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Development of a Cost-benefit Model for the Management of Structural Risk on Oil Facilities in Mexico

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ABSTRACT

A reliability-based cost-benefit model for the risk management of oil platforms in the formulation of optimal decisions based on life-cycle consideration is proposed. The model is based on structural risk assessments and the integration of social issues and economics into the management decision process. Structural risks result from the platform's exposure to the random environmental loading associated with the offshore site where it is located. Several alternative designs of a typical platform are proposed and assessed from the cost-effectiveness viewpoint. This assessment is performed through the generation of cost/benefit relationships that are used, later on, to select the optimal design.

Keywords: life-cycle cost, structural reliability, optimal design, cost function, risk management, damage assessment, marine platform.

1 Introduction

Risk is involved in the design, upgrading and inspection of marine platforms as uncertain damaging events may occur within the life - cycle of a platform. The estimation of structural reliability, reliability-based design and optimal design seem to be recurrent themes in the literature (Freudenthal *et al.*, 1966; Rosenblueth and Esteva, 1972; Ang, 1974; Rosenblueth, 1976; Rosenblueth, 1986). Recently, a number of studies have addressed the issue of optimal design of buildings on the basis of minimum expected life-cycle cost (Ang and De León, 1997, Ang, Pires and Lee, 1996, Rosenblueth, 1986) which involves the trade-off between the cost of system safety and expected cost of damage. However, the integration of social and economical consequences of failures or damage of engineering systems is a topic that requires further and continuing study.

The management of risk is particularly of increasing importance to developing countries where resources are limited and plant managers are more willing to apply innovative and new developments of risk assessment in order to achieve optimal decisions for life-cycle plant management, involving inspection and repair scheduling, system upgrading, etc.

For plant facilities that involve important economic activity, the total cost must include failure or damage costs as well as system's protection costs. Moreover, whenever damage to the system occurs, the resulting damage cost must include also the indirect economic losses, such as the adverse impact to other industries, besides the direct losses.

Realistic cost functions for direct and indirect losses must be formulated for plant facilities specific to a particular industry, such as offshore platforms. Meaningful implementation of the cost-benefit model must necessarily be with reference to the assessment of a particular industry.

The assessment involves the following two major tasks:

a) The development of appropriate damage assessment procedures for the platforms and the definition of the damage probability distributions of the respective structures.

b) The formulation of the cost functions of the structures

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as functions of the damage level. For the evaluation of indirect losses, appropriate economic models are examined and formulated.

Proper integration of the above tasks leads to a process for determining the risk-based optimal design based on minimum expected life-cycle cost.

2. Formulation of Cost Functions for Design

Given that most of the marine platforms in Mexico are located in the Bay of Campeche, a zone of low seismic activity, the loading resulting from ocean waves becomes the dominant loading condition. Accordingly, the following formulation considers the ocean wave height as the main design parameter for marine platforms in Mexico.

From previous design optimization studies (Ang, Cho, Lim and An, 2001, Ang and De León 1997; Ang, Pires and Lee 1996), the life - cycle expected cost corresponding to a proposed platform design, for a given structural shape and exposure to a specific wave height, may be expressed as

$$E[C_L^T] = IC + E[C_D] \tag{1}$$

where, IC=initial cost for a given design (Stahl, B., 1986), $E[C_D]$=expected damage cost for a given design and wave height.

The expected cost of damage includes the cost of the consequences of all potential damages that may occur within the life of the platform. For each consequence a cost function is proposed. As the damaging events may occur at different times in the future, the corresponding costs are estimated in terms of future dollars whereas the initial costs are in present dollars. A PVF (present value factor) is used (Ang and De León, 1997; Ang, Pires and Lee, 1996; De León, 1996) to update the expected cost of damage, which now is rewritten as:

$$\begin{aligned} E[C_D] = PVF(&E[C_R] + E[C_E] + E[C_{DP}] + E[C_{IN}] \\ &+ E[C_L] + E[C_{IL}]) \end{aligned} \tag{2}$$

Where $E[C_R]$=expected cost of structural repairs, $E[C_E]$=expected cost of damage to equipment, $E[C_{DP}]$= expected cost of deferred production, $E[C_{IN}]$=expected cost of injuries, $E[C_L]$=expected cost of loss of lives, and $E[C_{IL}]$=expected indirect loss. All cost components are related to the damage level which, in turn, depends on the structural response under a given wave height.

