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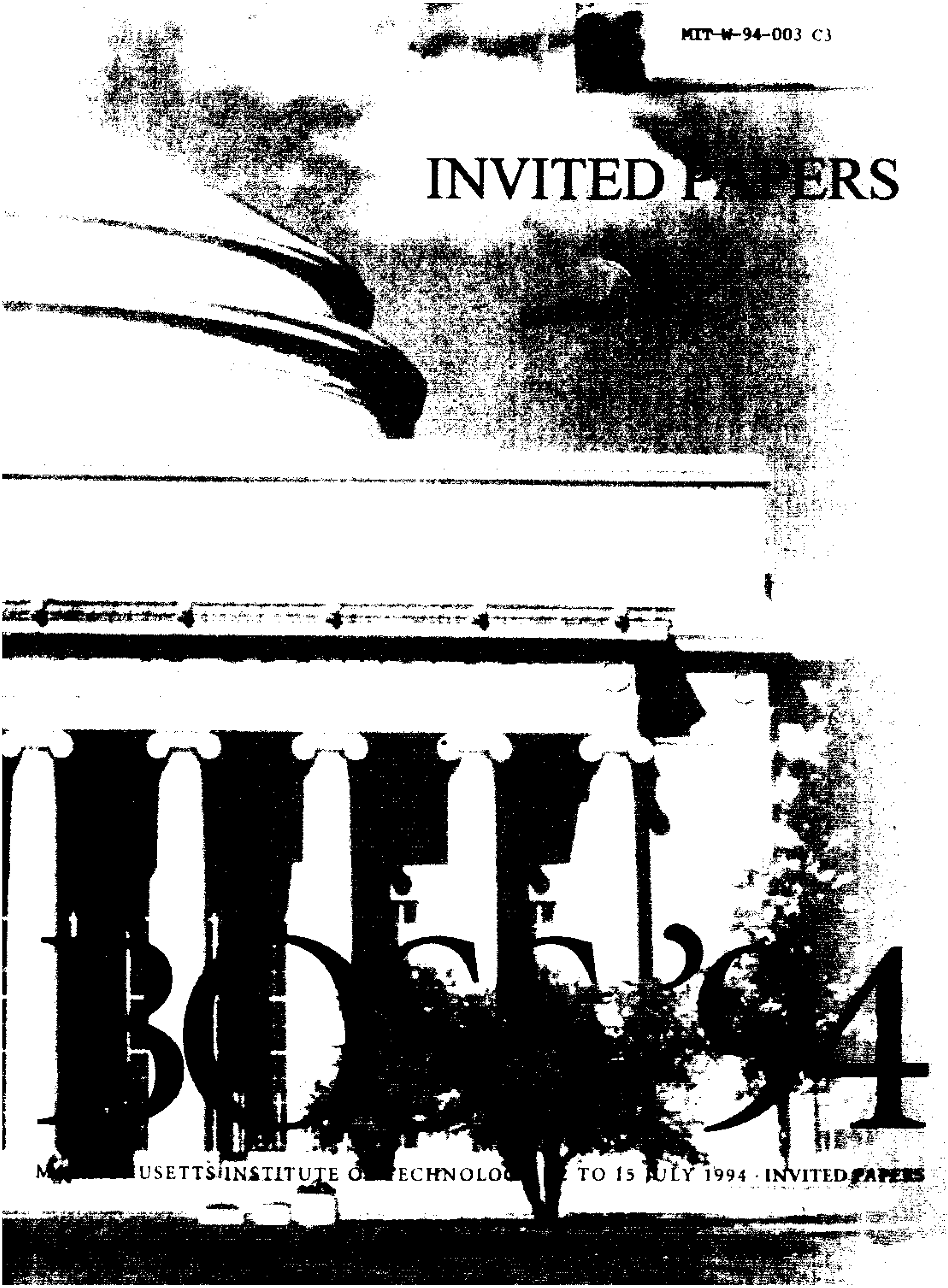

BOSS'94

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BOSS '94

Proceedings of the seventh International Conference on the Behaviour of Offshore Structures

Cambridge, Massachusetts, USA, July 1994

Edited by

C. Chryssostomidis, M. S. Triantafyllou, A. J. Whittle and M. S. Hoo Fatt

INVITED PAPERS

Massachusetts Institute of Technology Sea Grant College Program
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Preface

In the seventeen years since the first Behaviour of Offshore Structures conference took place in Trondheim, offshore engineering has been in the forefront of many diverse technological developments. While these advances have been specifically directed at the discovery and production of offshore oil and gas, the resulting technologies have also benefited other maritime and land based industries.

The BOSS conferences have been concerned with the design, construction and installation of structures used for the development of offshore oil and gas fields. BOSS '94 continues this tradition with technical sessions presenting more than 100 state-of-the-art technical papers in the following areas:

- GEOTECHNICS
- HYDRODYNAMICS & CABLE DYNAMICS
- STRUCTURES

Invited papers are also presented in plenary sessions where industry leaders address the key topics facing the future of the offshore industry. The major theme for BOSS '94 is *Deep Water Production and Research Strategies for the Nineties.*

BOSS '94 was organized by the Massachusetts Institute of Technology Sea Grant College Program. The effort and support of many individuals contributed to the success of the conference. I gratefully acknowledge financial support from ABS Americas, Exxon Production Research Company, the Massachusetts Institute of Technology's Department of Civil Engineering, Department of Ocean Engineering and Sea Grant College Program, McDermott International Inc. and the National Science Foundation. I thank Marge Chryssostomidis, Barbara Dullea Connolly and Helen-Marie Quinn for organizational support in compiling the proceedings and for logistical planning and coordination of the conference.

The Organizing Committee had a difficult task in selecting the papers to be presented. Nearly 200 abstracts of outstanding quality were received, but lack of time and space made it impossible to include them all. I would like to thank International Committee members Professor T. Moan, Norwegian Institute of Technology, Professor M. H. Patel, University of London and Professor J.H. Vugts, Delft University of Technology for their efforts in the selection process for BOSS '94 papers. National Committee Members Dr. M.S. Hoo Fatt, Professor M. S. Triantafyllou and Professor A. J. Whittle from the Massachusetts Institute of Technology deserve special recognition for their contributions during the paper selection process, in editing the proceedings and in organizing the conference sessions. Most importantly, thanks and congratulations to all of the conference presenters and session chairpersons for their outstanding contributions to the future of the offshore industry.

Chryssostomos Chryssostomidis
Chairman, Organizing Committee

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An Initiative to Facilitate Implementation of New Technology

Mark N. Silbert
Manager, Offshore Division
Exxon Production Research Co.

Thank you. I am indeed honored and pleased to have this opportunity to address what has become one of the most prestigious regular gatherings of technologists in our industry.

As I was planning my trip to MIT for this conference, I found myself reminiscing about my own college life. I especially remembered job interviewing, looking for one that would pay enough so I could repay my father the money I borrowed to get through school. Among the many opportunities, and they were prolific in those days of unlimited promise, the large oil companies offered a prospect of steady and continuous growth. I signed up with Exxon and, indeed, through the '70's and early '80's, the technical challenges, big new projects, and budgets to support them seemed almost boundless. As the price of oil passed $35/barrel, some economists were forecasting a continuing climb in oil prices. As most of us remember too well, however, by 1983 the climb in oil prices had ended. The dramatic oil price decline in the ensuing years caused a major contraction in our industry that may still not be complete.

It took us a little while to get over the shock of oil prices as low as $9/barrel. Eventually, we learned that we could still produce oil and gas offshore. But to achieve acceptable economic return in the face of soft product prices, we had to be more effective in our business. That effectiveness must also extend to how we develop and implement new technology.

In the following remarks, I will recount how our industry managed to survive the transition period, how our industry looks today, touch on a few of the key technology challenges, and then propose an initiative to facilitate implementation of the new technology that is so vital to our business success in the current, challenging business environment.

Let's go back to the '70's. A typical oil price forecast from that time showed the price of a barrel of oil reaching $100 by sometime in the middle '80's. Such optimism brought heavy investment throughout the offshore oil industry, including many giant oil production projects. The biggest were the massive platforms in the Norwegian and UK sectors of the North Sea. Other very large projects were undertaken in Australia and the US Gulf of

Mexico. Most of these project involved new technologies on a scalenever before attempted - huge concrete structures, very heavy offshore lifts, water depths up to 1300 feet.

In addition to the rising price of oil during this period, high interest rates influenced how projects were managed. The high cost of money created an incentive to minimize the time between financial commitment to a new project, and production startup. As a result of climbing oil prices, and high interest rates, many new projects were undertaken without careful and complete planning and with less than full understanding of the technology hurdles involved. There was a sense that even if project costs rose, higher oil prices would assure profitability. Not surprisingly, most big North Sea projects experienced substantial cost overruns and schedule delays.

Despite the problems, the general attitude of our industry was that technology was the only limitation to proceeding with major new offshore developments in severe environments like the North Sea and the Arctic, and in deep water. This meant that the major oil companies having the best technology would have the advantage in acquiring and exploiting the prime investment opportunities. Many of the majors expanded their research programs in these and related fields. Exxon, and its competitors, supported substantial research efforts on TLPs, compliant towers, and subsea systems for deep water, on caissons and artificial islands for the Arctic, and on numerous other offshore concepts for frontier areas. Major oil companies were suddenly building up staffs in previously unrepresented areas such as naval architecture and marine engineering, oceanography, hydrodynamics, and ice mechanics.

By the mid-'80's, oil prices were plummeting. The party was over. It was becoming increasingly clear that in an industry used to big price cycles, this downturn had the potential to be long and deep. All spending came under close scrutiny and most discretionary expenditures were taking big hits. Exploratory drilling and lease acquisitions were slashed. The few major projects undertaken before the oil price collapse kept parts of the offshore industry going.

Oil company R&D did not escape the cost cutting. Some companies reacted immediately. Others waited, perhaps hoping for an upturn. Eventually, everyone decided to pare research spending.

Simultaneously, however, the nature of the available development prospects was changing. The inventory of economically robust plays in mature areas was running out. The new opportunities fell into two categories, both considerably more challenging. There were either large reserves in immature areas with harsh design conditions and infrastructure challenges, like the huge fields in the former Soviet Union, in the ice-infested waters off east coast Canada, and the very deep waters of the Gulf of Mexico. Or, there were economically marginal fields in mature areas, like the numerous, small reservoirs in the North Sea. In either case, new and innovative technology was needed to turn them into viable business prospects.

So far. I think we have seen both successes and failures in meeting these challenges. Although at a substantially slower pace than years ago, there has been a fair number of new projects undertaken. For example, Saga and Esso's Snorre TLP came on stream last year in the Norwegian North Sea and Conoco's Heidrun, concrete TLP is nearing completion of construction. In the deep water of the Gulf of Mexico, Shell's Auger TLP was installed last Fall, and their MARS TLP is ready for construction. The Hibernia platform being designed for the Canadian east coast will face what may be the most difficult combination of water depth and ice conditions ever encountered by a production platform.

Meanwhile, numerous small fields are being developed, or considered, in the North Sea, Gulf of Mexico, and offshore South America, Australia, south-east Asia, and Africa. Just to give an idea of how many there are, - the January issue of "Offshore Engineer" lists 47 UK North Sea "upcoming field developments" that have reserves of less than 100 million barrels. Many are in the range of 5 to 10 million barrels.

Finally, an additional challenge has been to enhance our industry's performance with regard to safety and environmental protection. Accidents during past years have made it clear that we needed to upgrade our efforts in this area. Our response, and that of the governments and regulators where we do business, have been broad and pervasive, impacting almost every aspect of our offshore activity.

Upon reflection, the story of our industry over the last ten or twelve years is rather extraordinary. Oil prices have dropped by more than half in actual dollars. R&D and engineering staffs have been dramatically reduced. Our traditional areas have matured. What remains of them are predominantly smaller or more challenging opportunities. While new areas with large potential have opened up, they are fraught with daunting political and infrastructure challenges. And, we are devoting more resources to safety and environmental protection. Despite all of that, we are seeing a resurgence of activity. *How did it happen?*

I would propose that we have done it by learning to better manage our projects, and in particular, by better managing the technology we use. We now plan our projects better, spending more effort evaluating alternative development schemes, looking for the most cost-effective application of technology. And we do all of this well before committing to a project. We test the project plan by assuming the sorts of negative perturbations that we know can impact us. As a result, it is more common these days to hear that major projects have come in on-time and on-budget.

Another lesson we learned is that each of us can no longer afford, nor is there significant incentive to develop needed technology on our own. Instead, by cooperating, or leveraging our resources, we have been able to continue advancing our abilities. Indeed, in many instances cooperative efforts produce better technology than we could get individually, and also result in broader industry acceptance. In my own company, Exxon Production Research, we joined only seven joint industry projects in the '60's. That number grew to 349 in the '80's.

Finally, the managers of our companies are rightly insisting that we focus on the development of technologies that enhance our ability to make money with a flat oil price forecast. This means that most of the incentive for our limited R&D resources is cost reduction. One of the ways we have been getting more out of our R&D resources is by finding useful technology in related industries. A few examples are computing and information management, finite-element analysis, synthetic materials, welding and inspection.

So far, I have been speaking in rather general terms about the incentives for technology advances. I suspect many of you are wondering how these broad objectives relate to your particular field. Let me address a number of specific technology issues and problems that I believe have, or could impact our ability to cost-effectively develop offshore prospects. By the way, I notice that a number of these issues are addressed among the fine papers to be delivered in this conference.

In hydrodynamics, our industry is just coming to grips with the importance of several, highly nonlinear phenomena. One of them has received considerable attention recently. Even those of you not working in hydrodynamics may have heard about "ringing" response of TLPs and deepwater, large-diameter towers. This transient response apparently occurs in steep waves when a third-order hydrodynamic wave frequency coincides with a structural natural frequency. Ringing may lead to a substantial increase in peak design loads. We see this phenomenon in wave tanks, and in full scale, but we do not yet have the analytical tools to reliably predict it.

There are two other hydrodynamic phenomena for which we allow design margins to cover the inaccuracy of our predictions. We don't do very well in predicting hydrodynamic damping, especially as it affects steady-state springing response, and slow drift motions of compliant structures. We also must try for better understanding of the forces that affect the dynamic stability of semisubmersibles and ships.

In geotechnics, I believe that we must identify and reduce unnecessary conservatism in our foundation designs, and be more aggressive in pursuing novel approaches that have potential for cost reduction. This requires that we achieve better understanding of fundamental soil/structure interaction mechanisms.

Let me give you a few examples where there appears to be room for reduction in design conservatism.

- The continuing reliance on driven piles for situations where more cost-effective concepts are available.

- Conflicting and costly assumptions used in designing piles and in sizing hammers for driving them, especially in dense sand.

- Excessive conservatism in design of foundations subjected to uplift loading.

There are several other areas of geotechnics where advances could have significant payoff. For example, we should be able to do better at

- extending the meager, pile load test data base to larger piles and a wider range of soil conditions.

- identifying and avoiding shallow hazards with improved geophysical methods, as well as remote property determination.

- more reliable and accurate characterization of topography/baththymetry for siting templates, platforms, and pipelines.

- developing novel foundation concepts for all water depths. A good, recent example are the individual suction caissons being used on the Europipe riser platform and the Sleipner West treating platform.

- refining remote installation methods that we need for deep water.

Finally, and perhaps must important in the long run, we need

- better basic understanding of foundation behavior, both during installation and in service. This will allow our designs to be more cost effective, as well as avoid major problems, such as industry has experienced in underdesign of foundations for calcareous sand regions.

Now let me turn to structural analysis. Many of the biggest challenges in structures are associated with understanding and managing risk. There are also opportunities for substantial economies in structural maintenance costs.

Fracture mechanics continues to offer great potential in predicting and avoiding structural failure. We continue, however, to be slow in implementing the data into a readily usable design basis.

Although we have employed the ultimate strength criterion in assessing designs and existing structures for some time, we have not adequately facilitated automated ultimate strength calculations for use by designers.

In our drive to find economical ways to develop small offshore fields, we are reusing, or extending the lives of steel-piled-jacket platforms, drilling jackups and semisubmersibles, and tankers, for low-cost production systems. Yet we are really only beginning to develop practice for assessing fitness-for-purpose for structures that, for one reason or another, do not meet normal design standards.

A related matter is how we assure the ongoing adequacy of our installed structures during their lifetime service. We need guidelines for the preparation of lifetime inspection and repair plans. And by the way, more comprehensive offshore inspection would be possible if the available in-situ inspection techniques were more cost-effective.

I have saved for the end of my list what I consider to be a major challenge - making the best hydrodynamic, geotechnical, and structural analysis tools readily usable by the designer. Despite vast increases in computing power, most designers are faced with a hodgepodge of analysis packages, problems of model and data transfer, and of software and hardware compatibility.

So much for my brief list of technology challenges. It's surely not comprehensive. I'll bet each of you could add an issue or two as well.

But let me now summarize the situation in our industry, as I see it. There is no shortage of offshore oil and gas development opportunities in the world. But we will be able to make them economically viable only with the best possible technology. However, severely constrained resources means that we have to find more effective ways of developing that technology and of facilitating its use for design.

⟹ ***Display Implementation Constraints figure.***

This figure portrays how I see the issue. I believe that we in our industry clearly understand the incentive for having better ways of doing our business. Furthermore, we have many sources of new technology, including many of you who work on conceiving and developing it. However, to really impact our business, that technology must get into practice, that is, it must be implemented in user-friendly software for design and analysis, in reliable and proven hardware, materials, and in fabrication and construction practices. And finally, we must have well-founded industry codes and practices that establish the necessary reliability and confidence in the new technology.

My view is that the major choke point is in getting the new technology implemented and into use. Implementation includes refinement and optimization, validation, commercialization, training and education of users, and, of course, maintenance and upgrade. All of these are expensive activities that often do not get supported after new technology has been developed. The reasons are ones I have already touched on - limited staff and resources, as well as the recognition that very few proprietary offshore technologies produce a substantial competitive advantage for operating companies.

By fragmentation I am referring to the situation where each company has technology strengths based on the makeup of its staff, and its own particular areas of technology emphasis. But no one company covers all the needed technology areas. Limited cooperation has inhibited the integration of these capabilities.

There is an analog to this in the university research arena. The reward system there focuses on publication of research findings. There is often little or no recognition for implementation and use of the fruits of the research. The result is that much of the good work never reaches the hands of the designer.

I believe that we can find better ways to cooperatively promote technology development and implementation. With that purpose, I am proposing that we establish an informal organization of offshore technology users that I will call the **Offshore Engineering Association**, the **OEA**. It would be patterned after the Drilling Engineering Association that has been operating successfully for a number of years.

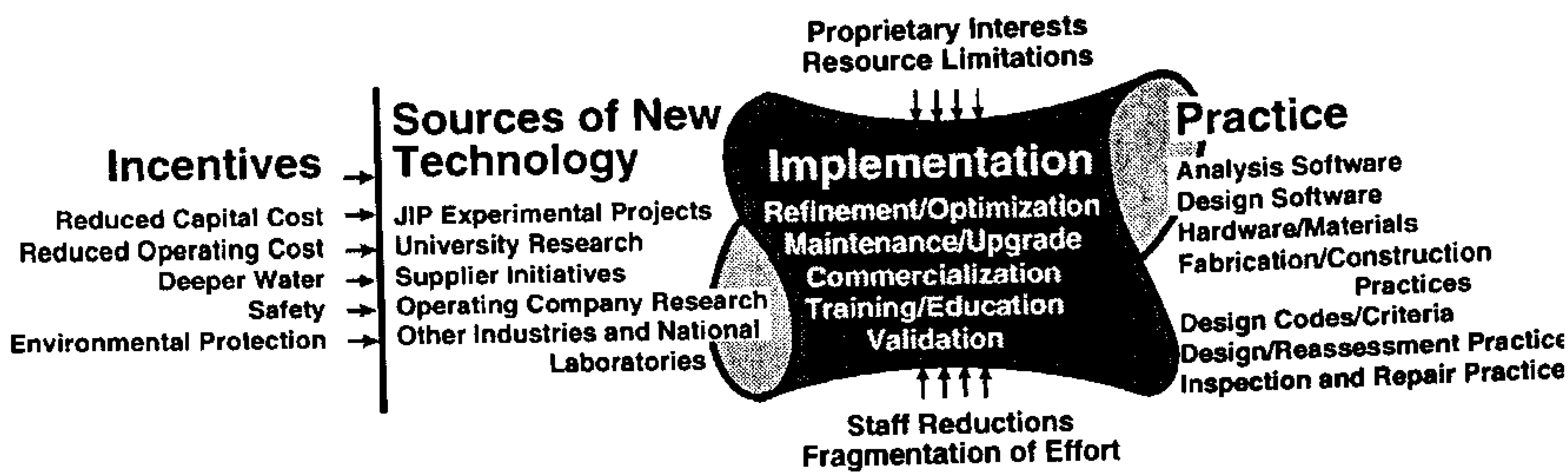
The principal objective of the OEA would be to provide a forum for offshore technology users to hear summary presentations of proposed joint-industry projects, JIPs, with the emphasis on the implementation of new technology. OEA members would meet periodically, perhaps monthly or bimonthly, and would hear summary presentations by contractors, suppliers, university researchers, etc., for JIPs. Any member of the OEA could sponsor, that is, invite a presenter and the coordinating member of OEA would schedule the presentations. After the presentations, OEA members would express their interest to the individual presenters and further details could be provided directly to those members. OEA would not itself directly organize or sponsor any of these JIPs.

Another role of the OEA could be to maintain a list of technology implementation needs. This information would be provided to researchers, contractors, and consultants as a guide in focusing their proposals to industry.

To see if such an initiative is of interest to our industry, in the near future, Exxon Production Research will contact technology users about the likelihood of their participation. If there is sufficient interest, we will offer to facilitate formation and formalization of the OEA, and its operation for the first year or two. If anyone here is interested, I would be happy to hear from you, or you could contact someone you know in the Offshore Division at EPR. I hope to hear from many technology users about this idea.

Thank you for your attention and best of luck with the remainder of the BOSS conference. I feel certain from the list of presentations that this year's conference will be as successful and valuable as the previous ones have been.

