

PETRONAS TECHNICAL STANDARDS

PRACTICE FOR THE DYNAMIC ANALYSIS OF FIXED OFFSHORE PLATFORMS FOR EXTREME STORM CONDITIONS

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The previous version of PTS **20.061 (January 1987)** will be removed from PTS binder / e-repository from herein onwards.

Document Approval

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1.0 SUMMARY

This document provides a review of the existing experience and procedures available within the industry in general, and PETRONAS in particular, for the prediction of the extreme storm dynamic response of conventional, bottom supported offshore platforms. The report focuses upon the analysis and design requirements for steel space frame towers or jacket structures.

Advantages and disadvantages of the various methods are discussed with respect to their application in different stages of the design process, and recommendations for the most useful techniques at present are made. Further developments are proposed, with particular reference to the computing facilities available in PETRONAS.

2.0 INTRODUCTION

Over the past ten years or so the fixed platform concept has slowly been pushed into deeper and more hostile environments. Designers of conventional, deepwater fixed platforms have had to cope with the increased flexibility of these structures and to develop analysis and design procedures which account for the resulting dynamic amplification of the applied loading which is associated with the mass inertia forces. In these structures the influence of structural dynamic response is evident both in terms of the amplification of the extreme storm design loadings and the increase of cyclic fatigue damage associated with dynamic response to less severe, but more frequently occurring, everyday sea states. The extent of dynamic response is associated with the relationships between the structure's fundamental modes and the frequency content of the applied loading. Design and analysis procedures for deepwater structures which respond dynamically must account for the random nature of the excitation and the response in an appropriate manner.

At the present time, there are relatively few structures which have been designed using dynamic, structural analysis tools. Even for those structures where dynamic response has been considered, there are often major differences in the methods used; at present there is little in the way of a single common approach. As a result, available experience is very limited and the state of the art is still under continuous development.

This document provides a review of the existing experience and procedures available within the industry in general, and PETRONAS in particular, for the prediction of the extreme storm dynamic response of conventional, bottom supported offshore platforms. The report focuses upon the analysis and design requirements and experiences for steel spaceframe towers or jacket structures; these structures have provided the initial stimulus for work in this area. However, much of the general discussion on analysis philosophy and analytical methods is also applicable to inertia dominated compliant structures which may represent a future generation of deepwater bottom supported platforms.

The first section of the report summarises some fundamental problems which need to be faced when evaluating dynamic response for extreme storm conditions and presents the various options which are currently available. This is followed by a review of some recent analysis experiences which will be used to highlight the benefits and the deficiencies of some of the various options. A recommended procedure is then outlined to provide an approach which is considered to be suitable for analysis and design requirements for the foreseeable (short term) future. The main emphasis here is on a procedure which can most readily fit within the framework of existing design codes of practice developed for shallow water structures (e.g. API or DNV), thus enabling an otherwise conventional design to be carried out. Finally, some recommendations for future development work in this area are outlined. These try to anticipate the outcome of ongoing, longer-term efforts geared to the development of a design approach which is better suited to the probabilistic nature of the random wave environment.

3.0 **APPROACHES TO DYNAMIC ANALYSIS**

3.1 **SOME FUNDEMENTAL PROBLEMS**

In formulating analysis and design procedures capable of predicting the response of a flexible deepwater platform under the influence of extreme storm environmental loading, a number of interrelated problem areas need to be addressed:

- i. The geometry, stiffness, mass and damping characteristics of the structure and its foundation.
- ii. Adequate numerical procedures capable of solving the dynamic response equations with the required accuracy.
- iii. The magnitude and spatial distribution of the wave and current loadings and their relationship to the structure's natural frequencies.
- iv. Procedures to represent and analyse the force mechanisms, and the interaction between the structure and the surrounding fluid.
- v. An analysis and design framework within which to combine the results of dynamic response predictions with those of the other load conditions which occur throughout the platform life.
- vi. Of these problem areas, and accepting the difficulties associated with an adequate representation of the damping mechanisms and the foundation, the first area probably poses the least difficulty, and can be dealt with adequately using presently available modelling and analysis techniques. As a result it will not be considered further here. The second area has been addressed in detail in Reference 1 and the conclusions and recommendations of this study do not need to be repeated. It suffices to say that adequate dynamic analysis methods do exist which are compatible with all levels of the design cycle; from preliminary concept screening to detailed member design and fatigue analysis.
- vii. The third, fourth and fifth areas remain more problematic and these will form the basis for much of the discussion which follows.
- viii. It is now widely recognised that the offshore environment represents a true random process. Despite this, most offshore structures have been, and are still being designed using regular wave (deterministic) static analysis procedures. This approach is well supported by many years of satisfactory service in which relatively few structural failures have occurred for shallow water structures which are relatively stiff and respond quasi-statically to the ocean environment. In the context of the overall design procedure used, the deterministic design wave approach has served the industry rather well.
- ix. Early, first generation dynamic analyses for deepwater offshore structures were also based upon deterministic procedures (e.g. preliminary analyses of Shell Oil's Cognac platform, Reference 2). The dynamic response was evaluated using time domain numerical simulations of the platform response when loaded by an infinite train of periodic design waves of fixed height and period.
- x. Whilst this approach represents a plausible and practical extension to existing design practice, it suffers from a number of fundamental flaws:
 - a. Using this procedure, design sea state energy is associated with a single discrete wave frequency. As a result, the frequency content of the applied loading is also artificially lumped at a number of specific frequencies; in the first instance, at the frequency of the deterministic wave but this component may also be supplemented by one or more higher harmonic contributions. The higher harmonics originate from several sources: from the non-linear velocity squared drag forces associated with the Morison force formulation, both with or without current; from the use of non-linear wave theories (such as Stokes 5th); or from free surface loading effects associated with the changing position and shape of the wave surface. Realistic relationships between the frequency content of the applied loading and the structure's natural frequency (or frequencies) are, therefore, not represented correctly.

- b. The non-linear elements in the procedure referred to above introduce higher harmonic components at discrete multiples of the fundamental wave frequency which may be tuned to the structure's natural frequencies and, therefore, can excite the platform in a resonant mode, causing substantially larger (and artificial) dynamic amplification effects.
- x. These problems are highlighted in Figure 2.1, taken from Reference 2, which shows results of some time domain dynamic analyses of a single degree-of- freedom structure when subjected to regular Stokes 5th design waves and an equivalent random sea with the same probability of occurrence. The single degree-of- freedom model was first loaded with the total force time history of the regular deterministic Stokes 5th wave used for the design of the Cognac platform. Simulations were then made using the random wave force history as developed from the corresponding storm wave spectrum.
- xii. The figure shows the resulting dynamic amplification factor of base shear as a function of the structure natural period. The Stokes 5th wave used has a period of 11.5 seconds and the SDOF system is seen to resonate with the second harmonic of the Stokes wave at 5.75 seconds and with the third harmonic at 3.8 seconds. The fundamental harmonic resonance (at 11.5 seconds) is not shown, since it is outside the structure period range of interest.
- xiii. Conversely the random simulation results (obtained by averaging the results of 20 separate simulations) show a much smoother variation with the structure period. This is much more representative of the actual broader band frequency content of a real sea, even in design storm conditions.
- xiv. As a result of the shortcomings illustrated in the above discussion, dynamic analysis using periodic regular wave loading is considered to be unreliable. Methods which account for the actual relationships between the frequency content of random seas and the fundamental mode natural frequencies of the structure are required.
- xv. Two possible types of solution enable the random nature of the environment to be represented. These are the stochastic approach, usually based upon linearised, frequency domain spectral analysis techniques, or the use of random time domain simulations. Both approaches are discussed briefly in the following sections, where attention is focused upon the basic features of the problem formulation and the treatment of non-linear effects.