2.1 Repair Cost

From previous studies on the cost of structural repairs (Ang, and De León, 1997; De León, 1996), a linear relationship between repair cost and global damage index D is proposed

$$\begin{array}{ll} C_R = (R_C/D_R)D & D < D_R \\ C_R = R_C & D \geq D_R \end{array} \tag{3}$$

Where R=repair cost, R_C=replacement cost, D_R=tolerable or repairable damage index.

2.2 Cost of Damage To Equipment

If C_E is the total cost of the equipment operating on the platform, the expected cost of damage to the equipment may be modeled (Ang, and De León, 1997; De León, 1996) as proportional to the damage index,

$$\begin{array}{ll} C_E = C_E D & D < 1 \\ C_E = C_E & D \geq 1 \end{array} \tag{4}$$

2.3 Cost of Deferred Production

The volume of deferred production depends on the platform's production rate, P_R, the estimated time to restore normal production, T_R, and on the profit obtained from commercialization of the product. Assuming that the profit is 10% of the current price of the product, P_P, the expected cost of deferred production is proposed as:

$$\begin{array}{ll} C_{DR} = 0.1 * P_P * T_R * P_R * D^2 & D < 1 \\ C_{DR} = 0.1 * P_P * T_R * P_R & D \geq 1 \end{array} \tag{5}$$

2.4 Cost of Injuries

The cost of injuries is composed of the cost of an injury, C_{1I}, and the expected number of injured personnel, N_I, which is low given the evacuation programs performed by platform managers once a storm approaches the facilities. The expected cost of injuries may then be expressed (Ang, and De León, 1997; De León, 1996) as

$$\begin{array}{ll} C_{1N} = C_{1I} * N_I * D^2 & D < 1 \\ C_{1N} = C_{1I} * N_I & D \geq 1 \end{array} \tag{6}$$

2.5 Cost Associated with Fatality

The cost associated loss of human lives (Ang, and De León, 1997; De León, 1996) is composed of the cost related to a life lost, C_{IL}, and the expected number of fatalities, N_D:

$$\begin{array}{ll} C_L = C_{1L} * N_D * D^4 & D < 1 \\ C_L = C^*_{1L} * N_D & D \geq 1 \end{array} \tag{7}$$

2.6 Indirect Losses

The expected indirect losses are related to the loss corresponding to collapse, C_{LC}, which is calculated in Section 3.6. The expected indirect loss is expressed as

$$\begin{aligned} C_{IL} &= C_{LC}{}^{*}D^{4} \quad && D<1 \\ C_{IL} &= C_{LC} && D\geq 1 \end{aligned} \tag{8}$$

2.7 Development of Expected Life-cycle Cost Functions

The expected life-cycle cost functions described above correspond to a platform's exposure to specific wave heights and therefore, the expected costs are conditional on the occurrence of the wave height; these need to be integrated over all possible wave heights according to the site's hurricane hazard curve.

The expected life-cycle cost conditional on the wave height h_j and related to the design i may then be expressed as,

$$\begin{aligned} E(C_L^T|h_j)_i = IC_i + PVF[&E(C_R|h_j)_i + E(C_E|h_j)_i + \\ &E(C_{DP}|h_j)_i + E(C_{IN}|h_j)_i + E(C_L|h_j)_i + E(C_{IL}|h_j)_i] \end{aligned} \tag{9}$$

where each expected value may be estimated by:

$$E(C_K|h_j)_i = \int_0^{\infty} C_K f_{C_K|h_j}(C_K|h_j)_i dc_k \tag{10}$$

in which *k*=*R*, *E*, *DP*, *IN*, *L*, *IL*. In order to estimate the expected values in Eq. (9), the specific damage distribution is required. In a simplified and preliminary damage assessment model, the distribution of the global damage will be taken as exponential (De León, 1996):

$$F_D(d) = 1 - \exp(-\alpha d) \tag{11}$$

where α is determined, for each wave height and each alternative design, from the condition:

