Ultimate Strength of Jack-up Rigs in Survival and Punch-through Conditions†

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Abstract

The ultimate strength is one of very important criteria for safety assessment of offshore structures. In this report, the ultimate strength of jack-up rigs is evaluated by the "Idealized Structural Unit Method". Two loading conditions are taken into account, i.e. survival and punch-through conditions, which may lead to total collapse of the rigs and, then, are very worthy of investigation.

The investigation draws the following conclusions.

(1) Two failure mechanisms are distinguished, i.e. yielding of chord which occurs ususally with fixed-type jacking units, and buckling or yielding of braces which occurs usually with floating type jacking units.

(2) In the case of jack-up rigs investigated in this study, the max. wave force in survival condition is 1.6-1.8 times of the design extreme wave load and allowable penetration in punch-through condition is 4 ~5m. This is believed to be typical for jack-up rigs. However, the present design may not be regarded as over conservative, considering the many uncertainties involved.

(3) In 3-legged jack-up rigs, failure of one leg would lead to total collapse of the rig. No redundancy is provided by the other two legs.

Based on these conclusions, a simple analytical model is developed and simplified formulae are proposed to estimate the ultimate strength of jack-up rigs in the above mentioned two loading conditions depending upon the failure mechanism and the type of jacking unit.

KEY WORD: (Ultimate Strength) (Design Load) (Jack-up Rig) (Survival Condition) (Punch-through Condition) (Plastic Collapse) (Idealized Structural Unit Method) (Jacking Unit)

1. Introduction

Ultimate strength of offshore structures is an important aspect in evaluating their safety. In this paper, jack-up rigs are considered, being among the most widely used offshore structures. The overall ultimate strength of the legs is evaluated using the Idealized Structural Unit Method. Two loading conditions are considered, the survival condition, and the punch-through condition which is receiving an increased interest in the last few years. These two loading conditions are especially important since they may lead to total collapse of the rigs. Two types of three-legged rigs are considered, their ultimate strength is evaluated and their safety is discussed. Simple equations to estimate the overall ultimate strength of jack-up rigs in these two loading conditions are presented.

2. Loading Conditions for Ultimate Strength of Jack-up Rigs

A jack-up rig is composed mainly of a platform and legs. Ultimate strength is directly controled by the legs. In the evaluation of safety of jack-up rigs, beside their static strength, other aspects, such as dynamic responce and fatigue are considered. This paper, however, concentrates on static ultimate strength and an evaluation of safety based on ultimate strength is performed. Relevent loading conditions include the survival condition, the towing condition and the punch-through condition which is receiving an increasing interest in recent years. Among these, survival and punch-through conditions are especially important since they have the potential to cause total collapse of the rigs with possible loss of human lives. These two conditions are considered in this paper.

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2.1 Deformation characteristics and load supporting mechanism of jack-up rigs

The legs of a jack-up rig directly control the overall strength of the rig. Generally legs are lattice structures composed of tubular members and usually have little redundancy. In the ultimate strength analysis of jack-up rigs, it is necessary to have a correct understanding of their load supporting mechanism and deformation characteristics. In the following, these are discussed in the two loading conditions considered in this paper.

2.1.1 Survival condition

When a jack-up rig is subjected to horizontal wind and wave loads, an overturning moment is generated. Meanwhile legs deflect and the platform is displaced horizontally. As shown in **Fig. 1**, leg deflection is characterized by a restrain of horizontal displacement at the leg's lower end (in contact with sea bed) and a restraint of rotation relative to the platform at the leg's upper end. This restraint of rotation is created partially by the teeth of the jacking unit and partially when the leg comes into contact with leg guides fitted in the upper part of the jacking unit and the lower part of the platform. The result is vertical reactions, V, generated in the jacking unit, and horizontal reactions, H, generated in leg guides. The values of V and H largely depends on the type of the jacking unit. The stiffer the jacking unit is, the larger is its share of the restraining moment and the higher is the ratio of V/H. This is discussed in the appendix.

2.1.2 Punch-through condition

When the legs of a jack-up rig come into contact with the sea bed at a new operating location, and before the platform is entered into operation, it is necessary to stabilize the soil under the legs. For this purpose, ballast tanks in the platform are filled such that the legs are subjected to loads similar to those expected in the survival condition. This is called the pre-load condition. In this case, when the soil has non-uniform properties, one leg may experience larger penetration than other legs. This is refered to as punch-through condition and is becoming a problem in recent years. Examination of the strength of jack-up rigs in this condition has become a requirement of many classification societies.

