

Review of the geotechnical aspects of jack-up unit operations

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Introduction

THE USE OF mobile jack-up drilling units for offshore oil and gas exploration has increased considerably in recent years. At present, approximately 400 units are available world-wide, with the potential to capture 60% of the exploration drilling market. The remaining offshore exploration is performed from drill-ships and semi-submersible vessels.

A typical independent leg jack-up is shown in Fig. 1. In 1985 units were being constructed with leg lengths of 157m and with a total weight during installation of 350MN. The cost of such a unit may range from 70 to 90 million US dollars depending on the customer preference of on-board equipment.

The foundations of jack-up units (sometimes called 'spudcans') can take many forms. Most modern footings are polygonal in plan, and in elevation have gently sloping soil contact surfaces with a central point or tip to provide horizontal restraint. The spudcans of the larger units may have plan areas of 260m² and during installation develop foundation contact pressures of 440kPa.

It is the engineering analysis of these footings which is often of interest to offshore geotechnical engineers, particularly as the safety and success of a project can be crucially dependent upon the unit's foundation performance.

Before addressing the geotechnical aspects of jack-up operations it may be useful to briefly discuss some of the practical points relating to the installation of these units.

At the commencement of operations the unit is floated to the desired location with legs in the elevated position. At the location, the legs are lowered to the sea floor and jacked into the foundation soils until adequate bearing capacity is obtained to support the unit. The hull is then raised about 1.5m out of the water and the unit is "predriven" or "preloaded" to a weight which results in the vertical loads under the spudcans equalling, or possibly exceeding by some margin, the anticipated vertical load expected during storm conditions.

Preloading is performed by pumping water ballast into various "preload tanks" within the hull of the unit. Preloading may be performed on units of four or more legs, and consists of loading a particular leg, or pair of legs, using the jacking system in conjunction with the weight of the hull. In this discussion the term preloading will refer to both kinds of procedure.

In soft soils leg penetrations of over 36m have been recorded during preloading. However, such penetrations would be

considered unusual in operational areas around the British Isles.

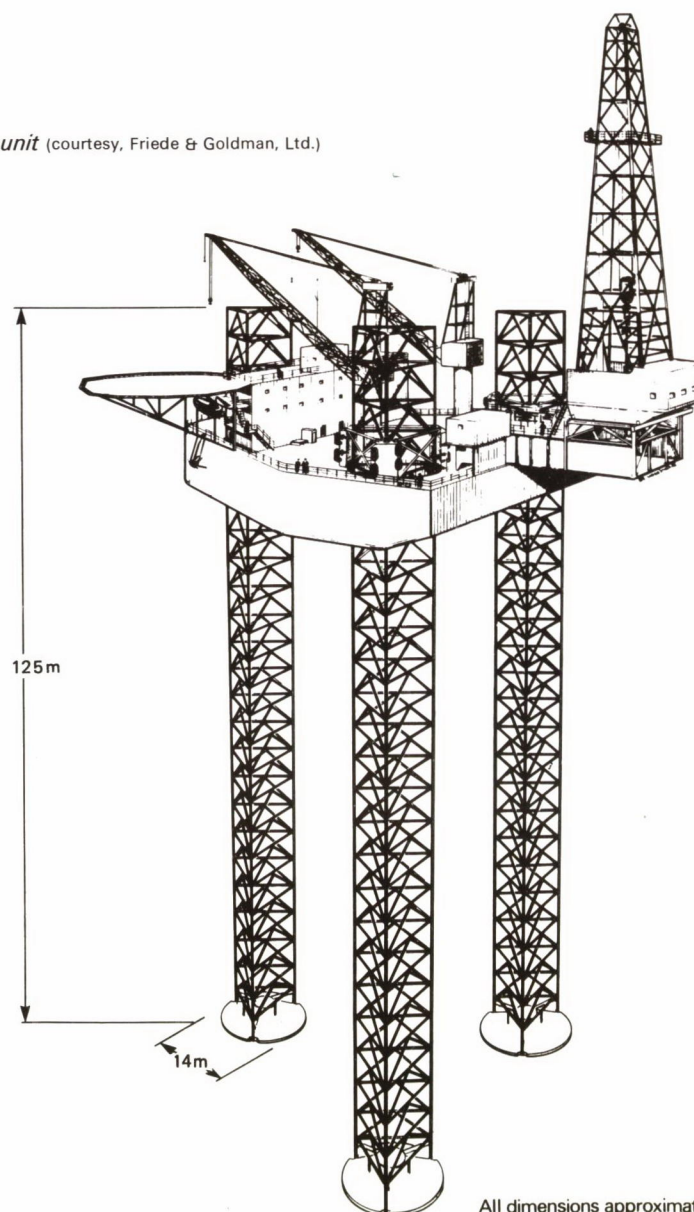
After the preloading procedure is completed and all preload ballast dumped, the hull is raised to the desired operating height above the sea level, which in the North Sea may be up to 22m to the hull underside, or even more if working over an existing installation.