Constraints on Implementation of New Technology



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RELIABILITY ISSUES AND FUTURE CHALLENGES IN GEOTECHNICAL ENGINEERING FOR OFFSHORE STRUCTURES

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ABSTRACT

The paper describes the role of reliability analysis in the geotechnical design of offshore structures, and attempts to put in perspective the interrelationship and dependence of the geotechnical aspects to related fields of offshore engineering. Predictions of foundation behaviour and soil-structure interaction cannot be made with certainty due to the spatial variation of soil properties, limited site exploration, limited calculation models, uncertainties in soil parameters and uncertainties in loads. It is increasingly important to adopt rational and "documentable" design approaches that inform about and account for the uncertainties in the analysis parameters. Reliability analysis enables one to map and evaluate the uncertainties. With the reliability tools available today, it is possible to establish, without too much difficulty, a probabilistic model for an existing deterministic solution. Probabilistic analyses are a useful addition to, and not a replacement of, deterministic analyses. That one finds it difficult to quantify the uncertainties is not a reason to omit defining them or establishing their significance on the quantities predicted. Future challenges and expected trends within offshore geotechnics are also highlighted.

KEYWORDS

Reliability, uncertainty in soil parameters, model uncertainty, requalification, gravity structures, piled structures, jack-up structures, suction anchors, bucket foundations, research needs.

INTRODUCTION

The organisers of the seventh BOSS Conference ('94) requested the Norwegian Geotechnical Institute (NGI) to address reliability issues for foundations of offshore structures and to identify challenges within geotechnical engineering that the industry has to face in the future.

This plenum presentation has three parts: (1) interrelationship with and dependence of geotechnics on related fields of expertise in offshore platform design, (2) review of role of geotechnical reliability analysis, including purpose, applications and development needs for more widespread use and (3) a prognosis of key future geotechnical challenges. While the paper is not at a specialist technical level, it attempts to give an overview of key aspects of geotechnical engineering of offshore structures.

GEOTECHNICS AND OFFSHORE PLATFORM DESIGN

The plenary sessions related to geotechnics at the earlier BOSS conferences presented various topics, from state-of-the-art reviews (Høeg, 1976; 1982; A.M. Muir Wood, 1979), to more specific discussions of static and cyclic stress-strain behaviour for piles (Verruijt, 1985), subsidence at Ekofisk (Åm, 1988), perspective of the past 20 years of offshore practice in the North Sea (Tjelta, 1992b) and insight in the geotechnical design and engineering for the 90's (Toolan, 1992). These useful contributions reviewed the building blocks for today's geotechnical offshore practice.

One of the missions of the present paper, in addition to describing geotechnical reliability issues, is to point out the need for bridging the gap between geotechnical engineering and other related fields of expertise. Reducing this gap is necessary if one is to achieve more cost-effective and safe offshore structures. Reliability analysis may be one of the tools that enables us to do so.

The geotechnical aspects of offshore structures play an important role as they often set the premises for ensuring the integrity and safe operation of the structure. However it is difficult to maintain a fruitful dialogue among environment, hydrodynamics, structures and geotechnics specialists. One reason is lack of time, but there is more to it than simply overworked engineers. During design, the geotechnical jargon and practice often present obscure, much discussed solutions. The geotechnical engineer often does not make himself understood by colleagues who do not have the background to appreciate geotechnical finesses. How many of us can claim that our reporting is complete and accessible to others than the ones who ordered the work?

Geotechnical engineers have the disadvantage that the stress-strain-strength characteristics of soil depends on the magnitude and nature of the imposed loads. It is therefore especially important to describe clearly the situation for which loads are required and how, for example, safety factor (or load and material coefficient) is defined.

The uncertainties in the loads, storm characteristics and load effects used as input to the geotechnical analyses can predominate the probability of non-performance of a concept. To quantify these effects, NGI, with the support of oil companies and regulatory agencies, initiated in 1990 a study on the effects of uncertainties in loads. A team of specialists was formed to bring in the expertise from the environment, hydrodynamics, structures and geotechnics. The work included (1) a study of the loads required for geotechnical analyses, (2) a survey of expert opinions and practice, and (3) an evaluation of the uncertainties in the environment by Statoil, uncertainties in hydrodynamic analyses by Shell Research BV, and uncertainties in structural analysis of jack-up structures by Veritec A/S. The uncertainties in the load effects were then included in bearing capacity analyses of a piled jacket and a jack-up structure.

Loads Required for Geotechnical Analysis. Depending on the geotechnical problem, different components and conditions of the environment are relevant, as listed in Table 1.

Uncertainties in Loads. The expert opinion survey concentrated on three types of offshore structures in the North Sea environment: jack-up, piled jacket, and gravity base structures. The survey asked advice on 4 topics: (1) method of analysis to obtain mudline forces, (2) uncertainties in prediction of extreme mudline forces, (3) uncertainties in long term distribution of mudline forces, and (4) uncertainties associated with gravity loads. Six experienced organisations replied. The key figures indicated good agreement between the organisations consulted. A global coefficient of variation on the extreme mudline wave forces due to the environment between 15 and 30%, with 20 or 25% as a best estimate for gravity, jack-up, and jacket structures, could be expected. The respondents who used the results of recent research tended to estimate lower uncertainties than the respondents basing their estimates on present practice. The uncertainties in the gravity loads were in all cases small.

Such dialogue among different specialists in the design of offshore structures should be encouraged for enhanced understanding and communication and for safer and more cost-effective designs. Vugts and Edwards (1992) correctly pointed out that methods for constructing probabilistic models for the resistance of foundation systems from limited and uncertain soil data are crucial for structural reliability assessment since foundations strongly influence the reliability of the structures.

Table 1. Environmental loads required for different geotechnical problems *

Structure	Geotechnical analysis	Relevant load effect
Jack-up	Bearing capacity Hydraulic stability Soil reactions Soil stiffness Displacements	Soil type and size of footing determine whether short term or long term loads are more critical; combined static and cyclic loads are important; distribution of loads among footings is needed.
Piled	Axial pile capacity Lateral pile capacity	Only worst characteristic storm is needed; distribution of loads among piles is needed; ratio between static and cyclic loads is important.
Gravity	Bearing capacity Hydraulic stability Soil reactions Soil stiffness Displacements	In most cases, long term effects (design storm or lifetime) need to be considered; combined static and cyclic loads are important.

* Earthquake analysis was not included in the review

GEOTECHNICAL RELIABILITY ANALYSIS

The applicability of reliability concepts and probabilistic models in geotechnical engineering is today emerging after a long development period and familiarization studies triggered at first by research in the universities. The role played by the offshore industry in promoting development and use of reliability methods have been very important. Geotechnical engineers first regarded probability theory with scepticism. Probabilists and geotechnical engineers did not converse in compatible languages. Since, a slow conversion has been observed: mathematical solutions to complex approximation and iteration problems now exist; the significance of different reliability aspects are well established in other fields; advances of research in reliability engineering and the advent of powerful personal computers have brought the exploitation of the available tools within everyone's reach; and the language barrier between probabilists and geotechnical engineers is gradually disappearing.

Other areas of civil engineering, such as structural and hydrodynamics analyses, lie ahead of geotechnical practice in the area of reliability. Geotechnical engineers have learned to use the advances and experience of structural reliability. As solutions become more straightforward, the use of probabilistic methods is closer to an application of a mathematical tool rather than a new development.

The following presents the role of reliability and probabilistic approaches for solving geotechnical problems. It discusses applications, available tools and the benefits of reliability estimates when used in conjunction with deterministic analyses. The presentation concentrates on the experience gained at NGI, and does not attempt to do a state-of-the-art on the many contributions of those who have been active in the area.

Purpose of Reliability Analysis

Predictions of foundation behaviour are uncertain because of spatial variation of soil properties, limited site exploration and observations, limited calculation models, uncertainties in the parameters obtained by various testing methods and not the least, uncertainties in the loads.

Figure 1 presents the results of the reliability analysis of the most loaded pile in an offshore jacket installed in 1976 and reanalysed in 1989 after a new soil investigation and new calculations of the environmental and gravity loads had been completed. The newer deterministic analysis gave a low safety factor (FS), a situation for major concern. According to the API RP2A guidelines, the required factor of safety under extreme loads is 1.50. However the added information reduced the uncertainty in both soil and load parameters. The pile with a safety factor of 1.40 is nominally safer than the case where the safety factor is 1.79. The newer analyses show that the pile, although with a lower safety factor, had higher safety margin than perceived at the time of design. The lower uncertainty in the parameters in the newer analysis caused a reduction in the probability of failure (P_f) by a factor of 2.

The factor of safety is therefore not a sufficient indicator of safety margin because the uncertainties in the analysis parameters affect probability of failure, but these uncertainties do not intervene in the deterministic calculation of safety factor. Figure 1 illustrates that it is "better to be probably right than to be exactly wrong" (Personal communication, Robert Olesen, Det Norske Veritas Research A/S, June 1993).

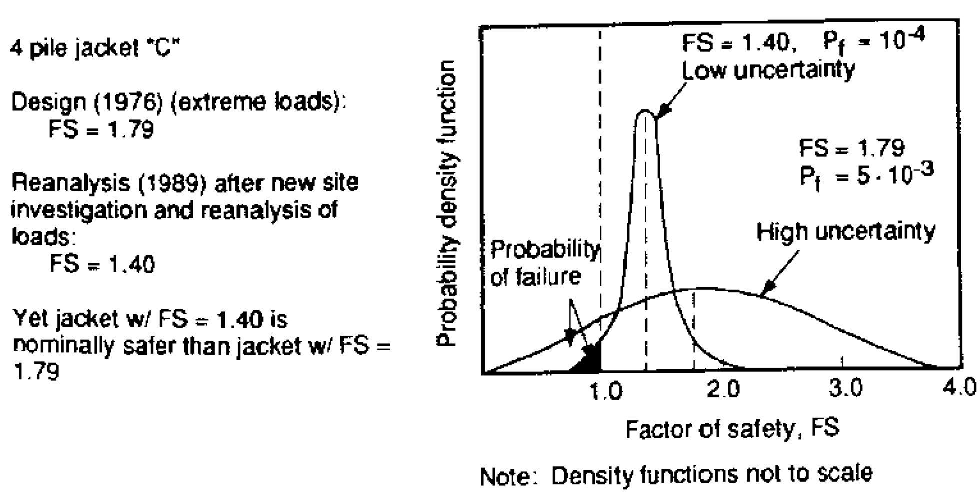


Fig. 1. Factor of safety and probability of failure of pile in a jacket

Reliability analysis enables one, and forces him, to map, discuss and evaluate the uncertainties that enter into the formulation and solution of a geotechnical problem. In all cases, probabilistic analyses are a useful addition to, and not a replacement of, deterministic analyses. Even if it is difficult to quantify the uncertainties inherent in each variable, there are no reasons to omit defining them or establishing their significance on the results obtained. On the contrary, the greater the uncertainties, the greater the need for reliability analyses.

As for deterministic calculations, the essential components of reliability estimates in geotechnics are (1) a clear understanding of the physical aspects of the geotechnical behaviour to model and (2) the experience and engineering judgement that enter into all decisions at any level, whether for parameter selection, choice of most realistic analysis model, or decision-making on the viability of a concept.

Application to Offshore Geotechnical Engineering

Probabilistic analyses exist for the following geotechnical calculations for offshore structures:

Piled structures
- Axial pile capacity (single pile and system of piles)
- Soil resistance to pile driving
- Lateral pile capacity

Shallow foundations (jack-up, anchor and gravity structures)
- Bearing capacity (single and several failure modes)
- Settlement (total settlement and settlement versus time)
- Penetration resistance of skirts, dowels and spud cans
- Equivalent soil spring stiffness for soil-structure interaction analysis

Earthquake response
- Site response under earthquake loading
- Effects of spatial variation of earthquake motion on response of a gravity platform and response of a "system" of interconnected platforms

Figure 2 compares deterministic and probabilistic analysis: reliability analyses do not need to be more complex than deterministic analyses: the input parameters are defined over a range of probable values rather than as punctual values; the equilibrium function describing failure (or non-performance) is defined by a "limit state function" which has the same form as the deterministic equation. Instead of a point estimate of factor of safety, the distribution of the resistance is compared with the distribution of the load. The probability of failure is the probability that the resistance is less than the load.

As input, the user must supply (1) the equation defining failure as in the deterministic case, and (2) the mean and distribution function for each variable in the analysis. Except for the distribution function of each parameter, the required input is therefore the same as for deterministic analyses.

If there exists a deterministic model to analyze a geotechnical problem, a probabilistic analysis model can be established using the tools described in the next section. These tools are ready-made software that are easily linked with the software describing the deterministic geotechnical solution. Preferably, the same software would solve the problem first deterministically, then probabilistically. In one rapid PC calculation, one obtains both results. Probabilistic analyses provide the following:

- Probability of failure (or probability of non-performance)
- Reliability index
- Sensitivity of probability of failure to change in input parameters
- Contribution of each parameter to overall uncertainty

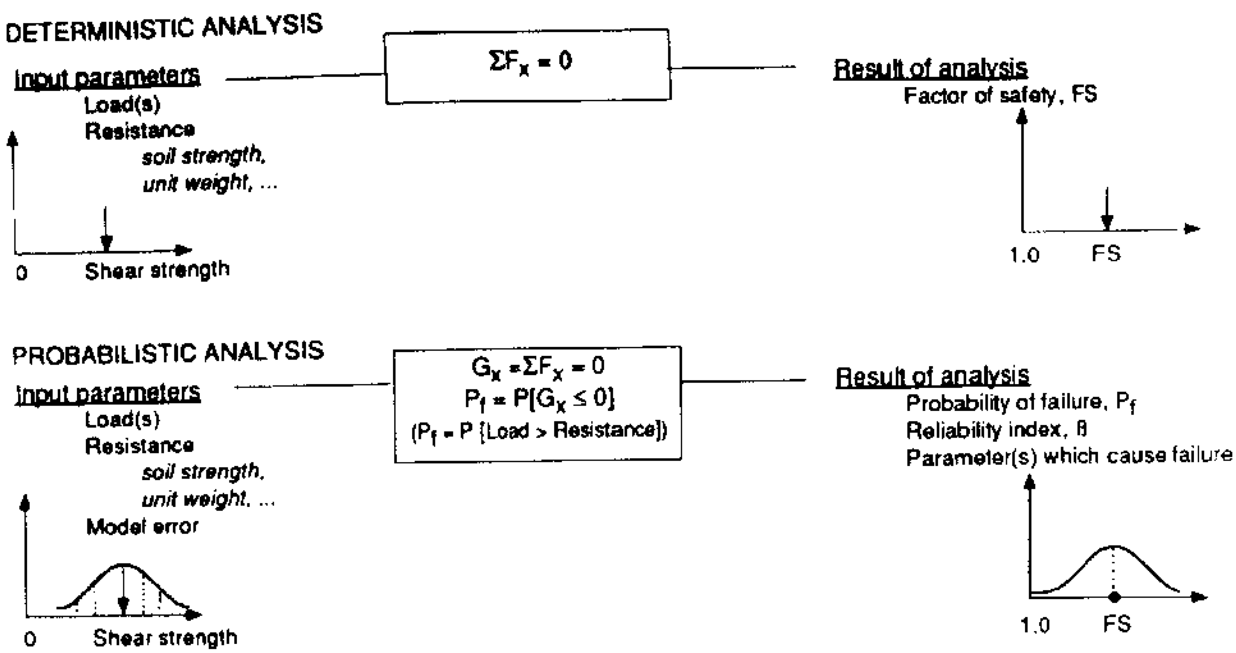


Fig. 2. Comparison of deterministic and probabilistic analysis

The reliability index is a measure of how far apart the most probable geotechnical response is from the conditions that would cause failure (or non-performance). There is a unique relationship between reliability index and probability of failure when the calculations are made with the first- or second-order reliability method (see next section). Figure 3 presents an example of the contributions of different parameters of axial pile capacity to the overall uncertainty in the distribution of the capacity of a pile in an offshore jacket. (In this case, the load components were taken as deterministic.) A single probabilistic analysis gives more insight into the significant components of a problem than deterministic parametric analyses (where the uncertain parameters are the parametric variables).

Alternatively, the results of a probabilistic analysis can be shown as a function of the applied load to determine the probability density function of the axial pile capacity, as illustrated in Fig. 4 for a single pile. Probabilistic analyses of the pile-soil capacity establish reliability index and probability of failure for relevant axial loads. The cumulative distribution function is then approximated by normal, lognormal or other appropriate probability density functions, for example on probability paper. By curve-fitting, mean and standard deviation can be obtained for the approximations. The distribution can be compared to, for example, the API RP2A guidelines, as shown on Fig. 4.

Uncertainties in Soil Parameters. The properties of a volume of natural soil inevitably fluctuate spatially and may be considered to be controlled by a random process (Vanmarcke, 1977; 1984). This inherent random variation suggests that the reliability approach can be better suited for the treatment of soils than other approaches.

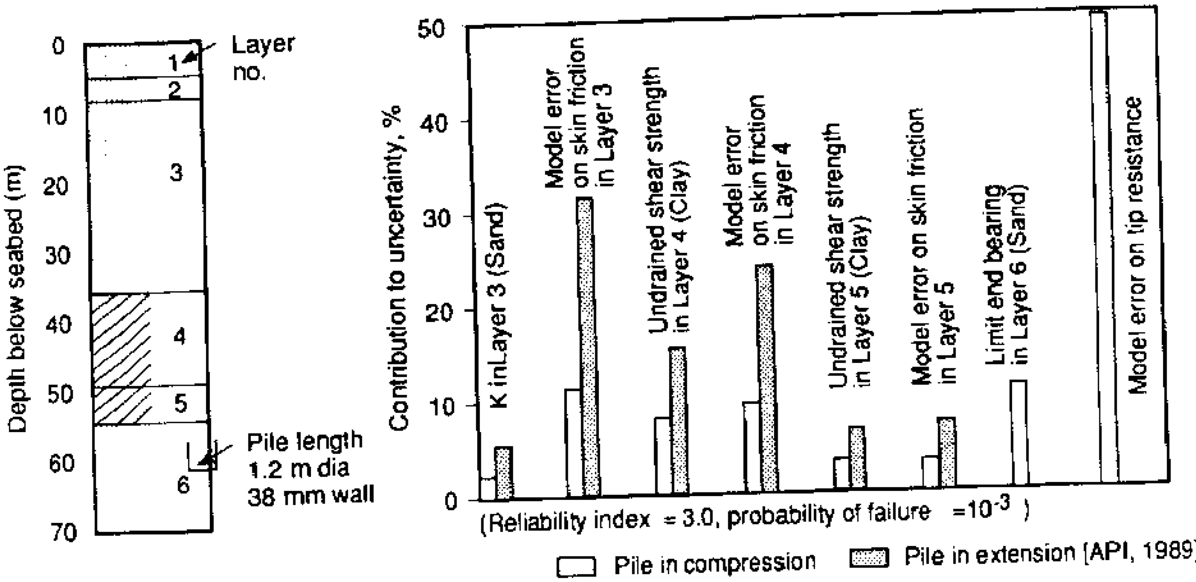


Fig. 3. Contribution of different variables on overall uncertainty in pile capacity

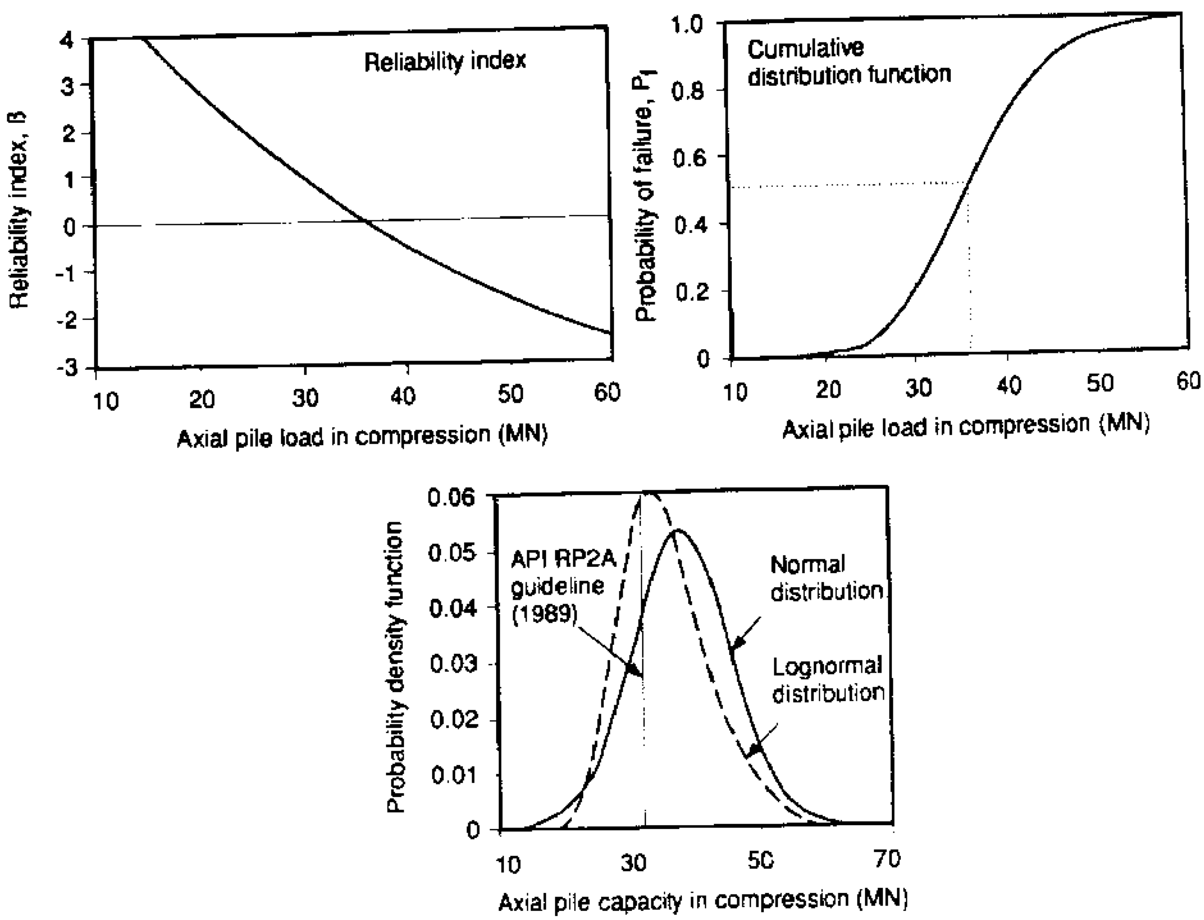


Fig. 4. Distribution of axial pile capacity

To obtain the statistics of soil parameters, stochastic interpolation is easy to implement and useful when a lot of data exist. It provides unbiased estimates of mean and variance (Keaveny et al, 1989). Alternatively one can establish histograms to estimate mean and standard deviation. Often though, due to lack of data, it is mainly experience and existing data banks for different types of parameters and geographical locations that enable one to evaluate the expected range of variation of a soil parameter. Such estimates can be biased by the beliefs of the designer. The probabilistic analysis will, however, single out the importance of such hypotheses on the results.

