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TOWARDS A BETTER EVALUATION OF SEMI-SUBMERSIBLE STABILITY

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Abstract

The purpose of this paper is to discuss the stability requirements for semi-submersible platforms. The rationale behind the current intact and damage stability criteria is first described. The effect of operational and design considerations on the practical implementation of stability rules is discussed. Criticism of existing criteria by different sources is then analyzed. The introduction of new regulations is investigated and the difficulties involved are outlined. Areas in need of further research are also highlighted.

The paper is concluded by proposing modifications on existing stability criteria. These modifications allow for gained operational experience and recent scientific developments to be incorporated.

Nomenclature

A	Projected area of the part
C_s	Shape coefficient
F	Wind force
GM	Metacentric height
I	Virtual roll moment of inertia
KG	Height of centre of gravity above base
$R(\Phi)$	Restoring moment
$W(\Phi)$	Wind heeling moment
V	Wind velocity at centroid of projected area
Φ	Heel or roll angle
Φ_1	Static angle of heel
Φ_2	Angle of second intercept
Φ_f	Angle of downflooding

1. Introduction

Operational experience has shown that one of the most efficient vehicles for offshore operations in deep and hostile water is the semi-submersible. In particular, a design with twin pontoons, connected to the working deck by four to eight vertical columns, has become the most popular, because it offers a good combination of transit speed, motion response and structural reliability.

One of the key design and operating parameters of semi-submersibles is stability. The importance of this aspect is fully recognized but the factors involved are very closely related to be readily translated into stability criteria.

The main purpose of all stability requirements is to ensure that the platform has sufficient ability to withstand capsizing in severe storm conditions plus flooding due to collision or other accidental flooding of the hull. However, until now there are no universally adopted rules and a floating unit must comply with:

- The rules of the country in which the unit is registered.
- The rules of the country that grants working licences.
- The rules of the society in which the unit is classified.

Since their first introduction, the stability criteria have been under attack. They have been accused of being arbitrary, too severe and unnecessarily penalizing the rig operators.

It would, therefore, be worthwhile to have a critical look into the whole issue of semi-submersible stability, and consequently the aims of this paper are as follows:-

1. To obtain a better understanding of the philosophy behind the current semi-submersible intact and damage stability criteria.

2. To discuss the different opinions of those with and those against the existing criteria and then to investigate possible modifications on these criteria.

3. To find areas in need of further studies in order to achieve a better evaluation of stability using a rational approach.

2. Intact Stability

2.1 The Philosophy Behind Current Criteria

When semi-submersibles first appeared there was no past experience to help formulate rational stability criteria. This is why semi-submersible stability regulations were originally based on ship experience and are to some extent empirical.

The intact stability criterion, commonly known as "weather criterion", compares the potential energy gained by the vessel through its restoring moment at some heeled position with the work done by the wind heeling moment. The energy balance is assumed to take place over half a roll cycle. This requirement may be deduced using an autonomous roll equation of the form:

$$I\ddot{\Phi} + R(\Phi) = W(\Phi) \qquad (1)$$

where

I = virtual roll moment of inertia

$\Phi, \ddot{\Phi}$ = roll angle and roll acceleration, respectively

$R(\Phi), W(\Phi)$ = restoring and wind heeling moments, respectively, depending only on the roll angle.

Equation (1) possesses a first integral, and if a half-roll cycle is considered beginning with $\dot{\Phi} = 0$ at $\Phi = 0$, this takes the form

$$1/2\, I\, \dot{\phi}^2 + \int_0^{\phi} R(\phi)\, d\phi = \int_0^{\phi} W(\phi)\, d\phi$$

The end of this half-roll cycle is given by $\dot{\phi} = 0$ again. This occurs at an angle ϕ_2, satisfying

$$\int_0^{\phi_2} R(\phi)\, d\phi = \int_0^{\phi_2} W(\phi)\, d\phi$$

In Fig.(1) $\int_0^{\phi_2} R(\phi)\, d\phi$ equals area (A+B) and $\int_0^{\phi_2} W(\phi)\, d\phi$ equals area (B+C). Both areas are measured up to either the second angle of intercept of the two curves ϕ_2, or to the angle of downflooding ϕ_f, whichever is the smaller angle.