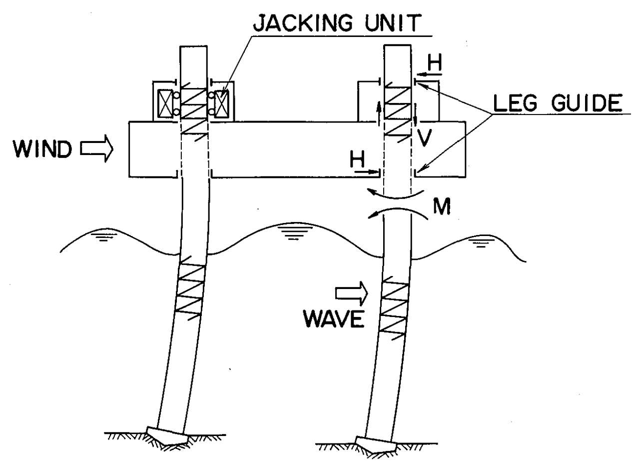

Fig. 1 Behavior of jack-up rig under survival condition

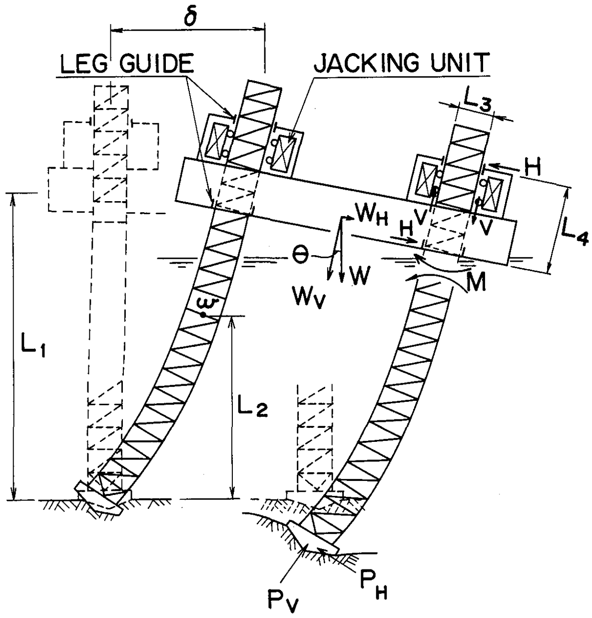

Fig. 2 Behavior of jack-up rig under punch-through condition

In this condition, with an unequal leg penetration, the platform is inclined and the weight of the legs and the platform develops a component parallel to the platform. This component causes the legs to deflect as shown in **Fig. 2**. Conditions of restraint of this deflection and load supporting mechanism are similar to those in the survival condition. It is to be noted that, pre-loading is performed in calm sea conditions. Therefore, it is not necessary to condsider wind and wave loads; and unequal penetration becomes the only external load.

2.2 Layout of rigs under consideration

In this study three-legged jack-up rigs are considered. A typical layout of the legs, as shown in **Fig. 3**, is considered. Each leg is a lattice structure composed of three chords, horizontal and diagonal braces arranged in K system as shown in **Fig. 4**. Each chord has two racks fitted symmetrically on the outside, and a center rib fitted on the inside, as shown in the same figure.

2.3 Evaluation of loads

In the following, evaluation of loads in the survival and punch-through conditions is discussed.

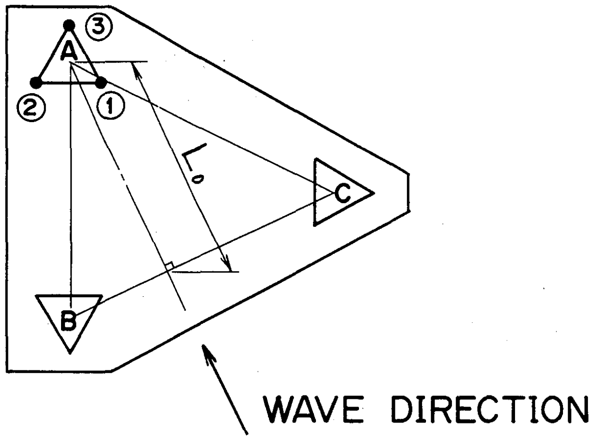

Fig. 3 Critical wave direction

2.3.1 Survival conditon

(1) Initial load

The following initial loads are taken into account. They are considered to be constant during the whole process of loading.

(a) Total weight of platform and objects on board are assumed to act at the center of gravity of the platform

(b) Wind load is evaluated according to the design wind velocity

(c) Weight and buoyancy of the legs

(2) Variable load

Generally, in the design of jack-up rigs, a sea condition with a very small probability of occurence is considered when evaluating external loads. It is not realistic to consider more severe sea conditions. However, considering an actual structure, many uncertainties are involved in the design, such as the accuracy of methods and assumptions used in evaluating the loads and structural responce. Many uncertainties are also involved in the construction and operation. However, evaluating each of these uncertainties separately and performing an accurate safety check is not possible at present. In this work, safety evaluation is based on the ratio between the ultimate strength of a rig when subjected to the extreme wave load pattern, and the design value of this load. This is considered as a factor of safety againest the above mentioned uncertainties. Therefore the design extreme wave load is considered to increase proportionally until the rig reaches its ultimate strength.

(3) Directions of wind and wave loads

It may be easily seen that with leg locations as shown in Fig. 3, the direction of wind and wave loads shown in the same figure produces the most severe condition for Leg A. This is also supported by experience with jack-up rig. This may be explained as follows. The overturning moment, M_{OT}, caused by wind and wave loads produces a compressive force M_{OT}/L_0 in Leg A. Moreover, the leg bending moment caused by the horizontal displacement of the platform produces a compressive force in chord ①. These compressive forces are superimposed on the compressive force due to gravity. Therefore, this load direction is adopted in the present study.

