to the impacts that the loss of a person produces on the subject, on their closest relatives, and on society.

For the application of utilitarianism to make sense in ethics and in rational decision-making, it is essential that it be formulated in terms of utility as happiness, which recognizes the effects that decision-making and implementation processes have on utility, and all the possible consequences, intentional or not, material or not, as well as making interpersonal comparisons.

We are now going to formalize the type of utilitarianism that we will use. Let us initially suppose that the decisions that we make can only influence the happiness of a sentient being in the universe. A decision will be good if it increases his/her happiness. The decision that maximizes the happiness will be the optimal decision. Now let us consider that the members of a group do not modify their respective happiness as a consequence of the variations in the happiness of the others. Let us also consider that our decisions can directly affect the happiness of one or more members only of this group and no other. We then have that the optimal decision will be the one that maximizes a certain linear function of the happiness of all the members of the group. Consequently, we must maximize the quantity [8].

$$U = E\int_0^\infty \sum_i \alpha_i f_i \mathrm{d}t \tag{15}$$

where E denotes expectation, i refers to the ith member of the group, $f_i = f(t)$, the felicity per unit time, and time t is counted from the current instant.

$\alpha_i = \alpha_i(t)$ is the *i*th weighting factor, necessarily positive, and it is of the form $\alpha_i(0)e^{-\gamma t}$, with γ = discount rate. The corresponding weights should be an increasing function of the decision maker's concern for the individuals under study, as we show in the next subsection.

The form of the exposition that we have made fits in the type of the act utilitarianism. In this kind of utilitarianism, the goodness of each decision is judged exclusively in terms of the direct consequences it may have, and if desired, the effects of the decision-making and implementation processes on utility are taken into account. There is a second type, known as rule utilitarianism, which seeks to maximize the utility of a person under the assumption that everyone will act like him.

If we are writing a building code, we must maximize the sum of the expected present value of the utilities of all the people who can be affected by the code, and assign a small weight to the utilities of the rest of humanity and the universe.

Weighting Factors

If our role is to legislate for a given subsystem, then the $\alpha_i = \alpha_i(t)$ for the initial time, that is, $\alpha_i(0)$, must be the degrees of belonging of the various individuals to the subsystem. If all are equal members, then $\alpha_i(0) = 1$. If the consequences of a potential decision affect with equal probability of all those who belong, partially or totally, to the subsystem, then we must also take all the $\alpha_i(0)$ equal to each other.

In general, we could quantify $\alpha_i(t)$ functions in three ways. These are, a purely universal one, another purely descriptive, and the third purely pragmatic. The first (Harsanyi [16]) postulates that we have to idealize all the members of the group under study, as if they profess the morality that we consider should govern our decisions. This approach is highly attractive because it eliminates any possible conflict between relative moral systems. The second way lies in exclusively accepting the sympathies and antipathies of those who make up the subsystem for which it is legislated. This approach complies with the agreement between the subsystem and the legislator. However, it is otherwise descriptive, even immoral and unfair, by ignoring previous agreements. Finally, the legislator in a now amoral position does not take into account more considerations than the purely pragmatic one of acceptance of his dictates, by the subsystem that has hired him. Given the limitations of these three approaches, and the objections they raise, we would be wrong to ignore them altogether.

When our role is not to legislate but to advise a person on their decisions, the proposed scheme subsists now, with the subsystem made up of a single member.

6.2. Alternative Ethics

The strongest ethical norm competing with utilitarianism is contractualism (Rosseau [17]). When a person decides to form part of society, he/she enters into a contract with it. The person agrees to abide by the laws of society in exchange for it to respect his/her rights. Good is whatever results of negotiations. The transfer of freedom that the social contract implies shocks the libertarian school