As seen from above, this approach involves a number of drastic assumptions. To allow for dynamic effects, the existing stability criteria require righting energy to be 30% in excess of wind heeling energy. The reader is referred to other papers [1,2] for detailed comparison of existing stability criteria. However a brief summary of the criteria is given below.

For heeling moments caused by wind of speed 70 knots for operating draft and 100 knots for survival draft, the stability is considered sufficient if, as shown in Fig.(1):

1. The GM is to be at least 1.0m (or 0.3m in temporary conditions).

2. The area (A+B) = 1.3 area (B+C).

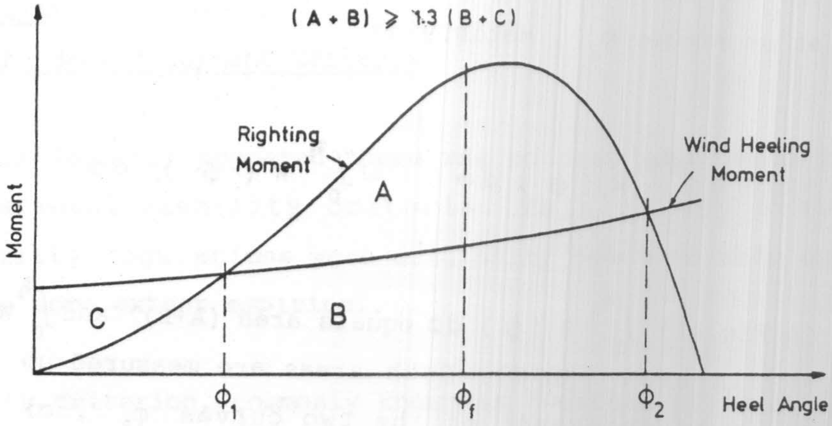
(A + B) ⩾ 1.3 (B + C)
Righting Moment
A
Wind Heeling Moment
Moment
C
B
Φ1
Φf
Φ2
Heel Angle

Fig. (1)

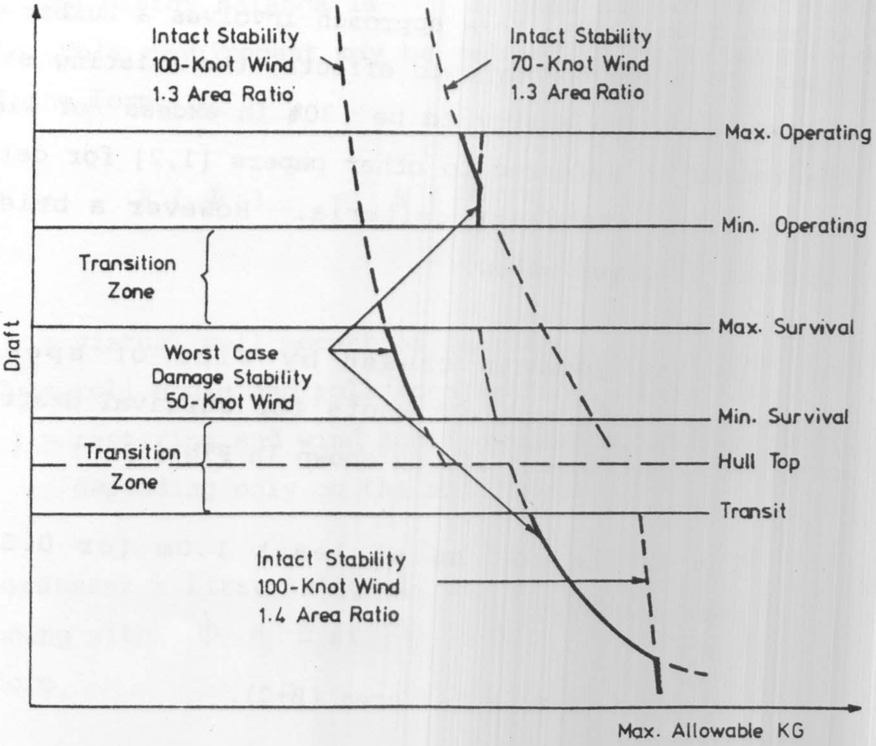
Intact Stability
100-Knot Wind
1.3 Area Ratio
Intact Stability
70-Knot Wind
1.3 Area Ratio
Max. Operating
Min. Operating
Transition Zone
Max. Survival
Worst Case
Damage Stability
50-Knot Wind
Draft
Min. Survival
Transition Zone
Hull Top
Transit
Intact Stability
100-Knot Wind
1.4 Area Ratio
Max. Allowable KG

