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Ice Load Assessment for Jack-Up Units

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ABS

ABSTRACT

Strengthened and efficient jack-up drilling units are considered viable for operations in shallow ice-infested waters with mild ice conditions because of their mobility which allows them to leave the site for a sheltered area when ice conditions warrant it. However, current recognized design standards and codes do not specifically address jack-ups in ice.

One of the key ice-jack-up interaction scenarios is an ice floe impact on the legs. While this is addressed in some of the codes in general terms, no specific requirements are given regarding the effects of the structural deformation and dynamic effects (compliance of the structure). In this study, ISO 19906 was used as the primary standard to assess the ice loads. A spring-mass system was developed to model the interaction between the ice and jack-up during the impact event. The jack-up legs are modelled considering local and global stiffness. The effect of the ice crushing against the jack-up structure is modelled as a nonlinear spring. The ice floe collision event and the dynamic behaviour of the Jack-Up are solved using numerical solution in time domain. The effect of floe size, strength of ice and the ice drift speed on the ice loads are evaluated, and the effects of the stiffness of the jack-up legs on the ice impact load are compared with a rigid structure and with the level ice case.

INTRODUCTION

Jack-ups were originally designed for ice-free water. Their capacity in resisting ice loads is limited; therefore, the drilling operation may not be practical in severe ice conditions. Hence, the drilling operations are expected to be under effective ice alerts/management.

The ice condition to be considered may range from complete ice coverage in the winter and early spring, to periods of partial ice coverage and finally an 'ice free' period during the summer and early fall. First-year ice that has not deteriorated may periodically encroach on the drilling area during the summer/autumn seasonal drilling.

Structure interaction with pack ice varies depending on the concentration of the ice floes. At low concentration, ice floes discretely collide with the structure, which causes momentum transfer and induces impact forces on the structure. At high concentration, besides discrete collisions with the structure, ice floes interact with each other (crushing, bending, friction, rafting, etc.) resulting in more complicated interaction with the structure. Ice floes building up and jamming between jack-up legs will also occur more easily at a high concentration condition than at a low concentration condition and may cause other undesirable problems, such as ice on the drill string. Therefore, highly concentrated ice conditions should be controlled by ice management. Similarly, the interaction with pressure ridges is also considered beyond the operational envelope for a jack-up in ice. This paper addresses the discrete pack ice impact loads on a jack-up leg as one of the key design scenarios.

Level ice is an ice floe with infinite size, which can be regarded as the unmanaged ice condition. The failure mode of level ice on a vertical structure, such as a jack-up's legs, includes bending, buckling, splitting and crushing, in which crushing dominates. The level of ice-caused crushing force is considered as the upper limit of the design load.

Conventional jack-ups are designed with open truss type legs for ice-free water to resist wind, wave and current. Open truss type legs typically consist of chords, diagonal, horizontal and internal braces, as shown in Figure 1 (a). This is not an optimal arrangement for resisting ice loads. Therefore, it is expected that the open truss type legs are shielded, as shown in Figure 1 (b), to protect the brace members from direct ice impact.

(a) (b)

Figure 1 - (a) Open truss type leg; (b) shielded Jack-Up leg

ICE IMPACT FORCE

ISO 19906 provides guidance for ice floe impact with a rigid body but provides no specific guidance accounting for the jack-up's responses. A limit momentum/energy mechanism is used for ice impact force prediction where the kinetic energy of the ice feature limits the ice forces. When ice floes collide with a jack-up, the kinetic energy induced by the ice floe's velocity will convert into strain energy produced by the jack-up's responses including the jack-up's overall deflection, leg bending and local deformations of leg members (or indentations of shield plate) where the impact occurred.

In this study, the kinetic energy was assumed to transfer into strain energy produced by the jack-up's overall deflection and the leg's lateral deflection induced by leg bending and the kinetic energy lost in the ice floe penetrating the leg. Accordingly, a spring-mass model including two (2) masses and three (3) springs was developed as shown in Figure 3. The jack-up is modelled as mass m_p, with spring k_p, connected to the ground. Spring k_p representing the jack-up's lateral stiffness for overall deflection is referred to herein as the "global spring". Mass m_p includes jack-up hull lightship weight and design variable deck load. Spring k_L representing the leg's local lateral stiffness is referred to herein as "local spring".

The ice floe is modelled as mass m_i with spring k_C. k_C referred to as "ice spring" herein is a nonlinear, unidirectional and compressive spring. The stiffness of the ice spring representing the required force for the unit ice penetration can be expressed by the relationship of ice contact pressure and area with the structure, which depends on the ice strength, the ice feature's geometry and the structure's configuration.

