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PROBABILISTIC STABILITY ANALYSIS FOR GRAVITY BASE STRUCTURES ANALYSE PROBABILISTE DE STABILITE POUR FONDATIONS GRAVITAIRES

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Synopsis: It is desirable to adopt a more consistent approach for prediction of foundation performance of offshore gravity base structures. This is especially important where novel designs or design procedures are involved. Reliability engineering has the potential to provide the framework for rational design decisions, as uncertainties in the design parameters and the associated likelihood of adverse performance can be accounted for directly. This paper presents probabilistic calculation techniques which are tailor-made for reliability assessment of gravity base structure foundations. The proposed calculation procedure includes a simulation method for estimation of uncertainty in cyclic shear strength and stress as a function of random load history. The method is based on well documented deterministic and probabilistic calculation procedures. The reliability analysis provides reliability indices and probability of failure for both single slip surfaces and for a complete reliability assessment where one considers several failure modes and different slip surfaces within each failure mode simultaneously.

INTRODUCTION

During recent years there has been considerable interest in probability theory for modelling of uncertainties in civil engineering design, and various probability-based design methods have been developed. However, foundations for offshore structures are generally designed using a deterministic approach. "Engineering judgement", based on previous experience, is employed to account for the uncertainties in the design parameters. It is increasingly important to adopt a more consistent approach, particularly where novel designs or design procedures are involved. Reliability engineering has the potential to provide the designer with a powerful framework to produce safe and cost-effective foundations. Only reliability analyses can provide full insight in the inherent risk level as a function of the uncertain variables that enter into the calculations.

RELIABILITY METHOD USED.

The calculation procedure proposed for bearing capacity analyses in the present paper is based on first- and second-order reliability methods (FORM and SORM). Details of FORM and SORM are available elsewhere (e.g. Madsen et al., 1986). The procedure require a knowledge of the joint distribution of all uncertain parameters and definition of a limit state function describing the foundation performance. Such a limit state function may be given as:

$$G(x) = \text{Resistance} - \text{Demand}$$

Unsatisfactory performance occurs when $G(x)$ takes a negative value, and the probability of failure, denoted P_f , is equal the probability of $G(x)$ taking on a negative value.

In order to predict this probability of failure one needs to know the joint density function for resistance and demand. The joint density function for this simple case is shown in Figure 1 together with probability density functions (pdf's) for resistance, $f(R)$ and demand, $f(D)$.

The 45 degrees line on the figure represent $G(x)$ equal zero, and thus the region to the left of this line represents failure. The probability of failure is equal the shaded volume of the joint pdf to the left of this line.

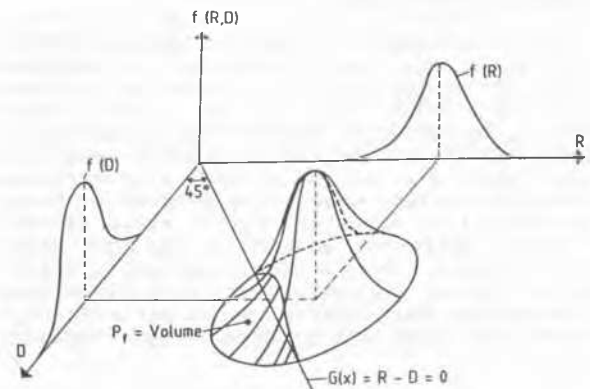


Figure 1. Joint probability function defining probability of failure.

The limit state function, $G(x)$ represents the geotechnical calculations and is generally a nonlinear function depending on many variables such as geometry, loading, soil parameters etc.. The joint density function and the corresponding probability of failure can generally not be solved analytically and approximations are rather obtained from the first and second order reliability methods. These transformations and the calculation of reliability indices and probability of failure are done with general probabilistic subroutines developed by Rackwitz and his coworkers at the Technical University in Munich, TUM 1988.

DESCRIPTION OF COMPUTER PROGRAMS

The formulation of the limit state functions used in this paper was taken from a series of four deterministic computer programs now in use at the Norwegian Geotechnical Institute. These four slip surfaces, also called the CAP-family, are shown on Figure 2. They are all based on limiting equilibrium methods, but cover different types of slip surfaces.

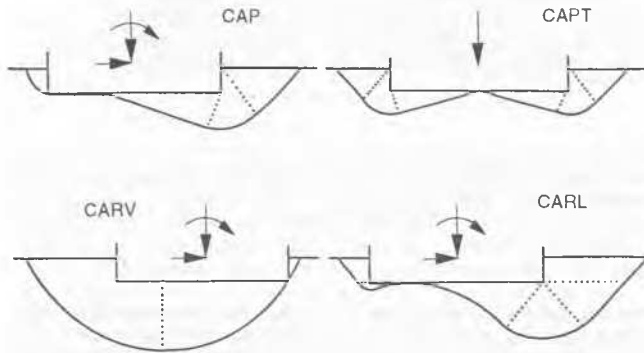


Figure 2 The NGI "CAP-family" - principle sketch

PROBABILISTIC BEARING CAPACITY ANALYSIS - MULTIPLE FAILURE MODES.

