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Cost/Benefit-Based Inspections: The Inspection, Maintenance and Repair Process for Fixed Offshore Structures

P.H. Wirsching, University of Arizona, Tucson, Arizona
D.A. Stewart, PMB Engineering, Inc., Houston, Texas
T.Y. Torng, Southwest Research Institute, San Antonio, Texas
C.J. Kung, University of Arizona, Tucson, Arizona

ABSTRACT

The integrity of a fixed offshore structure can be degraded by the occurrence of storms, boat collisions, and dropped objects, but reliability can be improved by a maintenance program of inspection and repair. A method for estimating the total expected life-cycle costs for a platform exposed to discrete damage events caused by storms, boat collisions, and dropped objects, and subject to inspection, maintenance, and repair (IMR) was developed. Presented is an example in which the results of a structural reliability and economic value analysis are illustrated for a fixed platform.

INTRODUCTION

A fixed offshore structure can experience damage, as it is exposed to such hazardous events as storms, boat collisions, and dropped objects. These events occur at random, and thus the instantaneous integrity of a structure will be a random process. The instantaneous health of a structure can be described by its ultimate strength, which will be a function of time; and structural performance can be quantified by reliability. Although reliability can be improved by a maintenance program of periodic inspection and repair, economic considerations complicate the process. The key question is: "Does the investment in a maintenance program offset the reduction in risk costs?"

The instantaneous strength of the structure will be a random process, and analysis of this process can produce reliability estimates. But the process which involves the discrete and random events of storms, boat collisions, and dropped objects is sufficiently complex that an analytical solution is not feasible. However, Monte Carlo simulation can be effectively employed to estimate not only reliability, but also failure rates, total life-cycle costs, etc.

This paper defines the models used to describe instantaneous structural strength, damage events, and discounted costs. Solution by simulation of structural reliability and total expected life-cycle costs is illustrated for a fixed offshore structure.

LIFE-CYCLE COSTS

Consider costs. First define the following terms: τ = time in years, γ = discount rate, C_f = present cost of failure of the structure, C_i = present cost of a single inspection, C_r = present cost of a single repair, I = total number of inspections during the service life, N_R = total number of repairs during service life, τ_j = time of jth inspection (years), τ_k = time of kth repair (years), and τ_f = time to failure of structure.

For a single structure, the present value of the total life-cycle cost can be written as

$$C = C_0 + C_F + C_I + C_R \ . \tag{1}$$

where C_0 = initial cost, C_F = discounted total failure cost, C_I = discounted total inspection cost, and C_R = discounted total repair cost. Assuming continuous discounting [1],

$$C_{F_j} = \begin{cases} 0 & \text{if structure survives} \\ C_f \exp(-\gamma\tau_f) & \text{if structure fails} \end{cases} \tag{2}$$

$$C_I = \sum_{j=1}^{I} C_i \exp(-\gamma\tau_j) \tag{3}$$

$$C_R = \sum_{k=1}^{N_R} C_r \exp(-\gamma\tau_k) \tag{4}$$

Because the event of failure and τ_f, τ_k, and N_R are random, the total cost C is a random variable. The goal of analysis is to determine the statistical distribution of C. Of specific interest, the expected value of C, E(C), is the expected present value of total life-cycle costs. E(C) and the variance of C, V(C), are estimated by simulation.

A secondary goal is to estimate the probability of failure, p_f, and the expected number of repairs, $E(N_R)$, as a function of not only the strength of the structure and the loading environment, but also of the inspection and repair policy.

INSTANTANEOUS STRENGTH

Let R(t) denote the instantaneous strength of the structure, normalized so that R is the fraction of the ultimate strength as a function of time. Thus, $R(t) \le 1.0$. Failure is defined as $R < 0$. Initially, at $t = 0$, $R_0 = 1.0$.

