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Acceptance Criteria for Offshore Platforms

A platform complex in the North Sea is used to illustrate development of reliability acceptance criteria. For platforms in the Norwegian sector of the North Sea, reliability acceptance criteria have their basis in progressive collapse limit state requirements and impairment/FAR (fatal accident rate) limits. A number of parallel supporting approaches to developing reliability acceptance are presented. These supporting approaches include economic risk assessment, in particular, the ALARP principle (as low as reasonably practicable), and historically accepted reliability levels associated with prior practices and experiences in various offshore operating arenas. The reliability acceptance criteria are found to be consistent with recommended or implied acceptance criteria in offshore design and assessment practices in other parts of the world. [S0892-7219(00)01003-7]

Introduction

Offshore platforms are subject to the ravages of time such as corrosion, fatigue, seafloor subsidence, scouring, and accidental damage. In addition, there is often a call to extend platform service lives under revised operating conditions such as additional wells and modified topsides. Structural reliability acceptance criteria are needed to help judge whether or not platform reliability analysis results fall within an acceptable range.

A number of investigators have discussed acceptance criteria including Bea [1], Lind [2], and Paté-Cornell [3]. Moan [4] presents an excellent summary of the methods and issues involved in deriving target reliability levels, but results are presented in a general rather than specific sense.

Cornell [5] observed that if an existing structure does not meet the safety target established for new structures, it should not be the cause for immediate repair or removal, but the signal that the structural source of life risk may be approaching the level where it is one of the more significant contributors of the project and thus the trigger for a detailed assessment of the structure. This observation conveys the guiding principle under which this paper was prepared, i.e., to seek balance between costs and risks in making the choice of a failure probability limit.

In the following, a simple reliability model is introduced along with several sets of reliability input parameters. The model is then related to the applicable progressive collapse limit state (PCLS) requirement to deduce acceptable probabilities of failure. This is followed by application of several parallel supporting approaches which confirm the earlier results and indicate consistency with recommended or implied acceptance criteria in offshore design and assessment practices in other parts of the world.

Platform Reliability Model

The reliability model used to develop the results herein is described, for example, by Efthymiou et al. [6] and Stahl [7]. The annual probability of failure is defined by the expression

$$Pf = P(L > R)$$

where Pf is the annual probability of failure, L is a random variable describing platform load, e.g., annual maximum base shear, and R is a random variable describing platform resistance (capacity). The random variable L has the functional form

$$L = GH^{\delta}$$

where G is a random variable that characterizes the load given wave height, and H is a random variable describing annual maximum wave height. All random variables are taken to be of the lognormal form. VH, VR, and VG are the coefficients of variation, respectively, of the random variables H, R, and G.

The coefficients of variation of key parameters, based on 1) the PCLS requirement by NPD [8], 2) values used by Efthymiou (EFTH) et al. [6], 3) suggested values by the authors (AUTH) and 4) values used by Krieger et al. [9], De [10], and Anderson et al. [11] in studies of API RP 2A LRFD code calibration and reliability assessment of existing platforms, are shown in Table 1. In addition, δ, the exponent in the load-wave height relationship, is taken at a representative value of 2.2 based on analysis of base shear as a function of wave height.

The coefficient of variation of annual maximum wave height, VH, was set at 0.16 for all models shown in Table 1. This value was derived from analysis of wave hindcasts and metocean data. The coefficient of variation of resistance, VR, of 0.15, was taken from PMB Systems Engineering [12] to be a representative value for platforms. It is higher than the 0.05 value in the EFTH model but believed to be more realistic for the present application.