In order to assess the complete reliability of a foundation one would require a complete probability evaluation of all sliding surfaces within the definition of the limit state function. In order to assess this probability, program CAPSYS was developed. CAPSYS considers several failure modes and several slip surfaces within each failure mode. This program is based on a reliability computer routine named SYSREL, TUM 1988. Different potential failure modes shown in Figure 2 form a simple series "system", where failure of any system component means that the foundation performance is not satisfactory. From analysis with this program it was concluded that:

One can omit slip surfaces with low probability of failure in the system reliability analyses. As a rule of thumb it is suggested to omit surfaces with probability of failure more than one order of magnitude lower than the probability of failure for the most critical slip surface.

- Slip surfaces close to each other for each failure mode mainly involve the same soil parameters and the same loading components. They are thus almost perfectly correlated, which means that one surface can be taken as representative for all neighbouring surfaces.

PROBABILISTIC BEARING CAPACITY ANALYSIS USING CYCLIC SHEAR STRENGTH.

Methodology

The cyclic shear strength bearing capacity analysis procedure developed at NGI, Andersen and Lauritszen (1988), was implemented in a probabilistic formulation. This approach represents an advanced method for calculation of the bearing capacity of offshore structures subjected to combined static and cyclic loading. The calculation procedure ensures strain compatibility in the soil along the potential failure surface and accounts for the redistribution of average stresses caused by the cyclic loading. The approach includes the following three steps;

- 1) Determination of cyclic shear strength.
- 2) Iterative probabilistic equilibrium calculations
- 3) System reliability analysis to evaluate the results from the iterative equilibrium calculations.

The methodology is described in detail by Guttormsen, 1991.

Uncertainty in Cyclic Shear Strength.

The key geotechnical item in the probabilistic formulation is the determination of the uncertainty in the cyclic shear strength of the foundation soil. The cyclic shear strength of a soil element is defined as the sum of the average and cyclic shear stresses that cause excessive shear strains (cyclic and/or average) after a given number of load cycles. The uncertainty in the cyclic shear strength is related to the uncertainty in the cyclic shear stress component of the cyclic shear strength for a given average shear stress and a given load history. The cyclic shear stress at failure is determined with a shear strain accumulation procedure, Andersen et al.1978. The function relating shear strain and shear stress is given implicitly in the form of a contour diagram. The uncertainty in cyclic shear stress at failure depends on the uncertainty in cyclic loading and the uncertainty in the cyclic shear strain contours. It is considered very cumbersome, if at all possible, to model probabilistically the function relating shear stress and shear strain with a closed-form mathematical solution. A Monte-Carlo simulation approach with Latin Hypercube Sampling (LHS) of the random variables was therefore used to get an estimate of the cyclic shear stress and strength as a function of random loading history. The procedure is described in detail by Guttormsen, 1991. Typical calculation results are given in the case study below.

APPLICATION EXAMPLE - NORTH SEA SITE

Platform Geometry

The gravity base structure used in the example calculation is a version of the CONDEEP SP4 platform, proposed by Norwegian Contractors for a deepwater site in the North Sea. Figure 3 shows the general layout of the platform and the foundation geometry. The base area was transformed to a rectangle with the same area and same moment of inertia as the actual platform. Key deterministic figures of interest for geotechnical stability analyses are listed below.

Key figures:

Platform base area:	A	= 15 618 m ²
Length (Y- direction):	L	= 126.6 m
Width (X - direction):	B	= 123.3 m
Skirt penetration depth:	Z _s	= 36.0 m
Submerged weight:	P _v	= 2215 MN

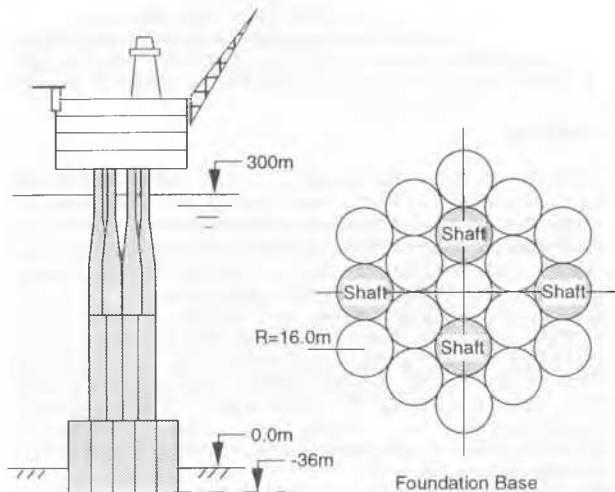


Figure 3 General view of CONDEEP SP platform

Environmental Loads and Other Calculation Parameters.

The probabilistic environmental loads at mudline were derived based on characteristic loads for an extreme event with 100 year return period. The expected values are given below.