3.2 RANDOM TIME DOMAIN SIMULATIONS

For a multi-member, steel space frame offshore platform the principal sources of non-linearity result from the wave loading (usually predicted using the Morison equation) soil characteristics and damping. The non-linearity within the velocity squared drag component of the Morison equation is further complicated by the influence of free surface inundation effects. Further uncertainty surrounds questions about how, and under what circumstances, the relative motion of the structure may influence both the applied loading and the system damping.

Accepting the basic Morison force formulation, it is now considered that solutions based upon random time domain solutions represent the most realistic representation of the response of an offshore platform in a real sea. The procedure involves a number of discrete steps which are shown schematically in Figure 2.2 and summarised here:

- i. Develop time histories of wave surface elevation and water particle kinematics either from measured wave data or using inverse Fourier transformations from specified storm wave spectra. This information is used to develop time histories of the applied hydrodynamic loading.
- ii. Using the applied loading history perform- numerical time domain integration of the equations of motion in order to develop time histories of the structural response include all the non-linear components of both the loading and the dynamic system.
- iii. Statistical analysis of the resulting time histories.

These solutions are able to incorporate system non- linearities, such as those outlined above, explicitly without the need for simplification or linearization of the components. This is achieved at a penalty of computational cost which depends upon the length and number of simulations required and the size and complexity of the platform model. The method carries an additional penalty in terms of the difficulties associated with the interpretation and application of the results. In modelling the random environment it is assumed that the wave surface elevation is a stationary, ergodic, Gaussian process. As a result of system non-linearities, the response is certainly non- Gaussian but it is also possible that it may not be stationary in a statistical sense as well. Therefore, a single realisation of the non-linear structural response only represents one of a theoretically infinite number of such realisations. In order to develop confidence in the short term statistical characteristics of the response it is necessary to carry out a number of such simulations. Information on the extreme values, which represent the tails of the peak response distributions, can only be obtained reliably by performing a very large number of simulations, or by performing extrapolations based upon existing or assumed extreme value distributions, e.g. the Weibull distribution.

3.3 FREQUENCY DOMAIN SOLUTIONS AND SPECTRAL METHODS

For loading and response problems that can be appropriately linearised, conventional spectral analysis procedures provide a convenient and efficient means to incorporate the random wave environment. In this context a linear spectral analysis (Reference 3) is now well established as the final design, state of the art industry standard for examination of the potential for cyclic fatigue damage. The frequency domain spectral approach, as shown schematically in Figure 2.3, can also readily incorporate the influence of structural dynamic response.

Simplified, first order screening tools have been developed within SIPM during the past few years, as a means to carry out a preliminary examination of the fatigue behaviour of steel spaceframe structures (References 4, 5). The procedures retain the fundamental benefits of a dynamic, spectral fatigue analysis, without incurring the high cost associated with a detailed 3-D analysis. These tools have proved to be invaluable in preliminary concept screening studies; some recent applications are documented in References 4 and 6.

For the prediction of extreme responses the linearised spectral method has a number of obvious limitations. These are associated with the difficulty of incorporating the non-linear effects and also, as with the time domain approach, in the extrapolation of short term statistics to predict the peak response levels. As stated previously, due to non-linearities in the system, the resulting response is actually non- Gaussian. The fact that the linearization procedures adopted in the problem formulation make the response as modelled truly Gaussian, does not change this basic characteristic of the response. In this sense the linear model does not reflect the actual situation. In design storm conditions the influence of non-linear drag components and free surface effects are more significant than in the fatigue environment. The choice of the linearization procedure is, therefore, of critical importance.