Fig. (2)

3. The static angle of heel has to be confined to 15° in any condition.

4. The second intercept of the righting and heeling moment curves is to be at/or beyond 30°.

The final finding of the stability investigation will be a diagram showing the maximum allowable KG for the operational range of drafts, Fig.(2). This diagram is always contained in the operating manual of the unit and it offers a simple check on stability by comparing the operating KG with KG_{max} from the diagram.

2.2 Operational and Design Considerations

Most semi-submersibles are designed to operate with GM values of 1.5 to 2.0m for normal operations, and 1.0 to 1.5m for severe storm conditions [2]. The height GM is determined by the position of two points, the metacentre M and the centre of gravity G. As far as M is concerned, two contradicting requirements must be compromised, because motion characteristics are inversely related to the stability characteristics of the semi-submersible. The best motions are obtained by reducing waterplane area to a minimum, thus reducing the stabilizing moment of the unit. On the other hand, the position of G is mainly affected by the deck load. Rig operators are tempted to carry as much variable load as possible in order to be competitive and to avoid resupply problems.

The other main requirement is the area ratio under the righting and heeling moment curves. The area under the righting arm curve tends to increase as draft is reduced. For this reason, designers tend to specify an operating draft range at, or close to, the maximum load line draft where motions are most favourable and a reduced survival draft at which motions are greater, and at which the 1.3 area ratio for a 100 knots wind can more readily be met.

Therefore both the GM and area ratio requirements of the rules can be easily met. Not only that, but sometimes GM values exceeding the rules minimum are applied.

2.3 Determination of Wind Heeling Moment

The wind force can either be evaluated theoretically using standard civil engineering formulas, or experimentally in the wind tunnel.

The general procedure for calculating the wind force theoretically is based on dividing the structure into separate parts. The force on every exposed part is assumed to act at the centroid of the projected area of the part and may be calculated from the following equation:

$$F = k\,V^2\,C_s\,A \qquad (2)$$

where

k = constant whose value depends on the system of units.

V = specified wind velocity at the centroid of the projected area.

C_s = shape coefficient whose value depends upon the shape of the part.

A = projected area of the part

The aggregate force on all exposed parts of the unit is assumed to be resisted by a reaction force acting at the centre of resistance of the underwater part of the unit.

There has been considerable debate over the validity and accuracy of present methods for calculating wind forces. As shown by Hoff [3], there are shortcomings in such an approach:

1. There are uncertainties with regard to shielding effects and interaction effects of below deck members.

2. In a real sea state, the air flow below deck in a heeled condition, will be very complicated due to the presence of waves.

3. The hydrodynamic reaction forces, especially for the heeled condition, will be very difficult to predict.

These uncertainties are reflected in the different calculation procedures prescribed by the classification societies and authorities. There may be differences of up to 30% in wind moment between different rules applied to the same semi-submersible [4].

Based on the above discussion, wind tunnel tests seem to be the logical step to obtain more realistic results, and Norway now requires wind tunnel tests instead of calculations. A comparison between results obtained from the ABS rules and results from wind tunnel tests was carried out by Bjerregaard et al [5] and showed that calculation methods are probably conservative when compared to wind model tests. However, there are also some problems with model tests because it may be difficult to obtain a relevant simulation of the wind profile. In addition, there will be scale effects and it is impossible to perform model tests at full scale Reynolds numbers. Thus, tests cannot give entirely reliable results for full scale structures.