For a round ice floe penetrating a vertical structure, such as the leg shield shown in Figure 4, k_C can be expressed as follows using the contact pressure and area relationship:

$$k_C = p_e \cdot 2h\sqrt{D_i / \xi_{(t)}} \tag{1}$$

Where, p_e is ice pressure, $\xi_{(t)}$ is ice penetration, D_i is diameter of the round ice floe and h is the ice thickness.

ISO 19906 suggests a power law to represent the contact pressure and area relationship for small ice penetrations. To simplify the problem, in this study, ice contact pressure is assumed to be constant for the entire impact process.

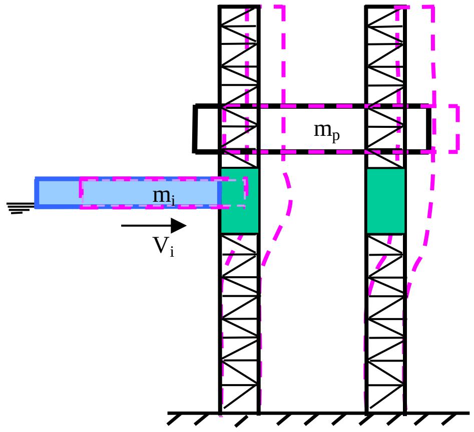

Figure 2 Sketch of ice impacting jack-up

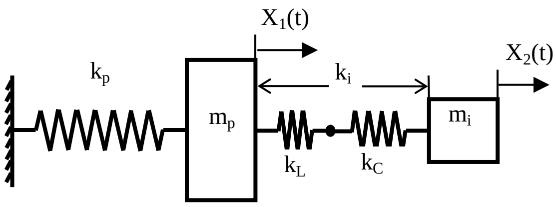

Figure 3 Mass-spring model for ice impacting jack-up

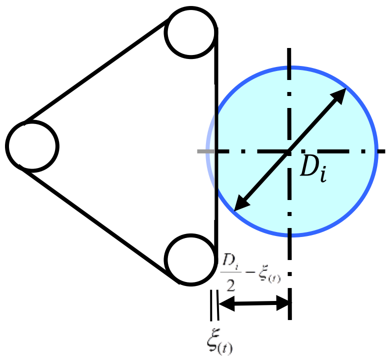

Figure 4 Local geometry of round ice floe impacting the shielded leg

The motion equations of the mass-spring model are expressed by the following matrix,

$$\begin{bmatrix} m_p & 0 \\ 0 & m_i \end{bmatrix} \begin{Bmatrix} \ddot{x}_1(t) \\ \ddot{x}_2(t) \end{Bmatrix} + \begin{bmatrix} k_p + k_i(t) & -k_i(t) \\ -k_i(t) & k_i \end{bmatrix} \begin{Bmatrix} x_1(t) \\ x_2(t) \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \tag{2}$$

Spring (t) is a nonlinear spring, in which the local spring and ice spring, are connected in series.

Rearranging terms in the above matrix (2) gives

$$\begin{bmatrix} m_p & 0 \\ 0 & m_i \end{bmatrix} \begin{Bmatrix} \ddot{x}_1(t) \\ \ddot{x}_2(t) \end{Bmatrix} + \begin{Bmatrix} k_p x_1(t) + k_i(t)[x_1(t) - x_2(t)] \\ -k_i(t)[x_1(t) - x_2(t)] \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \quad (3)$$

In the above equation matrix, the spring, $k_i(t)$, is the local spring k_L and ice spring, k_C, connected in series and has the following relationship:

$$\frac{1}{k_i(t)} = \frac{1}{k_C} + \frac{1}{k_L} \quad (4)$$

The equation (1) shows that the ice spring, k_C is dependent on ice penetration, $\xi_{(t)}$. Therefore, in addition to the equation matrix (3), the following equation is needed in order to solve variables, $x_1(t)$, $x_2(t)$ and $\xi_{(t)}$.

$$(1 + \frac{k_C}{k_L})\xi_{(t)} = x_1(t) - x_2(t) \quad (5)$$

Submitting equations, (1) and (4), into equations, (3) and (5), generates the three equations with three variables, $x_1(t)$, $x_2(t)$ and $\xi_{(t)}$.

The spring-mass model can be numerically solved in the time domain to obtain the forces induced by ice floe impact as shown in Figure 5.

