DAMAGE STABILITY OF TENSION LEG PLATFORM IN ICE ENVIRONMENT

Dr. S.L.Karlinsky (Central Design Bureau for Marine Engineering, Russia)
Dr. M.A.Kuteynikov (Russian Maritime Register of Shipping, Russia)

Abstract

The design of oil&gas production platform for middle and deep sea (200 m and more) of the Russian offshore, where a floating ice influence is essential, leads to a floating ice-resistant TLP, arranged by the strengthened anchor system including sloped mooring lines. This anchor system should be able to withstand against ice field influence. Usually, a tension leg platform (TLP) keeps its stability against submergence and inclination mostly due to tensioned tethers restoring force and moment.

A damage stability of TLP is considered in Classification Societies Rules and Notes under emergency conditions as follows:

- Breaking or slacking of any one tension leg (tether/mooring line),
- Flooding of any one watertight compartment/tank.

There are a number of specific requirements (safety factors including) for an overall stability of such a structure, but many of them are not sufficient as for a conventional TLP, as, especially, for an ice-resistant TLP.

A critical consideration of requirements of Rules of maritime classification societies for TLPs stability is done. Ice-resistant TLP needs special considerations on intact/damage stability requirements. These requirements should differ essentially from the stability requirements for usual floating TLP, including a conventional TLP for the operational both intact and damage conditions. This fact can be explained by: (a) tension tethers influence and a necessity of a damage stability analysis in case of a rupture of one or more of tension tethers, (b) inclusion of an ice force in a heeling moment. The considerable modernization or re-issue of the Rules for Classification and Construction for Offshore installations in part of stability requirements for ice-resistant tension tethers floating platform may be required.

The paper presented proposes the formulae for said requirements, their background and the calculations, for example, of the ice-resistant TLP. The time domain computer simulation had been fulfilled by use of the software program certified by the Russian Maritime Register of Shipping.

1 THE SUBJECT

The worldwide experience of design and construction of oil & gas production platforms shows, that TLP is the most acceptable type for sea depths from 200 to more than 1000 m. During last years (1996 and after) TLPs have been installed worldwide, for example, at 930 m depth (TLP Mars, 1996), at 2050 m (Roncador Field, 1998) and 2800 m (Petrobrass BC 200 Block, 2000). The number of TLPs rises year by year due to the development of deep water oil/gas fields. Today's variety of Arctic deep water is a TLP for cold regions, i.e. an ice-resistant TLP. Most TLPs are four column shaped TLPs. But, the gap between columns may be not sufficient for ice floes pass; this is a reason for the occurrence of a great value of the ice force. The need to withstand the ice action has led to a new TLP variety [1]. The specific ice-resistant TLP features are as follows:

- The mono column shaping is the first feature (for an ice force mitigation) of the ice-resistant TLP.
- The second feature is a need the additional mooring system – to keep the platform in due horizontal offset limitations under an ice influence.
- The third peculiarity is the need of considering stability under ice influence.
- The fourth peculiarity is a need in a consideration of a damage stability in case of a watertight tank flooding as well, as in case of any anchor line breaking.

Therefore the TLP-type platform, being a new for use in ice environment, needs in additional considerations on the platform intact stability in operation as well, as in a damage condition. The considerations /requirements of such a kind for an intact/damage stability are proposed as follows:

1) Consideration (in stability evaluation) of the total heeling moment as a sum of a moment due to ice induced force and a wind heeling moment;
2) Breaking of a cluster of several closely spaced mooring lines, arranged at a side of an ice influence direction,
3) Taking into account an influence of a watertight tank flooding on a corresponding tether tension and, hence, on a restoring moment,
4) Taking into account the heeling moment from tensioned still intact mooring lines as well, as an influence of the vertical platform offset on the initial metacentric height, and, then formulating requirements for damaged platform stability.