The coefficient of variation VG captures load uncertainties. It can include both aleatory (Type I) and epistemic (Type II) uncertainties. It was taken to be 0.1. This value is considerably less than the coefficient of variation of 0.25 used in API studies. Recent studies by Efthymiou et al. [6] and the Reliability of Marine Structures Program [13] support the choice of significantly lower VG values. The API model that led to higher values such as $VG = 0.25$ was based on the assumption of probabilistic independence between the individual wave heights and the error term that reflects the measured differences between predicted and observed base shears. Recent analyses by Kashef et al. [14] have shown that this simple model overpredicts the variability of the combined effect, e.g., the maximum base shear. The observed difference between the variability of maximum wave height and maximum base shear suggests that the difference is better explained either by

Table 1 Basic reliability parameters

Parameter	PCLS	EFTH	AUTH	API
VH	0.16	0.16	0.16	0.16
VR	0	0.05	0.15	0.15
VG	0	0.08	0.10	0.25

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a significantly more complicated model or by a simple independent error term with a much lower coefficient of variation, i.e., $VG=0.1$.

Progressive Collapse Limit State (PCLS)

This approach to development of platform reliability acceptance criteria is based on meeting a 10,000-yr ultimate load return period (ULRP). Given the VH value shown in Table 1, an RSR[3] of 1.63 will meet the PCLS requirement. The key point is that only the environmental event uncertainty is specified to achieve the 0.0001 probability of occurrence of the accidental event, in this case the 10,000 yr environmental load value. Consequently, the resistance and loading uncertainties are effectively set to zero. Reliability analysis results corresponding to the four sets of uncertainty values shown in Table 1 are summarized in Table 2.

Presuming the PCLS criterion defines acceptability, the other three columns in Table 2 represent implied acceptable annual failure probabilities under the assumption that the other sets of parameters are correct. These numbers, which correspond to the high-consequence case, will be interchangeably referred to as implied acceptable, acceptable or acceptance failure probabilities. In all cases, the ultimate load return period (ULRP) remains at 10,000 yr, thus indicating satisfaction of the PCLS requirement.

Reducing the load factor from 1.3 to 1.15 for unmanned, low-consequence structures, as specified in NPD [8], is equivalent to reducing the reserve strength ratio (RSR) from 1.63 to 1.44. The corresponding reliability results are shown in Table 3.

Utilizing the reliability parameters suggested by the authors shown in Table 1, the implied acceptable probabilities of failure are shown in Table 4 for both the low and high-consequence category. The ULRP of 10,000 yr for the high-consequence category is satisfied. For the low-consequence category, the load factor ratio of 0.8846 (1.15/1.3) has been invoked to yield the implied acceptable probability of failure of 0.0015 shown in Tables 3 and 4, which corresponds to an implied ULRP equal to 2666 yr. Risk-based cost/benefit analyses should provide governing acceptance criteria for the low-consequence category when such analyses are performed.

[3]RSR is defined as the ratio of mean system capacity to nominal design load. Satisfying the PCLS requirement generally calls for use of the nominal capacity in the resistance equations; but if the system includes at least one failure mode whose mean and nominal capacities are identical, the mean system capacity will generally be governed by this failure mode, and hence the choice of the mean system capacity in the definition of RSR is appropriate.

Table 2 Implied acceptable failure prob., p.a. (high consequence; RSR=1.63; ULRP=10,000 yr)

PCLS	EFTH	AUTH	API
0.00010	0.00017	0.00051	0.0022

Table 3 Implied acceptable failure prob., p.a. (low consequence; RSR=1.44; implied ULRP=2666 yr)

PCLS	EFTH	AUTH	API
0.00038	0.00057	0.00147	0.0049

Table 4 Acceptance failure probabilities, p.a.