Overtuning Moment:	M	= 116000 MNm
Horizontal Force:	P _H	= 610 MN
Excess pressure at heel, DELPH		= +0.006 MPa
Excess pressure at toe, DELPT		= -0.006 MPa

Horizontal load, P_H, and overturning moment, M, were assumed to have a correlation coefficient of 0.9. Overturning moment and horizontal load were assumed to be lognormally distributed,

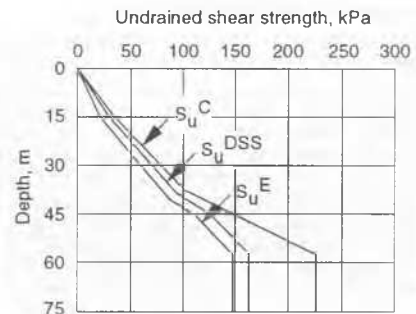
whereas the DELPH and DELPT values were assumed to be normally distributed. The random load history used for the assessment of cyclic shear stress and strength of the foundation soil was calculated based on a long term cumulative wave distribution. The extreme mudline response was calculated based on wave distributions for the 18 hr build-up/tail-off phase and the 6 hr extreme period, as required by the Norwegian Petroleum Directorate (1987). The uncertainty in the load amplitudes was assumed to be normally distributed with coefficient of variation equal to 15 per cent. A positive correlation among the 5 largest waves in the extreme event was also assumed.

Other major random calculation parameters used are listed below with probability density functions and expected values and standard deviations in parenthesis. LN denotes a lognormal distribution and N denotes a normal distribution:

Base/soil friction factor	: LN (0.5, 0.15)
Soil/soil friction factor	: LN (0.4, 0.15)
Model error load	: N (1.0, 0.05)
Model error resistance	: N (1.0, 0.05)

Soil data

The undrained shear strength profile is shown on Figure 4. Uncertainty in cyclic shear stress and strain contours were estimated with regression analysis to be 6 per cent. The contours were assumed to be perfectly correlated and to have a normal pdf. To estimate the cyclic soil shear stress at failure for direct simple shear and triaxial loading conditions, Monte Carlo simulations were carried out. The uncertainty in the estimated cyclic shear strength ranged from 9 to 17 % depending on the soil layer and loading condition, i.e. compression, direct simple shear, or extension loading.



S _u ^C	=	undrained shear strength, compression
S _u ^{DSS}	=	undrained shear strength, direct simple shear
S _u ^E	=	undrained shear strength, extension

Figure 4 . Undrained shear strength profile.

Calculation Results

For a Gravity Base Structure (GBS) with deep skirts on a soft clay site and with large environmental loads the failure modes CARV and CARL are most critical, Figure 2. Development of excessive cyclic shear strain is the critical failure state. Both CARL and CARV failure modes have a deterministic material coefficient around 1.6, $\gamma_{mCARL} = 1.63$ and the $\gamma_{mCARV} = 1.59$. However the CARV failure mode results in a quite different probability of failure, P_f . The reliability index, β for CARV was calculated to be 3.23 which corresponds to a $P_f = 0.6E-03$ and the CARV has a reliability index equal to 2.90 and a P_f equal to $0.2E-02$. This means that the CARV failure mode has a probability of failure, which is an order of magnitude higher than for the CARL failure mode. By studying the sensitivity factors from the analyses (not presented in the paper) one can see that the CARV failure mode was much more sensitive to the uncertainty in the loading than the CARL failure mode, resulting in a quite different probability of failure.

Three sets of system reliability analyses considering 60 random variables and six surfaces from each failure mode were also carried out to study the effect of considering multiple failure modes simultaneously. The results of the system reliability analyses are presented in Table 1.

Table 1 Summary of probabilistic calculation results.

CASE	Most Critical Component		System	
	β	P_f	β	P_f
SYS 1	3.23	0.626E-03	3.20	0.678E-03
SYS 2	2.90	0.186E-02	2.88	0.199E-02
SYS 3	2.90	0.186E-02	2.79	0.260E-02

From above table one can see that the probability of failure for these cases are almost unchanged compared with the single most probable failure surface in CARV. However, this may not be a general result, especially for sites with layered soil profiles with different uncertainties in each layer.

CONCLUSIONS

It is concluded that the reliability-based design gives increased insight in the design calculations compared with the deterministic approach. The most pronounced advantage is the ability to achieve a consistent risk level for different structure concepts, different loading situations, different soil conditions and different degrees of knowledge of the soil parameters.

However, it should be realized that the probabilistic method relies completely on the level of confidence in the input parameters. In many cases, it may be difficult to assess these parameters due to lack of data or simply lack of evaluated experience. Careful judgement should be combined with an analysis of the existing data base using both a frequentist's statistics and Bayesian statistics to evaluate the parameters entering into the reliability analysis.

ACKNOWLEDGEMENTS

The work presented in this paper was carried out while the author was an employee at the Norwegian Geotechnical Institute, and worked as a part of a project team on reliability assessment of offshore foundations. The work described in this paper was supported by Statoil, Elf Petroleum Norge A/S, A/S Norske Shell, Shell Research BV, Mobil Research and Development Corporation, U.K. Health and Safety Executive, the Norwegian Petroleum Directorate, and NGI. The author wishes to express his gratitude to all those at NGI that contributed to this work, in particular Dr. Suzanne Lacasse, Professor Kaare Høeg and Dr. Farrokh Nadim for their constructive criticism and valuable help.

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