2 THE WAY TO ICE-RESISTANT TLP

Conventional TLP, moored by vertical tension tethers, cannot resist efficiently against ice force. This is the main reason that the TLP don't put into wide practice under ice conditions. The calculations that had been carried out under certified ice weather conditions result in the conventional TLP sway under the wind, current and wave influence (total) less than 3-4 % of under keel depth, while the lateral offset exited by ice field influence is up to 25%, that is not acceptable.
Nevertheless, it is of considerable interest to design a platform, which would be stable under ice influence as well as under wave excitation, and will keep at the same time the main TLP features, as mentioned above.
Several possible ways to adapt TLP's anchor system to ice conditions may be considered. The first is the considerable increase of vertical tethers pretension by the subTLP buoyancy increase; this way does not prevent from the increased platform horizontal displacement. The second way is to arrange sloped tensioned legs instead of vertical tethers [7]. This way leads to an increase of natural frequency of horizontal oscillations and, further, to a negative effect under wave influence. The third way by the "Norsk Hydro/Kvaerner" design [1] for ice-resistant TLP (shown at Fig.1), for example, applies increased hull buoyancy combined with a double conic profile of column (narrow neck under water line) and the anchor system scheme shown below. An ice-resistant TLP conception leads to a

contradiction between a design solutions: one intended to resist against ice and other - to mimize a response to waves. This fact arises due to a very different way of ice or wave influence. Wave forces have mostly a symmetrical mode, and a tendon system rigidity shall be reduced to minimize a wave force amplitude. On the contrary, ice influence is of one-side direction and tendon system rigidity shall be increased to reduce sway and inclination due to ice. So, we have a rather difficult design task. All of listed should be a probable reason, why ice-resistant TLPs are rare in a world practice yet. The conception, that is presented in this paper, keeps the optimal relations between the floating TLP and the mooring system, as shown in [1]. The stableness in ice environment, as proposed, shall be provided by the mooring system including sloped tension legs, anchor system consists of vertical tethers preliminary tensioned by floating TLP buoyancy.

Proposed design philosophy assumes that the floating moored platform shall withstand maximum specified sea waves (in absence of ice) as well, as to maximum specified ice force (in absence of waves). The platform stability and tethers strength should be provided in both operation cases.

The statements are illustrated by an example of the ice–resistant hybrid TLP [1].

3 ICE –RESISTANT HYBRID TLP

The hull of TLP

The hull structure of ice –resistant hybrid TLP bases on the special column cone profiling, that improve ice wracking mostly by bending.

The sizing of the hybrid TLP is shown at the Figure 1 and Table 1.

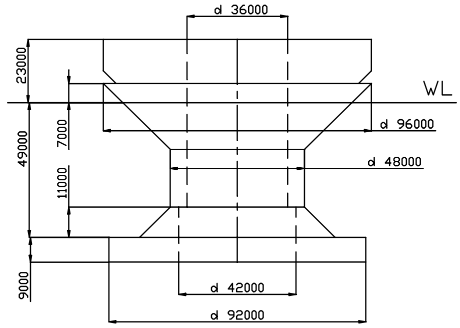

Fig.1 Floating monocon moored by sloped tensioned legs [1]

Table 1 - TLP Main Weight Particulars.

Parameter	Value
Operational draft, m	58
Topsides operational, tonnes	43000
Air gap, m	23
Displacement, m^3	133000
Floating hull, tonnes	44380
Solid ballast, tonnes	0
COG above base plane, m	50

3.2. Tether and mooring line configuration

Design peculiarities of the anchor system, proposed by Kvaerner in 2000 [1] are as follows:

1) Use of sloped lateral mooring lines together with vertical tethers.

2) Sloped lateral mooring lines should have a much less pretension, than the vertical, so that they should not be tensioned in storm conditions.

The hybrid mooring and anchor systems features are adduced in the Table 2:

Table 2. Hybrid Mooring and Anchor Systems Features

Feature	Mooring inclined lines	Vertical tethers
Number	6x4	3x5
Line portions material	Chain-Wire-Chain	Tube
Line portions length, m	20 – 800 - 50	260
Line portions diameter, mm	Chain 162 / Wire 154	1016/41
Pretension of Single line, KN	2450	18000
Design breaking load of Single line, KN	22000	53000

The hybrid mooring and tether systems arrangement of the ice-resistant TLP is shown at the Figure 2.