Before operating a jack-up unit at a specific location, the ability of the unit to withstand the envisaged 50 year return storm condition is usually assessed. This procedure ensures that structural failure resulting in either damage or catastrophic accident does not occur (Ridehalgh &

Edwards, 1982). The author's company is frequently responsible for performing these assessments and in addition to checking the structural strength of the unit, the overall foundation performance is checked for integrity under installation and storm loading conditions.

Much has been written in the past concerning the geotechnical considerations of jack-up unit operation (Baglioni *et al*, 1982; Endley *et al*, 1981; McClelland *et al*, 1981). This Paper does not propose to reiterate on the computations involved in the analysis of foundation bearing capacity, as these are now widely known. The object of this Paper is to describe the total

Fig. 1. Typical jack-up unit (courtesy, Friede & Goldman, Ltd.)



All dimensions approximate

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geotechnical appraisal made prior to the emplacement of a jack-up unit and discuss the assessment of foundation safety in marginal conditions.

Site evaluation

For a constructive appraisal of the foundation performance of a jack-up unit it is essential to understand the sea-bed and sub-seabed soils. It is a fact however, that the number of instances where quantitative soils information is obtained prior to jack-up installation are comparatively few. Oil companies and jack-up operators are, however, becoming increasingly aware of the need to obtain qualitative data prior to a jack-up emplacement. This greater understanding has been brought about by guidance from geotechnical consultants, the author's company, and, unfortunately, accidents, the cause of which has been foundation failure.

The majority of potential jack-up locations are assessed on the results of shallow seismic surveying techniques. These surveying methods are based upon the interpretation of reflected signals originating from a controlled acoustic energy source towed behind a moving vessel. In principle sonic reflections occur within the soil strata at boundaries of changing densities. The signature of the returned pulse can be interpreted in some cases to identify the nature or type of stratum, however the interpretation is an empirical procedure. The seismic survey will reveal sub-bottom features such as buried channels and bedrock and indicate the degree of uniformity of the soil conditions. At present, however, the interpretation of seismic surveys in terms of the mechanical properties of the soil is equivocal.

Most seismic survey procedures will include the collection of one or more gravity cores. For the purpose of providing information on which to perform engineering analyses these tests are unsatisfactory. In many cases recovery may be 1m or less which is of limited value considering that footing penetrations are likely to be in excess of this value. Gravity cores may, however, provide information on the susceptibility of the soil to scour around the jack-up footing.

In certain cases shallow seismic lines can be used to demonstrate stratigraphic continuity from a relatively well understood area to an unknown area. In these circumstances it is essential to ensure that the data density and quality allow a confident interpretation of the relevant stratigraphic variations.

There are very few instances where the results of seismic surveys should be used as the basis of assessing jack-up foundations in isolation from geotechnical data obtained from a site investigation. The southern North Sea is possibly one of the few local areas where a sufficient quantity of geotechnical and seismic data exist, together with experience of numerous successful unit moves to warrant approval of a location purely based on seismic information.