It is advisable to try to express the soil parameters in terms of variables that are easy to quantify. For example, most geotechnicians have less difficulty determining the mean and possible range of the normalized undrained shear strength ratio s_u/σ'_{vo} of clays than the mean and possible range of the undrained shear strength s_u. Thus, the skin friction (f) of a pile in clay, usually expressed as

$$f = \alpha \cdot s_u = ½(s_u/\sigma'_{vo})^{-½} \cdot s_u \tag{1}$$

can be transformed to

$$f = \alpha \cdot s_u = \beta \cdot \sigma'_{vo} = ½(s_u/\sigma'_{vo})^{+½} \cdot \sigma'_{vo} \tag{2}$$

where σ'_{vo} is the in situ vertical effective stress, and has much less uncertainty attached to it than s_u.

The standard deviation or coefficient of variation is of great significance in the reliability analysis (coefficient of variation is defined as the ratio of standard deviation to mean). In Fig. 5, standard deviation is shown for a normally distributed variable: 68 % of the data should then fall within one standard deviation about the mean, and nearly 100 % of the data should fall within 3 standard deviations about the mean. A coefficient of variation of 0.30 implies that the variable can be as much as 100 % lower and 100 % higher than the mean value. It is therefore important to consider, when evaluating the uncertainty of a variable, whether the variable can actually extend over the range implied by the coefficient of variation selected.

Defining the probability distribution function may appear as a problem. However, most geological processes are believed to follow a normal or lognormal law. One may also use bounded uniform distributions when all values within a range are equally probable. The existing software packages can take into account all or most of all distribution functions relevant for geotechnical analyses.

Model Uncertainty. In probabilistic analysis, a "model uncertainty" is defined by a mean and a coefficient of variation. A normal or lognormal distribution is often assumed. Model uncertainty is difficult to assess and should be evaluated on the basis of:

- Comparisons of relevant model tests with deterministic calculations
- Expert opinions
- Relevant case studies of "prototypes"
- Information from the literature

To make a reliable estimate of model uncertainty, all relevant mechanisms should be identified and included in the probabilistic models. An important aspect of model uncertainty is the form it takes in the equilibrium function. Model uncertainty is best included in one of three ways:

- Factor on each random variable in the analysis
- Factor on specific components (e.g. for piles, skin friction in each layer and end bearing)

- Global factor on the limit state function

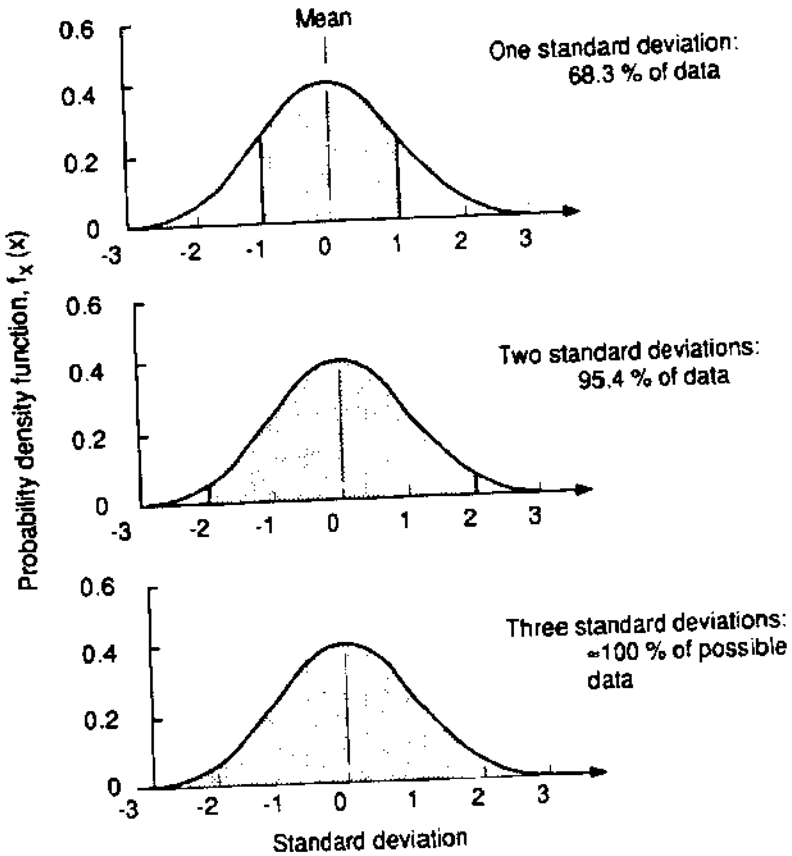
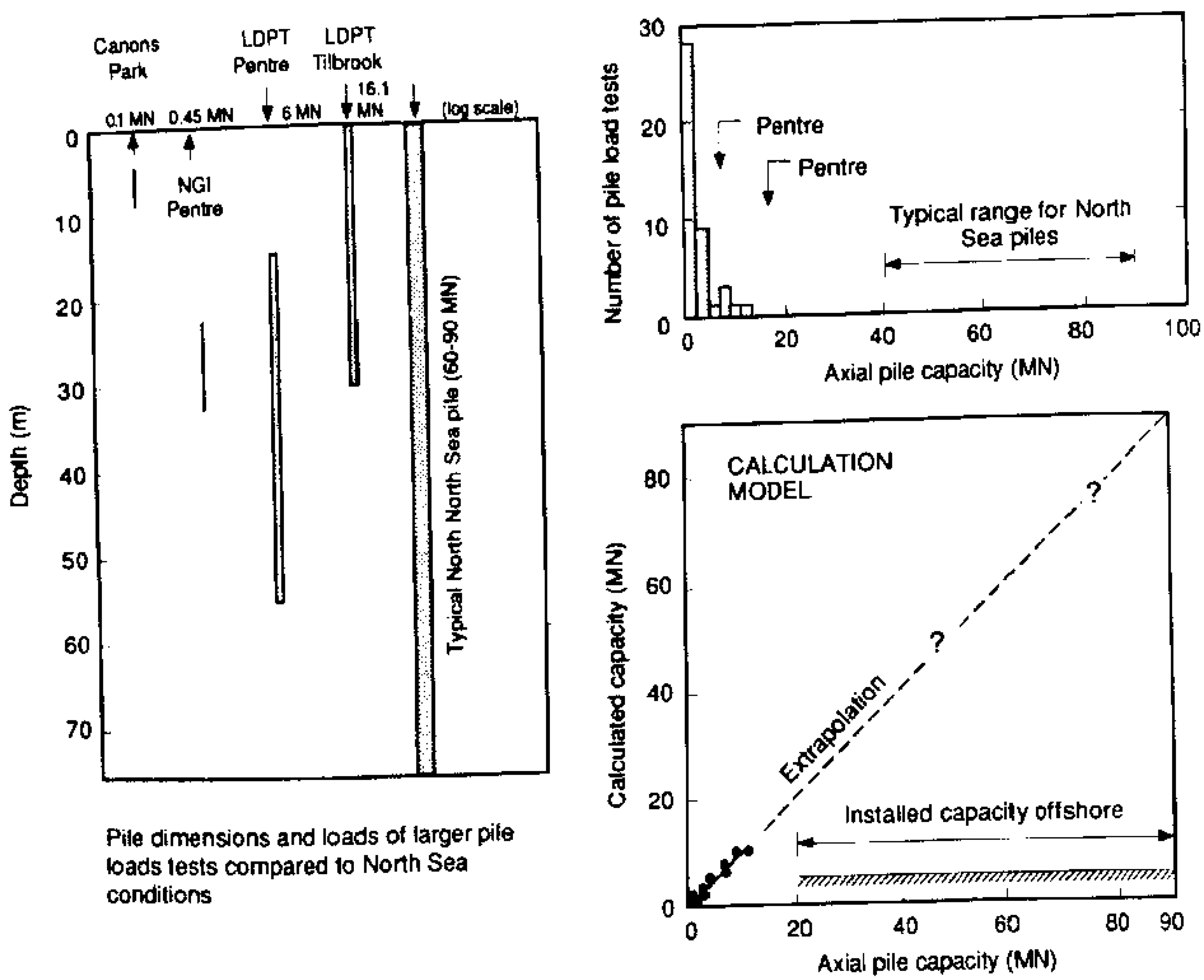


Fig. 5. Illustration of uncertainty in normal random variable

With modern computers and techniques, number of variables is no longer a limiting factor and it is recommended that model uncertainty be linked to each of the variables entering into the calculation. And yes, considerable reflection and engineering judgement have to be used to establish the values of model uncertainty. Including model uncertainty is nevertheless more rational than ignoring the uncertainties that come from the calculation model or the way of recovering soil samples.

The uncertainty that can arise from the choice of a calculation model based on model tests is illustrated in Fig. 6 (Personal communication, R. Hobbs, Lloyd's Register of Shipping, UK, London, May 1993). Current axial pile capacity calculation methods have been derived predominantly from onshore load tests on small piles. Penetration depth, pile length, pile diameter and ultimate load for the largest piles in the reference database are much smaller for the test piles than for those currently used in the North Sea. The larger test piles represent only a small portion of the reference database. The uncertainty due to the calculation model can therefore be large because the reference database of pile load tests applies to different pile and load conditions than normally used offshore. Figure 6 also illustrates the extrapolation implied when applying the calculation models derived from onshore tests to offshore conditions. Surely the uncertainty in this extrapolation needs to be included in the estimation of the possibility of a failure.

In a recent survey of regulatory organisations from Norway, France, USA and UK, undertaken by the Norwegian Geotechnical Institute, experts were asked to estimate whether their recommended calculation method for axial pile capacity contained an inherent safety margin. In most cases, the mean of the model uncertainty estimated by the organisations consulted indicated a conservative method, with coefficient of variation varying greatly, depending on analysis method and soil type considered. The detailed results are part of a joint-industry research project now underway at NGI for oil companies and regulatory organisations, and the results should become available shortly. Pooling of over 30 international experts on pile capacity done earlier by NGI gave the consensus that the currently most used pile design method (API RP2A method) is conservative in medium dense to very dense sand (Lacasse and Goulois, 1989).



Pile dimensions and loads of larger pile loads tests compared to North Sea conditions

Fig. 6. Database for offshore piles and extrapolation of calculation model (Personal communication, R. Hobbs, Lloyd's Register of Shipping, UK, London, May 1993)

The preferred method to obtain an estimate of model uncertainty is to evaluate the results of model tests run specifically to evaluate the mechanism of failure. Table 2 gives examples of the results of particularly successful model tests run to evaluate bearing capacity models. These predictions were made before the model tests were run:

Table 2. Comparisons of calculated and measured bearing capacities (Andersen et al, 1988; Dyvik et al, 1989; Andersen et al, 1989; Andersen et al, 1992b; Dyvik et al, 1993; Andersen et al, 1993)

Structure	Type of loading	Ratio between calculated and measured failure loads
Gravity foundation	Static failure, test 1	0.98-1.01
	Cyclic failure, test 2	0.99-1.15
	Cyclic failure, test 3	1.16-1.17
	Cyclic failure, test 4	1.06-1.23
Tension leg platform	Static failure, test 1	1.00
	Cyclic failure, test 2	1.06
	Cyclic failure, test 3	1.06
	Cyclic failure, test 4	1.02

Several factors, which relevance and significance for a given problem should be considered, can modify the value of model uncertainty:

Sampling disturbance, test method, scale of laboratory or in situ test, spatial averaging, anisotropy and rate of loading affect the undrained shear strength of clay; reconstitution of test specimen, change in density, test method and scale of laboratory test affect the friction angle of sand.

For calculation of axial pile capacity, important factors include: skin friction assumption (sand or clay), limiting values for skin friction and end bearing, subdivision in soil layers, pile installation and residual stresses, reconsolidation, rate of loading, plug condition, scour, stiffness of pile and pile length, cyclic loading, single pile versus pile group and extrapolation from reference database to prototype.

For calculation of bearing capacity of a shallow foundation (jack-up, anchor or gravity structure), important factors include: plane strain versus three-dimensional model, detection of critical slip surface, modelling of static and cyclic load history, strain-softening or progressive failure, testing procedures in reference tests, scale effect, rate of shear, stress conditions and redistribution of stresses, anisotropy, stiffness of structure, model of soil profile and drainage assumptions.

Overview of Probabilistic Tools

To do reliability analysis of components (e.g. one pile, one slip surface) or of systems (e.g. three spud-cans of jack-up structure, several slip surfaces), one needs an approximation routine. One can purchase either analysis routines that are used as subroutines in the geotechnical formulation (e.g. those developed at Stanford University and University of München) or a complete software package where one can code the limit state function [e.g. the general purpose computer code PROBAN (Det Norske Veritas Research A/S, 1993)]. Different techniques exit to approximate the distribution of all possible geotechnical responses under any random load situation (see Madsen et al, 1986 for details):

FORM, First-Order Reliability Method: probably the best practical method today, it approximates the limit state function by a first-order function. The method works well over a wide range of probabilities and is simple to implement when one has an explicit limit state formulation. FORM accounts for the probability distribution of uncertain variables with essentially any distribution.

SORM, Second-Order Reliability Method: as FORM, but the limit state function is approximated by a second-order function. The results of the SORM analyses have for all geotechnical problems modelled so far given probabilities of failure very close to the values obtained with FORM.

SORM improved with sampling around solution point: improved second-order approximation, with a search around the solution for an even more critical point. The results of the SORM improved analyses have also been found to be close to the results obtained with FORM.

SYSREL, system analysis: computer package for the analysis of the probability of failure of a system (several piles, several slip surfaces).

FOSM, First-Order Second Moment approximation: approximates mean and variance but cannot account for the probability distribution of the uncertain variables. The approach is used for complex formulations where the performance cannot be expressed explicitly, for example for the probabilistic analysis of finite element models.

Monte-Carlo simulation: repeated simulation of solution with randomly selected values of uncertain variables. The method applies to all problems but can require a large number of simulations. Latin hypercube sampling can optimize the Monte-Carlo simulation technique with an "organized" sampling method. The method has been used for example to model earthquake site response and the cyclic shear strength of soil under random storm loading histories.

Bayesian updating: method to relate predicted behaviour with observations. Application examples include: updating of factor of safety or settlement prediction on basis of pore pressure and settlement records; updating of pile capacity on basis of pile driving records and instrumentation results; updating of bearing capacity on basis of preload test.

The existing probabilistic tools do not yet provide an effective solution for the stochastic analysis of finite element models with non-linear soil modelling. This is an important drawback for geotechnical deformation analyses.

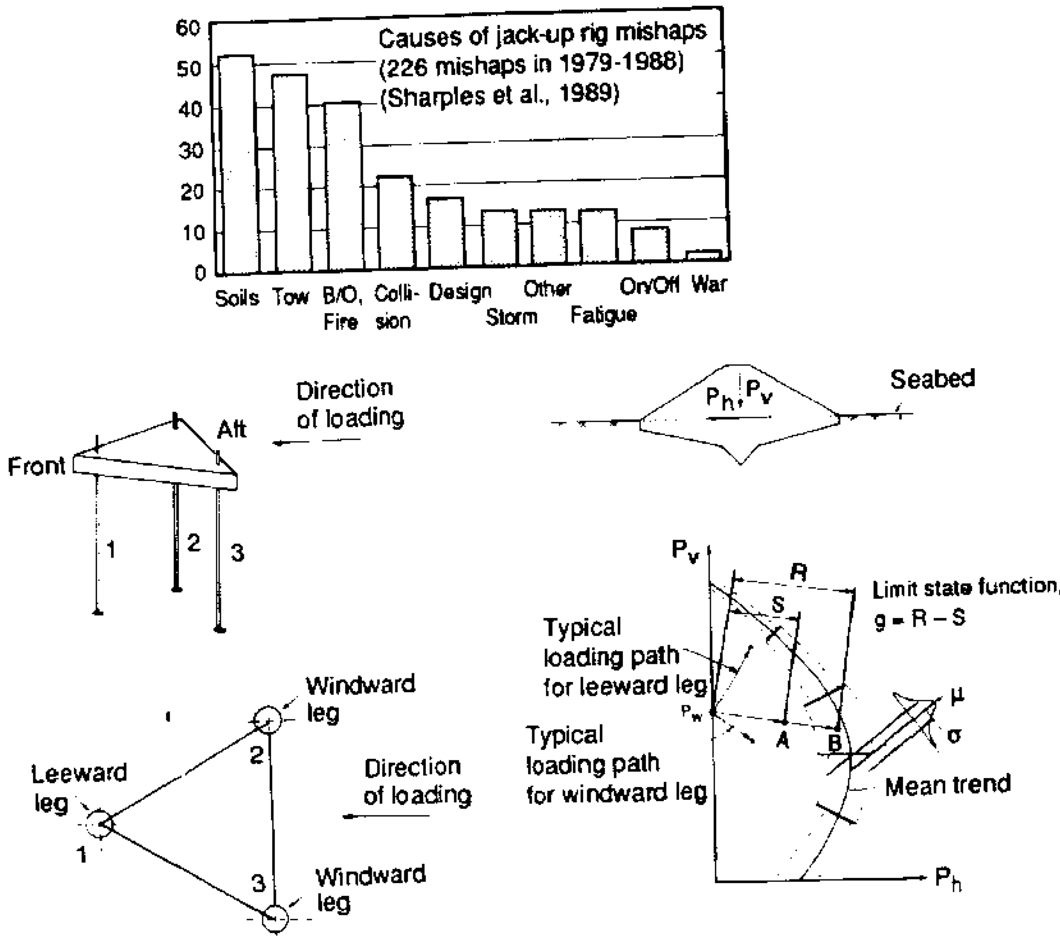
Results of Geotechnical Reliability Analyses

To illustrate different solutions that have been used, the following paragraphs present five examples of geotechnical reliability analyses.

Jack-up structure. Mobile jack-up rigs, although extensively used, apparently face far greater risks than most engineering structures. Accident rate averaged 2.6 % of the fleet annually between 1955 and 1980 (McClelland et al, 1982). Sharples et al (1989) presented the causes of jack-up rig mishaps over a more recent 10-year period (Fig. 7): out of the 226 accidents, over 50 were associated with "soils", with punch-trough, failure due to wave loading and scour as dominant failure causes.

The probabilistic approach developed to quantify the uncertainty in the bearing capacity analysis of jack-up structures includes three main steps: (1) a priori calculation of bearing capacity of spud can;

(2) updating of capacity of spud can from the observations made during vertical preloading; and (3) probabilistic bearing capacity analysis of spud cans under environmental loading. Figure 7 presents the model of the jack-up structure used, the a priori capacity diagram [mean (μ) and standard deviation (σ)] and the limit state function used. The soil foundation was a layered clay profile, with spud can penetration of 4 meters.

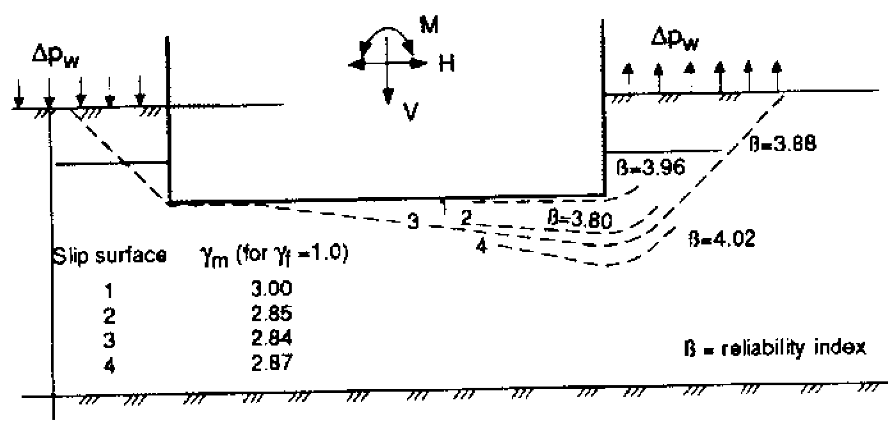


Analysis	Leg	Leeward leg (P_w=45 MN, P_h=4.5 MN, M=450 MNm) Reliability index	Probability of failure	Windward leg (P_w = 45 MN, P_h=9 MN, M=187.5 MNm) Reliability index	Probability of failure
FORM	1 (leeward)	3.18	$7.48 \cdot 10^{-4}$	3.23	$6.22 \cdot 10^{-4}$
	2 (windward)	5.40	$3.41 \cdot 10^{-8}$	4.44	$4.53 \cdot 10^{-8}$
	3 (windward)	5.40	$3.41 \cdot 10^{-8}$	4.44	$4.53 \cdot 10^{-8}$
SYSREL	System	3.18	$7.48 \cdot 10^{-4}$	3.22	$6.32 \cdot 10^{-4}$

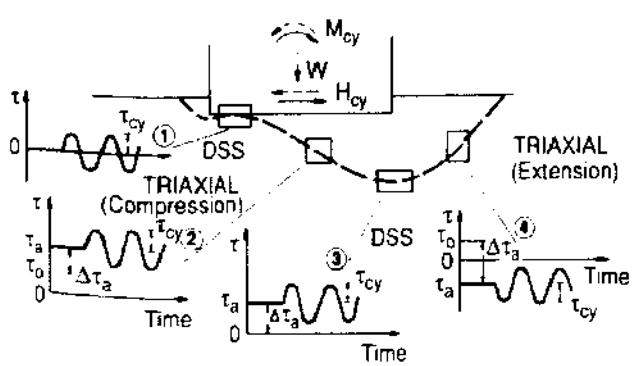
Fig. 7. Reliability analysis of jack-up structure (Nadim and Lacasse, 1992)

Two sets of probabilistic calculations were run: load combination typical for a leeward leg, and load combination typical for windward leg. A coefficient of variation of 15 % was used for the environmental loads, while the coefficient of variation of the bearing capacity diagram varied between 10 and 15 %. The horizontal load and moment had a correlation coefficient of 0.8. The results of the system reliability analyses are presented on Fig. 7. The reliability of the system of three spud cans is essentially equal to the reliability of the most critical component. It is interesting to note that for both load combinations, the probability of failure is much higher for the leeward leg than for the windward leg. The analyses showed that the uncertainties in the global loads and load effects are very significant and contribute about 50 % of the overall uncertainty. The model uncertainty and the uncertainty in the soil parameters contribute about equally the remaining 50 %.