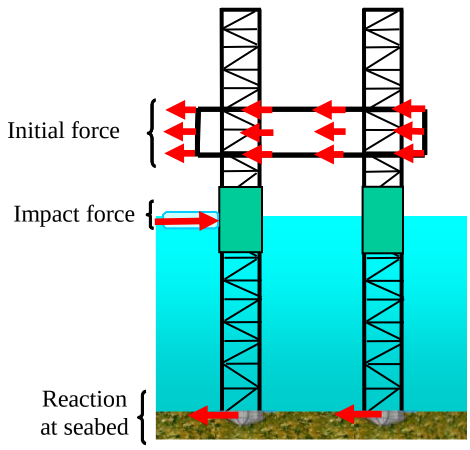

Figure 5 Ice impact force, initial force and the reaction at seabed using spring-mass model

Cammaert et. (1989) developed a formula for estimating the impact force caused by a square ice floe colliding with a rigid vertical cylindrical structure using the limit momentum/energy mechanism. The Cammaert formula was modified for a round ice floe colliding with a rigid vertical structure as follows for the purpose of comparison with the impact loads calculated using the mass-spring model:

$$F_i = 1.33h(p_e D_i v_i)^{2/3}[D_i \rho_i]^{1/3} \quad (6)$$

Where, F_i is the maximum impact force, p_e is the ice pressure, ρ_i is the ice density and v_i is the ice initial speed.

In the pack ice impact force calculations, the hydrodynamic effects of ice are modelled using the added water mass on the ice and the added mass factor, C_m, is obtained (Croasdale and Marcellus, 1981) as follows:

$$C_m = 0.9h/(2z - 0.9h) \quad (7)$$

Where z is the water depth.

Ice Impact Force Comparison

The results from the mass-spring and rigid body approaches were compared and shown in Table 1. It can be seen that the ice impact loads calculated by the spring-mass approach are smaller than those of the rigid-body approach.

In the comparison, an ice floe 2m thick, with a diameter of 25m, collides head-on with a jack-up on a single leg at a velocity of 0.5m/s. For the mass-spring approach, the Jack-up's global spring stiffness is 38.3 MN/m, local spring stiffness is 222.3 MN/m and the jack-up mass is 10,000 tons. The jack-up parameters are acquired based on the real jack-up and only for the calculation examples. The ice pressure is 2.0 MPa for the calculations using the rigid body model and mass-spring model. The water depth is 30m.

Table 1 - Ice impact forces comparison

	Ice impact force (MN)	Reaction at seabed (MN)
Rigid-body model	6.49	6.49
Spring-mass model	5.32	1.56

The force time histories calculated using the spring-mass approach are presented in Figure 6. It is observed that there is one impact between the ice and the platform during the ice impact process from the ice floe initially contacting the leg to finally being bounced away. The jack-up vibrates at its natural periods after the ice impact. This free vibration will decay and vanish finally due to damping. The force time histories verified that it may be inappropriate to directly adopt the ice impact force to check the foundation capacity of the jack-up. A large shear force may impact the jack-up created between the hull and the ice force action position.

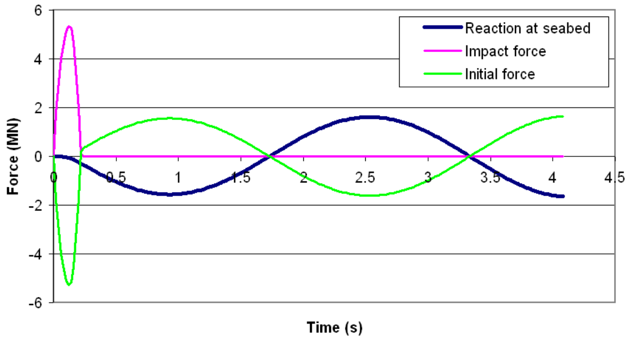

Figure 6 Time histories of ice impact force, initial force and the reaction at seabed

The same comparison was made for different sizes of ice floes, as shown in Table 2. Smaller differences between the rigid body and the spring mass model for smaller ice floes were observed, which can be explained as the jack-up acts more like a rigid body under the smaller ice floe impacts.

Table 2 - Ice impact forces comparison for different sizes of ice floes

Ice mass (kton)	Ice Diameter (m)	Rigid body model (MN)	Spring-mass model (MN)	Diff (%)

0.036	5	1.3	1.24	4.62
0.15	10	2.59	2.35	9.27
0.91	25	6.49	5.32	18.03
3.64	50	12.97	9.29	28.37
14.57	100	25.94	18.13	30.11
32.79	150	38.92	25.48	34.53

Figure 7 presents the impact force time history generated on a jack-up due to a high kinetic energy collision with an ice floe. The kinetic energy was induced by a 2m thick and 100m diameter ice floe traveling at 0.5m/s. It shows that more than one impact occurred because the kinetic energy was not totally converted to strain energy at the first impact. The second ice impact force peak may be bigger than the first one, because the second impact includes the remaining energy of the ice after the first impact and the jack-up's reaction energy caused by the first ice impact. The ice floe is bounced back after two impacts.