Where there is any doubt over the seismic interpretation, geotechnical information for the location is usually obtained. In most cases at least one borehole incorporating cone penetrometer testing and/or a soil sampling programme will provide geotechnical data on which to base the engineering analyses.

Modern geotechnical investigation techniques have been discussed by authors in the past (Semple & Johnston, 1979; deRuiter & Richards, 1983), and it is not proposed to amplify on this topic. Testing is

normally carried out to a depth of 30m below mudline. If during the testing, significant spudcan penetrations are predicted, then the borehole is continued until a depth of one spudcan diameter below the final estimated penetration is reached. In areas where the seismic results show confused or irregular bedding of the soils, a further borehole, or boreholes, might be considered. At the end of each borehole the seismic survey is consulted to establish correlations and to ascertain that the borehole is a true representation of the area. During the site investigation it is recommended that a competent geotechnical engineer should be in attendance to perform footing penetration analyses and advise on jack-up unit operations.

In special cases, where the remoteness of the drilling location poses difficulties in obtaining a site investigation prior to the installation of the unit, it may be considered appropriate to perform shallow soil exploration boreholes from the jack-up itself. In preparing for the drilling operations the leg are jacked down until the hull of the unit is raised as close above water level as is practicable (or the hull allowed to retain some draft if practicable). This precaution minimises structural damage in the event of sudden rapid leg penetrations. Performing soil borings from jack-up's may only be permitted in benign conditions and where an accurate weather forecasting service is available, as, when in the configuration required for the soil testing, the unit is very vulnerable to storm damage.

Foundation loads

The loads sustained by jack-up foundations fall into two categories:

- (i) Short-term loading encountered during installation.
- (ii) Loading encountered from environmental forces during operations.

Short term loads arising during the installation of the unit are straightforward to estimate as they are simply the net weight of the unit plus the preload added. The static weights of the jack-up are available from the designers/builders handbook. The following data are normally required to estimate the foundation loads before and after preloading:

- (1) Hull fixed weight including all legs.
- (2) Unit buoyancy of legs.
- (3) Water depth.
- (4) Variable load on board.
- (5) Installation preload.

It is usually possible to check approximately the weight of a jack-up unit prior to installation by reference to its displacement as indicated by the draught marks inscribed upon the hull. Typically a foundation load of 40MN and 64MN may occur at the footing prior to, and after preloading respectively.

The environmental loadings are established by consideration of the shape and area presented by the unit to wind, current and wave forces. The wind forces may be calculated according to American Bureau of Shipping Rules for Mobile Offshore Drilling Rigs (1980), and the wave forces using a wave theory appropriate to the wave height, period and water depth, taking account of the current velocity profile. Normally, loading directions towards the bow, stern and quarter of the unit are considered.

The environmental factors considered are the maximum conditions expected within a fifty year period at the proposed location. The

variable load of the rig should be estimated as a realistic maximum with respect to the type of operations being undertaken whilst on location. Analyses have indicated that a vertical load of 63MN and a horizontal load of 6.2MN may be experienced at the footings during a 50 year storm in some areas of the North Sea. The derivation of the environmental data is outside the scope of this Paper; however further information on these considerations may be obtained from the references (Blackham *et al*, 1984; Babbage & Lynagh, 1984).

Geotechnical analyses

Installation loading

The customary calculations performed are those for estimating footing penetration during installation. The final footing penetration depends upon the installation weight of the unit and preload, the area and shape of the spudcans and the bearing capacity of the seabed. Footing penetration estimates are important considerations when conducting operational feasibility studies, particularly in areas of deep water and/or normally consolidated clays. Instances are known where units have arrived at location with an insufficient leg length to allow for the spudcan penetration.

Several methods of analyses are available for the estimation of bearing capacity in homogenous soils. The most commonly used are methods proposed by Hansen (1968) and Skempton (1951). Works by McClelland *et al* (1981) and Endley *et al* (1981) describe the application of the bearing capacity formula to spudcan penetration prediction. It is not intended to repeat the techniques in this Paper.