DAMAGE EVENTS

The discrete damage events are: (1) storm damage, (2) boat collisions, and (3) damage due to dropped objects. Damage associated with each event is defined as D_i, $0 \le D_i \le 1.0$. The instantaneous strength R of the structure after a damage event is

$$R(\text{after}) = R(\text{before}) - D_i \ . \tag{5}$$

It is assumed that each damage event occurs according to the Poisson process [2]. The basic parameter is λ, the rate of occurrence, i.e., occurrences/year. Damage event occurrence rates are defined for all modes: λ_S = rate of occurrence of storms that potentially damage the structure, λ_B = rate of occurrence of boat collisions, λ_{DB} = rate of occurrence of dropped objects during drilling period, and λ_{DA} = rate of occurrence of dropped objects after drilling period. Note that the rate of dropped objects will differ depending on the drilling period.

Also note that the rate of occurrence of all damage events can be written as (after drilling period)

$$\lambda = \lambda_S + \lambda_B + \lambda_A \; . \qquad (6)$$

This is a property of the Poisson process, useful in simulation.

Boat Collisions and Dropped Objects

Given the event of a boat collision or dropped object, the amount of damage, D, is a random variable. It is assumed that D has an exponential distribution, the distribution function of which is [2]

$$F_D(d) = P(D \le d) = \begin{cases} 1 - \exp(-\alpha d) & d \ge 0 \\ 0 & d < 0 \end{cases} \qquad (7)$$

The median (50% point) of D is $0.693/\alpha$. To evaluate the parameter α, one must first define a probability of exceedance, P_e, associated with a given damage, D_e. It follows from the exponential distribution function that

$$\alpha = \frac{[-ln\, P_e]}{D_e} \; . \qquad (8)$$

Boat Collisions. For the example presented herein, it is assumed that the rate of boat collisons is λ_B = 0.001/year. Thus, the return period for a boat collision is approximately 1000 years. It is further assumed that the probability of platform collapse (D = 1) given a collision is 0.25. (This value was based on the engineering judgment of technical advisors from the petroleum industry.) Modeling damage as an exponential random variable, the parameter α_B, is 1.39 and the median damage is 0.50.

Dropped Objects. Because of increased activity during the drilling period, the rate of occurrence of damage due to dropped objects will be higher during the early life of the platform. In the example, the drilling period will be the first 2 years. Occurrence rates are λ_{DD} = 0.4 occurrences/year during drilling and λ_{DA} = 0.2 occurrences/year thereafter. It is assumed that P_e = 0.10, corresponding to D_e = 0.20. Thus, α = 23.0 and the median damage is 0.03.

Storms

The model for storm damage is described as follows:

1. Storms occur according to a Poisson process with parameter λ_S.
2. The "magnitude" of the storm is defined by L; L = 1, J, where J is the number of discrete levels chosen. L is a discrete random variable.
3. The return period T_{SL} of a storm of level L is the mean time between storms of level L or greater.
4. The rate of occurrence of storms of level L or greater is

$$\lambda_{SL} = \frac{1}{T_{RL}} \qquad L = 1, J \qquad (9)$$

But the rate of storms of level L only is

$$\lambda_L = \lambda_{SL} - \lambda_{L+1} \qquad (10)$$

where λ_{L+1} is the rate of occurrence of storms above level L.

5. Given a storm, the conditional probability that the intensity is equal to level L is

$$P[\text{storm} = \text{level } L] = \frac{\lambda_L}{\lambda_S} \; . \qquad (11)$$

The λ_L's satisfy

$$\sum_{L=1}^{J} \lambda_L = \lambda_S \; . \qquad (12)$$

6. Given a storm of level L, there is a corresponding resistance R_L which defines damage. Given the occurrence of storm L at $t = \tau$,

$$D = \begin{bmatrix} 0 & \text{if } R(\tau) > R_L \\ 1.0 & \text{if } R(\tau) \le R_L \end{bmatrix} . \qquad (13)$$

Collapse occurs if the instantaneous strength of the platform $R(\tau)$ is less than R_L, the minimum strength required for survival. In fact, R_L can be interpreted as a measure of the level of intensity of the storm. For analysis, it is necessary to specify λ_S and (λ_L, R_L) for L = 1, J.

For numerical analysis, the seastate distribution and R_L are discretized as illustrated in the following example that was provided by a technical advisor from a petroleum company. Assume that the wave height corresponding to the ultimate strength of the platform is H_F = 89 ft. Assume a wave height (H)-base shear (F) relationship: $F = AH^2$. For a normalized failure base shear of 1.0 at H_F, the coefficient is 1.26E-4. Now, R_L can be identified with the base shear. For example, at H = 70 ft, F = 0.62. Failure occurs if the instantaneous strength is less than 0.62. Thus, R_L = 0.62.