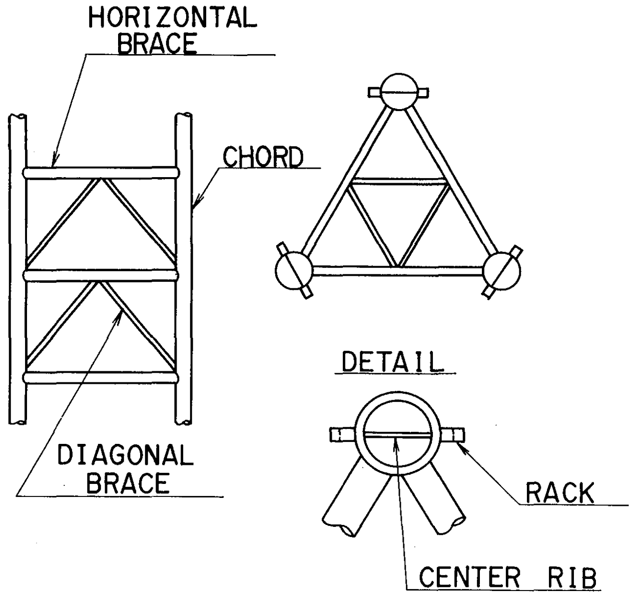

Fig. 4 Configuration of leg

2.3.2 Punch-though condition

This condition usually occurs during the pre-loading of a rig. Therefore ultimate strength is evaluated under the following loads.

(1) Conditions for load evaluation

(a) Pre-loading is performed in calm sea condition. Therefore wind and wave loads are not considered.

(b) Air gap (the distance between the still water surface and the lower side of the platform) is smaller than that in normal operating conditions and is assumed to be three meters.

(c) When the platform is inclined, a part of it may come back into the water generating some buoyancy force. This, however, is small and is neglected in this study.

(d) Based on the above conditions, only loads caused by leg penetration and platform inclination are considered.

(2) Evaluation of load

As shown in Fig. 2, when the platform is inclined, components of the weights of the platform and the legs are developed parallel to the platform. This is assumed to be equally distributed among the three legs. Reaction forces P_H and P_V acting at the lower end of the punching leg in directions parallel and normal to the platform respectively, may be expressed as follows

$$P_H = (W \sin\theta)/3 + w \sin\theta \tag{1}$$

$$P_V = R + P_1 + P_2 \tag{2}$$

where

W is the weight of the platform,

w is the weight of one leg – its buoyancy,

R is the reaction to the components of weight normal to the platform developed by the punching leg, $= (W \cos\theta)/3 + w \cos\theta$,

P_1 is the reaction to the overturning moment caused by weight components parallel to the platform, $= (W \sin\theta \cdot L_1 + 3w \sin\theta \cdot L_2)/L_0$,

P_2 is the reaction to the secondary overtuning moment caused by the parallel displacement, δ, of the platform, $= W \cos\theta \cdot \delta / L_0$,

L_1 and L_2 are the hights of the centers of gravity of W and w respectively from the sea bed as shown in Fig. 2,

L_0 is the hight of the triangle connecting the centers of the cross-sections of the three legs as shown in Fig. 3.

Usually θ is smaller than 5 or 6 degrees; and δ may be reasonably expressed as a linear function of θ, $\delta = k\theta$, where k is dependent on the stiffness of the Rig. P_H and P_V of Eqs. (1) and (2) may then be expressed as follows.

$$P_H = (W/3 + w)\,\theta \tag{3}$$

$$P_V = (W/3 + w) + [(WL_1 + 3wL_2 + Wk)\,\theta / L_0] \tag{4}$$

Therefore P_H and P_V may be considered to be linear with the inclination θ of the platform, i.e. with the differential penetration of legs.

3. Numerical Analysis

3.1 Method of analysis

The Idealized Structural Unit Method (ISUM)[1,2] is used in the analysis. In this method, geometric and material non-linearities, such as buckling and plasticity, are efficiently taken into consideration.

Depending on the dimensions of the structure, the effect of the flexibility of the joints on the behavior of the overall structure and its ultimate strength may not be neglected. However, depending on results of research by the authers[3], with dimensions typically used in jack-up rigs, this effect may be neglected without any sensible error. Therefore structural members are considered to meet at rigid joints.

3.2 Procedure of analysis

In the analysis of ultimate strength of jack-up rigs by the Idealized Structural Unit Method, legs structure is modeled by tubular elements[2]. Stiffness characteristics and ultimate strength condition for a circular tubular cross-section with racks and a center rib are derived in a similar way as presented in Ref. 2), to be used with leg chords. The stiffness equations of these elements are based on an exact solution of the differential equation of beam-column, and they take large deflection and plasticity into account. These equations are presented in the incremental form and are functions of the displacements and internal forces of the elements. Therefore the load is applied incrementally. At the beginning of the analysis, with no loads applied to the structure, the tangential stiffness matrix of each element is evaluated and transformed into the global coordinate system. The global stiffness matrix of the structure is then assembled and the first load increment is applied. The stiffness equations are then solved for the increments of displacements. Internal forces of each element may now be evaluated. These are checked to see if they satisfy the ultimate strength condition. Since the tangential stiffness matrices are functions of the displacements and internal forces, a new stiffness matrix is evaluated for each element. Stiffness matrices of elements which have reached their ultimate strength (have satisfied the ultimate strength condition) are evaluated tacking the ultimate strength condition into considration. The global stiffness matrix is reassembled and the next load increment is applied. As the load increases, internal forces of elements increase leading to successive failures (buckling or plasticity) in a number of these elements causing redistribution of internal forces in the structure. Intact elements, however, may continue to carry further loads caused by the increase of external load and the redistribution of internal forces. Finally the external load reaches its maximum value and further displacements are accompanied by a decrease of the external load. The structure is then considered to have reached its ultimate strength.