In layered soils special attention is given to the possibility of the rig "punching through". Punch-through generally occurs in situations where a strong soil of relatively thin thickness overlies a weaker soil. During installation the unit may obtain temporary support from the upper soil layer, but preloading or storm loading may critically stress the soil formation and one or more legs will penetrate into the underlying, weaker strata. Large horizontal loads are thus generated, which can result in bending or total fracture of the legs both above and below the hull. The sequence of events during a punch-through is so rapid that no remedial action to counteract the consequences can be taken. Many instances are known where punch-throughs have caused loss of, or extensive damage to jack-up units. Additionally, the personal risk to those on board the unit dictates that all necessary precautions are taken to avoid punch-through failures.

The estimation of the bearing capacity of layered soils is not as straightforward as for the single layer case. The methods proposed by Brown & Meyerhof (1969), Meyerhof & Hanna (1978) and Hanna & Meyerhof (1980) are probably most widely used in the analysis of punch-through problems.

Storm loading

It is well understood that the bearing capacity of a foundation subjected to pure vertical loading is reduced by the introduction of concurrent horizontal and moment loading.

During the storm condition environmental forces will impose both moment, vertical and horizontal load components onto a foundation. It is thus apparent that the ability of a foundation to withstand the preload condition (i.e. only vertical loading) does not indicate that the foundation has ability to sustain the same magnitude of storm vertical

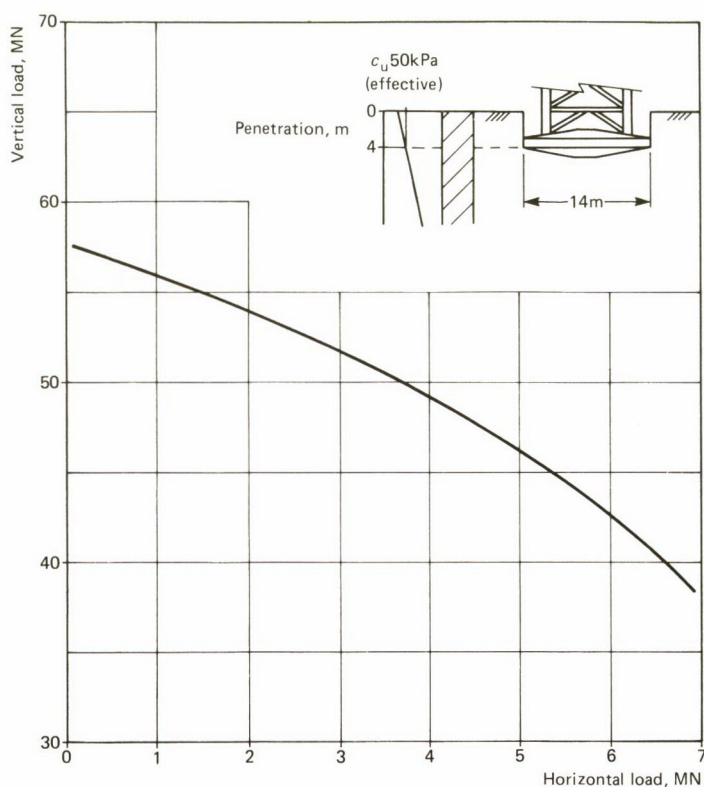


Fig. 2. Interaction diagram soft clay profile

loading when combined with concurrent horizontal loading.

NDA practice is to produce interaction diagrams which show the relationship between the vertical load and the horizontal load acting on the foundation at the time of soil failure. These analyses are performed with respect to the estimated spudcan penetration. A typical interaction diagram for a clay soil type is shown in Fig. 2. It is important to note that the resistance to one

applied load component is reduced when another applied load component is increased.