It is, therefore, believed that there is no point in making calculation procedures more accurate provided that everybody has to make these calculations the same way. As far as safety is concerned, conservative wind moment calculation methods are by no means a disadvantage.

2.4 Criticism of Existing Criteria

It is generally accepted that no semi-submersible unit has been lost or placed in serious danger because of any inadequacy in intact stability. Does that mean intact stability criteria are rational? The answer is "no". Semi-submersibles are inherently stable due to their special configuration. This was proved by model experiments such as those carried out by Numata et al [6]. Their extensive testing of a typical semi-submersible model under extreme wind and wave conditions showed no capsizing tendency, even at area ratio of less than 1.0.

Designers and operators have always accused the existing intact stability criteria of being extremely simplified and may lead to overly conservative designs [2,7,8]. The industry's criticism can be summarized as follows:

1. Present rules are empirical rather than based on scientific principles.

2. Mooring effects as well as wave and current effects are not considered.

3. The method of calculating wind moment is not sufficiently defined.

4. There is no requirement for limiting operating deck load in the survival condition.

Other points discussed in Ref.[2], regarding the characteristics of the GZ curve, are not valid because the inherent nature of the semi-submersible takes care of the shape of the righting arm curve.

3. Damage Stability

Damage stability is a more complex subject than intact stability. The unit is required to have sufficient stability and reserve buoyancy to remain stable and afloat after prescribed accidental events that have a realistic probability of occurrence. Experience has shown that semi-submersibles are vulnerable to three main types of damage:

1. Accidental flooding, which can be a result of leakage of the hull, broken piping, taking waves through openings or improper ballasting.

2. Flooding due to collision with other vessels.

3. Severe damage with extensive flooding such as that resulting from a catastrophic failure of the hull structure.

3.1 Existing Damage Stability Criteria

Damage stability criteria are also based on the "weather criteria" philosophy, Fig.(3). The basic requirements can be summarized as follows:

1. Under a wind of 50 knots, all openings should be at least 0.6m above the final damage waterline.

2. In the above mentioned condition of equilibrium the angle of heel ϕ_1 , Fig.(3), should never exceed 15°.

3. The area ratio under the righting and heeling moment curves is reduced to 1.0.

4. The righting arm curve shall have a positive extent of at least 20° beyond equilibrium and the righting arms should reach the height of at least 1m.

The rules have also defined the extent to which watertight subdivision is required and the intensity of any impact from an external source. These are stated below and Fig.(4) shows the damage zones of a semi-submersible.

1. The extent of damage due to a low energy collision is taken as 1.5m deep, 3.0m (or 1/8 the column periphery) wide and 3.0m high.

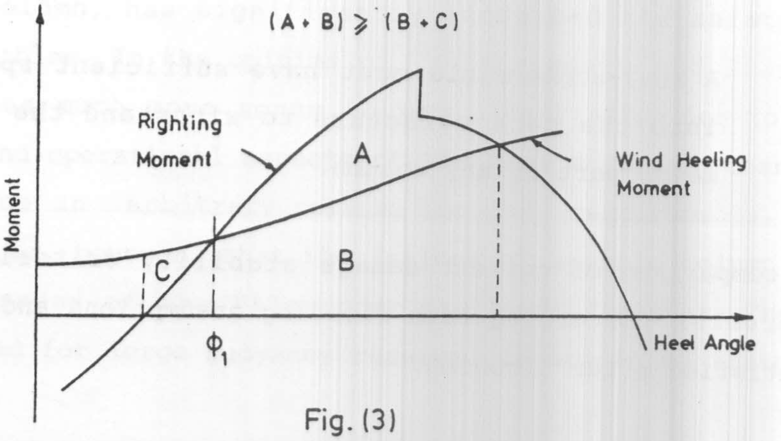
(A + B) ≥ (B + C)
Righting Moment
A
Wind Heeling Moment
Moment
C
B
ϕ_1
Heel Angle