3.3 Rigs considered in the study

Two types of rigs as shown in **Table 1** are considered. Both rigs are designed according to the rules of classification societies to operate in the North sea. Rig A is fitted with a fixed-type jacking unit, while Rig B is fitted with a float-type one. Usually loads are supported by the jacking unit. However when the load applied on the jacking unit reaches its maximum supporting capacity the brakes of the jacking unit slip and the load can not be increased any

Table 1 Principal particulars of Jack-up rigs A and B

	RIG A	RIG B
PLATFORM DIMENSION L × B × D (m)	84 × 90 × 9.5	70 × 76 × 7
MAX. WATER DEPTH (FEET)	350	205
WAVE HEIGHT (m)	30.0	23.1
CURRENT VELOCITY (m/s)	0.8	1.3
WIND VELOCITY (m/s)	45.0	42.5
AIR GAP (m)	21.0	16.8
LEG PENETRATION (m)	5.0	7.5
WIND FORCE (ton)	413	272
WAVE FORCE (ton)	1,775	1,049
O.T.M. BY WIND (ton-m)	59,830	26,600
O.T.M. BY WAVE (ton-m)	154,610	58,660
GRAVITY LOAD IN SURVIVAL CONDITION (ton)	16,100	8,600
TYPE OF JACKING UNIT	FLEXED TYPE + CLANPING DEVICE	FLOATING TYPE
OPERATING SITE	NORTH SEA	NORTH SEA

further. In cases where the jacking unit can not support the loads applied in the survival condition, as in Rig A of this study, a clamp is fitted to support the load instead of the jacking unit. In Rig A this clamp is fitted with teeth to match the chord racks and, therefore, no slip can occur. In pre-load condition, however, in order to take quick corrective measures in case of a punch-through, clamps are usually not applied. Yield stress of all structural members, except few braces, is 70 kgf/mm^2.

3.4 Model and boundary conditions

3.4.1 Survival condition

When a rig is subjected to an increasing load, and when one leg collapses, redistribution of load to the other legs may take place. Therefore a three leg model is used in the analysis. The platform (deck) is considered as a regid body. The model is shown in **Fig. 5**. Modeling of the connections of legs to the platform is shown in **Fig. 6**. The jacking unit is modeled by equivalent bilinear springs parallel to the chords of the legs. The properties of these springs are such that when the load applied on a pinion of the jacking unit reaches the maximum carrying capacity of this pinion, slip of the brake of this pinion is taken into consideration by allowing increments of displacement at constant pinion reaction. Leg guides are modeled such that legs may deform until the clearance between chords and guides are closed up. Once chords come in contact with guides, relative motion normal to chords is prevented, while friction is neglected.

3.4.2 Punch-through condition

As will be discussed later, results of analysis carried out by a three leg model under survival load have shown that failure of members is concentrated in one leg. Successful load redistribution to other legs does not take place. Since the natures of the survival load and punch-through load are similar, only one leg is considered to be sufficient for the analysis. The connection of the leg to the platform is similar to that in the survival condition.

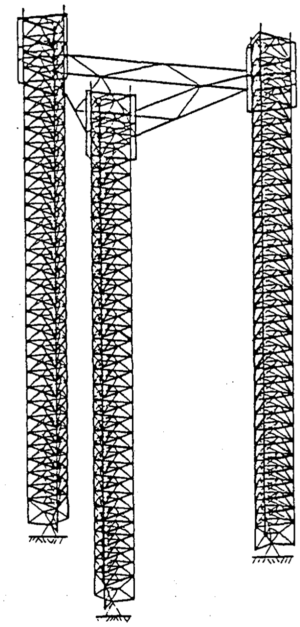

Fig. 5 Calculation model for survival condition

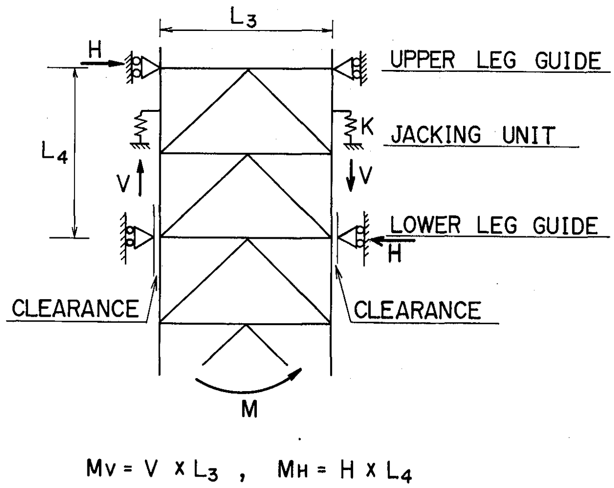

Fig. 6 Reaction forces on jacking units and leg guides

3.5 Results of the analysis

The relationship between the applied wave load (non-dimensionalized with respect to the design wave load) and the horizontal displacement of the deck for Rigs A and B in the survival condition are shown in **Figs. 7** and **8**. In