Consequence Category	Acceptable Probability of Failure
High	0.0005
Low	0.0015

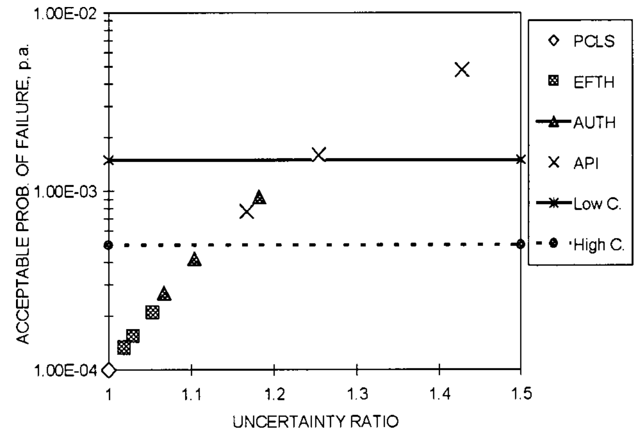

Fig. 1 Acceptance criteria

Failure probabilities similar to those shown in Table 2 were also calculated with region-dependent coefficients of variation of wave height ranging from 0.13 to 0.22, or, alternatively, the exponent δ ranging from about 1.8 to 3.0. Results are plotted in Fig. 1 as a function of an uncertainty ratio, which is defined as the ratio of the coefficient of variation associated with the limit state function to that of the coefficient of variation of loading due to environmental parameters only. Calculations were made for the four sets of uncertainty parameters shown in Table 1, but with three values of wave height coefficient of variation covering the range previously indicated. It is clear that as the uncertainty ratio increases above the value of 1.0, the implied acceptable probability of failure becomes larger than 1.0E-04. For the example platform, the uncertainty ratio, using the authors' suggested reliability parameters, is 1.12. It can be seen in Fig. 1 that the acceptable probability of failure at this uncertainty ratio is 0.0005, as shown in Table 2 for the high-consequence category. The acceptance probabilities of failure for the low and high-consequence categories are summarized in Table 4 and superimposed on Fig. 1.

Utilizing the reliability parameters in Table 1 defined by the authors (AUTH), the RSR values required to meet the probability of failure levels indicated in Table 4 are 1.63 for the high-consequence category and 1.44 for the low-consequence category.

Acceptance Criteria Based on Fatal Accident Rate (FAR)

FAR [15] is defined as the number of fatalities per 1.0E+0.8 h of exposure to an activity. For the example platform installation, quantitative risk acceptance criteria for personnel risk have been stated as follows. The safety level of an installation is considered acceptable if:

1 The frequency of accidents impairing the *Safety Function* is less than 1 per 2000 yr for any area of the platform for all identified accident scenarios.

2 The average FAR-value shall not exceed 10 for the entire installation and 35 for any area on the installation.

3 If the frequency of impairing the safety function exceeds 1 per 2000 yr for an area, the safety level may still be accepted if the FAR-value does not exceed 35.

Quantitative risk assessment studies of the example installation indicate that the FAR value for the entire installation is 3.44. This value includes all accident scenarios except extreme weather.

The FAR formula can be written as follows:

$$\mathrm{FAR}=(\mathrm{PLL}*1.0\mathrm{E}+08)/(\mathrm{POB}*T)$$

where PLL is the potential loss of life (expected number of fatalities per year), POB is the number of persons on board, and T is the number of hours of exposure per year, i.e., 24*365=8760 h per year.

Given the limit of FAR=10, the remaining FAR which can be allocated to structural collapse due to extreme weather is 6.56, i.e., 10.00−3.44. Then

$$(PLL*1.0E+0.8)/(POB*8760)=6.56$$

But, PLL=Pf*POB, where Pf is the annual probability of platform failure. Substituting

$$Pf=6.56*8760/1.0E+0.8=0.00058 \text{ per annum}$$

This is the maximum allowable platform failure probability due to extreme weather (environmental overload).

The acceptable failure probability shown in Table 4 for high-consequence platforms can be increased to 0.001, provided that the FAR limit for the example installation can be increased from 10 to 15 and the ULRP associated with the PCLS requirement can be reduced from 10,000 to 5000 yr. The low-consequence case is not dependent on FAR values. Hence, the acceptable failure probability in Table 4 for low-consequence platforms can be increased to 0.003, provided that the ULRP can be reduced from 10,000 to 5000 yr. These results are consistent with precedents in practice, in which the reliability targets are relaxed for existing facilities; see [16] and [3].