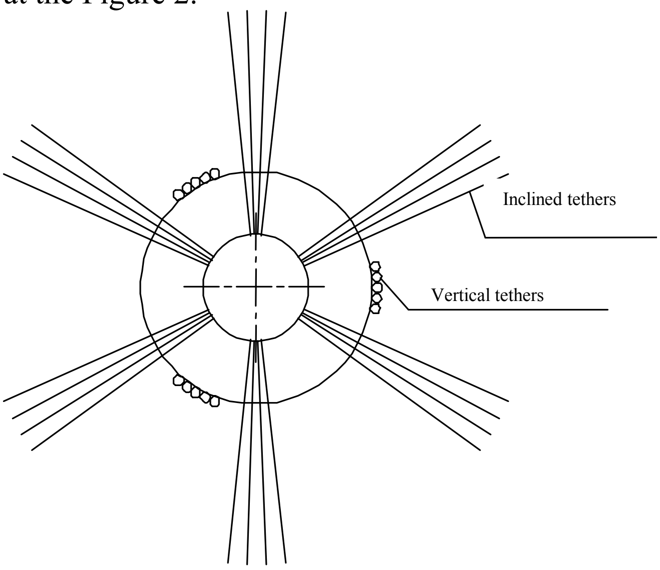

Figure 2. Hybrid Mooring and Tether Systems Arrangement

The main advantages of hybrid are as follows:

(a) The hybrid TLP provides a good resistance to storm and ice environment both,

(b) Hybrid mooring and tether systems is flexible relative to uncertainties in ice loads, because a change in ice loads can be met by a redesign of the mooring system only.

(c) The criticality and risk of the installation is reduced since the two positioning systems guard against loads which occurr during the marine operation.

4 DESIGN STABILITY CONSIDERATION

In this Part design stability considerations are done, and then, in Part 5 these considerations are applied and checked by calculations for an example of the hybrid ice-resistant TLP

4.1 Critics of existing stability parts of Rules

There are well known (also formulated in [2]), intact stability requirements for a conventional TLP type platform influenced by wind, current, sea wave, as follows:

(1) tension of tethers provided by a redundant TLP buoyancy shall be enough to prevent from the tethers slacking; at the same time a permissible tethers stress shall not be exceeded,

(2) tether tensions shall be enough to ensure the TLP angular stability (especially in case of a negative metacentric height of the free floating subTLP);

(3) the wind heeling moment is considered as a main influence on a floating TLP, added by a wave second order heeling moment.

But, the ice-resistant TLP type of a TLP, being a new one for use in ice environment, needs in additional (as regards to a conventional TLP) requirements for operational stability, those should be shown in regulative issues including the Rules for Classification and Construction. The consideration of the existing Rules ([3],[4],[5]) in part of requirements for floating platforms stability needs comments as follows:

(a) The requirements for intact/damage stability envisage the wind heeling moment as a main influence on a floating TLP (taking rolling process into account), added (in the most of the Rules) by a wave of second order heeling moment. The heeling moment exited by an ice force is not taken into account anywhere.

(b) All Rules have been considered, assume not to take into account an influence of tethers and/or mooring connections in stability calculations for intact/damaged TLP stability, except of special cases. It is not acceptable for TLP, whose stability is provided mostly by tethers tension.

(c) There are no recommendations on a TLP stability change after a watertight tank flooding and following tethers slacking.

The specified ice force value to an ice-resistant TLP is not less (as a rule), than wind force value applied to the platform topside, and often exceeds the last one considerably. As example, the calculated maximum forces to a TLP type hybrid platform (shown at Fig. 1) are:

Due to a wind (specified wind speed is of 100 knots): the horizontal force -30 MN, and the heeling moment – 2940 MNm

Due to an ice (ice ridge): 130 MN, the vertical force – 55 MN, and the heeling moment – 7690 MNm (See Table 3)

Table 3 Ice load calculations

The component of the load		Force lever, m	Load value
WIND	Horizontal force **Fx**, MH (applied at 40 m above WL)	98	30
	Heeling moment **My**, MHм		2940
ICE	Horizontal force **Fx**, MH (applied at 5 m below WL)	0.8	130
	Vertical force **Fz**, MH (applied to the ice cone at WL level)	20	40
	Heeling moment **My**, MHм		7690