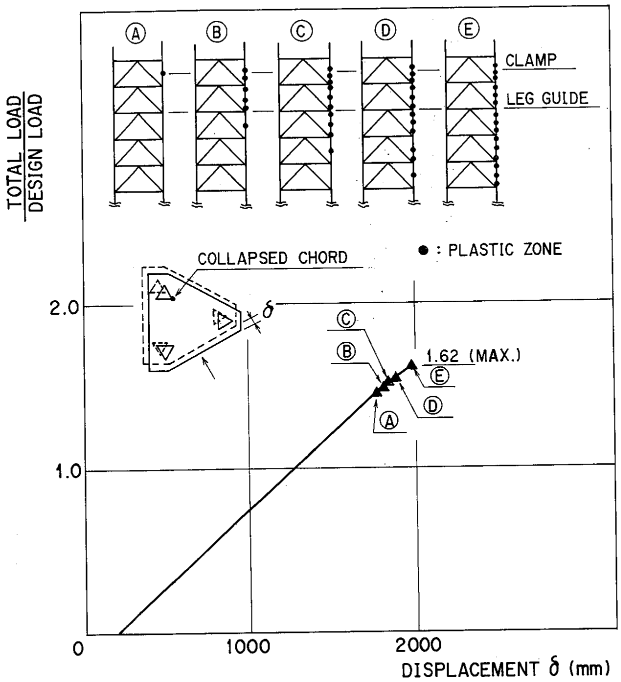

Fig. 7 Ultimate strength in survival condition (Rig A)

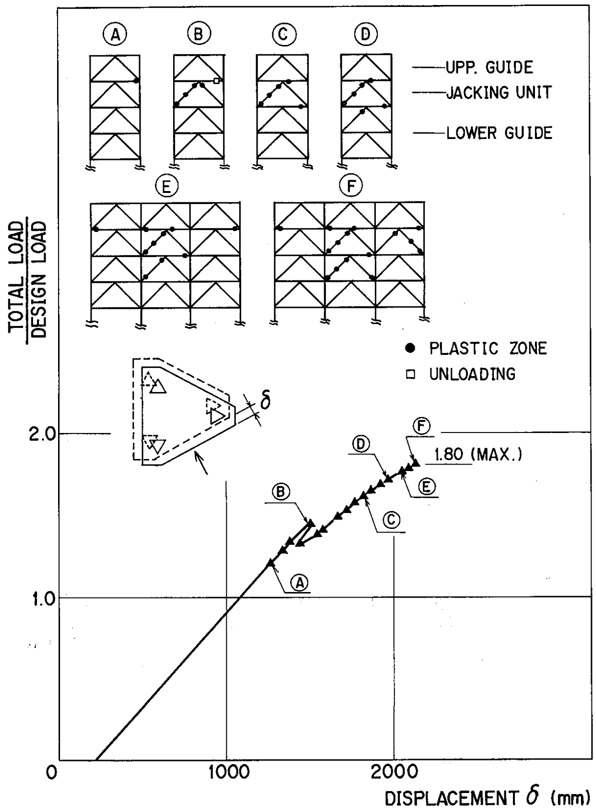

Fig. 8 Ultimate strength in survival condition (Rig B)

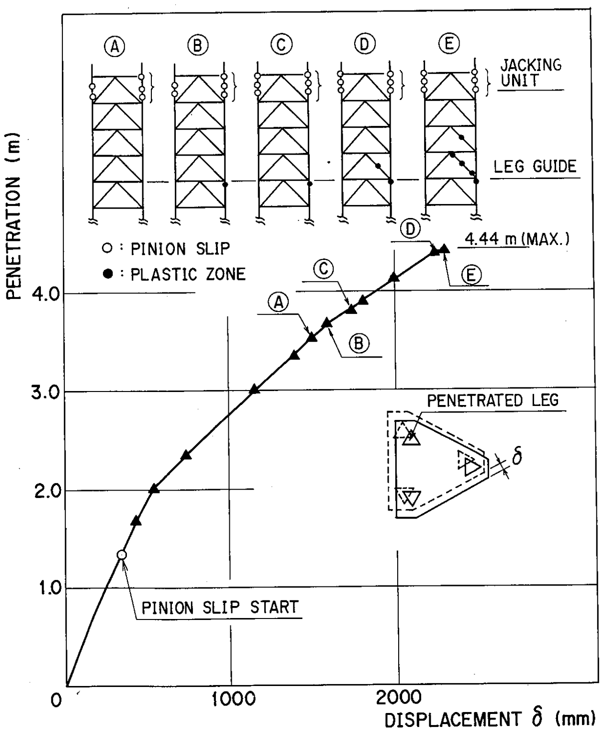

Fig. 9 Ultimate strength in punch-through condition (Rig A)

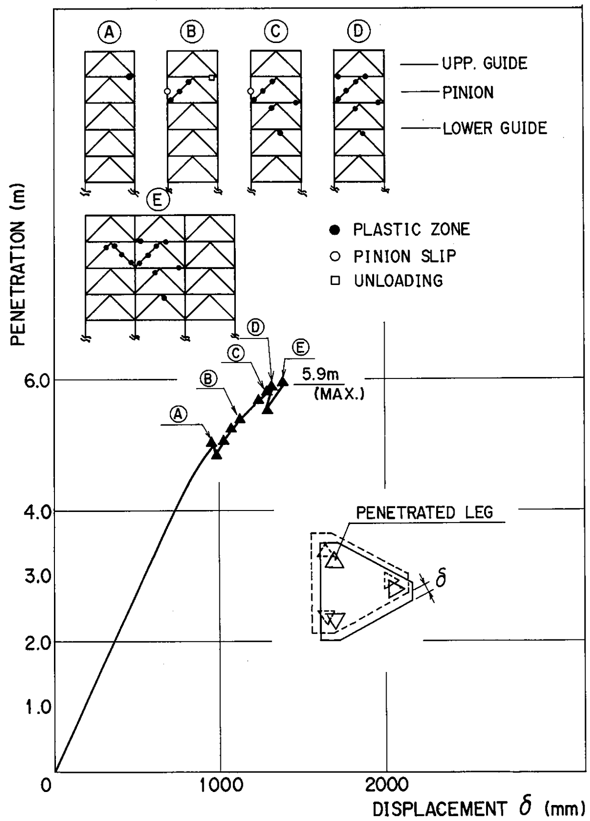

Fig. 10 Ultimate strength in punch-through condition (Rig B)

this case, initial displacement caused by the wind load (which is applied as an initial load) may be observed. The relationships between the penetration and the parallel displacement of the deck relative to the undefomed configuration of Rigs *A* and *B* are shown in **Figs. 9** and **10**.