(Nozick [18]), in which individual freedom is sacralized. Preventing this objection, Rousseau states that the person acts in freedom when he decides to join society. After that, a part of his/her freedom has become the freedom of society to make decisions for him/her. Now, the postulate of the categorical imperative (Kant [19] [20]) tells us that from the point of view of a group, we must seek the maximum amount of happiness, giving equal weight to all members of the group, including ourselves. If a decision of ours meets this criterion, it will be independent of who makes it, thus our decision will be equivalent to a universal norm for the members of the group. Even admitting the categorical imperative uncritically, we soon realize that it is not operational. The categorical imperative is not very useful as a principle for solving conflicts between moral norms that satisfy it. On the other hand, Rawls [21] formulates a conceptual experiment in which members of society negotiate the content of a constitution among themselves, imagining that each one covers himself with the veil of ignorance, and can occupy any social role adopting a maximin policy (the greatest good in the most unfavorable circumstances). The egalitarianism of Sen [22] does not match with the resourcism of Rawls. In his capability theory, Sen includes functionings and capabilities. Thus, he analyzes social problems that affect human well-being, such as inequality, poverty, quality of life, lack of human development and social injustice. The goal of the theory is to assess the well-being and freedom people have to achieve the things they choose and the value of being or doing.

6.3. An Anonymous Life

Let us first consider the amount that society should invest in preserving a human life, taking into account the personal impact that would be caused by his/her loss. It is reasonable to define what society is willing to pay as the sum of the amounts that its members should be willing to contribute if each one covers that amount. Therefore, the value that society must assign to the *i*th life is equal to the sum of the values that its members assign to it. Now, since every member of society has the same probability of dying, society should value an anonymous life as the societal mean of the values that its members assign to their own lives.

In the case of society's investment in safety, what was previously proposed regarding that each member can pay a fair loan when it is more convenient to him no longer applies. Each member of society contributes to safety mainly through the tax structure, the increase in the cost of some products, and the reduction in public services that the member receives. The contribution of each member is an increasing function of $w(t)$ (Rosenblueth [9]). From an ethical point of view, we can say that each member's contribution should reduce his/her utility by an amount independent of time. This is the criterion that is followed to calculate the value that society is willing to invest to preserve a human life. Since at each instant $\Delta w = \Delta u / u'$, with Δu constant, the following equation is obtained:

$$L_2(x) = \int_x^\infty R(t)\exp\left[-\gamma(t-x)\right](1/u')\mathrm{d}t\left(U(x)+I_p\right) \Big/ \int_x^\infty R(t)\exp\left[-\gamma(t-x)\right]\mathrm{d}t \tag{16}$$

where the probability of being alive at age x $R(\ )$ may be expressed in terms of the mortality rate $h(\ )$ as: $R(x)=\exp\left[-\int_0^x h(t)\mathrm{d}t\right]$ ([10]). The social value of an anonymous life is then:

$$\bar{L}_s=\int_0^\infty L(x)f(x)\mathrm{d}x \tag{17}$$

where $f(x)$ is the relative frequency of age taken from **Figure 5** (Mexico's Census Bureau, INEGI, [23]).

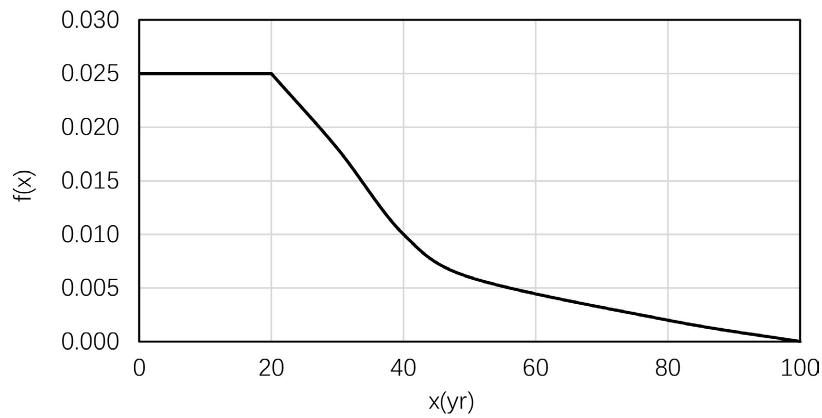

Figure 5. Probability density function.