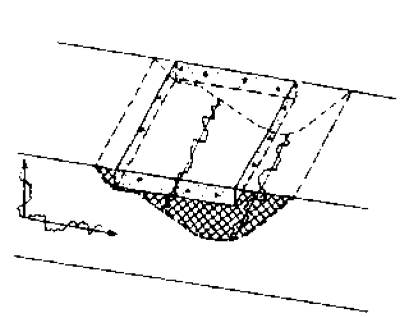
Stability of gravity foundations. Reliability analyses were run for of gravity platforms installed at a stiff clay site and at a uniform soft plastic clay site. As for a deterministic analysis, the approach took into account the different stress conditions along the potential slip surface since the probabilistic formulation is exactly the same as the deterministic one. The potential slip surfaces (Fig. 8) were analyzed individually and as a system. Spatial variability, which reduced the uncertainty in the soil properties such as undrained shear strength of the clay, was included. The coefficient of variation of the extreme environmental loads was taken as 15 %, horizontal load and moment were taken as perfectly correlated (little or no current effects). The uncertainty in the soil parameters at the soft clay site was very low because of the exceptional homogeneity of the deposit.



γ_m= material coefficient, γ_f = load coefficient



Stress conditions along potential slip surface
(Andersen et al., 1988)



Spatial variability

Fig. 8. Results of probabilistic analysis of bearing capacity of shallow foundation

The reliability analyses indicated the following:

- The critical slip surface based on the highest probability of failure was different from the critical slip surface based on the results of deterministic analyses. This is seen repeatedly for different soil profiles and illustrates well that the uncertainty in the analysis parameters plays an important role on the margin of safety.

- Based on the results of analyses of gravity structures on both soft and stiff clay, model uncertainty and moment were very significant uncertain variables. For the soft clay, this was partly due to the homogeneity of the site.

- First-order, second-order and improved second-order approximations gave same probability of failure. The simpler first-order approximation is therefore sufficient.

- Changing the probability distribution of the soil parameters from normal to lognormal had only a modest effect on the computed probability of failure.

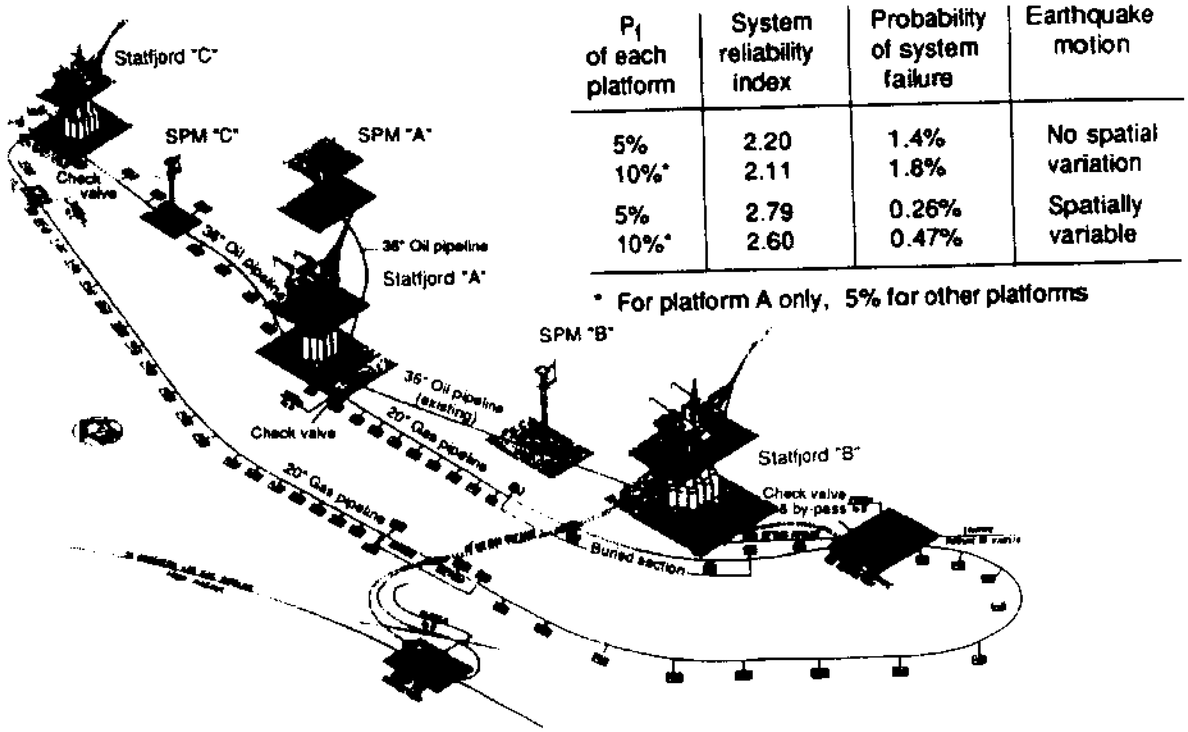
- The system reliability analysis resulted in a probability of failure equal to that of the most critical failure mode. The most critical slip surfaces were essentially perfectly correlated.

Earthquake response. Figure 9 presents an application of the seismic reliability analysis of a group of offshore platforms that answers the following question: given that a strong earthquake with 10^{-4} annual occurrence probability takes place at the Statfjord oil field, what are the chances that oil production must be stopped completely?

The seismic reliability was evaluated by considering the possible failure modes of the platform network, the correlation between the failure modes, the seismic reliability of each platform and the spatial variation of the earthquake peak ground acceleration. A typical gravity platform designed on the basis of the Norwegian Petroleum Directorate guidelines has an implied probability of failure of 5 % under the 10^{-4}/year earthquake. Analyses were done with 5 % probability of failure for each platform taken individually. The effect of increasing the failure probability of the Statfjord A platform to 10 % was also considered. As listed on Fig. 9, the reliability of the system was much greater than the reliability of each platform. Accounting for the spatial variation of the earthquake loading parameters reduced the probability of failure by a factor of about 5.

Importance of uncertainties in loads on jack-up and piled structures. The effects of the uncertainties in storm loads and soil parameters on the reliability of a jack-up structure on dense sand were studied by Nadim et al (1993). The study included the development of a stochastic wave climate model, time domain simulations of jack-up response, and a probabilistic description of the soil properties. For 100-m water depth and wave climate similar to that at Ekofisk in the North Sea, a coefficient of variation was calculated as 12% on the annual maximum vertical load, and 26% on the annual maximum horizontal load. The reliability calculations of the spud can foundation under the annual maximum loads showed that the uncertainties in the loads and the uncertainties in the soil shear strength parameters contributed about equally to the total uncertainty in the foundation performance.

For a piled jacket placed in the Statfjord environment with 47 m long piles, global coefficients of variation of 10 and 15% on the extreme 100-year axial load were used. The lower value of 10% corresponded to an estimate based on recent research results (Personal communication, P. Tromans, Shell Research BV, Netherlands, May 1992). The reliability analyses showed that the uncertainty in the 100-year storm causes 25 to 50% of the total coefficient of variation in the axial pile load



P_f of each platform	System reliability index	Probability of system failure	Earthquake motion
5% 10%*	2.20 2.11	1.4% 1.8%	No spatial variation
5% 10%*	2.79 2.60	0.26% 0.47%	Spatially variable

* For platform A only, 5% for other platforms

Fig. 9. Platform and pipeline layout at Statfjord field and probability of system failure (Nadim and Gudmestad, 1994)

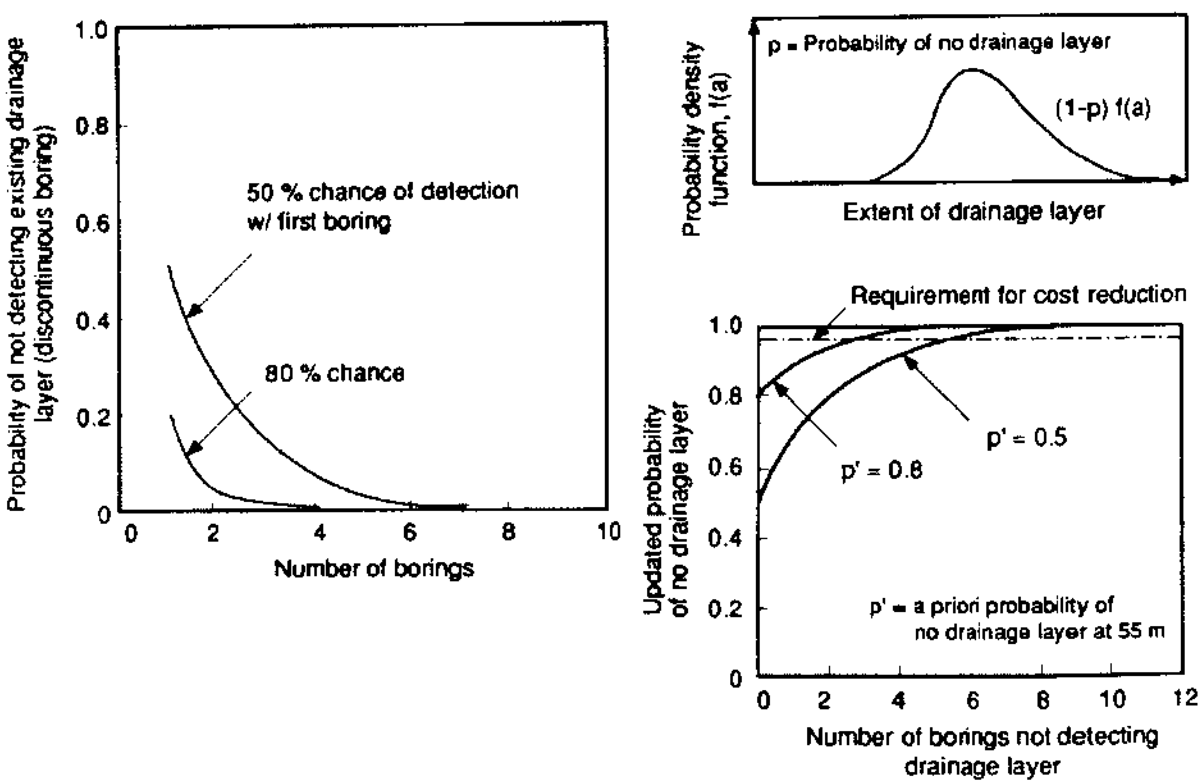


Fig. 10. Cost reduction with increased number of boreholes to detect drainage layer

bearing, depending on whether the uncertainty of 10 or 15 % was used. This sensitivity of the results to a relatively modest change in the uncertainty in the axial load is very important, and highlights the need to better define the uncertainties in the loads.

Optimisation of site investigation. The uncertainty in a geotechnical calculation is often related to the uncertain presence of an "anomaly", for example boulders, soft clay pockets or even drainage layer. Probability approaches can be used to establish the cost-effectiveness of additional site investigation to detect such "anomalies". Figure 10 presents an example where the procedure developed by Tang (1987) was used. In this application, having no drainage layer present at a depth of 55 m was determinant on the resulting lifetime settlement. A settlement of less than 50 cm would mean a reduction in costs by N millions. If the probability of no drainage layer at a depth of 55 m was less than 2 %, the settlement would not exceed 50 cm. With drainage layer detectability for each boring of 50 % or 80% and distribution of drainage layer extent as shown on Fig. 10, one would need 3 to 6 boreholes to ensure a cost reduction of N millions.

Benefits of Reliability Methods for Practice

It is increasingly important today to adopt rational and "documentable" design approaches that inform of and account for the uncertainties in the analysis parameters, particularly when "novel" design or design procedures are involved. Only reliability analyses can provide the designer with insight in the inherent risk level of a design or when comparing different solutions. The probabilistic approach is therefore a necessary complement to the conventional deterministic approach and they provide added knowledge to help decision-making in the presence of uncertainty.

Probabilistic solutions are not a panacea, but they provide a rational framework to include in a consistent manner the relevant uncertainties and to illustrate the effects of these uncertainties on failure probability. In many cases, it will enable improved concept optimization or site investigation planning by pointing out the most important uncertainties. A design with safety factor or partial safety coefficients does not enable such optimization. One word of caution: a probabilistic solution does not improve faulty or insufficient input. If the deterministic model is weak, the probabilistic model will also be weak.

Other benefits include: (1) ability to assess or reassess structures for extended life, (2) ability for new designs to benefit from optimisation and reduction of inherent conservatism, and (3) ability to set cost-effective criteria that can rationally distinguish between manned structures, structures de-manned during adverse weather and unmanned structures (Vugts and Edwards, 1992). Finally, but none the least, reliability provides an improved basis for discussing safety issues between geotechnics, structures, hydrodynamics and environment specialists, regulatory parties and management.

Development Needs for More Widespread Use of Probabilistic Analyses

At the International Conference of Soil Mechanics and Foundations in 1985, the use of statistical and probabilistic methods in geotechnical engineering was the subject of a vigorous debate. One even said that application of probability theory to soils was wrong in principle. Hopefully such conceptions have changed. To make reliability analyses more beneficial to geotechnical engineering, we have the following research needs:

- Make the reliability analysis methods more accessible: "mathematical" papers with little or no reference to the practical use of the equations are difficult to implement. There is a need for simple and flexible methods, and especially good examples and case studies.

- Quantify model uncertainty with systematic mapping of good case studies and model tests.
- Contribute to code development by establishing the implicit probability of failure for "conventionally accepted" designs.
- Establish target failure probability: in geotechnics, there is no standard allowable failure probability. One can compile observed recurrence rate from natural events [left diagram in Fig. 11], or estimate probability of failure based on engineering judgement or "beliefs" (right side of Fig. 11). These give indications of accepted failure probability.

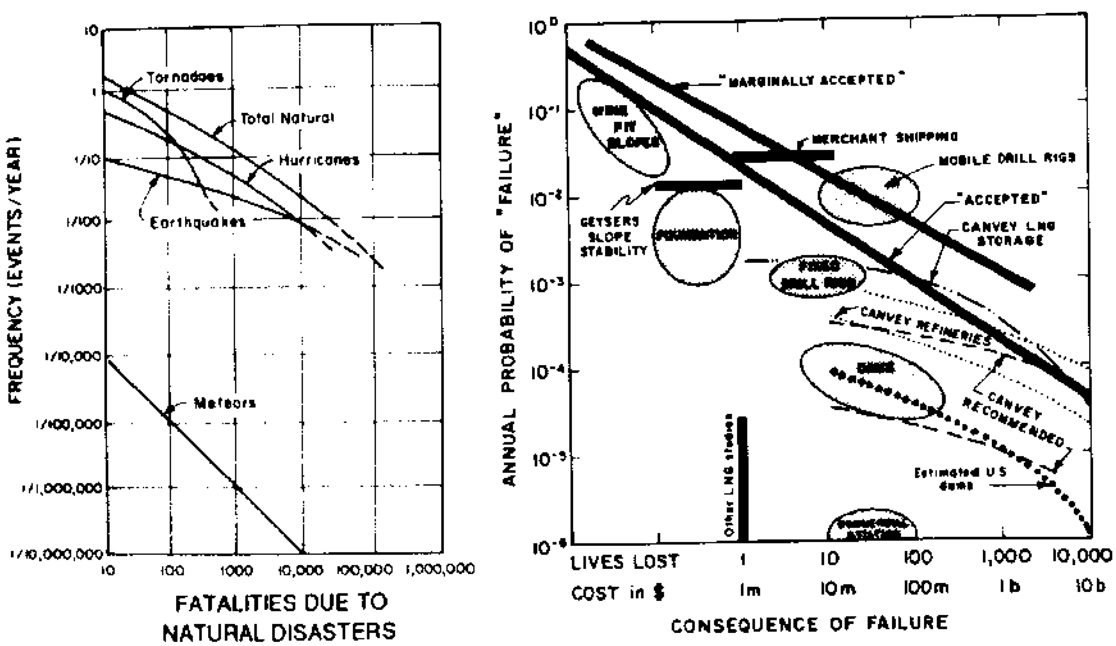


Fig. 11. Failure probability of events and structures (reproduced from Whitman, 1984)

Rasmussen (1979) suggested four requirements for setting evaluation criteria such as target failure probability:

- the criteria must be defined on a logical and understandable basis
- there must be reasonable, acceptable methods for demonstrating that the criteria are met
- the criteria must increase reliability over that inherent in current practice
- imposing the criteria must not lead to severe economic penalties

Discussion of a target probability of failure cannot be made independently by geotechnical engineers. The selection of a target does not represent uniquely a technical issue, but should be integrated in the entire system [risk to human life, structural elements, environmental considerations (both extreme storm loading and pollution), economy, etc].

The profession does not seem quite ready to apply the system reliability approach to all aspects of the design. This can only be done as a concerted effort. However, even simplified calculations using the tools described herein will raise the state of understanding and will help make decisions when comparing different designs.

- No one single university, consultant, research institute, operator or authority can achieve these benefits or answer to these needs on their own. Dialogue with related civil engineering specialists to disseminate the views and results and to establish the uncertainties in different effects, such as loads, is essential.

MAJOR GEOTECHNICAL ACHIEVEMENTS AND FUTURE CHALLENGES

Major contributions have shaped the development of our practice. Much of the "judgement" used in geotechnical engineering, which is necessary for geotechnical design, comes from what was learned from earlier designs.

It is of interest to note that at the BOSS conference in 1979, concrete gravity structures were doomed in the plenary session to have a "reduced likelihood of further orders". Whereas it is true today (1994) that there will be few new very large gravity structures of the types at the Statfjord, Gullfaks and Troll sites in the North Sea, an increased demand is expected for the smaller, more cost-effective concrete gravity structures now under development for shallow waters and difficult soils (Røland and Høeg, 1993).

New fields, often marginal, require new and innovative solutions. The creativity already shown in extending the frontiers of application of established solutions is expected to promote better, cost-effective and safe solutions: new solutions for deep water applications seem to be cost-effective and are also applicable for fields in shallow water, thereby making them more commercially attractive.

Major Geotechnical Achievements

Among the many achievements, one needs to mention:

- The use of physical models (small or large-scale, field or laboratory tests, 1-g or multi-g centrifuge tests) to understand behaviour and to adjust calculation models, and the trend to accept only predictions made before the tests are run to ensure calculations unbiased by the test results (e.g. Andersen et al, 1989; 1993; 1994).
- The advances in the interpretation of offshore in situ tests (Lunne et al, 1989; Baligh, 1985; Campanella and Robertson, 1988)
- The understanding of soil behaviour during cyclic loading, including the development of a framework to account for the significant parameters (Andersen and Lauritzsen, 1988; Andersen and Høeg, 1992)
- The Load and Resistance Factor Design (LRFD) approach adopted as recommended practice by the American Petroleum Institute (API, 1993). The approach is based on reliability concepts. Safety factors are replaced by partial coefficients on the significant components of the analysis (Hamilton and Murff, 1992; Tang, 1988; Tang, 1989; Tang and Gilbert, 1992).

A number of achievements have shaped and will shape the future of offshore structure design:

Piled foundations	Increased awareness of (1) limitations in existing calculation models and (2) need for rational approach (Pelletier et al, 1993); European EURIPIDES research project with full scale pile load tests in sand
Gravity foundations	Skirts at Troll (North Sea) extending down to 36 m; suction used as driving force in clays or sands; design variables of gravity structures combined to give favourable resistance in any soil conditions
Bucket foundations	Caisson (bucket) foundation now being designed for jacket instead of a piled solution, including extensive field and model tests for EUROPIPE 16/11-E jacket in the North Sea (Tjelta, 1994)
Anchors	Caisson suction anchors now being designed to replace tension piles for tension leg platforms (Christophersen et al, 1992; Andersen et al, 1992), and conventional anchors.
Jack-up structures	Multi-disciplinary work on safety of jack-up structures (Joint Industry Jack-Up Forum, 1993) and development of new design procedures (van Langen and Hospers, 1993; Murff et al, 1992; Murff (1994); Jostad et al, 1994)

Future Challenges

This section identifies critical research and development issues for the geotechnical offshore structure community in coming years, these aiming at cost-effective solutions that "are robust for low oil prices" (Tjelta, 1992b).

In his state-of-the-art paper at the BOSS'82 conference, Høeg (1982; 1984) suggested a number of improvements and developments based on a survey of 15 geotechnical colleagues around the world. These are listed below, along with a value judgement on the progress made since then:

Improvement and development needs (Høeg, 1982; 1984)	Progress (1994) since 1982
Develop in situ testing techniques and improve interpretation of test results	Good progress has been made (e.g. Lunne et al, 1989)
Improve integration of geological, geophysical and geotechnical site investigation and use probabilistic method for investigation strategy and site characterization	Much remains to be done
Improve ability to evaluate seafloor slope stability and run-out distance	Marginal progress has been made
Include geotechnical design considerations to ensure safety of pipeline installations	Practice is now going in this direction

Improvement and development needs (Høeg, 1982; 1984)	Progress (1994) since 1982
Develop more rigorous analysis of dynamic soil-structure interaction for gravity structures; develop procedure to estimate permanent deformations due to cyclic loading	Improvements have been done (e.g. Hansteen and Høeg, 1994; Andersen and Høeg, 1992)
Improve ability to predict generation of excess pore water pressures due to cyclic loading (clays, sands and silts)	Improvements have been done (e.g. Andersen et al, 1992a; Andersen et al, 1994)
Use long foundation skirts in soft soils	Such installations not considered a problem any more
Investigate caisson installation procedures with the use of suction	Gullfaks C; suction anchors in sand (Tjelta et al, 1986; 1992; Tjelta, 1992a; 1994)
Plan, execute and follow-up field instrumentation and performance observations programs	Only few results have been published since 1982
Improve pile installation techniques, control and maintenance for large water depths	Progress has been made
Develop further the analysis and use of dynamic measurements of piles during pile driving	Much remains to be done
Obtain pile load-deformation behaviour from load test on oil conductors	Remains to be published
Perform load tests on long piles to study the "length-reduction effect"	Underway (recent pile conferences), more work needed
Obtain measurements of pile behaviour under a platform during storm conditions	Remains to be done
Improve practice of geotechnical site investigation and analysis methods for jack-up rigs	Much improvement done (e.g. van Langen and Hospers, 1992; Murff et al, 1992; Murff, 1994; Jostad et al, 1994)
Study static and cyclic engineering properties of silts, permafrost and calcareous deposits	Some progress has been made (Murff, 1987; Poulos, 1988; Røland and Høeg,1993)

Many of the needs identified earlier are still relevant today. Based on the earlier recommendations and in light of the progress made, the authors now propose the future most pressing needs. These are divided into four categories:

- on-going general issues
- specific geotechnical issues
- cooperation projects and requalification of structures
- funding of research

A challenge is also raised for the organisers of future BOSS Conferences.