History of collapse in each case is shown in the relevant figure. From these results, the following may be observed.

3.5.1 Survival condition

(1) In both Rigs *A* and *B*, as the load increases, failures (buckling and/or plasticity) occur in only one leg close to the jacking unit and leg guides.

(2) In Rig *A*, because of the presence of clamps, which have large stiffness, the bending moments applied on the legs at their connections with the platform are supported directly by axial forces in leg chords. Forces in braces between guids do not grow very large while axial forces in chords continue to increase. Therefore, buckling of braces is not observed while plasticity spreads in one leg chord until the rig collapses. Almost no redistribution of internal forces to the other two legs is observed after the first yield until collapse. This indicates that redundancy of three-legged jack-up rigs is very small.

In this case the collapsed leg may be regarded as a cantlever which collapsed in bending.

(3) On the other hand, in Rig *B*, with a float type jacking unit, failures (plasticity and buckling) occur in braces leading to the collapse of the rig. In this case, due to the low stiffness of the jacking unit, the bending moment of the leg is supported mainly by leg guides reactions which act in a direction parallel to the deck (see 2.1 and Fig. 6). This leads to large shearing forces in leg portions between guides accompanied by large axial forces in braces. As the external load increases, local failures occur in braces while no plasticity is observed in chords. Brace buckling in a leg is accompanied by a reduction of the load carrying capacity of the leg. However, redistribution of internal forces between braces successfully occurs and the load carrying capacity increases once more as displacement increases. Failures continue to occur in other braces until redistribution of internal forces can not successfully take place and the rig collapses. In this case failures spread on larger area of the structure than in case of Rig *A* providing the rig with some redundancy. The failure in this case may be considered as a shear failure.

(4) In the rigs analyzed in this study, the ultimate load in the survival condition is about 1.6 ~ 1.8 times the design extreme wave load. This is believed to be typical for jack-up rigs designed according to the rules of classification societies. This, however, may not be regarded as an over-conservative design because of the many uncertainties involved in design, construction and operation of rigs.

3.5.2 Punch-through condition

(1) In the punch-through condition also, failures are concentrated in one leg (the punching leg) close to the jacking unit and leg guides.

(2) In punch-through condition, clamps are not applied and the load is supported by the jacking unit. In Rig *A*, after slip of pinion brakes, further moment is supported only by leg guides, leading to an increase of the horizontal reactions provided by these guides.

This results in large axial forces in braces between guides causing them to fail (yield and/or buckle) and finally causing final collapse of the rig. Rig *B* collapses in a similar mode as Rig *A*. However spread of failures (and hence redundancy) is more pronounced in Rig *B* than that in Rig *A*.

(3) In the rigs considered in this study, which are designed with no consideration of the punch-through condition, up to four to six meters of differential penetration may occur before collapse.

4. Ultimate Strength Equations for Jack-up Rigs

Based on results of the numerical analysis presented above, equations to estimate the ultimate strength of three-legged jack-up rigs are derived.

4.1 Basic assumptions

(1) Numerical analysis has shown that collapse of one leg leads to the overall collapse of the rig. Therefore ultimate strength equations are derived based on the collapse of one leg.

(2) From results of the analysis, it may be seen that jack-up rigs have only a little redundancy; i.e. not much reserve strength is expected after first failure. Therefore ultimate strength equations are derived based on first failure as a conservation criterion for ultimate strength.

(3) Collapse modes of legs depend on the load supporting system (clamps and types of jacking units) and may be classified into two modes, bending collapse and shear collapse. In bending collapse, a leg is assumed to collapse when the internal forces in the most loaded chord satisfy the full plastic condition of the chord cross-section. In shear collapse, a leg is assumed to collapse when the most loaded compressive diagonal brace buckles.

(4) From experience with many jack-up rigs, the secondary moment developed in the legs due to the parallel (horizontal) displacement of the platform is found to be about 10 ~ 20% of the primary moment. This is assumed to be 15% (average value).

(5) As shown in the appendix, the moment supported by the jacking unit (or clamp) in case of a fixed-type jacking

unit is about 80% of the total moment at the connection between a leg and the platform. In a float-type jacking unit, 70% of the total moment is supported by leg guides.

4.2 Ultimate strength equations

In this section equations to estimate the ultimate strength of jack-up rigs are derived having the dimensions of legs, wind and wave loads, and the overturning moment they develop as parameters. As results of the numerical analysis show, two modes of collapse, bending collapse and shear collapse, are possible. The rig collapses in the mode which has a smaller ultimate strength.