Fig. (3)

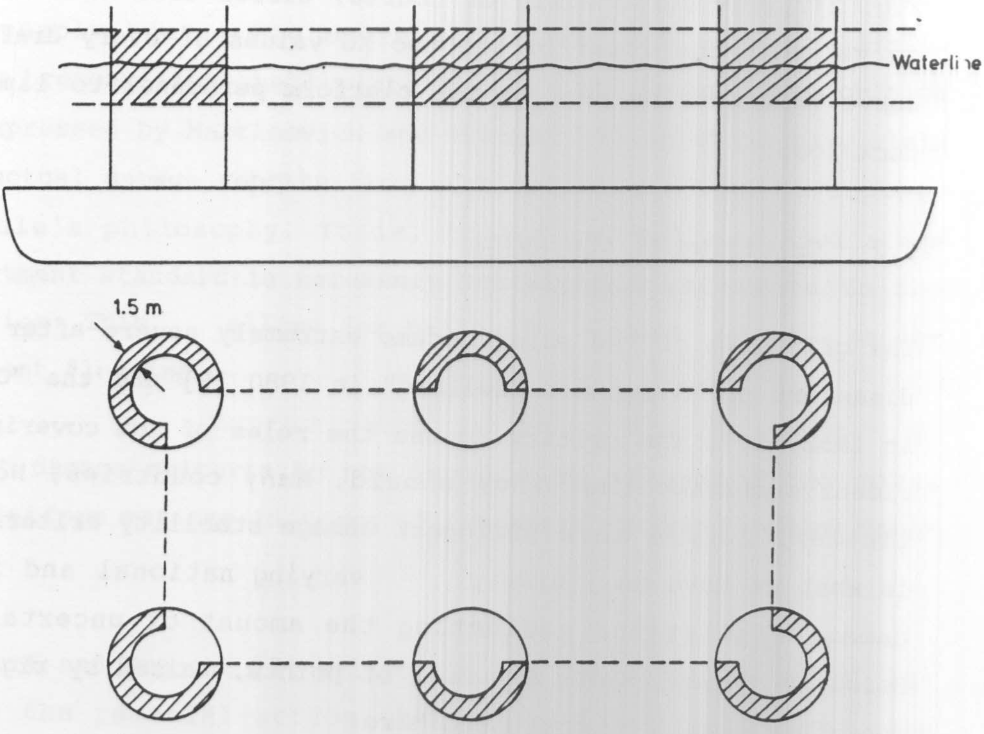
Waterline
1.5 m

Fig. (4)

2. The damage is confined to a zone of 3.0m below and 5.0m above the intact waterline (except in the ABS rules where this is taken as 1.5m above and 1.5m below waterline).

3. A semi-submersible must have sufficient spare buoyancy built into the deck structure to withstand the loss of a whole or major part of any column.

A comparison of current damage stability criteria shows large differences concerning both flooding assumptions and also criteria to be satisfied after flooding.

If calculations are made for every assumed damage case, a maximum allowable KG curve for the full draft range can be generated, Fig.(2). This curve will, of course, differ from the intact stability curve, and the lower of the two KG values at every draft defines the curve that must be used by the platform personnel to limit operating deck load.

3.2 Criticism of the Rules

The criticism of the rules became extremely severe after the two major disasters of "Alexander Kielland" in 1980 [9] and the "Ocean Ranger" in 1982 [10]. The critics accuse the rules of not covering all the accident scenarios that they should. Many countries, Norway in particular, issued more stringent damage stability criteria. The result is what we have now, widely varying national and international damage regulations reflecting the amount of uncertainty involved. Being very important, a number of points, raised by rig designers and operators, shall be discussed here:

1. Rig owners are not convinced that introducing the buoyant upper hull design, with the ability to resist the loss of buoyancy of an entire column, has significantly increased the safety of semi-submersibles. In the opinion of Springett and Praught [2], it makes much more sense to pay closer attention to the structural and operational aspects of the unit's design than to require vague an arbitrary reserve buoyancy requirements. One should remember, however, that the failure of a whole column was the actual cause of the "Alexander Kielland" disaster. Therefore, the need for large buoyancy reserves is something that can be justified.