***Heeling moments calculations*:**

WIND**:** My = Fx (T–40) = 30 (58+40) = 2940 MHм

ICE**:** My = Fx (T–5) + Fz *44 = 130 (58-5) + 40*20 = 7690 MHм

Evidently, an ice influence to a drifting TLP is negligible as compared with a wind drifting force. On the contrary, when a moored ice-resistant TLP contacts with ice field, the ice force exposes completely, and a heeling moment appears. This heeling moment is equal to ice force value multiplied by a depth of mooring lines hawses under sea surface, as it is shown by formula (2) (see also the ice heeling moments curves at Fig. 3). In this case the angular stability as well, as the common TLP stability against shear and offset, depends essentially on the hawses arrangement and on the preliminary mooring tethers tensions (or, the same, excess TLP buoyancy).

Also it has to be noted, that damage TLP stability deteriorates considerably in case of damage of one (or more) tethers; that fact causes an appearance of a heeling and yawing moments due to redistribution of tethers tensions. Also in marine operations (the free floating TLP), such as a TLP sea towing and an installation on site, forces and jerks of tow ropes or mooring lines can excite a heeling moment, that also shall be taken into account in stability calculations.

4.2 Initial stability of ice-resistant TLP

An influence of tension tethers on an initial stability of ice-resistant TLP can be evaluated preliminary under usual assumptions. Then the simple equation for an initial metacentric height can be written as:

$$\mathbf{h = (z_C - z_G + r) + \Delta P/D(z_H - z_C) + T_0 B/2D} \quad \mathbf{(1)}$$

where **h** = initial metacentric height,
$\mathbf{z_C, z_G}$ = vertical distance of center of buoyancy and center of gravity from a base plane,
r = metacentric radius,
$\mathbf{\Delta P}$ = excess TLP buoyancy equal to the summary tethers tension,
D = TLP weight,
$\mathbf{z_H}$ = vertical distance of the hawses from the base plane.
$\mathbf{T_0}$ = total tethers pretension
B = distance between opposite tethers

The all characteristics regard to the operational TLP draft for the completely tensioned tethers. The last two members of equation (1) is an addition to the metacentric height due to the tethers influence. The second member can be «+» or «-» as depends on a fact - are the hawses below or above the TLP center of buoyancy. The third member always increases TLP stability, while the first two may be negative. Usually, conventional TLP have a negative initial metacentric height in a free floating position.

In the same time, the ice influence overturning moment can be evaluated by formula:

$$\mathbf{M_{ICE} = F_{ICE}\,(T - z_H)} \qquad \mathbf{(2)}$$

Therefore, the angle of the TLP inclination under ice influence depends on the hawses arrangement as well, as on the excess TLP buoyancy and, hence, the minimum angular TLP inclination does not correspond to the draft of the maximum TLP metacentric height (as it takes place for usual floating TLPs).
The illustration of the TLP stability diagramm is show at Figure 3.

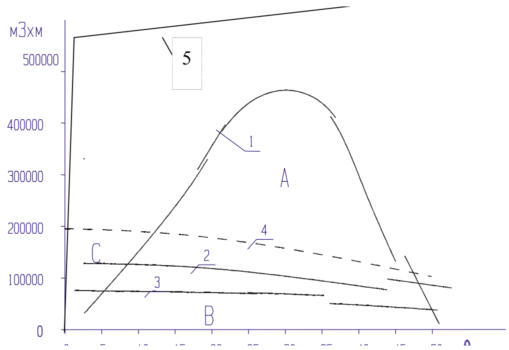

Figure 3. Illustration of curves for TLP of ice (2), wind (3) and total (4) heeling moment and righting moment for a free floating TLP (1), and for a tethered TLP (5).

As it can be seen from the Figure 3, the total heeling moment (4) is much more, than wind heeling moment (3)

4.3 Conclusions on TLP stability consideration

The conclusions below are based on stability diagrams calculated under existing Rules recommendations (i.e. do not taking into account the tethers influence), but take into account ice heeling moment as well, as the heeling moment of the sum “Ice + Wind”.