At present, no account is taken of the moment acting about the spudcan. The exact mechanisms of spudcan restraint are poorly understood and therefore reliable estimates of the moment acting about the footing are difficult to obtain. This is an area which is currently being researched by the author's company (Knott, 1985) and results are

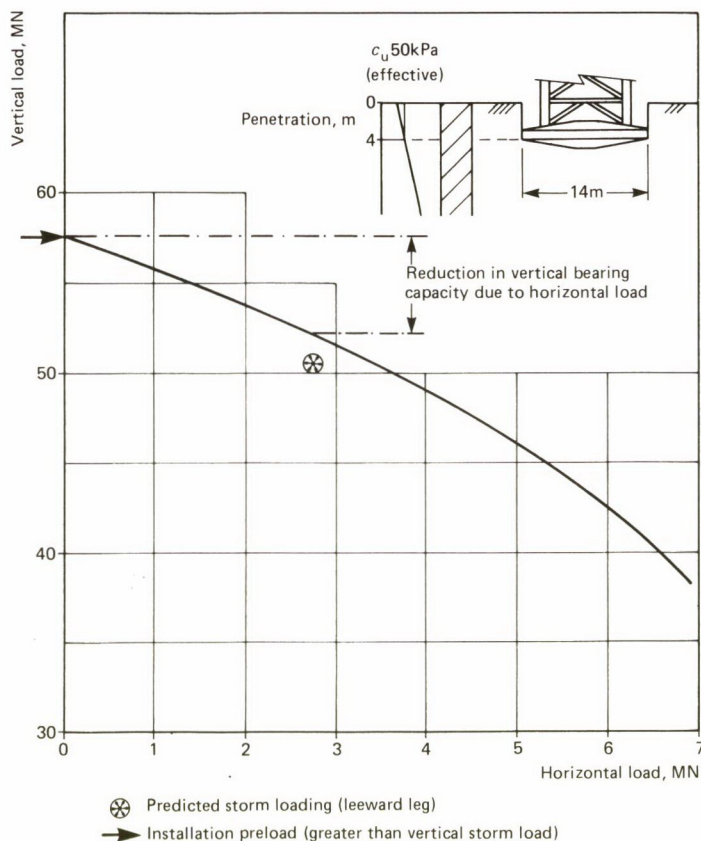


Fig. 3. Design of preload soft clay profile

⊗ Predicted storm loading (leeward leg)
→ Installation preload (greater than vertical storm load)

expected in the near future. For the time being, however, simplifying assumptions are adopted.

Preload design

It is common practice during installation to preload the unit to its maximum capability. However, at locations where excessive leg penetrations or a risk of punch-through is envisaged it is appropriate to limit the amount of preloading applied to a designed value.

The preload is designed to the maximum vertical storm load plus some margin to compensate for any effects of the combined loading. The required margin can be estimated from the interaction analyses although it is only in extreme cases that significant compensations are required. Fig. 3 shows the situation where the minimum design preload has been determined to ensure that the combined vertical and horizontal storm loads fall within the soil failure envelope.

Factors of safety at punch-through locations

The risk of punch-through is a serious concern to all involved in jack-up unit operations, and every effort is made to minimise exposure of rigs to this hazard.

The factor of safety against punch-through during preloading can be determined from the bearing capacity of the strata and the installation footing loads. The assessment of the factor of safety against punch-through during storm conditions again is not obvious, as the precise relationship between moment, horizontal loading and vertical loading at the footing is not known.

An overall indication of these considerations is given in Fig. 4. It should be noted that, in this case, a factor of safety exists against punch-through during installation (i.e. installation preload is less than the soil bearing capacity under pure vertical load). Additionally, the predicted storm loading lies within the soil failure envelope.

The required factor of safety at a punch-through location is a difficult parameter to establish. The choice of a factor of safety is directly influenced by the following considerations:

- The quality of the site investigation,
- The quality of the geotechnical data available,
- The uniformity of stratigraphy across the location,
- The variation of strength characteristics across the location,
- The degree of confidence in the methods of analysis,
- The severity of the possible punch-through, and
- The consequences of the punch-through in terms of personal risk and structural damage.

The assessment of the interrelationship of these factors is open to interpretation, and the ultimate choice of an appropriate safety factor lies in the judgement of the competent geotechnical engineer. In such a position, the engineer must be privy to the installation and environmental foundation loads and aware of the strength characteristics of a particular unit.