On-Going General Issues. Much of the work underway is going in the right direction. The pursuit of present trends as listed below is highly recommended:

- Continue to extend the knowledge acquired to develop new concepts. Recent examples of such creativity are the use of skirts and suction for anchors and bucket foundations in clays and sands and for the spud cans of jack-up structures.

- Continue to duplicate in both laboratory and model tests as closely as possible the problem to analyze to grasp all factors that affect the behaviour. As the importance of model testing grows, owners should insist on "before the test" calculations to ensure "unbiased" predictions.

- Continue to learn from experience and to document through instrumentation. One cannot overstate the need and usefulness of instrumentation and performance monitoring for verifying hypotheses, evaluating new conditions, and providing the background for continued safe operation. Instrumentation results were one of the decision-making tools for continued operation of the Frigg CDP1 platform towards the end of its operation life (Lacasse et al, 1991; 1992). Well documented recalculations of failures that have occurred (e.g. McCarron and Broussard, 1992) are also very useful.

- Information Technology: a rational, modular and documented approach for the design of engineering software for the analysis of offshore structures is needed (Parnas et al, 1993). In a world of computer codes with many offers but few verifications, such approach would enable easier debugging and verification of the code and help avoid duplication. A database with the abilities and drawbacks of the better known computer codes on the market to solve different geotechnical and other problems should be established.

Specific Geotechnical Issues. The following issues are believed to be the most relevant and urgent:

- Develop improved methods to obtain geotechnical engineering parameters from the results of geophysical investigations

- New sites and new soils: future petroleum exploration suggest more complex soils, greater water depths, and different environmental conditions, with the need to develop data, databases, and static and cyclic behaviour patterns for:

    - calcareous and/or cemented sands and clays
    - silts and silty sands or clays
    - soils with hydrates, gas, and less than 100 % saturation
    - other conditions related to large water depths (e.g. oozes, pelagic clays)

- frozen or partly frozen soil in Arctic and sub-Arctic regions, including new design problems related to a freezing environment and iceberg scours

- Develop deterministic and probabilistic methods for analysis of stability of submarine slopes and run-out distance

- For piled structures, there is a need for:

  - pile-load deformation behaviour from load tests relevant for offshore conditions
  - establishing a better manner effects of rate of loading and cycling
  - documentation of skin friction and end bearing in sands with relevant pile load tests
  - use of results of instrumentation during pile driving to assess pile capacity
  - status and effect of pile plugging during driving
  - deterministic and probabilistic models for pile/soil failure

- Further documentation of the analysis procedures for jack-up structures in clays and sands

- Further development of calculation procedures for anchors and bucket foundations in sands

- Further development of procedures to calculate stresses on base and skirts, and redistribution of these stresses during storms, for gravity, bucket foundation and anchor skirted structures

- With respect to reliability analysis, the following geotechnical needs are seen:

  - reduce model uncertainty with good and relevant model tests
  - do series of probabilistic sensitivity analyses to identify significant aspects
  - prepare easy to follow application examples for the profession
  - obtain the probability of failure of "conventionally" accepted designs with today's deterministic calculations and work towards establishing a target probability of failure

<u>Cooperation Projects and Requalification of Structures</u>. As geotechnical engineers, we see the need for cooperation projects between the different specialties involved in offshore structure design:

- Dialogue among offshore specialists: at nearly all levels, there is a need for greater interaction between the geotechnical engineer and other disciplines of engineering: environmental conditions, hydrodynamics, structural analysis, operational conditions, and policy makers. The paper has stressed the importance of such interaction for reliability analyses and for safe and cost-effective structures. Multidisciplinary dialogue is also essential for requalification of structures and for the interpretation of performance observations: interpretation of soil-structure interaction response requires knowledge from both the geotechnical and structural engineer; reanalysis of foundation stability during a storm depends entirely on the loads derived from wave heights.

- Plan and accumulate multidisciplinary databases of case studies with high quality experimental and observation data. For example, well documented case studies after especially harsh events such as the hurricanes in the Gulf of Mexico, the analyses presently under the API umbrella on reevaluation of failures during Hurricane Andrew and the North Rankine piling experience, would be extremely useful if multidisciplinary assessments could be made.

Early platforms are now the first generation of structures to be subjected to requalification.

There is a need for improved record-keeping and storage of geotechnical related information. Lessons from the past show the frequent need for comprehensive data for a range of purposes, none the least is requalification (Murff et al, 1994).

- Throughout the years, performance data have been accumulated, but the data and their geotechnical content have not been fully exploited with respect to interpretation of soil behaviour and understanding of the soil-structure response. Such information has the potential of providing long-awaited answers to many aspects of soil behaviour or soil-structure response as they effectively represent model tests at a very large scale, and the results can probably be applied to other types of structures. It is recommended that structure operators allocate resources to promote an adequate exploitation of the existing measurements. One should establish a data bank of the information and instrumentation that exist and set up a priority for the interpretation of the results on the basis of their expected usefulness.

- There exist a large database of platform upgrade case histories which could be exploited, but have not been. Both the decision-making process and the upgrade solution selected could be documented. It is highly recommended that projects be undertaken to establish this reference database of foundation upgrades.

  Documentation of upgrade solutions is also essential: one drawback today is that seldom does one find out whether the upgrade solution chosen really works out, since the design (most critical) conditions are probably not experienced after the upgrade. One only knows that the adverse conditions of concern before the upgrade is probably averted. Means of evaluating the effectiveness of the strengthening solution adopted are needed. Hopefully in the future there will be less need for remedial actions and upgrades as the designs should get better.

- Contribution to writing of codes, standards and guidelines: through good interaction, all disciplines should contribute to the development of standards based on reliability concepts. In some ways, other branches of engineering seem to adapt with less difficulty than the geotechnical profession to formulations of regulatory restrictions and codes. On the other hand, geotechnical specialists believe that their state of knowledge is gradually moving towards less uncertainty. The details of the geotechnical procedures for foundation assessment and the large number of parameters and relevant factors are such that it is important to keep flexibility in the design rules and to avoid imposing too restrictive constraints.

Funding of Research and Development. Even with the pressure of daily problems and low oil prices, operators, research organisations and regulatory agencies need to ensure that funding for research and development (R & D) is available to solve tomorrow's problems. Due to low oil prices, research funding has become increasingly short-term and specific-oriented. Reducing R & D is not the solution to dwindling resources, and it is important to invest in long term research efforts. Research and development activities should also be organised to ensure that technology transfer actually takes place. There is also a need for improved interaction between researcher, practitioner and contractor. Only in cases where research and development and advisory activities strengthen each other will the solutions prove to be optimum.

Future BOSS Conference(s). Each year, there are many worldwide conference offers each year related to offshore structures: BOSS, OTC, OMAE, ISOPE, SUT, CMGC plus a number of specialized conferences. The advantage of the BOSS conference is that it focuses on the Behaviour of Off-Shore Structures. If the BOSS conference is to continue to be successful, the contributions at the conference and the dissemination of the results should be made even more accessible to interested parties from the industry.

SUMMARY AND CONCLUSIONS

Reliability Analyses

The most important contribution of reliability concepts to offshore geotechnical engineering is increasing the engineer's awareness of the existing uncertainties and the consequences of these. Reliability analyses provide a consistent framework for comparing different designs or analyses and distinguishing the contribution of each of the uncertain variables to failure probability.

Reliability analyses are especially useful in (1) establishing an estimate of the safety margin and probability of non-performance given the uncertainties (which a deterministic safety factor or partial coefficient cannot do), and (2) documenting which parameters are most significant. This enables the designer to define where efforts should be directed to reduce uncertainties and thereby probability of failure. Whereas the failure probability numbers themselves are not absolute numbers, the reliability analyses are especially useful for comparing the significance of different design aspects, and as a tool for decision-making. Of importance though, human error, which is probably the cause for the majority of all mishaps, is generally not accounted for in reliability analysis. The risk associated with human error can be minimized only by improving the quality assurance/quality control systems.

The use of probability theory should improve the design codes, and hence lead to more cost-effective structures. Probabilistic analyses should be used to verify the implicit failure probability of "conventionally" accepted designs, thus "calibrating" the safety factors/coefficients for different structures and soil conditions. This would also lead to an improved definition of the target reliability.

The results of geotechnical reliability analyses should be used as a complement to the deterministic analyses, with due respect paid to the model uncertainties. Probabilistic analyses cannot however improve "poorly selected" data or improve knowledge in the case of insufficient data or if important failure mechanisms have been overlooked. The probabilistic analyses will give insight in the consequences of large uncertainties, but wrong input data will give wrong results, just as for deterministic analyses.

The advance in probability theory is such that the implementation of the first-order reliability method is very simple and requires modest computer resources. Doing reliability analyses is therefore an increase in knowledge with little increase in costs. It is hoped that the gradual acceptance of reliability analyses now seen in the geotechnical profession will continue and even be enhanced in the next few years.

Future Challenges

The future poses many challenges in offshore geotechnical engineering, where multidisciplinary cooperation projects, requalification of structures, and extended use of reliability analysis are only a few of these.

Whatever the difficulties of geotechnical analysis, the need for quantitative risk and reliability assessments will not disappear. Whitman (1984) described, a bit facetiously, the application of reliability analysis in geotechnical engineering: "(1) Not enough is known about soil or rock and its behaviour in situ to do an accurate evaluation of risk; (2) geotechnical engineers will be criticized no matter how they do the analysis; but (3) geotechnical engineers must proceed just the same to make such studies." Doing so in a meaningful and responsible manner is a major challenge to the profession.

Specific challenging geotechnical issues include:

- Develop correlations between geophysical results and geotechnical parameters
- Develop data, databases, and static and cyclic behaviour for new soils and new soil conditions: calcareous and/or cemented sands and clays, soils with hydrates and shallow gas and Arctic conditions
- Improve offshore pile design by investigating (1) pile load tests relevant for offshore conditions, (2) skin friction and end bearing in sands and (3) the use of results of instrumentation during pile driving to assess pile capacity
- Further development of calculation procedures for jack-up structures in clays and sands, for anchors and bucket foundations in sands, and for stresses and stress redistribution during storms on base and skirts
- Develop analysis methods for stability of submarine slopes and run-out distance
- Increase the use of reliability methods of analysis in geotechnical calculations. Improve following aspects: reduce model uncertainty with good model tests; prepare easy to follow application examples for the profession; and obtain the probability of failure of "conventionally" accepted designs with today's deterministic calculations

In closing this paper, attention is also drawn to the following challenges for the entire offshore community:

- Multidisciplinary databases of case studies with high quality experimental and observation data, and improved record-keeping and storage of geotechnical related information. Structure operators should allocate the required resources to promote an adequate exploitation of the existing measurements.
- Improve the dialogue and understanding among the different engineering specialists working on the design of offshore structures. The preferable way to do this is through joint-industry research programmes, with contributions from industry, research organisations and regulatory organisations.
- A large database of "exploitable" upgrade case histories is available. Both decision-making process and upgrade solution could be documented. Projects should be undertaken to establish a database of upgrade references.
- Develop codes and guidelines using reliability analysis concepts and results, in cooperation with other offshore design expertises and with the understanding and contribution of regulatory organisations.
- Funding of research and development: even with daily pressures and low oil prices, operators,

research organisations and regulatory agencies need to ensure that funding for research and development is available to solve tomorrow's problems. Interaction between researcher, practitioner and contractor should be enhanced. The solutions will be optimum only when research and development and advisory activities strengthen each other.

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DeepStar II: Continuing Industry Cooperation For Technology Development

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1. INTRODUCTION

DeepStar is a Texaco-administered consortium of 17 offshore oil/gas producers (participants) and 46 supplier/vendor organizations (contributors). The program is consistent with Texaco's vision for development of the deepwater Gulf which is closely tied to the concept of cooperation and evolution of a synergistic relationship with other members of the oil community. In today's competitive business environment, development of the deepwater Gulf will be difficult, if not impossible, outside a jointly funded, cooperative effort. This partnering may take many forms; it can include joint exploration programs (something already common in the Gulf) and joint research projects (JIP's), but it can also be expanded to areas in which the industry does not now normally cooperate - joint research into regional development strategies and universal technology needs, joint development of hardware (and hardware interfaces), software, and other new/innovative tools, joint ownership of central processing facilities, production sharing operations, and other innovative concepts. The DeepStar project is a major step in the right direction with a number of major operators considering a common development strategy for the deepwater of the Gulf. This cooperative project also maximizes the value of the respective operator's limited resources for developing new technology which will be needed to make deepwater production commercially viable. The DeepStar project, now in its second year of operation, is aimed at developing technology to facilitate commercial development of deepwater tracts, using subsea technology. Participants in the Phase II program are shown in Figure 1.

Joining together in this industry cooperative effort, progress is being made toward the common goal of having an economic deepwater production strategy and the necessary technology and equipment ready for field use by the latter half of this decade. The major technology goals for DeepStar include evolving a development concept capable of:

- Production in water depths down to 6000 feet,
- Accommodation of a broad range of produced fluid properties and rates

DeepStar II Participants

Texaco	Exxon
BP	Agip
Mobil	Elf - Aquitaine
Shell	Marathon
Chevron	Conoco
BHP	Phillips
Petrobras	Deeptech
Kerr - McGee	Arco
Amoco	

Figure 1

from various reservoir types,

- Subsea satellite production to host platforms up to 60 miles distant (platform depths 600-800 ft),
- Installation of the subsea facilities in a staged program,
- Minimum maintenance requirements for the subsea facilities,
- Remote operated vehicle installation and maintenance capability, and
- All production operations remotely controlled from the host platform (or potentially, in early field life, from the overhead drilling vessel).

2. COOPERATIVE TECHNOLOGY DEVELOPMENT

The current business climate in the US has seen a considerable shift of emphasis in investment capital going overseas where better rates of return are anticipated. Thus, domestic production operations have been in a down-sizing mode for the last several years. Similar reductions are also being made in the service industry that supports production operations. This imposes an additional challenge on development of deepwater opportunities in that these projects cannot just be technically viable, but they must be commercially attractive as well. Preliminary DeepStar study work has indicated that world-class returns can be made on investment from deepwater plays provided that the appropriate technology is available, the development concept is one that links capital expenditure with increases in production, and risks are minimized.

The US domestic oil industry of the 90's has been characterized by a number of other major trends:

- The down sizing of the major operators has resulted in fewer people to implement ongoing operations, this in turn, requires increased productivity from the remaining personnel.

- Lower product prices resulting in an ongoing need to lower operating costs.

- Limited suite of investment opportunities which has increased the importance of new, and potentially significant, deepwater reserves.

- Limited funding available for research which has resulted in the formation of strategic technology partnerships or alliances.

All of these factors tend to focus the industry on the need for improved technology. When the price of oil is low, the industry can only rely on new technology to increase the margin between the cost of producing oil and its selling price. In a low oil price world, the need for technology becomes preeminent.

The cost to progress new technology through to "field proven" or "project ready" status, however, is considered prohibitive for any one company to undertake in today's economic climate. Assuming that many of the hardware components evolve through prototype systems requiring field testing and performance evaluation, a considerable lead time may also be necessary which could significantly impact the implementation of new projects if the testing program is not progressed rapidly. The desired technology will probably only evolve if it is undertaken as a cooperative industry effort; however, it will first be necessary for the industry to agree on which is the appropriate technology to progress. This is an area that the DeepStar project is providing a valuable role as it allows the participants to focus on a deepwater development strategy and prioritize technology based on the agreed DeepStar concept. A cooperative feed-back dialogue by the project participants will also help to keep vendors/ manufacturers appraised of the anticipated future deepwater equipment/services needs of the oil industry.

3. DEEPSTAR DEVELOPMENT STRATEGY

To reduce risk and to minimize initial capital requirements, the DeepStar concept employs a staged development strategy. It also focuses on a system approach versus random component designs. The three major stages of the development approach are as follows:

Stage 1 - Exploration/Delineation Drilling

Development stage 1 consists of prospect appraisal during a field's exploration and delineation to confirm the type and extent of a field's reserves and determine initial production traits (such as, probable fluid characteristics, flow rates, pressures, and composition). Assuming drill-stem tests are encouraging, a decision may be made to complete these exploration/delineation wells with equipment suitable for longer term testing using three to five wells as producers during development stage 2.

Stage 2 - Evaluation/Early Production

Development stage 2, or the evaluation/early production stage, will confirm the basic operability of the production system with relatively low capital commitment. At the same time, the produced oil and gas will both furnish revenue to help defray stage 2 costs, and also provide still more (longer-term) reservoir information to augment the stage 1 drill-stem tests. During this stage, the operator would produce the three to five delineation wells to determine if field performance is sufficient to warrant full field development. If, during stages 1 or 2, a conclusion is reached that the field is not worth developing, then an abandonment decision may be made. Under the circumstances, the objective is to minimize financial loss, assuming production revenue is insufficient to provide a net profit.

Stage 3 - Full Field Development

Stage 3 development depends on the reservoir size and type. For reservoirs requiring only 10 to 15 producing wells, a small development concept is appropriate. For 30 to 40 wells, a large development effort would be pursued. Data and experience gained in earlier stages would be employed in decision-making regarding the optimum stage 3 development approach.

Long Offset Subsea Tie-Back Systems

One of the critical assumptions for this study was that the field would be offset a significant distance (25 to 60 miles) from a shallow water host platform. The system schematic for such a subsea tie-back development is shown in **Figure 2**. Under the DeepStar concept, initial

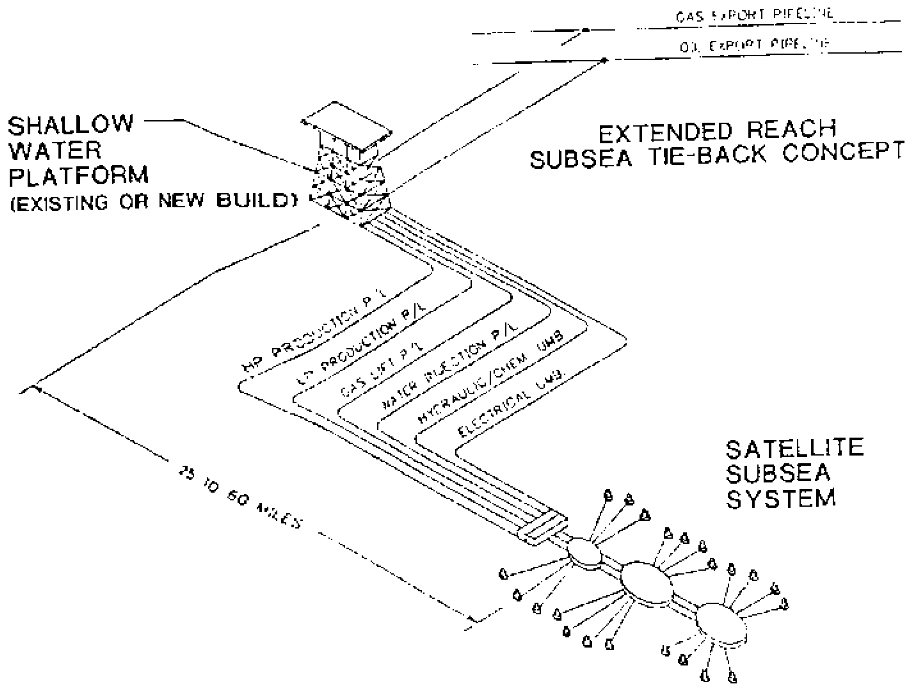

Figure 2

deepwater subsea production operations will attempt to use existing platforms as host processing facilities. As confidence in the deepwater prospect is established, a staged expansion of the subsea facilities would be initiated as described above. Such an expansion would most likely require the construction of a new dedicated processing center. Once established, this center would be capable of handling production from a number of other deepwater prospects within a 60 mile radius (**Figure 3**).

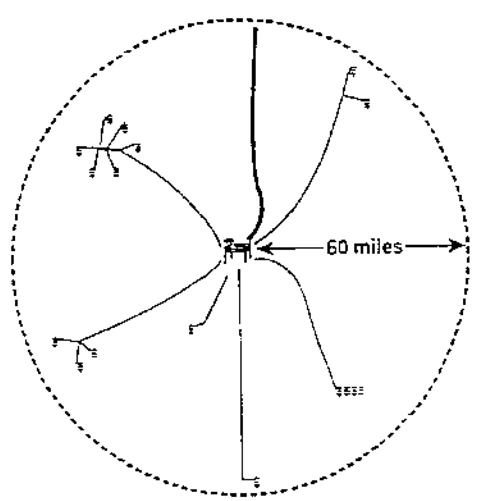

Figure 3 - Central Processing Center

Subsequent developments in the area will be achievable at a reduced cost (estimated at 75 to 80 per cent of original cost per barrel) compared to the first project, which established the processing center. The existence of new deepwater infrastructure will facilitate the commercial development of small fields (50MMBOE or less) which would normally not be considered economically attractive on their own. An opportunity exists here for the industry again to cooperate and establish joint processing centers that could service an entire region (Figure 4). A joint industry processing center approach could still prove attractive even if the

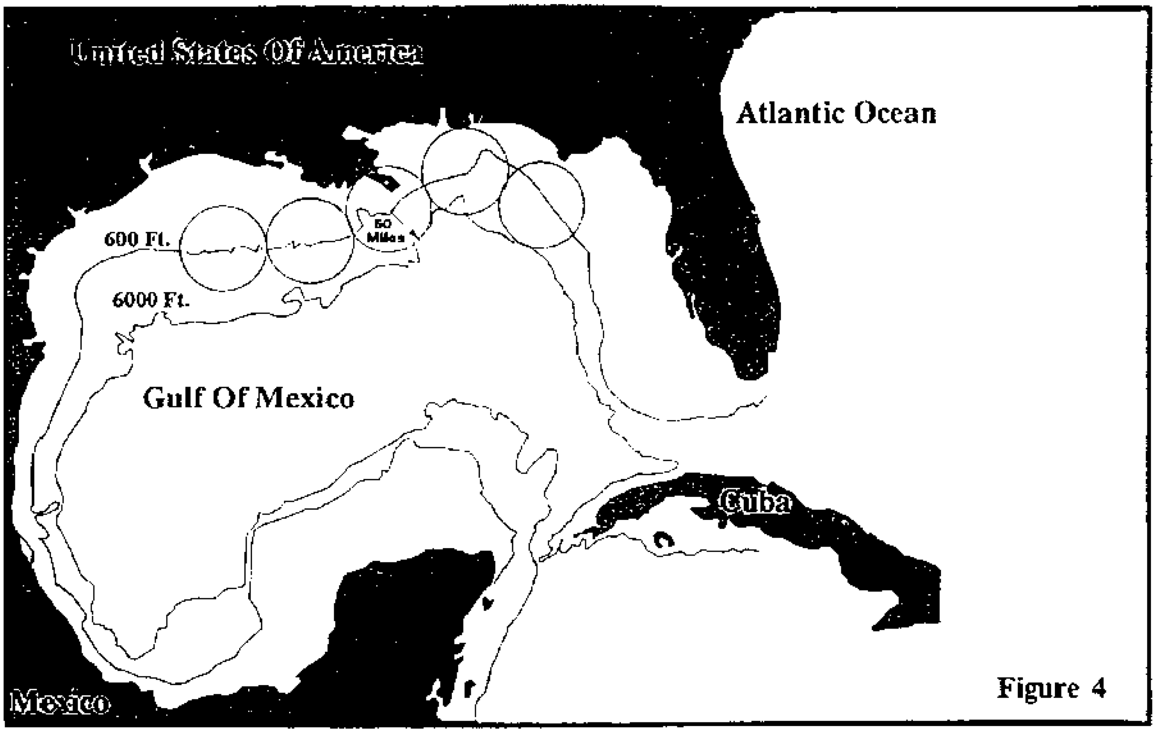

Figure 4

development concept adopted by several of the venture operators did not involve subsea production wells.