7. Numerical Results

We make estimations for Mexico. Using Equation (13) and (14), we compute the curves for u, u', and U with $a=0.5$; $\kappa=1.1$, and $w_{\min}=400/\mathrm{yr}$. Yearly contribution to GDP is presented in **Figure 6** and mortality rates in **Figure 7** are both taken from García-Pérez [10]. In **Figure 8**, we show $L_1(x)$ (continuous line) and $L_2(x)$ (dashed line) calculated from Equations (11) and (16), respectively, using $I_p=U_{\min}$ and **Figure 7**. From these curves, we obtain $\bar{L}_s$ computed from Equation (17), which results in 398,000 US dlls and 204,500 US dlls for individual and social approaches, respectively.

In order to compute optimal seismic design coefficients, the total expected present value given by the sum of Equation (1) and (9) is minimized. We use $c_0=0.05$, $\alpha_2=0.5$, $\alpha_3=1.3$, $\alpha_4=12$, $\alpha_6=3.75\times10^{-4}$, $\alpha_7=3.3$, $C=2.25\times10^6$ US dlls. We consider three cases, with $\bar{L}_s=0.0,204500,398000$, which results in $c_{opt}=0.15,0.16,0.17$, respectively. The greater the value of $\bar{L}_s$ the greater the value of c_{opt}.

8. Concluding Remarks

We have computed how much society is willing to invest to preserve a human life, based on the willingness to pay approach, which requires the use of utility curves. In our proposal, we have included the age of the individual and the societal impact. The results thus obtained are used in an objective function to be maximized in order to find optimum design parameters. We find that the

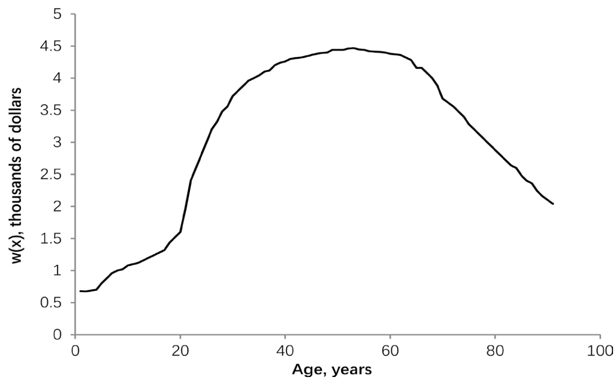

Figure 6. Yearly contribution to GDP.

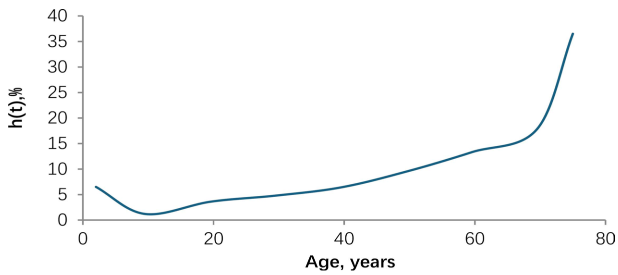

Figure 7. Mortality rates in terms of age.

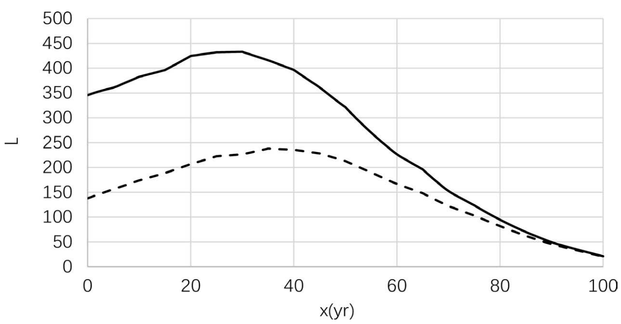

Figure 8. How much we must invest for preserving a life in terms of age.

greater the quantity that society is willing to invest to preserve a human life, the greater the value of the optimum seismic design coefficient. Several concepts need in-depth study, especially regarding the selection of utility curves, losses due to physical and psychological damage to people, and impacts on relatives and friends.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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