Innovation and site investigation requirements

Jack-up unit designers and operators are continually striving to extend the safe operating areas of units. For example, designs capable of operations in up to 95m

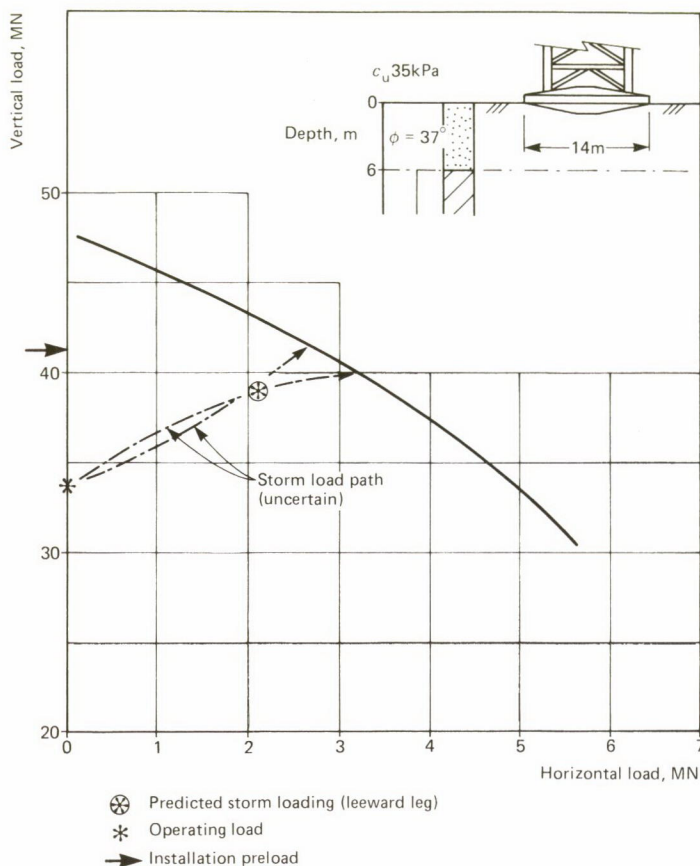


Fig. 4. Safety margins punch-through profile

water depth are currently available with a capacity for summer operation at many North Sea locations where jack-up operations are previously unknown. (For example, some parts of the Forties and Beryl Fields). Accordingly, there is an increased need for a good quality geotechnical appraisal prior to installation of these types of unit if punch-through locations or other hazards are to be identified.

Another design consideration currently being addressed is the effect of the rotational restraint of the spudcan upon the leg bending moments. Traditionally in the design process, the fixity at the spudcan has been assumed as zero i.e. the foundation behaves as a pin joint and cannot therefore, sustain any bending moment. Intuition and practical experience suggest that this may be a conservative approach and some sectors of the offshore industry take the view that consideration should be given to the rotational restraint, or foundation fixity, mobilised below the footing. The significance of allowing for foundation fixity is realised when assessing the structural strength of the legs of the unit, as inclusion of rotational restraint results in a less onerous distribution of leg bending moments. This may lead to the view that a given unit may be suitable for operations in considerably harsher environments than if fixity is discounted. However, it should be noted that a safe design will be based on minimal soil fixity for the design of the upper part of the legs, jackhouses and hull, and maximum soil fixity for the lower part of the legs and spudcans.

Modern design methods can produce substantial savings in material and construction costs by designing to the minimum requirements of the appropriate regulatory bodies. As a result, the reserve strength of legs in the event of a sudden change of attitude of the unit can be minimal.

A hypothetical comparison of the likely damage sustained by a modern design, and a more classical design under identical accident conditions will indicate the frailty of the lightweight modern units in this respect.

As these new design considerations increasingly influence practice, a greater appreciation of the importance of a site investigation prior to jack-up emplacement is required, if the safety of the unit is to be unimpaired. In future, exploration campaigns involving jack-ups may have to be planned sufficiently well in advance to budget for, and allow time for an adequate site investigation. This philosophy, although possibly difficult to apply, is being practised successfully by a few major oil companies.