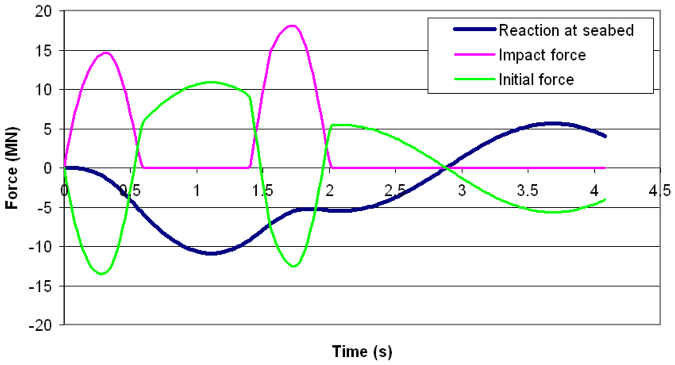

Figure 7 Time histories of ice impact force, initial force and reaction at seabed

The above results illustrate that when the kinetic energy of the impact is high, more than one impact may occur. The later impacts may induce a higher force than the first impact. The duration of impact is very short and thus, the impact force may not have sufficient time to overturn a jack-up, but the inertia loads generated by free vibrations may cause overturning if they are large enough. The rigid body model derives only the ice impact force. The mass-spring model results showed that using the rigid body model derived impact force for checking overturning will be conservative.

Ice Strengths Effects to Impact Load

Figure 8 presents the predicted ice impact force on a jack-up by 25 m and 100 m diameter ice floes for soft ice and hard ice. The thickness of the ice floes is 2.0m and drifting velocity is 0.5 m/s. The comparison between rigid body model results and spring-mass model results showed that in the higher strength ice impact event, a bigger ice force difference is observed, which can be explained as more kinetic energy is absorbed by the jack-up's deformation during impacts. The higher ice strength causes the higher ice impact loads on the jack-up.

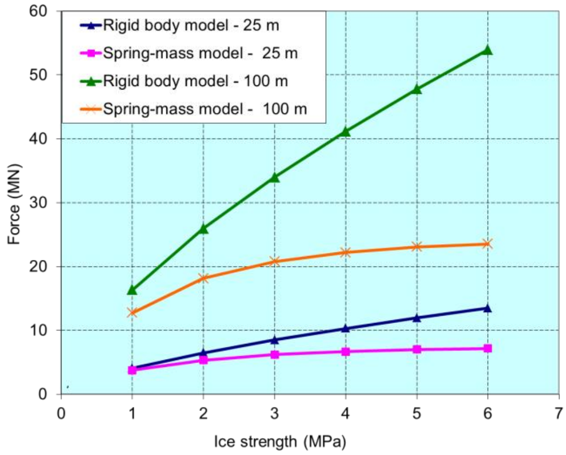

Figure 8 Ice impact forces at different ice strengths

Ice Drifting Effects to Impact Load

Figure 9 presents the predicted ice impact force on the jack-up by the 25 m and 100m diameter ice floes. The thickness of the ice floes is 2 m and the ice strength remains 2 MPa. The comparison results between the rigid body model and the spring-mass model shows that when the ice impacts the leg with lower velocities, the kinetic energy absorbed by the jack-up deformation is lower and the difference of the predicted ice force is also smaller. Higher ice drifting velocity causes the higher ice impact loads on the jack-up.

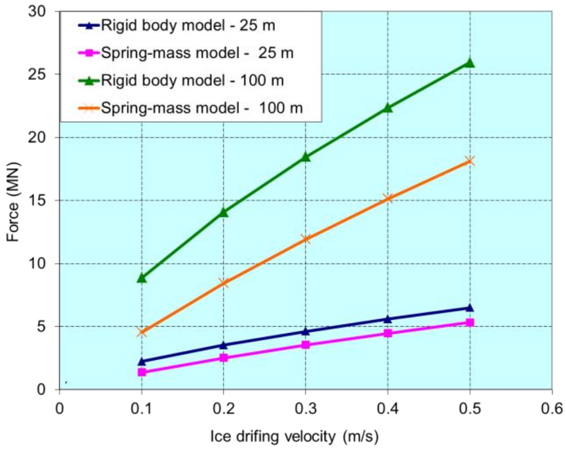

Figure 9 ice impact force at different ice drifting velocities.