The storm damage model for the example is given in Table 1. Columns 1 and 2 are constructed from seastate statistics at the site. Column 4 is obtained as described above. Columns 5 and 6 are derived from Eq. (9), (10), and (11).

Table 1. Model of storm damage.

Storm Level L	Return Period T_R (yrs)	Wave Height (ft)	R_L	λ_L	Conditional Probability[a]
1	10	50	0.32	0.060	0.600
2	25	59	0.44	0.023	0.233
3	60	65	0.53	0.007	0.067
4	100	70	0.62	0.009	0.090
5	1000	89	1.00	0.001	0.010
λ_S				0.100	1.000

[a]Given the event of occurrence of a storm, P[storm = level L].

INSPECTION AND REPAIR

Regarding strategy, inspection can be specified (1) at regularly scheduled inspection times, (2) after a damage event, or (3) for both cases. The probability of detecting damage is defined by a probability of detection (POD) curve, i.e., POD versus total damage, D, defined as D = 1.0 - R. An illustration of a POD curve is given in Figure 1.

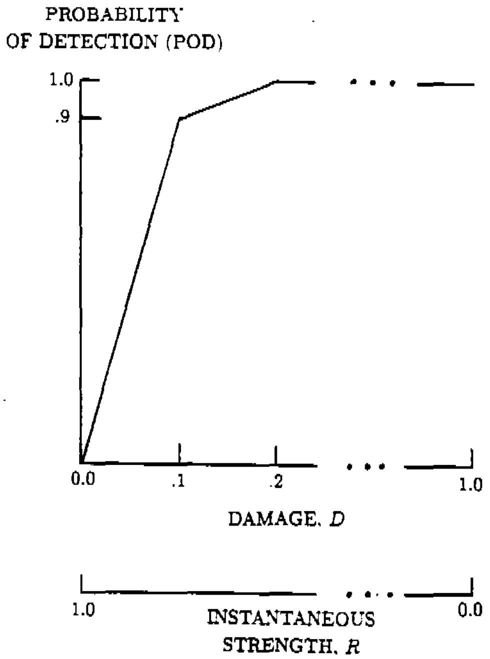

Fig. 1. Probability of detecting damage: an example.

The decision to repair is based on the amount of damage. At scheduled inspections, a repair decision level $R_p(t)$ is defined. Inspection is at t_i. The repair algorithm is

$$\text{REPAIR IF} \ldots R(t) \le R_p(t) \,. \qquad (14)$$

A possible model for R_p is

$$R_p(t) = A - Bt \,. \qquad (15)$$

The negative slope relates to a possible decision to relax the requirements on an aging structure because of its diminished economic value.

Repairs are also made at any time when it is obvious that the damaged structure is unsafe. The repair algorithm is

$$\text{REPAIR IF} \ldots R(t) < C \quad \text{for any } t \qquad (16)$$

where C would be some fraction of the initial quality.

After repair, it is assumed that the structure is restored to its initial quality, i.e., R = 1.0.

SIMULATION PROGRAM

The goal of reliability anlaysis is to estimate the probability of failure, expected number of repairs, and the distribution of total cost, C. Simulation is employed to obtain an approximate solution because of the difficulty in deriving an analytical solution.

A Monte Carlo simulation program was developed. The program procedure for a single structure is:

1. Sample random times to the failure events where the occurrence rate is $\lambda = \lambda_S + \lambda_B + \lambda_{DA}$ for $(0, T_S)$.

   During the drilling period, add the increase in the rate of dropped objects, $\lambda_{DB} - \lambda_{DA}$. Actually, sampling is from the exponential distribution (parameter λ) representing time between damage events.

2. All damage events are sorted with times to failure ranked in ascending order.

3. Given the occurrence of a damage event, the type of damage event is obtained by sampling a uniform variate, Y (0 to 1), and making a decision based on percentages, e.g., for a boat collision, $P_B = (\lambda_B)/(\lambda_S + \lambda_B + \lambda_{DA})$. Then, if $0 \le Y \le P_B$, assume that the damage event was a boat collision. Clearly, the percentages would differ during the drilling period.