4. DEEPSTAR PHASE 1 TECHNOLOGY STUDIES

The DeepStar team documented and evaluated the capability, cost and availability of basic components and subsystems that would potentially be required for a remote subsea development, through a series of foundation studies, which included:

- Multiphase subsea pumps and subsea separators
- Multiphase and single-phase pipeline systems
- Control systems and umbilicals
- Chemical injection systems
- Templates and manifolds
- ROV systems
- Diverless/guidelineless modularization requirements, and
- MODU production support operations and safety.

The results of specific investigation into these areas provided recommendations as to the best types or family of components for use in deepwater subsea systems to meet an actual field development within the next two to five years.

5. DEEPSTAR PHASE 2 WORK PROGRAM

The work program for 1993-94 of the DeepStar project is broken into 10 major technology areas: regulatory issues; multiphase flow and equipment; subsea controls issues; production risers; MODU and mooring; flowlines and umbilicals; reservoir performance and engineering; manifolds/trees and connection systems; produced fluids; and drilling and completion issues. Work in each focus area is overseen by a chairman and a technical committee consisting of representatives from each of the participating companies (**Figure 5**). The following engineering organizations have been contracted by the project to perform a number of specialized technology scoping studies:

- Intec Engineering (program technical advisor)
- Aker Omega
- Paragon Engineering
- H O Mohr Engineering
- Loes & Associates
- Oceaneering Prod. Systems
- Stress Engineering
- Sonsub
- MCS International
- Project Associates Inc.
- Sea Troll Engineering
- Brown & Root Seaflo
- DNV Technica

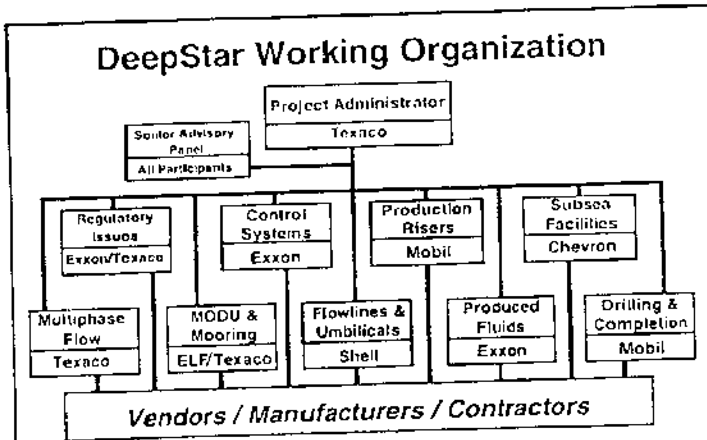

Figure 5

One of the unique aspects of DeepStar is that participants are sharing prior technical research in an effort to "leap-frog" technology development in these key focus areas and to do so at minimum cost. The following is a very brief synopsis of progress to-date in each of the technology development areas:

Regulatory Issues - A number of regulatory related barriers exist for development of the deepwater Gulf of Mexico. Representatives of the DeepStar participant companies have been meeting on a monthly basis with the Minerals Management Service (MMS) to discuss technology issues and current regulations in an effort to identify areas where existing regulations are not in step with technology capabilities. Areas of discussion have included production monitoring and testing, underwater safety valves, system shut-down requests, suspension of production, and subsea installation, maintenance and repair. Extended well test operations have also been the subject of discussions based on a special report the program issued on this topic.

Multiphase Flow & Equipment - Texaco has released to DeepStar participants the results of an in-house transportation options study that focused on the pressure boosting and transport of multiphase fluids over long distances (up to 60 miles) in extreme water depths (2000 - 6000 ft). This work formed the basis for further joint study work by the DeepStar group on issues related to multiphase transport and the options open to the industry to add energy to multiphase fluid systems. Many of the major technical hurdles associated with deepwater production revolve around the challenges that arise from production in the cold environment associated with deepwater. Examples include produced fluids problems such as hydrates and paraffins, and the phase behavior of the fluids being transported.

Initial study work focused on the Gulf of Mexico and showed that:

- Reservoir depletion through natural flow is possible for a period of time, depending on reservoir and fluid properties. The period of time is likely to be in excess of that required for the initial reservoir evaluation/early production stage of a DeepStar type development.

- An economical method of controlling hydrates will be essential for any extended reach development producing significant quantities of water.

- Hydrates may be controlled either by prevention of hydrate crystal formation or by controlling agglomeration of the hydrate crystals once formed. The method of hydrate control will be either by chemical, thermal or mechanical means, and the method used will have a major impact on the type of multiphase flow system that can be used, and vice versa. This arena of work promises to be one of the key areas of focus in ongoing DeepStar activities.

The multiphase flow issues that impact deepwater system configuration and operation are being documented in the Phase II program in the form of logic decision flow diagrams to help focus and guide the conceptualization of future developments.

This committee is being supported by contributor representatives from Bardex, Paragon Engineering, Southwest Research Institute, Battelle and Leistritz.

Control System Issues - The purpose of this committee is to evolve the architecture and direction of control equipment development for the next generation of deepwater control systems. Areas investigated in the Phase II program included basic control system architecture, downhole and production sensors, electric and hydraulic connectors and qualification testing of a number of these connectors, umbilical improvements, and interface of control systems with subsea pumps, separators and meters. This group has met on several occasions with representatives of the various vendors and contractors that are acting as contributors to the DeepStar work. A scope of work has been issued to interested parties identifying areas of concerns, technology requiring further development, and basic questions the operator community has concerning system capabilities for deepwater deployment.

This committee is being supported by contributor representatives from FSSL, GEC, Hydril, Ocean Design, Marston Bentley, Pirelli, Tronic, Multiflex and Koomey.

Deepwater Production Risers - This committee is attempting to focus the industry's deepwater riser development efforts on a small number of promising production riser concepts. These include flexible, rigid/buoyant, steel catenary, composite, and hybrid approaches. The program for 1993-94 has been to compare and perform a screening analysis of possible options. In the 1994-95 work program the surviving concepts will be developed and modelled in greater detail, with a possible progression to wave tank testing or hardware development. To assist in their analysis work, the committee has a clearly defined design basis complete with environmental conditions for a variety of potential deployment sites in the Gulf of Mexico.

This committee is being supported by contributor representatives from Coflexip, Wellstream, Cooper, and Hydril.

MODU & Mooring - One of the key aspects of DeepStar will be the ability of existing drilling vessels to simultaneously drill, moor, and accommodate limited production functions in deep water. Study efforts by this committee are targeted at addressing issues such as these, in addition to exploring innovative mooring system designs that could dramatically lower the cost of deepwater mooring systems.

The first part of the effort concentrated on evaluating the ability of existing drilling semi-submersibles to moor and drill in water depths between 3000ft and 6000ft. Given that this is economically feasible, the next step was to add minimal process facilities for extended well testing/early production and finally use the vessel to produce the field long term. Mooring design criteria for both extended well testing and long term production are more onerous than for drilling alone and may require the modification or replacement the existing mooring system. The additional deck load due to the modified mooring system, deepwater drilling equipment and consumables, production risers, and the process system can easily exceed the buoyancy capacity of existing drilling vessels. The vessels, therefore, may require structural upgrades as well, to increase their buoyancy and deck load capacity.

The second part of the committee's study concentrated on cost reduction measures. These included alternative mooring designs such as taut leg systems or DP-assisted mooring, synthetic mooring lines, process system weight reduction, and the effect of downtime due to disconnecting and retrieving the drilling riser.

This work effort is being supported by several contributors. Reading & Bates, Sonat, and Sedco-Forex are evaluating vessel and drilling capabilities and determining upgrade requirements to accommodate increased water depth, deck load and space requirements. Baker-Hughes is evaluating process system alternatives and Imodco is evaluating FPSO and mooring system options.

Flowlines & Umbilicals - This committee is charged with identification and development of innovative, low cost methods of flowline/pipeline installation and repair as well as development of alternative umbilical concepts for ultra deepwater. The committee is currently at work on a number of topical concerns. These include two alternatives for pipeline repair in water depths to 6000 ft, new (low cost) J-lay techniques and tooling, pigging studies for deepwater systems, and fabrication/testing of umbilicals manufactured from alternative carbon steel and titanium materials. The committee also established a database and map of the existing infrastructure and associated capacity availability that could potentially be used to support new deepwater developments in the GOM.

This work effort is being supported by contributors including OPI, Heerema, Sonsub, Multiflex, Pirelli Cable, Stena Offshore, Marston Bentley, and Oceaneering.

Reservoir Performance & Engineering - This committee's activities are focused on identification and documentation of characteristics of deepwater reservoirs in the Gulf of Mexico. Characteristics of deepwater reservoirs, including their size, productivity, and fluid make-up, will have a direct bearing on the economic viability of deepwater development. The participants in DeepStar are pooling data collected to-date on deepwater reservoirs in an effort to understand better what design parameters should be used in planning deepwater developments.

Manifolds, Trees & Connections - The focus of this committee includes all aspects of subsea facilities or hardware. This includes preferred facility arrangements (such as template vs. manifolds with clustered wells or satellite wells), interface connections, installation considerations, standardization of equipment and interfaces, manifold configurations, tree layout, intervention, maintenance, and repair. The committee is also attempting to evolve and adopt standard designs for workover or completion equipment, trees, and manifolds.

Efforts within this committee are being assisted by the following contributors: Heerema, Cooper, Hydril, National Oilwell, FMC, ABB Vetco, Wellstream, and Coflexip.

Produced Fluid Problems - Second only to reservoir questions, produced fluids problems are seen as the major barrier to economically viable production from the deepwater Gulf. Of primary concern to the participants is paraffin production and deposition, followed closely by hydrate formation and asphaltene production. The participants are evaluating data on these fluids problems in an attempt to identify where to focus expenditure of joint funds. Alternative methods for handling produced fluids problems in the production system, including thermal, chemical, and mechanical treatments, are being evaluated. As is the case with the reservoir committee, the produced fluids committee is collecting data on the different produced fluids problems that have been encountered in the deepwater Gulf. This data will be used to focus the committee's activities on those aspects of the problem that will most favorably effect the potential for future development. One of these areas is the need to develop standardized produced fluid test procedures and the potential need for new tools to obtain improved (or more representative) samples from exploration wells. The committee has issued a letter of inquiry to a number of manufacturers in the downhole tool industry with the intention of developing a standard tool for use in taking downhole fluid samples.

The committee has focused on remediation alternatives for produced fluid problems due to the limited ability of the industry to adequately model or predict these problems. A comparative analysis is currently being undertaken to identify the effectiveness and consistency of a number of new modelling techniques.

Drilling & Completion Issues - The single largest expenditure for deepwater developments will be well drilling and completion costs. This activity alone accounts for approximately 40 and 70 per cent of the capital cost of deepwater developments. When viewed in the light of total development costs, this could exceed $700 million for a large development. Cost control and reduction is critical to the effort to make the deepwater Gulf commercially viable. The participants are focused on identifying those actions that can be taken to reduce drilling, completion, and intervention costs.

Current committee activities are centered on generating an efficient deepwater well drilling/casing design and a corresponding completion design. Load impacts on the drilling vessel have been identified and alternatives for reducing vessel loading are being explored. Completion component reliability is being assessed in an effort to minimize well workover requirements and improve safety.

Participants are being assisted in this area by the following contributors: Reading & Bates, Sonat, Sedco-Forex, Profco, CTC International, Baker Hughes, Halliburton, Hunting Oilfield, Hydril, OSCA, and Bardex.

6. CONCLUSION

There are many ways for the oil industry to cooperate in a manner that benefits all. Texaco believes that it will indeed take a cooperative effort to facilitate the commercial realization of the deepwater of the Gulf. What is required is a common vision on the best way to proceed. We are enthusiastic that DeepStar may provide that common vision as well as the vehicle that moves the industry forward into the new deepwater frontier. DeepStar is redefining the way that major operators, suppliers, and government agencies can work together to promote development in technically challenging environments such as the deepwater Gulf. The program has now been operational for over two years. As can be seen from this report, many technology issues critical to the progress of deepwater development are being addressed and innovative development concepts and approaches are being evolved.

PETROBRÁS TECHNOLOGICAL INNOVATION PROGRAM ON DEEPWATER EXPLOITATION SYSTEMS - PROCAP - 2000

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ABSTRACT

Petrobrás, the Brazilian State owned oil Company, celebrated its fortieth anniversary as one of the leading companies in the world's oil patch. In December 1992, Petroleum Intelligence Weekly tagged Petrobrás as the world's fastest - growing oil company over the past few years. This expansion is directly linked to the Company's cutting edge in deepwater exploration and production technology.

Petrobrás has been making important oil strikes in waters deeper than 400 meters in the past few years. This exploratory success is not only mainly reflected by the Albacora (1984) and Marlim (1985) giant fields but also the discoveries of other deepwater fields in the Campos Basin.

The reserves in those fields, located in waters of 400 to 1000 meters (classified as deep) and those in depths over 1000 meters (classified as ultra-deep), account for 64% of total reserves in Brazil. The importance of deepwater technology is also stressed by the fact that over 60% of the potential oil discoveries (future new discoveries) will be in deep and ultra - deep waters. These figures demonstrate that the production of its deepwater fields is a vital issue for Brazil.

In order to face technological challenge of producing oil in deep waters, Petrobrás established a special program named PROCAP, aiming at maximizing the technological capability of the Company on deepwater oil exploitation between 1986 and 1991.

The excellent results obtained by that program encouraged Petrobrás to create a new one called PROCAP - 2000 (Technological Innovation Program on Deepwater Exploitation Systems), far more daring than the previous one, that intends to change the current way of producing in such water depths.

This paper presents the driving forces to go beyond 1000 meters water depth, a review of the first PROCAP and its main results achieved, besides a detailed description of the PROCAP -

2000, including the goals, the strategies and the systemic projects considered essential to boost the development of deep and ultra - deepwater oil and gas production in Brazil.

KEYWORDS

Deepwater; Exploitation; Technology; Strategies; Brazil

INTRODUCTION

Campos Basin, the main petroleum province in Brazil, is located offshore Rio de Janeiro State, on the southeast region of the country. Its area covers 110 sq. km. ranging from 50 m to 3,400 meters water depth (figure 1).

The first production system installed in this basin began its production in 1977. Today, seventeen years later, the overall production system comprising 14 fixed platforms and 13 floating systems distributed among 33 oil fields which account for the production of 421,000 bpd (which stand for 63 % of the domestic production) and 7,9 million daily cubic meters of gas (which represent 40 % of Brazilian gas production). The accumulated production has far overcome the one billion barrels of oil milestone. This production is handled and exported to shore through over 2500 km of oil and gas pipeline networks.

Petrobrás's experience of 16 years using floating production systems (FPS), shown on table 1, has allowed the evolution of this production system originally conceived as a temporary solution for anticipating production of offshore fields to become a highly recommended option to the production of marginal and deepwater fields. The main deepwater projects employing this well proven technology to be implemented in the next years by Petrobrás, are summarized on table 2.

With respect to Subsea Trees, which consist of a group of valves settled on the sea floor aiming at controlling the flow rate of the well, Petrobrás has up to now 192 installed and 42 planned to be installed between 94 / 95 that will correspond to an overall of 234 Subsea Trees. This figures represent about 30 % of the total subsea completion all over the world (table 3).

Figure 2 shows the successive water depth world records that have been established by Petrobrás in subsea completion since 1979 , culminating with the MRL - 04 well, which is the current world record located at the remarkable water depth of 1027 meters.

THE IMPORTANCE of DEEPWATER PRODUCTION to BRAZIL

At the end of 1993, the total volume of both exploitable and non-exploitable crude oil reserves in Brazil came up to 7.04 billion barrels and about 285 billion cubic meters of natural gas. From that total, the oil reserves located onshore represent 14.1 %; the ones located in shallow waters, below 400 m, account for 22.5 % and the ones in deep water, between 400 and 1000 m, for 43.8 %. The oil reserves situated in depths over 1000 meters, classified as ultra-deep waters, represent 19.6 %, but in this case, it is now necessary to develop technology to produce in such water depths. Summarizing, the oil reserves located in both deep and ultra-deep waters stand for about 64 % of the Brazilian exploitable and non-exploitable total reserves while the natural gas reserves placed in these water depths account for 26 % of the total. The importance of deepwater technology can be also emphasized by the fact that according to Petrobrás Exploration staff over 60 % of the potential oil and gas discoveries, that is, new fields where favorable characteristics indicate the existence of hydrocarbons, will be in deep and ultra deepwaters,. These figures reveal that Brazil's future regarding oil production is strongly related to offshore fields located over 400 m water depths.

During 1993, Petrobrás achieved an accumulated oil production of 244 million barrels, corresponding an average daily production of 668,000 barrels. This production is not enough to meet the Brazilian market demand which is nowadays of 1,2 million bpd. From the total produced , 28,4 % came from onshore fields, 54,8 % belonged to shallow waters and 16,8 % was produced in deep waters.

Figure 3 shows the oil production potential forecast up to year 2003. As one can see, it is a must for Petrobrás to work out its deepwater fields in order to increase its domestic oil production in the next 10 years. Otherwise, this increase would not only be unfeasible but also the oil production would actually drop from the current 710,000 bpd to about 600,000 bpd. In 2003, the estimates indicate that Brasil's oil production will be able to reach 1,526,000 bpd and also that about 60 % from this production will come from deep waters. So, Petrobrás would jump from today's 17% up to 61 % by the year 2003.

From those figures expected for the near future, one can easily conclude that Petrobrás is on the way to substantially increase its offshore activities by the end of the century. The amount of the reserves to be exploited during this period is two times as big as the amount of the reserves already developed.

THE FIRST PROCAP

The economic significance of the deep water reserves determined the creation, in 1986, of Petrobrás Technological Development Program on Deep Water Production Systems - PROCAP . The main objective of this program was to improve the Nation's technological expertise in oil and natural gas production in waters as deep as 1000 meters, aiming at the Albacora and Marlim field developments.

The program also aimed at :

- Consolidating Petrobrás operational experience, mainly in floating production systems (FPS) ,to achieve cost reduction and reliability improvements.
- Extending shallow waters offshore technology to deeper waters.
- Developing new alternatives to improve deep water oil exploitation.

The PROCAP was carried out in 6 years, from 1986 to 1991, and undertook 109 interdisciplinary projects. A summary of the projects is shown as follow :

– Mooring Systems (8 projects)

• Design criteria, mathematical models, software, fatigue behavior, development of component for mooring lines (metallic and non - metallic);

– Semi - Submersible Hulls (1 project)

• Quality control of hull construction;

– Production Facilities (4 projects)

• Equipment weight and size reduction, electrical system stability;

– Risers (7 projects)

• Design criteria, mathematical models, software, large scale monitoring, development of rigid or flexible riser elements, to be used in drilling, production and completion operations;

– Wet Christmas Trees (2 projects)

• Development of WCT for water depths up to 1000 m;

– Manifold / Template (9 projects)

• Design criteria, mathematical models, software and development of manifold / template components;

– Subsea Pipelines (7 projects)

• Pipeline repair using ROV, laying methods, hydrates formation problems, multiphase flow, heavy oil flow;

– Well and Reservoir (10 projects)

• Directional drilling, formation damages, gas lift in deep water, kicks control, downhole subsea safety valves reliability, control of sand production ;

– Structures (9 projects)

• Design criteria, mathematical models, software, thick plate welding, vibration monitoring, cathodic protection, costs reduction program for offshore structures ;

– Process Ships (3 projects)

• Design criteria, mathematical models, multipurpose swivel for dynamic positioning ships in production activities;

– Remote Operated Vehicles (6 projects)

• Development of special tools for ROVs;

– Multidisciplinary Projects (28 projects)

• Ocean-meteorological data, soil structures, oil properties, semi-submersible design and large scale monitoring, hiperbaric center, anticorrosive protection, hydroacoustic signal transmission, hyperbaric welding ;

– Innovative Systems (15 projects)

• Subsea multiphase pumping, semi-submersible with dry completion, compliant towers, tension leg platforms, subsea separation systems.

Table 4 shows the selected systems studied in the first PROCAP. Petrobrás dedicated about 80 % of total human available resources to the alternatives based on technological extension, that is, those that had already been used in shallow waters but still needed further developments of some components or subsystems in order to be applied in deep waters. These systems consist basically of either semi - submersible platforms or ships equipped with a process plant and a set of subsea equipment. The wells are drilled, completed and have the subsea trees installed .The produced fluids are sent directly to the platform or through subsea production manifolds by means of flexible lines. This flow is separated in the process plant and the oil is pumped either to the tanker that is anchored in a monobuoy or to another platform located in shallow waters. The produced gas is normally compressed to shore.