4.2.1 Survival condition

(1) Bending collapse

In this case, ultimate strength is decided by plastification of the most loaded chord. Subtracting the axial force developed in this chord by the weight of the platform and wind load from the axial force which can be supported by this chord in the fully-plastic condition, the remaining is the axial force available to support the wave load. On the other hand, due to the bending moment developed in the chord, the axial force which it can support in the fully-plastic condition is found from experience with many jack-up rigs to be about 85% of the fully-plastic axial force. Therefore, the axial force available to support the wave load may be expressed as follows

$$Q = 0.85\,\sigma_y A - F_G - F_1 - F_2 \tag{5}$$

where

σ_y is the yield stress of the chord,

A is the cross-sectional area of the chord,

F_G is the axial force developed in the chord by the weight of the platfrom, $= W/9$,

F_1 is the axial force developed in the chord by the wind overturning moment M_{OTWIND}, $= M_{OTWIND}/3L_0$,

F_2 is the axial force developed in the chord by the leg bending moment at the leg-platform connection due the wind load, $= 1.15\,M_{WIND}/L_3$, allowing 15% for the secondary moment,

M_{WIND} is the primary moment developed in the leg at the leg-platform connection by the wind force P_{WIND}, $= P_{WIND} \cdot L_1/3$,

L_3 is the distance between chords as shown in Fig. 6.

Next, the axial force F_3 developed in the chord by the overturning moment M_{OTW} due to the extreme wave load may be expressed as follows

$$F_3 = M_{OTW}/(3L_0) \tag{6}$$

On the other hand, the primary moment M developed in the leg at the leg-platform connection by the extreme wave load, causes an axial force F_4 in the chord as given by the following equation, allowing 15% for the secondary moment

$$F_4 = 1.15\,M/L_3 \tag{7}$$

Now, the ratio α of the ultimate strength wave load to the extreme wave load may be written as follows

$$\alpha = Q/(F_3 + F_4) \tag{8}$$

(2) Shear collapse

(a) Pinion brakes do not slip

In this case, ultimate strength is decided by buckling of a diagonal brace between the lower and the upper leg guides. Subtracting the axial force F_{WIND} developed in such a compressive diagonal brace by wind force from the buckling strength F_{cr} of this brace, the remaining, $F_{cr} - F_{WIND}$, is the axial force available to support wave loads. F_{WIND} may be evaluated from the horizontal reactions of leg guides as follows

$$F_{WIND} = (\gamma M_{WIND}/L_4)\,(l_D/l_H) \tag{9}$$

where

l_D is the length of the diagonal brace

l_H is the length of the horizontal brace $= L_3$

L_4 is the length between upper and lower leg guides

γ is a factor to take account of the secondary moment ($0.15M$) and the distribution of moment between leg guides and the jacking unit ($0.7M$ supported by guides in case of float-type jacking unit and $0.2M$ in case of fixed-type).

$= 1.15 \times 0.7 = 0.805$ for float-type jacking unit

$= 1.15 \times 0.2 = 0.23$ for fixed-type jacking unit

Similarly, the axial force P developed in the diagonal brace by the design extreme wave load may be evaluated as follows

$$P = (\gamma M/L_4)\,(l_D/l_H) \tag{10}$$

The ratio α between the wave load which causes a diagonal brace to buckle and the design extreme wave load may then be written as follows.

$$\alpha = (F_{cr} - F_{WIND})/P \tag{11}$$

(b) Pinion brakes slip

Considering the secondary moment, the total moment caused by the design extreme wave load may be approximately evaluated as $1.15M$. On the other hand, leg moment is supported by a moment M_{pn} provided by the jacking unit and a moment M_G provided by leg guides. The maximum value of these moments may be expressed as

$$M_{pn} = P_{pn} \times L_3 \tag{12}$$

$$M_G = (F_{cr} - F_{WIND})\,(l_D/l_H)\,L_4 \tag{13}$$

where

P_{pn} is the maximum supporting froce provided by the pinions of the jacking unit.

The ratio α may then be written as follows

$$\alpha = (M_{pn} + M_G)\,/\,(1.15M) \tag{14}$$

Pinion brakes slip when the following condition is satisfied

$$(1.15 - \gamma)\,\alpha M > M_{pn} \tag{15}$$

4.2.2 Punch-through condition

In this condition no wind or wave loads are applied to the rig. Therefore terms in Eqs. (8), (11) and (14) related to wind load are removed and those related to wave load are replaced by terms related to unequal penetration load. The ultimate inclination angle θ of the platform may be expressed as follows, depending on the collapse mode.

(1) Bending collapse

$$\theta = (0.85\sigma_y \cdot A - F_G)\,/\,(1.15M_0/L_4) \tag{16}$$

where

M_0 is the leg primary bending moment at the lower leg guide corresponding to one degree inclination of the platform $= P_H \cdot L_1$

P_H is the reaction parallel to the platform acting on the lower end of the punching leg (see Fig. 2)

(2) Shear collapse

(a) Pinion brakes do not slip

$$\theta = F_{cr}/\,[(\gamma M_0/L_4)\,(l_D/l_H)] \tag{17}$$

(b) Pinion brakes slip

$$\theta = [(l_D/l_H)\,F_{cr} \cdot L_4 + M_{pn}]/(1.15M_0) \tag{18}$$

Pinion brakes slip when the following condition is satisfied

$$(1.15 - \gamma)\,\theta M_0 > M_{pn} \tag{19}$$

4.3 Comparison with numerical results

In **Table 2**, results of ultimate strength analysis by the above equations are compared with those obtained by the Idealized Structural Unit Method. It may be seen that these equations provide sufficient accuracy for practical purposes. When better accuracy is necessary, numerical analysis is recommended. It may also be observed that in punch-through condition, ultimate strength equations predict lower allowable penetration than that predicted by the numerical analysis. This may be refered to the conservative ultimate strength criterion (first failure) adopted in deriving these equations. It is difficult, however, to predict the amount of reserve strength after first failure without a detailed numerical analysis and it is not recommended to include such reserve strength in ultimate strength equations.