Acceptance Criteria Based on ALARP and ICAF

Other operators have recently used ICAF (implied cost to avert a fatality) to demonstrate ALARP (as low as reasonably practicable) acceptance criteria [17]. Based on work by Efthymiou [18], the following can be derived:

$$COSTRA=DeltaPf*PVF*(FAILCST+POB*ICAF)$$

where

COSTRA = cost of remedial action, e.g., $50 million
Delta*Pf* = change in annual probability of failure
PVF = [1−exp(−i*LIFE)]/i, present value function applied to all costs; see Lind [2]
i = net discount rate, say 7 percent annually
LIFE = remaining service Life, e.g., 30 yr
FAILCST = failure cost in the event failure occurs, e.g., $1 billion (comprised of deferred production, replacement cost, etc.); see Stahl [7]
POB = personnel on board, e.g., 170
ICAF = implied cost to avert a fatality, $10 million; see Fryman [19]

The illustrative numbers were considered appropriate by Amoco engineering and economics personnel involved in or consulted regarding the North Sea platform complex study. Solving for Delta*Pf*

$$DeltaPf=COSTRA/(PVF*(FAILCST+POB*ICAF))$$

Substituting the values given in the foregoing

$$DeltaPf=50/(13.64*(1000+170*10))=0.00136$$

This is the change in Pf that must be achieved to justify the cost of the given remedial action. Adding a nominal value of 0.0001 for Pf of the platform in its remediated state, the implied acceptance value is

$$AcceptPf=0.00136+0.0001=0.00146$$

which is the value that can be accepted before a $50 million remedial action (raising the deck) is justified. This value applies to a high-consequence platform for which the failure cost in the event of failure (asset losses and potential pollution) are estimated to be about $1 billion, based on a number of cases analyzed. It should be noted that the acceptance failure probability of 0.00146 is higher than the 0.0005 value indicated in Table 4. It also falls slightly above the ALARP range of 10^{-3} to 10^{-5} p.a. [17], so Accept*Pf* would have to be limited to 0.001. Furthermore, it is interesting to note that the acceptance value of 0.0005 implies that ICAF is $48 million in this case, which is larger than the $10 million used by Fryman [19]. ICAF values found to be applicable in different countries and parts of the world are presented by Skjong and Ronold [20]. These ICAF values tend to be considerably smaller than the values discussed.

Offshore California Acceptance Criteria for Seismic Hazards

API sponsored development of seismic acceptance criteria offshore California by a group of experts from the California Institute of Technology and Stanford University. Their findings as reported by Iwan et al. [16], based on estimated reliability levels for onland buildings designed to the Uniform Building Code, showed that a target failure probability of 0.001 per annum is appropriate for existing manned facilities.

Due to the higher cost of upgrading existing facilities (as opposed to new construction), precedents in industry indicate that the probability of failure associated with new construction is typically relaxed by a factor of 2 for existing facilities; see, for example, Paté-Cornell [3]. Relaxing the acceptable annual failure probability of 0.0005 (Table 4) by a factor of 2 would bring the acceptable probability of failure to 0.001 per annum, in line with the requirement of 0.001 per annum offshore California for existing platforms. For the example platform, however, use of 0.001 would require that the present FAR limit of 10 be raised to 15. Precedents exist for operating existing offshore facilities with average FAR values in excess of 10; e.g., FAR≈15.

Acceptable Risk Based on Historical Experience (Whitman-Baecher Diagram)

The Whitman-Baecher diagram shown in Fig. 2 (see Whitman [21], Bea [1], and Madsen [22]) indicates how historically accepted failure rates vary with accident severity (asset values and number of lives lost). As the severity increases, the trend is toward lower acceptable failure probabilities. Whitman [21] concludes that the diagram gives some indication of accepted risks and, thus, of allowable risk.