4. For the event of a boat collision or dropped object, damage is sampled from the exponential distribution as indicated above. Instantaneous structural strength R(t) is computed.

5. If step 3 identifies the event as a storm, then a sampled uniform variate identifies the level L using conditional probabilities (e.g., Table 1). R_L is identified. If $R_L \le R(t)$, failure occurs. Otherwise, no damage is assumed to occur.

6. Finally, simulation of inspection results and repair would be straightforward, as would the calculation of discounted costs.

Example simulations of damage histories for three structures having the same parameters are provided in Figures 2, 3, and 4.

EXAMPLE: PLATFORM SIMULATION RESULTS

Parameters for the example analysis are summarized in Tables 1 and 2. Simulation results for various inspection and repair strategies are summarized in Table 3. These results illustrate the impact of various inspection strategies on lifetime risk. Estimated costs associated with investment, risk, and maintenance for the example platform are given in Table 4. Total expected life-cycle costs are presented in Table 5 for a discount rate of 12%.

It should be noted that simulation solutions are only approximate. For example, 90% confidence intervals for the probability of failures given in Table 3 are roughly plus or minus 8% for simulation sample sizes of 10,000. For reference, 10,000 simulations on the CONVEX C240 (a super-mini) at The University of Arizona uses only 4 seconds of CPU time.

SUMMARY

The example presented herein demonstrates the capabilities of a simulation solution to the random damage and repair process of a fixed offshore structure. The solution provides, for various inspection and repair strategies, estimates of the expected number of repairs, the platform failure probability, and expected life-cycle costs including continuous discounting.

REFERENCES

1. B. Stahl, "Reliability Engineering and Risk Analysis," Chapter 5, *Design for Fixed Offshore Structures*, Van Nostrand, 1985.

2. A. H.-S. Ang and W. H. Tang, *Probability Concepts in Engineering Planning and Design*, Wiley, 1975.

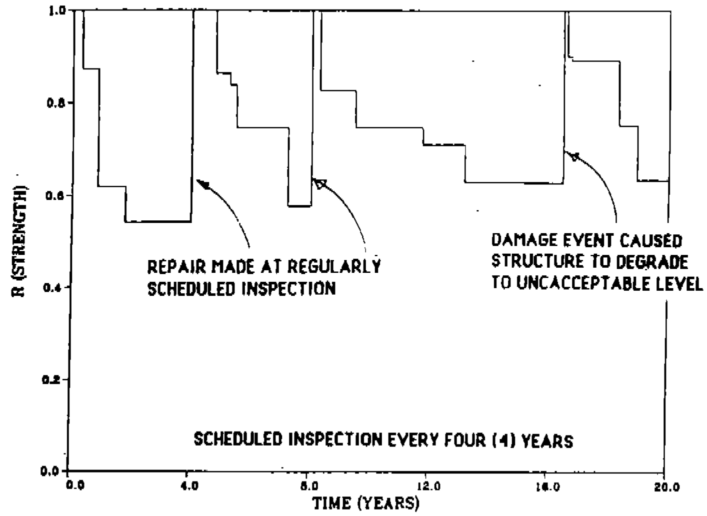

Figure 2. Simulation of damage process: example 1.

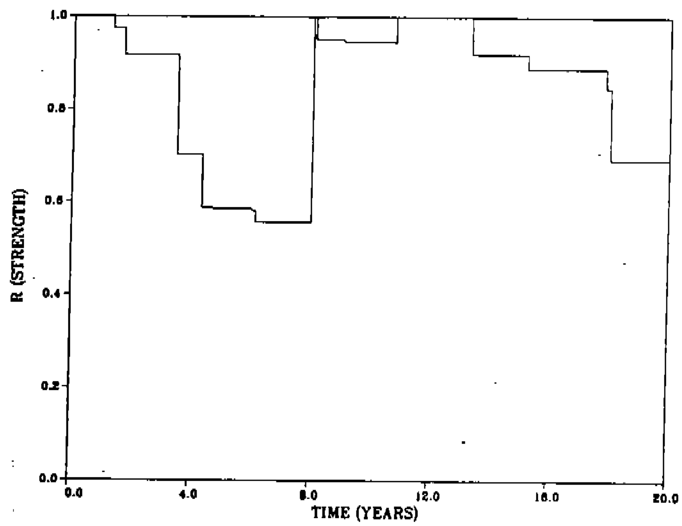

Figure 3. Simulation of damage process: example 2.