5. Conclusions

From results of ultimate strength analysis of two jack-up rigs, the following conclusions may be derived.

Table 2 Comparison between results obtained by ISUM and those obtained by ultimate strength equations

RIG NAME	SURVIVAL CONDITION TOTAL LOAD / DESIGN LOAD			PUNCH-THROUGH CONDITION ALLOVABLE PENETRATION (m)		
	SIMPLE FORMULA	FIRST FAILURE	MAX. LOAD	SIMPLE FORMULA	FIRST FAILURE	MAX. LOAD
A	1.41	1.53	1.62	4.13	3.80	4.44
B	1.56	1.50	1.80	3.53	5.00	5.90

(1) In the survival condition as well as punch-through condition, failures (plasticity and buckling) occur in one leg in the region close to leg guids and the jacking unit.

(2) Collapse modes of legs depend on the load supporting system (fitting of clamps and the type of the jacking unit) and may be classified in the following two types.

(a) Bending collapse, in which the bending moment applied on the leg causes the most loaded chord to yield leading to collapse of the leg.

(b) Shear collapse, in which the shearing force developed by guides horizontal reactions causes the most loaded brace to buckle leading to collapse of the leg.

In both modes, not much reserve strength is observed after first failure until ultimate strength, i.e. only a little redundancy is provided.

(3) In the survival condition, it was found that the ultimate wave load is about 1.6 ~ 1.8 the design extreme wave load. Considering uncertainties involved in design, construction and operation, it may not be said that the present design regulations are over-conservative.

(4) In the punch-through condition, for the two rigs considered in this analysis, which are designed according to the present practice without consideration of this loading condition, the allowable penetration is about 4 ~ 6 meters.

Ultimate strength equations are derived and found to have sufficient accuracy for practical purposes.

References

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Appendix: Moment Sharing between Leg Guids and Jacking Unit

In both the survival and punch-through conditions, the moment M developed at the connections of legs to the platform is supported by the moment M_V developed by the vertical reactions V of the jacking unit, and the moment M_H dveloped by the horizontal reactions H of leg guides, as shown in Fig. 6.

$$M_V = V \cdot L_3$$

$$M_H = H \cdot L_4$$

The ratio of M_V to M_H largely depends on the type of

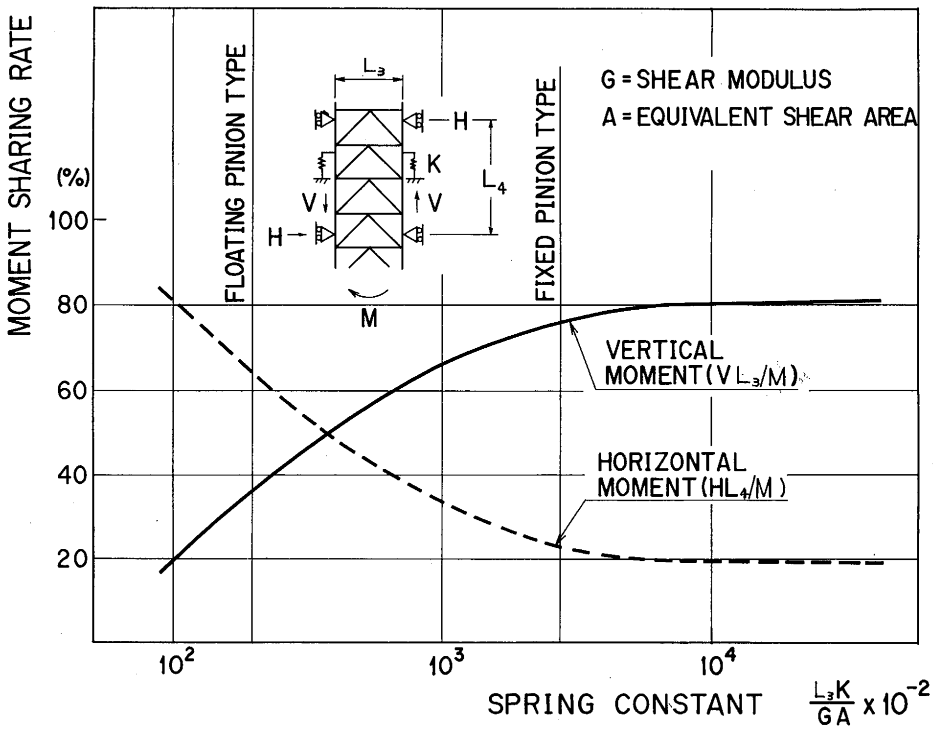

Fig. 11 Moment sharing rate v.s spring constant of jacking unit

the jacking unit. The housing of a jacking unit may be directly mounted to the platform, fixed-type jacking unit; or may be placed such that the loads are transmitted from the housing to the platform through an elastic shock pad, float-type jacking unit. In fixed-type, the stiffness of an equivalent spring as shown in Fig. 6 is much larger than in float-type. **Figure 11** shows the relationship between the jacking unit spring constant, nondimentionalized with respect to the leg shear stiffness, and the moment sharing rate, M_V/M and M_H/M as obtained by the investigation of existing jack-up rigs. Typical values of spring constants in case of fixed and float-type jacking units are shown in the figure. It may be seen that in case of fixed-type jacking unit, M_V is about 80% of M, and in case of float-type, M_H is about 70% of M.