$$p_f = F(1) = 1 - \exp(-\alpha) \tag{12}$$

2.8 Formulation of Optimal Design

In order to select the optimal design, the "composite" curve corresponding to the unconditional expected life-cycle cost function needs to be obtained. The conditional cost function is given by Eq. (9); its convolution with the occurrence probability of the hurricane wave heights for the platform's site should yield the unconditional cost function. If the pdf of these wave heights is $f_H(h)$, the unconditional expected life-cycle cost is:

$$E(LCC)_i = \int_0^{\infty} E(C_L^T|h_j)_i f_H(h) dh \tag{13}$$

The optimal design is the design for which the expected life-cycle cost is a minimum.

3. Application to the Design of a Typical Marine Platform

Information from a typical marine platform in the Bay of Campeche, Mexico is taken into account in order to illustrate the procedure described above for optimal design.

3.1 Initial Cost.-

The cost and reliability analyses were performed for the original as well as two stronger and two weaker designs. These calculations included the material, transportation, installation and engineer- ing costs, whereas the reliability assessments were performed using a simplified computer program (Stear, Zhaohui and Bea, 1997). The results are shown in Fig. 1.

3.2 Repair Cost

From previous studies on the assessment of existing platforms in Mexico (Ramos, 1996; Xu and Bea, 1998), the repair cost from Eq. (3) gives, in million US dollars:

$$\begin{aligned} C_R &= 45D \quad && D<0.6 \\ C_R &= 27 && D\geq 0.6 \end{aligned} \tag{14}$$

3.3 Cost of Damage to Equipment

From reported (Ramos, 1996) cost of equipment, the expected cost of damage to equipment, becomes:

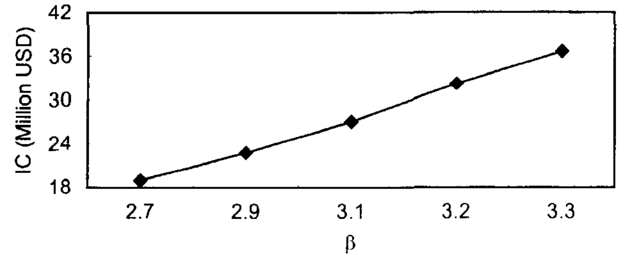

Fig. 1. Initial cost versus global reliability index.

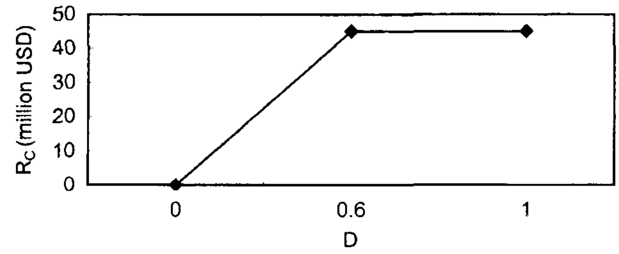

Fig. 2. Repair cost versus global damage index.

$$\begin{array}{ll} C_E = 107D & D<1 \\ C_E = 107 & D\geq 1 \end{array} \qquad (15)$$

3.4 Cost of Deferred Production

For a typical compression platform in Mexico, the following constants have been reported (Ramos, 1996):

P_R=300 million ft^3 of sour gas and 30 million ft^3 of combustible gas per day, T_R=27 months, P_P=60,000 USD per million of ft^3 of sour gas and 508,889 USD per ft^3 of combustible gas.

On the basis of these, the expected cost of deferred production would be:

$$\begin{array}{ll} C_{DP} = 2,848.6D^2 & D<1 \\ C_{DP} = 2,848.6 & D\geq 1 \end{array} \qquad (16)$$

3.5 Cost of Injuries

It is assumed that the maximum number of people that could potentially be left on the considered platform, to perform operations to close the well and valves and shut down all systems, is 4 at each one of the 5 platforms comprising a complex. If it is assumed that half of this number gets injured (N_I=10) and the costs of injuries are taken from a previous study (De León, 1996), the expected cost of injuries is expressed, in million USD, as:

$$\begin{array}{ll} C_{IN} = 0.13*D^2 & D<1 \\ C_{IN} = 0.13 & D\geq 1 \end{array} \qquad (17)$$