(1) As it can be seen from the stability diagrams for TLP at Fig. 4, superposition of the wind and ice heeling moments redistributes essentially the points of intersection between the heeling moment curves and the righting moments curves and, correspondingly, changes by a dangerous way the equation for areas **A, B, C: (A+B)>1.3(B+C)**, that are to be checked for an <u>intact TLP</u> accordingly to requirements of all the Rules. The mentioned changing appears rather more dangerous, keeping in mind that the wind speed in calculations of 100 knots is a very rare event and, at the same time, an ice floe influences on the TLP for a long

time. Therefore, appears a requirement to take into account the ice heeling moment in stability calculations for ice-resistant TLP.

(2) A breakage or malfunction of one or more tension tethers in presence of a drifting ice leads to appearance of a heeling moment in the plane which direction depends on the simultaneous platform yawing angle. Also this heeling moment redistributes cross points between the heeling moment curve and the righting moment curve, and, correspondingly, changes by a dangerous way the equation for areas**: (A+B)> (B+C)**, that shall be checked for a damaged TLP accordingly to requirements of all the Rules. Therefore appears a requirement to take into account a damage or malfunction of one or more tension tethers in stability calculations for damaged ice-resistant TLP. There are good reasons to accomplish special requirements for towing and mooring devices as related to TLP stability during marine operations.

5 STABILITY EVALUATION OF INTACT /DAMAGED HYBRID TLP UNDER ICE INFLLUENCE

The example of the TLP position and stability change after TLP has been damaged in an ice environment is considered. Such a consideration being new in a TLP design practice, is carried out in purpose to formulate requirements on a TLP intact/damage stability in an ice environment.
The TLP five main states are considered as follows:

- Operational intact position under ice influence (see Figure 4),
- Damaged position out of ice influence with a watertight tank flooded,
- Damaged position under ice influence with a watertight tank flooded,
- Damaged position out of ice influence with one cluster of tethers broken
- Damaged position under ice influence with one cluster of tethers broken (see Figure 6).

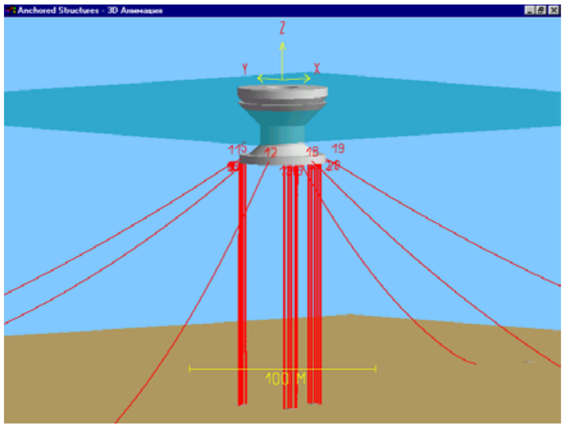

Figure 4. TLP operational intact position under ice influence

The main parameters used for the stability analysis of the tethered TLP are as follows:

- Horizontal shift, m
- Vertical displacement, m
- Inclination, degree
- Relation: - (Minimum Residual tether tension / Pretension) - shows tether slacking if <0
- Relation: (Maximum Residual tether tension / MBL) is equal (1/Safety Factor)

The volume of the flooded tank was evaluated as 9400 m^3. The breakage of one tether does not cause noticeable changes (see Figure 5). So, the breakage of a whole cluster of 5 tethers is considered, since the breakage may be probable in ice environment due to ice hammock pressure.

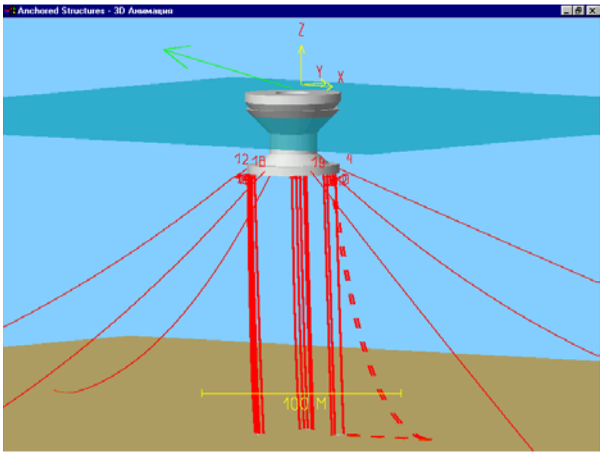

Figure 5. TLP damaged position under ice influence with one of 15 tethers broken

The main results of the time simulation (fulfilled by program [6]) for the listed TLP positions are shown in the Table 5. There are: the initial metacentric height of the free and tethered TLP, the displacements of TLP under ice influence and relational tether tension in the most tensioned tether line. The damaged position of the hybrid TLP under ice influence is depicted at the Figure 6.