The Floating production systems (FPS) based on semi - submersible for water depths up to 1000 meters have Petrobrás's preference for the following reasons:

- To provide a reduced time for both construction and installation ;
- To allow proven technology systems utilization such as semi - submersible platforms, Subsea trees, flexible risers and flowlines among others;
- To make possible drainage grid with flexibly spaced wells from the use of subsea manifolds ;
- To enable an available drilling unit conversion at low cost;
- To provide both high flexibility and production units re-utilization opportunities;
- To enable the unit's removal from the site at the end of the field's exploitation;
- To provide low sensitiveness to water depth variations

Some favorable aspects of those systems for the use in Brazil are:
- Existent environmental conditions;
- "Smaller air - gap" structures for operational conditions;
- Structure behavior under fatigue;
- Both proven operational safety and reliability.

In order to make feasible the production up to 1000 meters water depth in Campos Basin using that technology, the first PROCAP studied in details the following important points:
- Semi - submersible weight reduction (production facilities and hull) - specific design and drilling to production conversion;
- Platform positioning and mooring systems ;
- Subsea completion and subsea connection systems (pull in) ;
- Subsea production equipment such as subsea trees, wet and atmospheric manifolds, template - manifolds;
- Rigid and flexible risers and flowlines;
- Monitoring and remote control systems ;
- Installation, maintenance, retrieval and inspection of subsea equipment.

In addition to the developed projects related to technology extension, the first PROCAP dedicated about 20 % of its total human resources to the study of Innovative Systems.

These systems are the ones Petrobrás has not used so far, but they were considered attractive alternatives for our deep water oil fields.

In the innovation technology projects, the following alternatives were studied :

- Compliant Towers ;
- Tension Leg Platforms (TLP) ;
- Semi - Submersible with dry completion ;
- Subsea separation systems ;
- Subsea multiphase pumping systems.

The Brazilian technological community - universities, engineering consultants, industries, science and technology centers - came up with important contributions to these projects. The international community also played a key role through Joint Industry Projects, service contracts, technology transference programs, cooperative agreements, consultancy and in - service training (figure 4).

During the whole program, ended by December 1991, PROCAP expenditures came up to US$ 70 million. A total of 400 Petrobrás's experts and over 1000 staff members from other institutions were involved, representing around 200,000 man / hours per year.
As a major result, full technological capability through the floating production system based on semi - submersible at water depths up to 1000 meters was acquired. Main deep water accomplishments obtained by the program in relation to production systems are listed on Table 5.

Figure 5 presents the result of preliminary analyses regarding the application range of Stationary Production Units for Campos Basin conditions, as a function of the number of wells and water depth.

Petrobrás won international recognition for its work in deepwater oil production technology, when was honored by the Offshore Technology Conference (OTC) with the 1992 Distinguished Achievement Award for Companies, Organizations and Institutions.
The first PROCAP represented a major contribution to this technology development and played an important role in helping Petrobrás to get that award.

PROCAP - 2000

Petrobrás started by the end of 1992, a new program called **PROCAP** - 2000 - Technological Innovation Program on Deepwater Exploitation Systems - which has been implemented to give continuity to the efforts of the first program to improve Brazilian technological skills in deep waters. The new program has got the following goals :

- Focusing efforts on technologically innovative projects as well as in advanced development projects where Petrobrás has not fully mastered available international technology yet. The ultimate aim is to reduce investment and operational costs related deepwater production systems operating between 300 and 1000 meters, and to enhance final recovery of oil and gas, besides extending the useful life of wells located in waters over 300 meters deep.

• Development of offshore drilling and production technologies, enabling Petrobrás to produce oil and gas from fields situated in ultra - deepwaters (1000 - 2000 meters) .

PROCAP - 2000 STRATEGIES

The strategies chosen for PROCAP - 2000 reflect not only the today's level of oil prices - expected to hold steady or climb only slightly in the near future - but also Brazil's current situation, particularly as a developing country. The program endeavors to optimize reliance on know - how and resources available locally and abroad, and reduce the costs of the development of deepwater technology. This strategy stresses :

a) Links with the Brazilian Technological Community (Sharing Efforts)
The participation of the Brazilian technological and industrial communities is of paramount importance. That is the reason why Petrobrás has struggled to maximize the participation of the local universities and technological institutes, engineering consultants and high tech industries, in addition to the National Government,in order to concentrate the efforts towards the desirable achievements.

b) Links with the International Technological Community (Complementation)
Petrobrás must intensify its contacts with the international technological community - oil companies, universities and technological institutes, engineering consultants and foreign suppliers - in order to have access to technologies not available in Brazil. Another important issue is to monitor technological feats worldwide. The ways found to pursue this goal are through Joint Industry Projects (JIP's), Cooperation Agreements, Service Contracts, Consultancy and Mutual Visits.

c) Focus on Essential Technologies (Selectivity)
Efforts going towards improving technological know - how should be concentrated on the objectives considered essential to the program.

d) Links with Governmental Funding Agencies (Financial Resources)
PROCAP - 2000 is considered as a boosting program by the Government. Therefore, it may get external funding for both Petrobrás and the participant companies.

PROCAP - 2000 PORTFOLIO

After a 200 Petrobrás and local universities technical brainstorm, 11 systemic projects were chosen to be developed throughout 4 years by PROCAP - 2000 , from 1992 to 1996 (table 6). These projects represent the essential technologies for Petrobrás to come up to the goals of that program. Once more, the aim is to get a steep reduction on production costs, increasing productivity at deep water fields while enabling oil production in water depth over 1000 meters. In order to assure significant and effective

results in these projects, the final products should be presented as prototypes, field tests, small scale models or basic design
A brief overview of each one of those 11 projects are presented as follow :

STABILITY IN HORIZONTAL AND HIGHLY DEVIATED WELLS

The Albacora and Marlim non - consolidated sandstone reservoirs increase the risk of wellbore instability when the drilling and production of horizontal wells are considered. This is so due to the contribution of the overburden acting in the vertical direction.

The knowledge of the formation mechanical properties, the stress state and the development of a constitutive model associated to a failure criteria will allow us to foresee the well stability during the drilling phase and also the production period. It will be possible to anticipate the need for a gravel pack or a liner or casing or even the well feasibility, bringing about considerable cost reduction on the exploitation of offshore gas or oil fields.

This project aims at the development of a tri-dimensional wellbore stability simulator taking into account the effects of the multiphase flow of fluids in the reservoir rock and the non-physical linearity of formations. Field tests as micro-fracs and oriented cores will be performed to validate the simulator results. Another objective is to identify how the borehole stability is affected by the mechanical properties of the rock and the in situ stress state.

This project will be conducted in two steps. The first one will consist of the development of a bi-dimensional wellbore stability simulator using plane strain deformation state. The second step will start after the validation of the first one and will consist of the development of the tri-dimensional well stability simulator, which is the final product of the research project.

DRILLING HIGHLY DEVIATED WELLS IN UNCONSOLIDATED SANDSTONES AND UNSTABLE SHALES

In order to minimize the costs of development of the deep water oil fields, several inclined and horizontal wells are planed to be drilled. When the rocks are geologically recent, serious problems are faced during the drilling of some shales and unconsolidated sandstones, mainly in the inclined wells

The aim of this project is to find the real causes of the three main problems encountered:

- Mechanical stability;
- Cutting removal;
- Well design.

The mechanical stability of the formation will be investigated by using rock mechanics laboratory tests to characterize the shales and verify the main aspects that cause instability. This study will indicate the best geometry (direction and inclination) for the wells.

To ensure effective removal of the cuttings, even at risk of stability problems, some procedures will be studied and some tests will be performed in a surface simulator. These tests will define the best approach for the numerical simulator of cuttings removal to be used during the design of the wells.

The last step of the project is the development of a novel Drilling Integrated System for Design and Follow UP of the wells. This system will run at workstations and all geological and drilling data will be available to be used by the several simulators working in an integrated manner. The system will allow the engineer to use all the simulators and also to obtain all the necessary data from different computer hosts.

Once the design is completed, the system will check all the options and verify conditions. This system will also allow for an effective follow-up during all drilling operations. The system will reduce a great amount of time usually wasted while drilling through the increase of the quality of the design and by allowing the engineers to spend less time making the most appropriate decisions during the operations.

KICK AND BLOWOUT CONTROL IN DEEP WATER WELLS

As the oil industry advances into deep water exploration the risks of having a blowout increase due to difficulties related to kick detection and control procedures under this condition. The main objectives of this project are the development of new systems, devices and the definition of adequate well control procedures to minimize the possibility of blowouts.

The first task is the definition of kick scenarios. Afterwards, a kick simulator is used to evaluate and define control procedures. This approach allows the calculation of more realistic kick tolerance margins, safer well operations and cost effectiveness.

Improvement of BOP's operation reliability during an emergency disconnection will be analyzed since those safety margins cannot be applied in waters deeper than 1000m.

The development of a system to control the BOP operations is another purpose of this project. As the oil industry heads towards deeper waters, the BOP operation becomes more difficult. This condition is critical due to the emergency disconnection, when a complex set of procedures must be executed in a short period of time.

With respect to blowouts, the goal of this project is the development of a contingency plan. Capping and relief well drilling may be considered as concurrent alternatives to control a subsea blowing wells.

The contingency plan must still cover topics such as personal evacuation, oil spill containment, and salvage of the reservoir, rig, and well. In the event of a blowout, a quick and efficient response is essential for the preservation of life, property and environment. As a part of strategy, resources and infrastructure must be devised and supported in order to assure an immediate reaction.

ELECTRICAL SUBMERSIBLE PUMPS IN SUBSEA WELLS (ESPS)

The Electrical Submersible Pump method offers huge possibilities due to both the increase in flowrates and the final oil recovery, as well as by providing more flexibility to the subsea layout, since the production platform can be located further away from the well, in shallower waters.

The challenge in this project is to adapt the technology used in onshore wells and in offshore platform completions to subsea environment. Much has still to be done, mainly regarding reliability of pumping units and subsea power transmission.

This project should encompass the following activities:

1 - Scenario Study - evaluation of the state-of-the-art in ESP technology, check of deepwater field parameters, such as oil characteristics, production rates and expected costs.

2 - Pumping System - evaluation of components, to detect which items still need development for subsea applications.

3 - Energy Transmission - evaluation of components, with the same objective.

4 - Installation Procedures - procedures now followed to be checked for sub-sea suitability. Alternative methods like cable and coil tubing deployment will be studied.

5 - Subsea Equipment - Conceptual designs for Wellhead/Tubing-Hanger/Subsea Tree to be devised.

6 - Artificial Lift- artificial lift methods other than ESP to be evaluated; such as the Hydraulically Driven Submersible Pump and the Jet Pump.

A pilot installation of an ESP in a subsea well of Campos Basin is expected for mid 1994 on the RJS - 221 well in 90 m water depth. This installation will be the first one of this kind in the world.

SUBSEA SEPARATION SYSTEMS (SSS)

The Subsea Separation System (SSS) is a new concept in the offshore exploitation scenery and has received special attention from the oil operators, who consider it attractive for applications in deep water fields, besides marginal fields in shallow water.

Higher production rates and final oil recovery, reduction of required number of platforms and potential reduction of operational and investment costs are the main benefits that the SSS use will bring to the oil industry.

The basic configuration of the SSS includes a vessel or a tube for liquid separation and a pump or another device to furnish energy to the liquid. The pressure of the separator will be enough to transport the gas to the host platform. Four main technological alternatives will be carried out, namely:

1 - Electrical Submersible Pumping (ESP) in a dummy well. Several helix separation steps and a multistage centrifugal pump installed in dummy production well define the main features.

2 - Displacement by gas. The pressurized gas is injected into separator vessels or dummy wells to send liquid to the host platform.
3 - Conventional (Drop-Off). This classification means the separator vessel, the pump and the other system elements similar in configuration to the conventional ones used at surface will be "dropped off "to the sea floor.
4 - Gas-Lift in dummy well - The differential density between a liquid and a gaseified liquid column provides, in a deep dummy well, a net pressure enough to transport the production.

The main project steps are:
- conceptual design of the four technological routes. This step is now being made in order to find out how cost-effective each route is and to enable the best SSS alternative to be picked out for each scenario.
- development of components and subsystems. Both electric and electronic components, motor, pump, valves, mechanical and electric connectors,...
- design, fabrication and field tests of a complete subsea prototype.

To date, the four technological lines here described are being as much as equally pursued, because each one seems to solve specific groups of problems.

SUBSEA MULTIPHASE PUMPING SYSTEM

This innovative system is considered economically advantageous in deep water exploitation, where the installation and operation of standard production platforms is either too expensive or technically impracticable. Economical benefits increase as water depth increases.

Aimed initially at production depths of up to 1000 meters, with a future extension to 2000 meters, the subsea station will be designed to withstand operating conditions at the three giant fields off the Rio de Janeiro coast: Albacora, Marlim and Barracuda. These conditions differ significantly from those of the North Sea and the Gulf of Mexico: heavier and more viscous fluids, relatively higher gas void fraction, and increased boosting requirements.

The first phase of the project involves onshore performance and endurance testing of existing multiphase pumps under operating conditions as close as possible to those specified above, using actual oil from the giant fields. The second phase will be the topside or onshore application of pumps to boost production and increase automation. The third and final phase will address the design, construction, installation, and testing of a complete subsea pumping station to be deployed in the Campos Basin.

An onshore testing site is under construction at the Atalaia Production Facility in the State of Sergipe, northeast of Brazil, and is scheduled to be completed by June 1994. The design capacities for the closed loop liquid system are 10,000 bopd and 5,000 bwpd, with gas fraction as high as 95%. the gas system is open, with gas brought to the facility from a compressor station located nearby. Both intake pressure from up to 15 bar and discharge pressure from up to 45 bar complete the design operating range. This facility will also be used for testing multiphase meter and other devices applied to the multiphase flow production. Investigation of flow phenomena, using fluids and operating conditions closest to those encountered in real applications, is another capability of this facility.

A twin-screw multiphase pump has been already purchased for the first tests at the Atalaia site. In parallel to determination of its performance curves and the six month endurance tests, it will carry out the engineering design of the marinization phase for this type of pump. Subsea electrical system, including transformers frequency converter, motor, connectors and switches, control and data transmission system, and the use of subsea multiphase meter, are integral parts of the development plans. A rotodynamic pump is also being considered and is expected to follow the screw pump path.

FLOW ASSURANCE IN DEEP WATER CONDITIONS

The environmental conditions in which crude oil flows during offshore production may give rise to changes in the physical properties of the crude as well as on the flow dynamics. Consequently, some problems may be present during the multiphase pipeline flow: a) Oil-water emulsions (formed as long as water is present in the produced fluids) at low temperatures may increase viscosity to high figures, with reological behavior other than that shown by non-emulsified oil. b) Organic deposits are formed in lines and production equipment due to paraffinic compounds of high molecular weight present in the oil; these compounds precipitate at low temperatures, thus blocking the lines and equipment, and also reducing flow rates.

In this scenario, the following developments can be foreseen:

- Validation of the both commercial and in house existing models with field data;
- Development of new models, if necessary.

Production losses due to organic deposition in the flow lines of the wells located far from the production platform, are to be avoided by studying the deposition phenomena and feasible operational techniques.

Thus the project should deal with the following issues:

- To develop techniques to identify paraffin deposits in pipelines;
- To study and define the influence of both flow rates and GOR in deposition;
- To test techniques based on chemical inhibition thermo-chemical (SGN-SUPER), mechanical (PIGS) and thermal (electrical generation of heat and pipe insulation) principles to prevent, correct or avoid these phenomena;
- To develop innovative techniques to avoid paraffin deposition. Study on generation and dissipation of waves under certain frequencies is also to be undertaken.

The project includes the proper design of all facilities needed to apply the corrective or preventive techniques developed, as well as the design of suitable underwater equipment required to their implementation.

The main benefit would be the availability of numerical tools to predict the operational problems during pipeline flowing and to avoid the pull-out of paraffin-blocked pipelines after a shut down.

REDUCTION OF RIG DOWNTIME DUE TO BOP HANDLING

The goal of this project is to improve BOP reliability, increasing the safety during the operations, preserving the environment conditions and reducing BOP downtime costs.

Therefore, it is intended to gather BOP Reliability Data with all standard failure information in order to provide a regular report with reliability data analysis, procedure and maintenance recommendations, critical points, orientations, etc...Also, it is our intention to evaluate the most recent technology available for a modern BOP Control System, providing a more reliable BOP.

The plan is to obtain a rig regular report to orient the field main action on BOP, so a comprehensive BOP reliability analysis can be carried out. The actual BOP failure data will be standardized to feed a computer expert system. Laboratory tests on BOP components will bring additional information to the study.

Since the available technology on BOP Control System has been developed for quite a long time the real chance to have a more reliable BOP Multiplexed Control System are considered.

The kill and choke line union failures is one of the most important problems pointed out on BOP failure data. The failures may be correlated with equipment project, operational and maintenance procedures, materials, etc...

The immediate actions are to analyze the operational procedure, the manufacture guidelines and also to implement a field monitoring policy. After these preliminary phases, a definitive plan will be implemented to improve the reliability the kill and choke line couplings.

STATIONARY PRODUCTION UNITS WITH DRY COMPLETION

The main goals of this project are the development of the Grid Tensioning interface up to the point of operational usage and the investigation of new concepts of platforms using tension legs as mooring elements.

The project is divided in two parts; the first consists of a preliminary design considering the conversion of a semi-submersible drilling platform into a dry completion unit, whose a grid tensioning system will be tested. The system to be developed is composed of a grid structure, where the christmas trees will be installed, and a set of tensioners supporting this structure. The tensioners will hold the risers and also keep the grid and risers motionless with respect to seabed. The purpose is to carry out a study of the system, focusing on technical questions that may arise in order to make this technology available.

The same basic concept of dry completion, but with new configurations, will be considered in the second part. Feasibility of these platforms will be investigated, bearing in mind that they are not as developed stage as the first one.

One of the configurations is the TLP with Reduced Water Plane Area, which is an extension of the conventional TLP concept, aiming at minimizing environmental actions upon the structure.

The tension and fatigue damage of the tendons is reduced by replacing the columns by a truss structure, and therefore reducing initial costs.

Another configuration is the Riser Tensioned Platform, with the main feature of replacing the tendons by the risers as mooring elements of the platform. The riser would tension the unit avoiding big displacement between the unit and the subsea trees on the deck. It can be feasible in mild environmental conditions, such as the ones found along the Brazilian coast.

STATIONARY PRODUCTION UNITS WITH SUBSEA COMPLETION

The main objective of the project is the analysis of the well proven floating production technology, together with subsea completion concept, in order to make it suitable to be used in the range of 1000 and 2000 meters water depths. The main concern to achieve this are the following three major stages, namely: platform positioning systems, optimization of existing semi-submersible platform and production ship.

In the first stage, present experience is in the use of conventional cable / chain combinations of mooring systems in water depths up to 1200 meters. The use of the technology where depths up to 2000 meters are involved will call for further studies such as: materials, fresh mooring ideas and perhaps considering the use of thruster-aided mooring systems.

Proper definition of system configuration implies a more precise cost analysis, regarding the fact of being ready for the use of non-conventional materials such as polyesters. Degradation and fatigue tests of cable wires are required as much as testing facilities need to be built. The acquisition of prototypes is also intended, to be used in some field tests. In such tests, many sensored parameters will provide useful information concerning the residual strength and dynamic behavior of the system.

Stage two will considered the development of a conceptual design for a semi-submersible production platform. The purpose is to devise a design for a given site, including some deck and inside hull lay-out changes, and use of non-conventional equipment. Hull size optimization will involve plant lay-out, stability, motions, structural and fabrication / installation analysis. Special attention is to be paid to the flow lines and umbilicals connection system.

Stage three, will deal with the conceptual design of one alternative for a semi-submersible production platform in deep waters, using a production ship linked to turret system. The ship/turret alternative study will consider an existing ship which will have to be picked out to undergo the required modifications. Special attention is to be paid to the turret system in order to maximize the number of production risers.

ACQUISITION AND TREATMENT OF GEOTECHNICAL, GEOPHYSICAL, GEOLOGICAL AND ENVIRONMENTAL DATA

The main purpose of this project is to come up with environmental loads, substrate geotechnical behavior, active geological processes and detailed morphology of the sea floor along Brazilian Continental Slope at the Campos Basin, to be understood from the engineering standpoint.

There are 5 tasks to be tackled under this project, namely:

- Sea floor detailed morphologic evaluation of deep water production fields - detailed sealer mapping for relief, structural and geohazard identification;
- Oceanographic and meteorological data acquisition - development of an ocean-meteorological buoy and instrumental moorings, both for depth of 2000 m and devising of a prototype for bottom current monitoring;
- Geological approach to continental Slope-Establishment of former and recent sedimentary processes based on the data collected from other jobs under the project, in order to describe the geologic settlement of Continental Slope and Neighborhood.
- Geotechnical monitoring of Continental Slope - Study and establish the phenomena related to mass movements (such as creeping, slides, etc...) and seismological activity on continental Slope at Campos Basin, and eventually develop, a prototype to monitor both of them.
- Determination of sea floor elastic properties by seismic methods - development of an algorithm for the determination of soil elastic properties based on 3D seismic data.

The results of these 5 tasks will provide the parameters related to environmental loads and geohazards, enabling the proper planning and design of production structures and pipelines to take place in terms of safety, cost and greater saving at both designing and installation stages.

PROCAP - 2000 - BUDGET

The overall estimate budget is US$ 56 million encompassing all activities such as technological developments, prototypes, field tests and Petrobrás's labor costs, excluding infrastructure and support expenditures for test accomplishments, which are evaluated in approximately US$ 60 million.

CONCLUSIONS

Analyzing the cost breakdown of some of the Brazilian deepwater field developments, it can be noticed that 50 % of the investment costs are due to the number of wells, that is, drilling, completion, flowlines to FPS or subsea manifold. In the same way, stationary production unit stands for 30 % of the investment costs of such projects.

Therefore, technologies that will help to decrease the number of wells needed (through increasing their productivity) and their individual costs, as well as those which will reduce or eliminate the use of Production Units, will contribute in a very significant way to reduce the investment costs of the deepwater field developments.

Based on that, the use of horizontal well or fitting subsea wells with Electrical Submersible Pumps (ESP), or a combination of both, are some of the possibilities to reduce the number of subsea wells. The use of some innovative equipment and techniques to save rig / vessel time is another alternative to cut down the cost of wells.