2. The definition of the damage extent in the vicinity of the waterline was mainly intended to safeguard against collision with supply boat.. Rig operators claim that such a collision rarely breaches the shell plate at all [2]. An opposite opinion was expressed by Martinovich and Praught [7] in which they claim that actual damage reports from such collisions tend to support the rule's philosophy. It is, therefore, believed that a one compartment standard is necessary but without reference to the waterline. This allows for ballasting errors as well as inadvertent flooding.

3. Current damage criteria do not include an allowance for waves and platform motions in terms of freeboard to downflooding openings.

4. Springett and Praught [2] criticized the rules philosophy of ignoring the remedial action that can be taken by the crew. The

"Ocean Ranger" accident [10], however, supports the rules philosophy, when the crew were unable to take any corrective action.

4. Introduction of New Regulations

4.1 Before Any Rule Amendments

As pointed out by Kuo and Vassalos [11], rule changes for the sake of changes would not necessarily improve safety. On the contrary it could penalise the operators because revised criteria are likely to be more rigorous. The logical step forward must be to identify the shortcomings in the rules and then to seek rational ways to take the missing parameters into account, in order to improve safety without making the rules themselves more restrictive.

Before thinking of any rule modification or changes the impact of these on existing units should be very much taken into consideration. To satisfy new or modified criteria rig owners of existing platforms have to select one of four options [12]:

1. To modify the platform itself and leave the loading capacity untouched.

2. To modify the platform itself to a certain extent and reduce the deckload correspondingly.

3. To change solely the platform's operation, i.e. considerably reducing the deckload.

4. To withdraw the platform from service.

Therefore, amendments of the rules will require extensive effort and knowledge from both the designers and the authorities. Future regulations should maintain certain features. They should be fair, cost efficient, rational and simple. Also they should be flexible, i.e. they should not put restrictions on technological improvements and developments. Some of the points mentioned above are partly self-contradictory, but stability regulations are, to a certain extent, based on compromises.

4.2 Areas for Future Studies

Ideally the problem is solved through the development of a "full dynamic" solution in which the stability of the semi-submersible is judged from a study of its motion equations, which accurately represent extreme responses in realistic environmental conditions. Unfortunately this is not a feasible task. The basic problem is that a vessel as complex as a semi-submersible responding to wind and random waves, is impossible to define mathematically, and therefore, any developed criteria must be based on engineering assumptions that can be shown to be inadequate.

On the other hand model experiments as those carried out by Hoff and Naess [13] showed that dynamic effects from waves and wind do not appear to be decisive and that capsizing is mainly governed by hydrostatic effects. The only dynamic effect discovered was successive water flooding in damage conditions due to waves.

Future studies should, therefore, be directed towards the definition and evaluation of key parameters of the environment and their effect on the prediction of stability and motions of semi-submersibles. Future studies should also be directed specifically towards the stability in the damage condition which is more critical than the intact condition. As shown by Welaya [14] studying the dynamic behaviour of heavily listed semi-submersible would be very beneficial in this respect. Risk analyses should also be carried out to define damage conditions of semi-submersibles.

5. Concluding Remarks

Based on the above discussion of various aspects of semi-submersible stability, the following modifications of existing stability criteria are proposed:

1. Existing intact stability criteria are adequate. However, operational experience indicate that the area ratio minimum of 1.3 is very conservative and could therefore be reduced without jeopardizing the safety of the unit.

2. The value of the minimum GM should primarily be determined from platform operational considerations, so that routine movement of cranes or deckload does not produce excessive list or trim.

3. With regard to the definition of the damage extent, a one compartment standard is satisfactory but the condition of damage confinement to the waterline zone should be dropped. Flooding could be in any compartment. This allows for ballasting errors and inadvertent flooding.

4. Dynamic analysis should be performed for the platform in the damage condition, i.e. after a list angle is developed, in order to evaluate proper location of floodable openings.

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