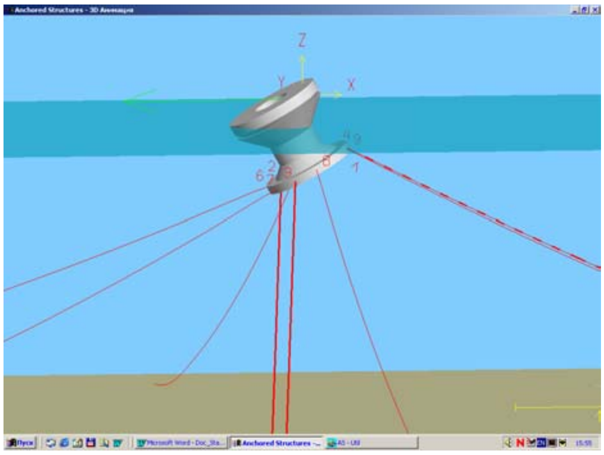

Figure 6. TLP damaged position under ice influence after one of three clusters of tethers broken

Table 4. Parameteres of the hybrid TLP position after has been damaged in ice environment (tethers system: 3x5)

Parameter	Operational intact position under ice influence	Damaged position out of ice influence with a watertight tank flooded	Damaged position under ice influence with a watertight tank flooded	Damaged position out of ice influence with one of three clusters of tethers broken	Damaged position under ice influence with one of three clusters of tethers broken
Initial hydrostatic metacentric height of the free TLP, m	-16.3	5.2	5.2	3.6	3.6
Initial metacentric height of the tethered TLP, m	1080	10.9	10.9	4.8	4.8
Horizontal shift, m	18.4	0	20.6	17.6	23.0
Vertical displacement, m	-0.6	0	-1.7	-1.7	-6.2
Inclination, degree.	0.3	0	3.7	32.5	33.0
Minimum Residual tether tension / Pretension	2.5	0.12	2.56	2.06	3.09
Maximum Residual tether tension / MBL*	0.85	0.04	0.87	0.7	1.05
* MBL – Minimum Breaking Loading for the tether					

As it can be seen from Table 4, the actual platform stability depends essentially on the tethers tension. The tethers tension differ in many times in case of a watertight tank flooding as well, as in case of one cluster of tethers broken. The TLP is stable in the both damage cases. Safety factors for tethers are sufficient, except the last case. But, in case of a watertight tank flooding, the residual tether tension is very small, so that after this damage the TLP cannot withstand any wave influence (except of possibility, when the variable ballast would be pumped out of the due ballast tank). Also, in the case, when one cluster of tethers is broken, the TLP inclination angle (see the Figure 6) is much more than acceptable. So, the position of the damaged TLP is not sufficient for the both damage cases.

Evidently, as regards to the last case (when one cluster of tethers is broken), the TLP position may be improved by use of a more even tethers arrangement.

In purpose to seek better (more uniform) tethers arrangement, three tether clusters were replaced by six clusters (scheme 6x3).
The main results of the time simulation (fulfiled by program [6]) for positions of the TLP arranged by six tether clusters are shown in the Table 5. The damaged position of the hybrid TLP of 6 tether clusters under ice influence after one of six cluster of tethers broken is depicted at Figure 7.