Conclusions

Seismic surveys provide valuable information on sub-bottom features such as buried channels and bedrock. They cannot at present, however, indicate the mechanical properties of soils. Every possible attempt should be made, therefore, to correlate the seismic survey with a geotechnical investigation comprising cone penetrometer testing and/or soil sampling.

The loads imposed on the foundation during installation and operation can be estimated. Knowledge of the loading is essential in determining the suitability of a particular unit/site combination.

Geotechnical analyses can be performed to estimate spudcan penetration. In marginal cases where excessive leg penetrations or a risk of punch-through is likely, the required preload can be designed to an acceptable minimum. Account is taken of the interaction effects of combined vertical and horizontal loading in this procedure.

The factor of safety required at punch-through locations is influenced by many factors and its choice is left to the judgement of the competent geotechnical engineer.

As units are operated in more onerous environments and designs are optimised in the interests of costs, it is essential to ensure that safety of the units remain unimpaired. If the analyses performed to establish the foundation integrity are not to be compromised, it will become increasingly necessary to require a geotechnical investigation prior to the installation of any jack-up unit.

This Paper does not cover all of the geotechnical problems related to the installation of jack-up rigs. The determination of moment restraint at the spudcan, and the analysis of foundation behaviour in calcareous soils are topics yet to be addressed. It has attempted, however, to cover the current considerations made prior to the installation of a jack-up unit.

References

- American Bureau of Shipping (1980): "Rules for building and classing mobile offshore drilling units", American Bureau of Shipping, New York
- Babbedge, N.H. & Lynagh, N. (1984): "The calculation of extreme wind speeds from visual observations with particular emphasis on the choice of Beaufort Scale", Proceedings Oceanology International Conference, Brighton
- Baglioni, V.P., Chow, G.S. & Endley, S.N. (1982): "Jack-up rig foundation stability in stratified soil profiles", Proceedings Offshore Technology Conference, Houston
- Blackham, Capt. A., Ridehalgh, J. & Cowling, G.A. (1984): "Construction and use of contour maps of environmental extremes", Proceedings Oceanology International Conference, Brighton
- Brown, J.D. & Meyerhof, G.G. (1969): "Experimental study of bearing capacity in layered clays", Proceedings 7th International Conference on Soil Mechanics and Foundation Engineering, Mexico
- Endley, S.N., Rapoport, V., Thompson, P.J. & Baglioni, V.P. (1981): "Prediction of jack-up rig footing penetration", Proceedings Offshore Technology Conference, Houston
- Hanna, A.M. & Meyerhof, G.G. (1980): "Design charts for ultimate bearing capacity of foundations on sand overlying soft clay", Canadian Geotechnical Journal
- Hansen, J.B. (1968): "A revised and extended formula for bearing capacity", Danish Geotechnical Institute Bulletin
- Knott, T. (1985): "Down amongst the spudcans something is stirring", Offshore Engineer, October 1985
- McClelland, B., Young, A.G. & Remmes, B.D. (1981): "Avoiding jack-up rig foundation failures", Symposium on Geotechnical Aspects of Offshore and Nearshore Structures, Thailand
- Meyerhof, G.G. & Hanna, A.M. (1978): "Ultimate bearing capacity of foundations on layered soils under inclined load", Canadian Geotechnical Journal
- Ridehalgh, J. & Edwards, A.J. (1982): "Design operation and towing of jack-up rigs", Royal Institution of Naval Architects
- de Ruiter, J. & Richards, A.F. (1983): "Marine geotechnical investigations, a mature technology", Proceedings Geotechnical Practice in Offshore Engineering, American Society of Civil Engineers, New York
- Semple, R.M. & Johnston, J.W. (1979): "Performance of Stingray in soil sampling and in-situ testing", Proceedings International Conference on Offshore Site Investigation, Graham and Trotham, London
- Skempton, A.W. (1951): "The bearing capacity of clays", Proceedings Building Research Congress, Institution of Civil Engineers, London