Pack Ice and Level Ice

The impact force is calculated based on limit momentum/energy mechanism. With increasing ice floe size, the kinetic energy to crush the ice floe also increases. If the kinetic energy is large enough, the impact force reaches the maximum value when the leg completely penetrates into the ice sheet. The maximum ice impact force is limited by failing the ice feature adjacent to the structure (compressive, shear, tensile, flexure, buckling, splitting), therefore it is the limit stress force. Once the pack ice is big enough to make the leg completely penetrate into the ice sheet, pack ice can be regarded as the level ice and the ice load on the jack-up is equal to the global level ice force.

ISO 19906 provides equations (8) and (9) for predicting global level ice crushing loads, which is the limit stress force, on the vertical surface.

$$F_G = p_G hw \quad (8)$$

$$p_G = C_R h^n \left(\frac{w}{h}\right)^m \quad (9)$$

Where p_G is global average pressure, w is width of structure, h is ice thickness, m and n are empirical coefficients, and C_R is ice strength coefficient. Two approaches are suggested in ISO 19906 to determine C_R. One is to use measured ice strengths and the other one is to derive it from site-specific air temperature and ice salinity. In the second approach, the strength coefficient is directly determined by brine volume of ice, as listed in Table A.8-3 of ISO 19906. The brine volume accounts for the influence of both temperature and salinity using the following equation:

$$v_b = S_i\left[\frac{49.2}{|T_i|} + 0.53\right] \quad (10)$$

Where, S_i is salinity in parts per thousand (ppt). T_i is the temperature between -22.9 °C ≤ T_i ≤ -0.5 °C.

The equations of ISO 19906 are based on the data from full-scale measurements in the Cook Inlet, the Baltic Sea and the Bohai Sea, where the ice cover is not very thick and is likely to be in the range encountered by a jack-up. The leg shield is a vertical surface. Therefore, the ISO 19906 equations are adopted for the global level ice force prediction.

In the calculations, the chord-chord span of the investigated jack-up is 12.4m. The thickness of the ice floe is 2.0 m and the initial velocity is 0.5 m/s. The air temperature is -12^o and ice salinity is 5‰.

The predicted pack ice impact forces and level ice force on the jack-up leg are shown in Figure 10. It can be seen that when the ice size reaches 150m, based on the rigid-body model results, the pack ice-caused impact force reached the maximum value, the level ice force. Therefore, an ice floe bigger than 150 m can be thought of as level ice. That critical floe size from the pack ice to the level ice is 230m, if the spring-mass model results are utilized.

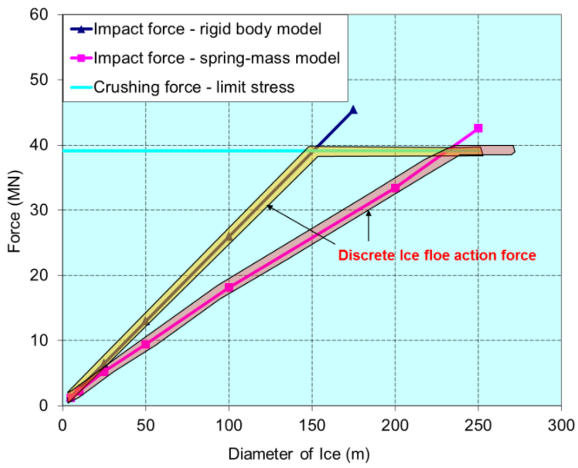

Figure 10 Pack ice impact force and level ice force on Jack-Up leg

CONCLUSION

This paper presented the ABS study on ice loads and the assessment of jack-up leg structures. A spring-mass model was developed to provide more realistic ice loads than a rigid body model for structural analyses for jack-ups interacting with pack ice floes.

Several impacts may happen from an ice floe initially impacting a jack-up through to being bounced back. The maximum ice force may not happen at the first impact due to the combined effects from the remaining energy of the ice and the reaction energy of the jack-up.

The spring-mass model predicts a lower ice impact load than the rigid model due to the effects of the jack-up's deformations on impact. A rigid body model is reasonable only for small ice floe impacts.

The hard ice impacts cause more kinetic energy to be absorbed by the jack-up's deformations, therefore, the jack-up's flexibility influences the ice force and needs to be considered.

ACKNOWLEGEMENT

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