The industry is investing great amounts of money in the development of subsea production systems, such as Subsea Separators and Subsea Multiphase Pumps. That has been done in such way because of their breakthrough characteristics, which mean the possibility of completely changing the face of a field development, virtually eliminating expensive production platforms and extending the productive life of the wells by allowing them to produce at lower wellhead pressure.

The idea behind the boosting systems (ESP's, Subsea Separation & Multiphase Pumping) is to provide additional energy to overcome the higher hydrostatic head, as a consequence of the deeper water depth, using the reservoir energy to get the oil up to the mudline at a lower pressure, thus increasing not only the flowrate but also the total recovery of the fields.

Around 17 % of the current Brazilian oil production come from wells in waters deeper than 400 meters. Barring any major onshore or shallow - water finds, Petrobrás expects this figure to come up to 61 % by the year 2003. Despite the limited availability of proven deepwater production technologies, the country needs to exploit these reservoirs

It is Petrobrás belief that PROCAP - 2000 will pave its way to reach that target by using either one or the combination of the developed technologies by the year 2000. Therefore, we hope to cut down about 30 % of the total costs (capex + opex) of those field developments.

For that reason, Petrobrás set up the first PROCAP program, and its successor PROCAP - 2000. Both programs are considered vital tools to boost the development of deepwater oil production in Brazil.

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FIRST PROCAP
DEEPWATER ACHIEVEMENTS

1	Semi - submersible Production Platforms: General Conversion Designs
2	The Vitória Régia Semi - Submersible Production Project
3	Mooring Systems - Design Criteria, with optimization developed by PETROBRÁS
4	Cathodic Protection for Hydraulic Control Line on Wet Xmas-Trees
5	OCTOS - 1000, Diverless, Guidelineless, Template / Manifold Project, 7 Wells, 1000 m water depth
6	Subsea Production Manifold, Diverless, Guidelineless, 8 Wells, 1000 m water depth
7	Atmospheric Production Manifold, 8 Wells, 600 m water depth
8	Subsea Connection Systems
9	Wet Xmas-Trees - Diver Assisted in water depths up to 300 m and Diverless up to 1000 m
10	Remote Control and Supervision System for Subsea Production Facilites MUXCOM Project
11	Flexible Risers - Design Criteria
12	Rigid Risers for Drilling, Completion and Production Basic Design
13	Rigid Lines - Evaluation of Lauching Methods
14	Methodologies for Predicting Paraffin Build - up on Offshore Production Lines - Prevention and Removal Methods
15	Acquisition and Treatment of Oceanographic, Meteorological, Geophysical and Geotechnical Data on Deepwater Fields (up to 1000 m)

TABLE 5

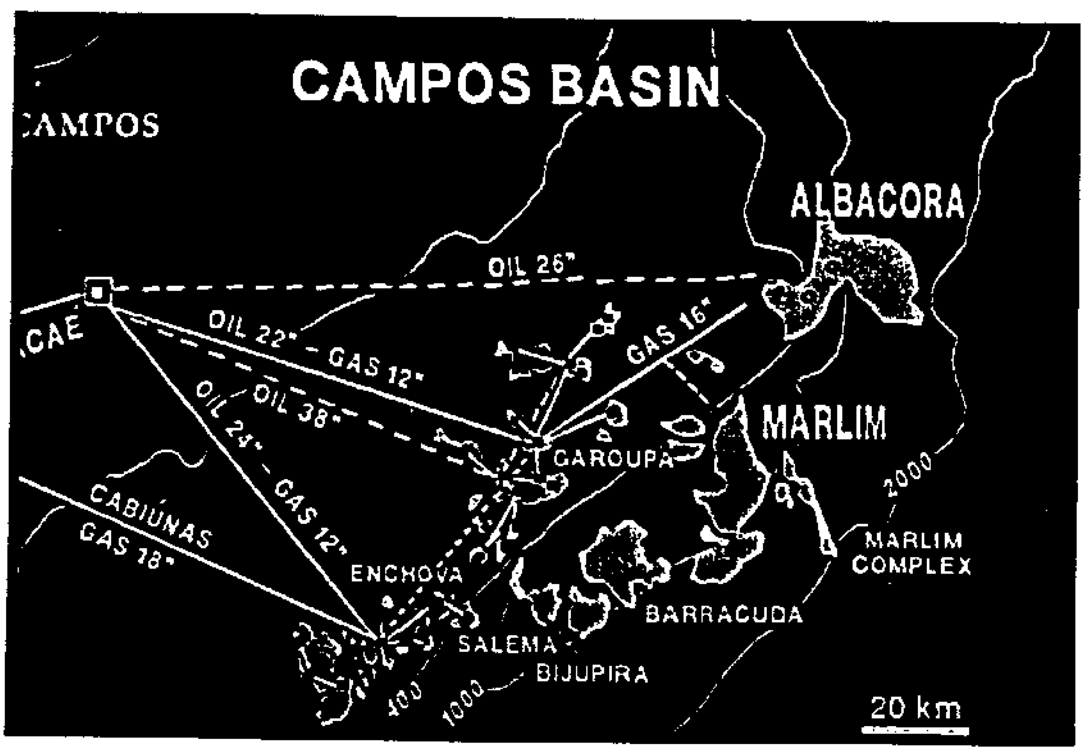


FIGURE 1

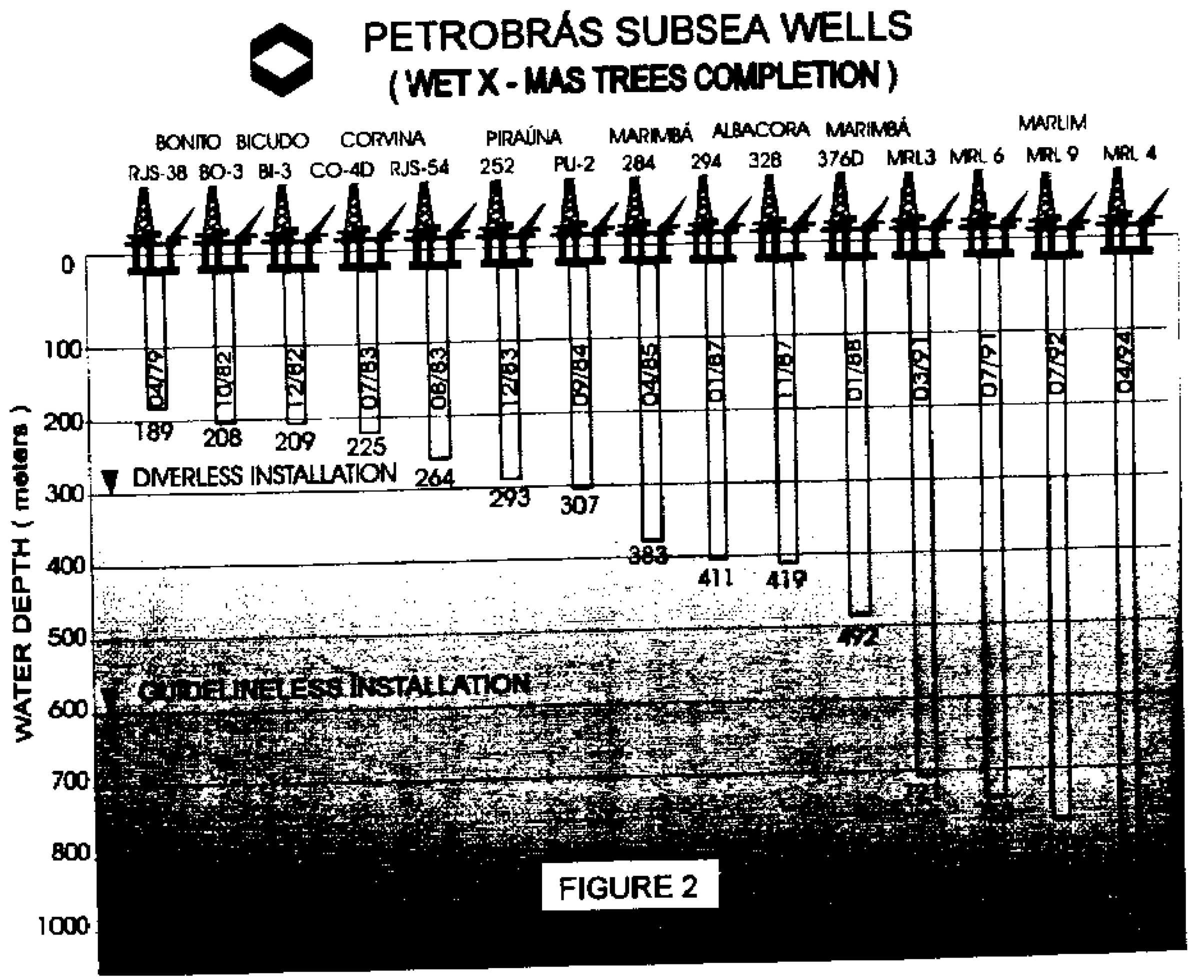


FIGURE 2

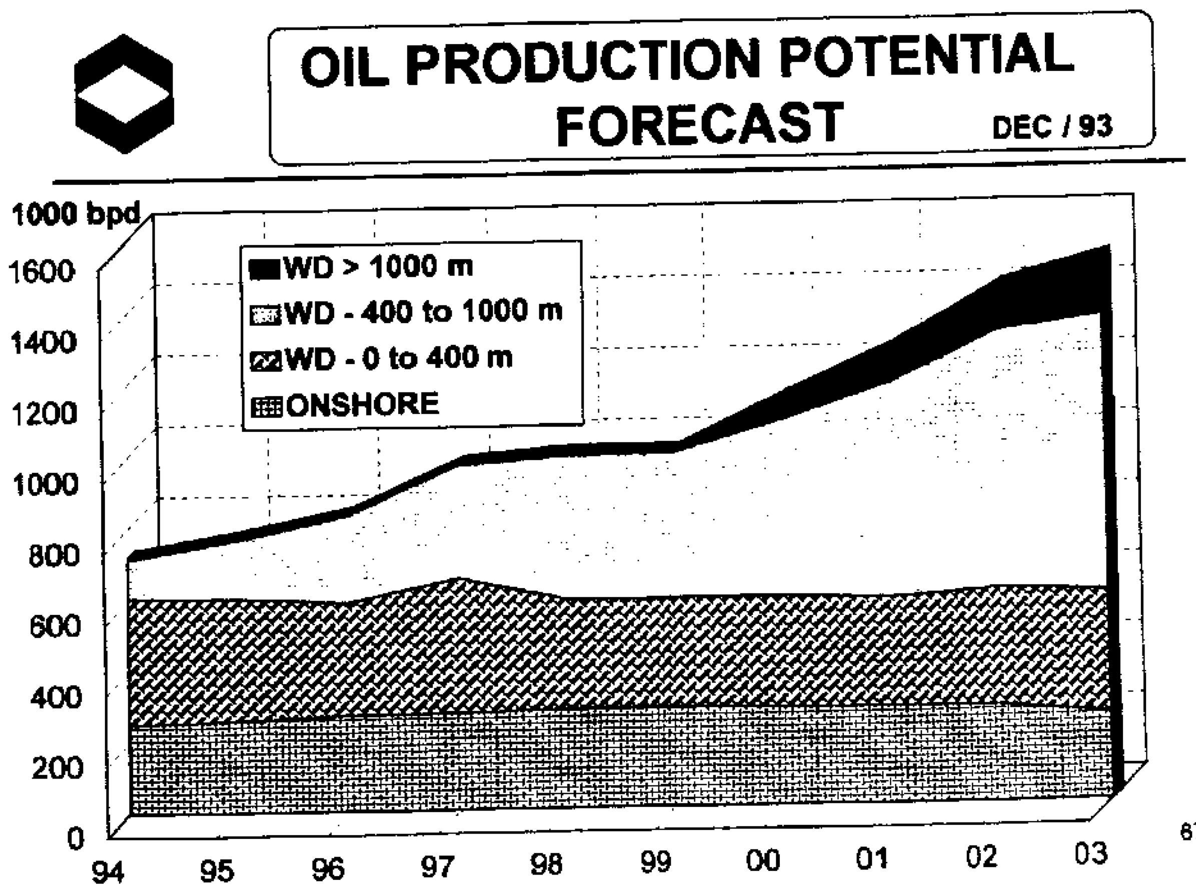


FIG. 3

FIRST PROCAP

EXTERNAL PARTICIPATION

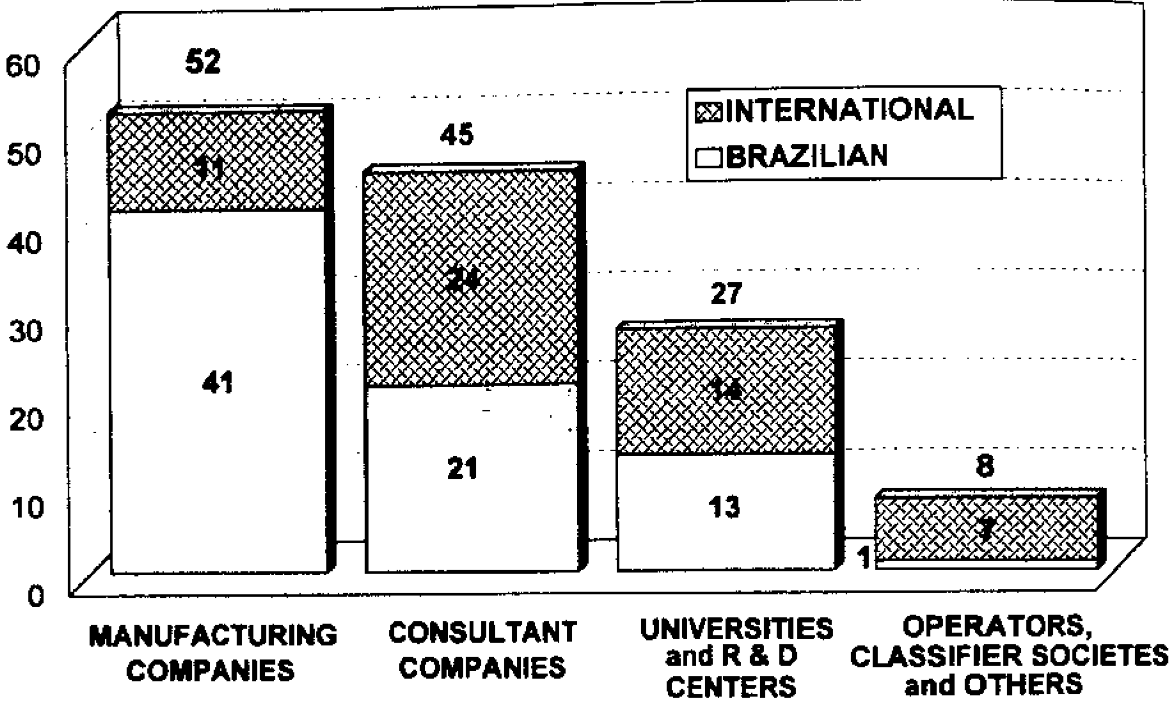
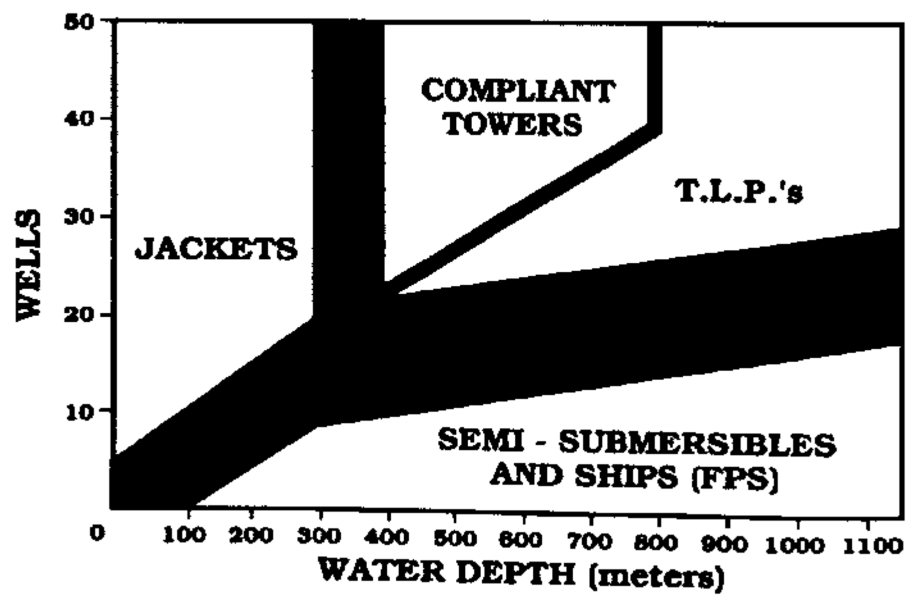


FIGURE 4

STATIONARY PRODUCTION UNITS APPLICATION RANGE IN CAMPOS BASIN



NOTE: THE SUBSEA MULTIPHASE PUMPING AND THE SUBSEA SEPARATION SYSTEMS IS APPLICABLE IN ANY WATER DEPTHS

FIGURE 5

FLOATING PRODUCTION SYSTEMS OPERATING IN CAMPOS BASIN

SEP / 93

FIELD	STATIONARY UNIT WATER DEPTH (m)	STATIONARY UNIT	NUMBER OF WELLS	WATER DEPTH RANGE OF WELLS (m)	PROCESSING CAPACITY OIL (1000 Bpd)	PROCESSING CAPACITY GAS ($1000\ m^3/d$)
Badejo / Trilha	100	Petrobrás - XXI	11	94 - 111	40	1200
Linguado	100	Petrobrás - XII	17	96 - 108	50	1000
Moréia	114	Petrobrás - XXII	5	113 - 120	10	200
Viola	127	Zephyr - I	9	125 - 126	25	200
Bicudo	209	Petrobrás - VII	16	130 - 209	50	1500
Bonito	190	Penrod - 71	20	118 - 209	40	900
Corvina	226	Petrobrás - IX	7	225 - 255	40	200
Piraúna / Marimbá	244	Petrobrás - XV	11	230 - 492	45	300
Albacora	230	Petrobrás- XXIV	16	250 - 450	60	500
Enchova	120	Sedco - 135D	20	110 - 179	30	400
Marlim	625	Petrobrás - XX	10	721 - 781	52	1000
Bijupirá / Salema	625	Petrobrás - XIII	4	551 - 737	10	300
Marimbá	429	Petrobrás - VIII	13	380 - 550	52	1500
Coral *	150	Diamond Century	1	150	10	300
Caravela *	195	Petrobrás - XIV	1	195	10	—
TOTAL	15 FPS		161	94 - 781	534	9500

* SANTOS BASIN

TABLE 1

FLOATING PRODUCTION SYSTEMS PLANNED FOR CAMPOS BASIN

SEP / 93

FIELD	SPU WATER DEPTH (m)	STATIONARY PRODUCTION UNIT (SPU)	NUMBER OF WELLS	WATER DEPTH RANGE OF WELLS (m)	PROCESSING CAPACITY OIL (1000 Bpd)	PROCESSING CAPACITY GAS ($1000\ m^3/d$)	PRODUCTION START UP
ALBACORA	375	P - X	36	250 - 420	100	3250	1998
ALBACORA	515	P - XXV	27	475 - 950	100	3250	1996
MARLIM	910	P - XVIII	26	880 - 970	100	2100	1994
MARLIM	770	P - XIX	26	720 - 840	100	2100	1997
BARRACUDA (PILOT)	835	PP MORAES	11	725 - 915	60	950	1995
BARRACUDA	800	SPU - 1 (TLP)	32	700 - 850	80	2000	2000
BARRACUDA	850	SPU - 2 (TLP)	41	750 - 950	80	2000	2002
BARRACUDA	980	SPU - 3 (FPS)	46	900 - 1100	80	2000	2004
BIJUPIRÁ / SALEMA	745	TO BE DEFINED	27	630 - 830	75	1000	1997

TABLE 2

WET XMAS - TREES

CAMPOS BASIN

FEB / 94

WATER DEPTH (m)	INSTALLED	PLANNED (94 - 95)	TOTAL
Up to 99	18	1	19
100 - 199	88	8	96
200 - 299	49	1	50
300 - 399	5	———	5
400 and up	32	32	64
TOTAL	192	42	234

TABLE 3

FIRST PROCAP
ALTERNATIVES STUDIED

PRIORITY	TECHNOLOGICAL EXTENSION (80% HUMAN RESOURCES) COMPONENTS DEVELOPMENT	TECHNOLOGICAL INNOVATION (20% HUMAN RESOURCES) SYSTEMS DEVELOPMENT
1	FLOATING PRODUCTION SYSTEM (FPS) BASED ON SEMI-SUBMERSIBLE (400 - 1000 m)	TLP's (400 - 1000 m) SUBSEA MULTIPHASE PUMPING (400 - 1000 m) SUBSEA SEPARATION SYSTEM (400 - 600 m)
2	———	FLOATING PRODUCTION SYSTEM WITH DRY COMPLETION (400 - 1000 m) SUBSEA SEPARATION SYSTEM (600 - 1000 m)
3	FLOATING PRODUCTION SYSTEM (FPS) BASED ON SHIPS (400 - 1000 m)	COMPLIANT TOWER (400 - 600m)

TABLE 4

PROCAP - 2000 PORTFOLIO

NUMBER	SYSTEMIC PROJECT
1	STABILITY IN HORIZONTAL AND HIGHLY DEVIATED WELLS
2	DRILLING HIGH - ANGLE WELLS IN UNCONSOLIDATED SANDSTONES AND UNSTABLE SHALES
3	KICK AND BLOWOUT CONTROL IN DEEP WATER WELLS
4	ELECTRICAL SUBMERSIBLE PUMPS IN SUBSEA WELLS (ESPS)
5	SUBSEA SEPARATION SYSTEMS (SSS)
6	SUBSEA MULTIPHASE PUMPING SYSTEMS (SMPS)
7	FLOW ASSURANCE IN DEEP WATER CONDITIONS
8	REDUCTION OF RIG DOWNTIME DUE TO BOP (Blowout Preventer) HANDLING
9	STATIONARY PRODUCTION UNITS WITH DRY COMPLETION
10	STATIONARY PRODUCTION UNITS WITH SUBSEA COMPLETION
11	ACQUISITION AND TREATMENT OF GEOLOGICAL, GEOPHYSICAL, GEOTECHNICAL AND OCEANOGRAPHICAL DATA

TABLE 6