Superimposed on the diagram are two lines indicating 1) accepted probability of failure, and 2) marginally accepted probabil-

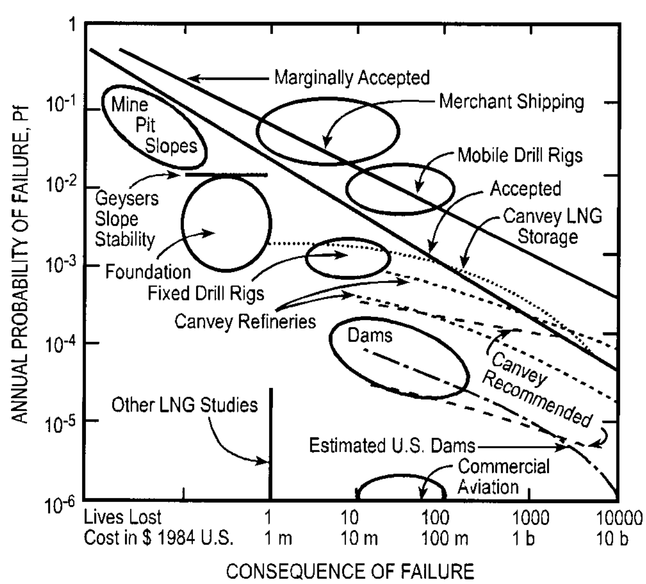

Fig. 2 Whitman-Baecher diagram (after Bea [1])

ity of failure. Bea [1] indicates that the position of these lines is based on evaluations of how the public, industries, and individuals have made tradeoffs of consequences and risks. Madsen [22] suggests that these limits provide a range of acceptability instead of just one specific target.

The manning level at the example installation is about 170. Utilizing this value with the formulas provided by Bea [23], the corresponding acceptance criteria are:

- Accepted failure probability. . . . . .0.0006 p.a.
- Marginally accepted failure prob. . . . . .0.003 p.a.

These values are consistent with the values for high-consequence platforms suggested in Table 4.

Implied Reliability Levels for the Gulf of Mexico

For high-consequence, manned platforms in the Gulf of Mexico which cannot be evacuated, for example, during a winter storm for which there may be little warning, the implied tolerable failure probability is 0.001, as shown by De [10] and in work of an API Committee, i.e., Krieger et al. [9]. The value of 0.001 is also the implied tolerable failure probability for existing, high-consequence platforms subject to wave loading offshore California, although this value has been as high as 0.0025 per annum in some applications.

Economic Optimization

An example study of design criteria development for a North Sea platform was undertaken by Stahl [7]. Taking into account the ICAF values recommended by Fryman [19], the optimum platform failure probability is estimated to be 0.0005 per annum. This value applies to new platforms. Relaxing this value by a factor of 2 indicates an acceptable probability of failure of 0.001 per annum for existing platforms.

Conclusions

A number of parallel arguments have been presented which indicate that the acceptable probability of failure for high-consequence platforms such as the example installation may be taken as about 0.0005 per annum. This value has its roots in the progressive collapse limit state requirement applicable to the Norwegian sector of the North Sea and is consistent with typical quantitative risk acceptance criteria. The value of 0.0005 is equal to one-half of the probability of failure considered tolerable for existing, manned, high-consequence platforms in the Gulf of Mexico and offshore California. Other approaches to determining reliability acceptance criteria support this conclusion.

Precedents exist for increasing the acceptable probability of failure by a factor of two for existing facilities relative to new designs. Increasing the FAR limit from 10 for new designs to 15 for existing facilities is accepted practice. For the example platform complex, if the ultimate load return period of 10,000 yr were lowered by a factor of two to 5000 yr for existing offshore platforms and if the FAR limit were increased to 15, an annual probability of platform failure of 0.001 would be acceptable. This value would be consistent with acceptance criteria recommended for existing, manned, high-consequence facilities offshore California and implied tolerable probabilities of failure for high-consequence platforms in the Gulf of Mexico.

For low-consequence platforms, where personnel safety and damage to the environment are not issues, the acceptance level can be raised to 0.0015 per annum. If the acceptable failure probability for existing facilities were increased by a factor of 2, as discussed in the foregoing, the acceptable value would be 0.003 for low-consequence platforms. Acceptance criteria for low-consequence platforms are best established through cost/benefit analyses, but the suggested values can be used in lieu of such analyses. It should be noted that acceptance criteria for low-consequence platforms are independent of FAR values since life risk is not an issue in the low-consequence case.

The foregoing criteria are associated with use of a specific platform reliability model described herein.

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