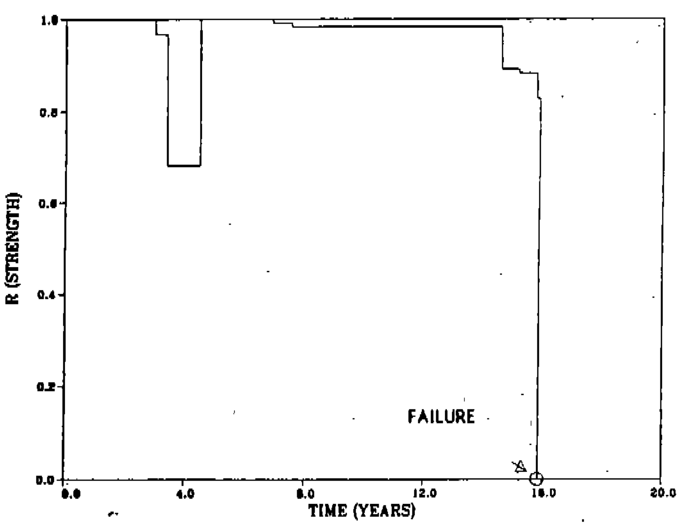

Figure 4. Simulation of damage process: example 3.

Table 2. Parameter values.[a]

Storm	λ_S	0.10
Boat Collisions	α_B	1.39
	λ_B	0.001
Dropped Objects	α_D	23.0
	λ_{DD}	0.40
	λ_{DA}	0.20
Repair Parameters	A	0.70
	B	0.01
	C	0.50
Service Life	T_S	20 years

[a] λ in occurrences/year.

Table 4. Cost data.

	Costs in 10^6 Dollars
Initial cost, C_0	100.00
Failure cost, C_F	90.00
Inspection cost, C_I	0.08
Repair cost, D_R	1.00

Table 3. Summary of simulation results.

Inspection Cases	Expected Number of Repairs During Service Life: Total	At Scheduled Inspections	Because of Excessive Known Damage	Probability of Failure (%)
No inspections	0.028	0.000	0.028	2.80
Three scheduled inspections[a]	0.040	0.018	0.022	2.75
Four scheduled inspections[a]	0.043	0.022	0.021	2.71
Yearly inspection	0.048	0.031	0.017	2.66
Inspection after storm or boat collision, plus three scheduled inspections[b]	0.041	0.029	0.012	2.53
Inspect after storm or boat collision	0.036	0.016	0.020	2.64
Higher requirements on repair decision[c]	0.245	0.244	0.001	2.36

[a] Equal intervals.

[b] Also includes repairs after boat collision or storm.

[c] A = 0.9, B = 0.01, C = 0.70; three scheduled inspections.

Table 5. Summary of cost estimates (present value).

	Costs in 10^6 Dollars				
	Discounted (Rate = 12%) (expected values)				Total Life Cycle (ignoring C_0)
	C_0	C_F	C_I	C_R	E(C)
No inspections	100	0.927	0.000	0.006	0.969
Three scheduled inspections[a]	100	0.871	0.080	0.012	0.963
Four scheduled inspections[a]	100	0.856	0.110	0.012	0.978
Yearly inspection	100	0.828	0.559	0.016	1.403
Inspection after storm or boat collision, plus three scheduled inspections[b]	100	0.800	0.141	0.012	0.953
Inspect after storm or boat collision	100	0.835	0.060	0.010	0.905
Higher requirements on repair decision[c]	100	0.750	0.081	0.096	0.926

[a] Equal intervals.

[b] Also includes repairs after boat collision or storm.

[c] A = 0.9, B = 0.01, C = 0.70; three scheduled inspections.