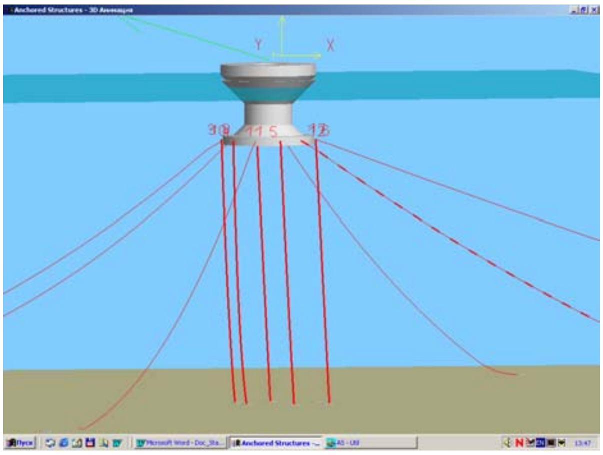

Figure 7. Damaged position of the hybrid TLP under ice influence after one of six cluster of tethers broken

Table 5. Parameteres of TLP position after has been damaged in ice environment
(Tethers system :6x3)

Parameter	Operational intact position under ice influence	Damaged position out of ice influence with one of six clusters of tethers broken	Damaged position under ice influence with one of six clusters of tethers broken
Initial hydrostatic metacentric height of the free TLP, m	-25.7	-26	-27.4
Initial metacentric height of the tethered TLP, m	2390	1260	1260
Horizontal shift, m	14.2	1.0	14.4
Vertical displacement, m	-0.36	0	-0.32
Inclination, degree.	0.12	0	0.36
Minimum residual tether tension / Pretension	0.25	0.12	0.07
Maximum residual tether tension / MBL	0.27	0.45	0.7

The Table 5 and the Figure 7 show, that the TLP position is good, and the TLP stability is well enough. Safety factors for tethers are sufficient. So, the TLP position in ice environment after one of tethers cluster of broken, may be done safe by correct arrangement of tether lines. But, the residual tether tension after this damage is much less than pretension, so that the TLP cannot withstand any subsequent wave influence (except of possibility, when the variable ballast would be pumped out of the due ballast tank and, so, the tether tension is restored).

6. CONCLUSIONS

6.1 The ice-resistant TLP intact/damage stability can be provided in ice environment as well, as in storm conditions. Safe stable TLP position is possible by the correct uniform arrangement of tether lines coupled with the strong enough tethers tension. Design criteria, established above, need a further development.

6.2 It is stated that the stability requirements for ice-resistant TLP have to differ essentially from the stability requirements for usual floating offshore units. That can be explained by:

(a) Tension tethers essential influence on TLP stability and a necessity of a damage stability analysis in case of a rupture of one or more of tension tethers, including ice influence,

(b) Inclusion of an ice force in a heeling moment,

(c) Necessity of a damage stability analysis of TLP with a watertight tank flooded under ice influence.

A computer simulation of statics and dynamics for two TLPs may be carried out by special software package ([6]) developed by St.-Petersburg Technical University and certified by the Russian Maritime Register of Shipping.

6.3 The modernization of the Rules of maritime classification societies in part of stability requirements, as applied to TLP, is demanded. The initial propositions are:

(1) In stability of an intact/ damage TLP it is necessary to take into account the arrangement and variations of the tether tensions.
(2) In stability calculations for ice-resistant TLP the ice exited heeling moment shall be taken into account as well, as wind heeling moment.
(3) In stability certification of a damage TLP should be considered at least two damage cases: a watertight tank flooding and a tether leg breakage.

7. REFERENCES

[1]. 1 K.I.Stokke, S.Botker, Ice Resistant Platforms for Shtokman Gas Field, comparison of TLP, Buoy and Spar Concepts and Proposal of a Hybrid TLP Concept, RAO-01, St.-Petersburg, 2001.

[2]. 2 API RP 2T for TLP, Second Edition, American Petroleum Institute (August 1997)

[3]. 3 DNV, Rules for Mobile Offshore Units, 1996.

[4]. 4 ABS, Rules for Classification of Offshore Units, 1994.

[5]. 5 Rules for the classification, construction and equipment of MODU/FOP - RMRS, 2001.

[6]. 6 S.Frolov, A. Bolshev, Software Package “Anchored TLPs”, S.-Petersburg State Technical University, Approval Certificate of the Russian Maritime Register of Shipping No 02.001.010, 2002.

[7]. 7 S.L. Karlinsky, Conception of the Ice-Resistant Production Platform (**TLP** type) for Deep Sea, POLARTECH’96, S.Petersburg, 1996.