Procedures based upon a sea state dependent, statistical linearization of the drag loading, as developed by Borgman (Reference 7) and implemented by Malhotra and Penzien (Reference 8), are considered to be the most consistent of those available at the present time. However, these methods do not enable the influence of variations in the free surface wetted area to be taken into account. Free surface effects are known to be of major importance in defining both the local and global force distributions on the structure during extreme event conditions (Reference 9). Furthermore, most of the existing applications of the Borgman approach (e.g. in SIPM's FREERISE program, Reference 10) are restricted to first order expansions of the original Morison drag force formulation. The full linearised wave force expansion contains higher order terms which require convolutions of the wave velocity spectra. This introduces higher order components in the wave force spectrum in the vicinity of three times the principal wave frequency of the storm. These terms are relatively unimportant for structures which respond quasi-statically. However, they may be significant for flexible structures which respond dynamically since these higher harmonic components may coincide with the fundamental mode natural frequencies and could excite the structure in a resonant manner.

A non-linear spectral formulation which incorporates these terms, and which includes the influence of current, is described by Eatock Taylor and Rajagopalan in References 11, 12, 13. These papers contain results of some analyses for a flexible, multi-member, steel spaceframe structure. Linear and non-linear spectral formulations are compared with random time domain simulations in terms of the resulting second order response statistics (e.g. standard deviations of response). These results demonstrate the significant influence of the higher harmonic components and indicate that the nonlinear stochastic approach may represent a suitable alternative to random time domain simulations for the prediction of short term statistics. This approach is discussed further in section 4.2.

Hybrid time/frequency domain analysis has been proposed by Kan and Petroukas (Reference 24) as a method for overcoming some of the limitations of the linearised spectral approach. The method still relies upon the use of a transfer function and spectral analysis techniques to determine the short term statistical responses. However, in this case, the transfer functions are determined from a random wave, time domain analysis, with transformation into the frequency domain being achieved via Fouler transforms. The procedure used is outlined in Figure 2.4. The hybrid approach was originally proposed as a means to include non-linear effects within the scope of a spectral fatigue analysis, but applications for the extreme storm condition also appear feasible.

As with random time domain solutions, difficulties remain, however, in predicting the extreme response levels experienced during the design storm condition. These are the values which are ultimately required in order to perform actual structural sizing operations which are consistent with existing design practice. In order to facilitate predictions of the peak response values using the results from a linearised frequency domain analysis, use has been made of the probabilistic description of Morison type wave force loading when acting on a single vertical pile (References 14 and 15). For a linear Gaussian model the Most Probable Maximum (MPM) value is approximately 3.7 times the Standard Deviation (SD) value, assuming 1000 peaks which correspond approximately to a three-hour storm. However, if the process is non-linear and hence non-Gaussian (i.e. as a result of drag loading) the ratio of the MPM and SD of wave force may be significantly higher (as high as 8.6 in a totally drag dominant, non-Gaussian system). For most practical situations a mixture of linear and non-linear contributions are evident in the loading and the actual MPM/SD ratio will be somewhere within this range. It should further be noted that the mix and, therefore, the degree of non-Gaussianity will vary from one location in the structure to another and from one response variable to the next.

Using this information, some approximate methods have been proposed, to enable solutions to be obtained in the frequency domain. These are engineering approximations to enable the most probable maximum loading and response values to be estimated for situations (and response parameters) other than the single vertical pile, waves only problem (i.e. no current) for which the distributions were originally developed. This is achieved by making assumptions regarding the nature of the peak distributions. It is postulated that the probabilistic descriptions of the response variables in the amplitude domain may be directly related to those of the Morison wave force formulation for a single vertical pile. This implies that the probability distributions derived for the Morison wave force formulation for a single vertical pile, are also applicable to other response parameters (e.g. member forces and stresses) and to more complex structures comprising a large number of individual, spatially distributed and non-vertical loading elements. It must be stressed that these procedures remain engineering postulates which attempt to incorporate the effects of the non-Gaussian nature of the response on the resulting statistical distributions. It is almost certain that such postulates are not valid. However, at present there is no theoretical or experimental evidence available to resolve the matter and by lack of a better model the approach described above is pragmatically adopted. They do provide a practical framework for the interpretation of the frequency domain results, however, there is clearly very little experience with the consequences of applying these methods in order to perform design member sizing.