3.6 Cost Associated with Human Fatality

By using the Figures and statements above mentioned, the expected number of dead people N_D=10 and the expected cost related to life loss becomes, in million USD:

$$\begin{array}{ll} C_L = 1.17*D^2 & D<1 \\ C_L = 1.17 & D\geq 1 \end{array} \qquad (18)$$

3.7 Indirect Losses

On the basis of a modified version of the I/O Leontief's model and information about the Mexican economy, the indirect loss corresponding to the collapse of the platform due to hurricane waves, C_{LC}, is calculated as follows:

A modified version (Boisvert, 1992) of the Leontief's I/O model is implemented with the 1985 I/O matrix of Mexico as reported by INEGI (Instituto Nacional de Estadística, Geografia e Informática, 1986). It was considered that the sectors of Fishing and Hunting would lose 10% of their respective production incomes due to a hurricane passing through the area. In addition, the Figures shown in Table 1 were assumed for the region.

Finally, the indirect loss is 95,639 million USD and the expected indirect loss is expressed as a function of the damage level, D,

$$\begin{array}{ll} C_{IL} = 95,639*D^4 & D<1 \\ C_{IL} = 95,639 & D\geq 1 \end{array} \qquad (19)$$

See Fig. 3 for a comparison between the cost components C_E, C_{DP}, C_{IN}, C_L and C_{IL}.

3.8 Expected Life-cycle Cost Functions

The expected life-cycle cost function in Eq. (9) is estimated after the integrations in Eq. (10) for all the cost components k, all the conditional wave heights and all the alternative design cases. Eq. (12) is evaluated for each conditional wave height and each alternative design.

The expected life-cycle cost function is assessed by using Eq. (13), the cost components above detailed and a Present Value Factor of 1.73 obtained with the assumptions that the occurrence rate of significant wave heights is 0.142/year, the life of the platform is 50 years and the discount rate is 8% for Mexico's economy. A plot of the resulting life-cycle cost function is shown in Fig. 4.

Table 1. Additional economic parameters for the region

Added value per dollar of the output vector	0.10
Affected population / total population	0.5

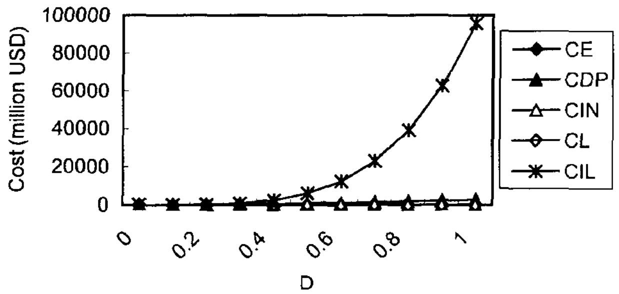

Fig. 3. Cost functions versus global damage index

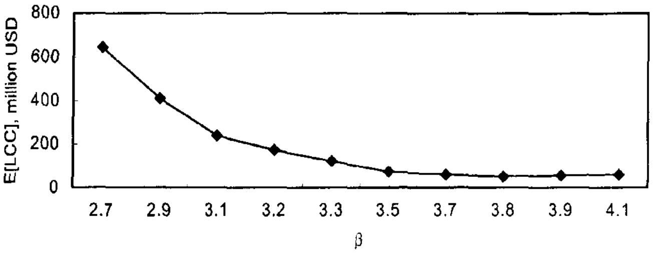

Fig. 4. "Composite" curve: unconditional expected life-cycle function

As observed in Fig. 4, the optimal design corresponds to the global reliability index β=3.82. Observe also that the expected life-cycle cost function is relatively flat for $3.7 < \beta < 4.1$.

4. Conclusions

A life-cycle cost formulation is proposed and applied to the design of marine platforms. The formulation is based on the assessment of uncertainties, structural damage and reliabilities and expected cost associated with consequences of failure. More research should be undertaken in order to calibrate and refine the damage model and cost functions proposed. This kind of formulation will enhance the current procedures for optimal decision making, through risk management, regarding the areas of design, inspection and maintenance of marine platforms.

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