POAC'11
Montréal, Canada

Proceedings of the 21st International Conference on
Port and Ocean Engineering under Arctic Conditions
July 10-14, 2011
Montréal, Canada

POAC11-027

PERFORMANCE OF MINIMAL OFFSHORE PLATFORMS IN ICE ENVIRONMENTS

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ABSTRACT

The main purpose of the paper is to analyse the suitability of certain "minimal" platform concepts for oil and gas production in marginal cold regions developments, with a view to comparing static and dynamic ice loads, and to investigate the response of the platforms in drifting level ice.

Various structural concepts such as monopiles, jackets, and caissons have already been used in shallow-water areas such as the Bohai Sea, Cooke Inlet and the Baltic Sea. Such concepts will be reviewed, together with a comparison of any published data on the static and dynamic ice loads to which they have been subjected. Reference will be made to other types of minimal platform designs which have been installed in non-ice regions, but which may be suitable for ice environments as well.

The specific problem of ice-induced vibrations will be addressed. Several case studies will be investigated in the paper, and example calculations will be demonstrated for three case studies, based on algorithms suggested by the ISO19906 standard and simplified dynamic models. Finally, the paper provides conclusions and recommendations regarding ice-induced platform vibrations in the regime of frequency lock-in. The concepts cited may be of interest for the design of foundations for wind turbines and other types of offshore and coastal structures.

INTRODUCTION

The economic viability of an offshore oil or gas development in any part of the world depends not only on the quality of the discovery itself, but is also heavily influenced by the cost of the offshore facility that will extract and distribute the hydrocarbons. Offshore fields which have questionable economic viability are generally considered to be "marginal fields". By reducing the cost of the offshore facilities, platforms for some marginal fields have become economically viable – these types are generally termed as "minimal platforms" (Dunn et al, 2009).

According to a WS Atkins study (WS Atkins, 2002) minimal platforms reduce platform costs by:

- reduction in steel weight,
- simplified fabrication methods,
- reduction in production equipment, and
- elimination of heavy lift vessels (HLVs).

Other studies add an additional factor for the definition of minimal platforms - not usually manned installations, or NUIs.

In 2001 a global review of platform designs was completed in order to define structures that would be applicable for the above minimal structures definition (Albaugh et al, 2001). From this global survey 8 main structure types were defined:

- Caisson
- Braced caisson
- Monotower
- Tripod
- Jacket
- Jack-up (self elevating)
- Concrete (or steel) gravity base
- Guyed structures

The survey reported that more than 1500 minimal structures were in service by 2001. The paper by Dunn et al. identified a number of additional structures in these categories prior to 2009. However none of the installations quoted in both references covered installations in ice-covered waters.

One paper which does describe minimal platforms in ice was published by Visser, 2005. The paper describes two minimum-cost, self-erecting, platform designs and one caisson structure design that could be installed in Cook Inlet, Alaska without the need for heavy lifting equipment. (In the 1960’s HLVs were used when there was more construction activity in the area). One such design has been built, and a second proposed concept allows platform installation in deeper water, again without the need for heavy lifting equipment. The third design concept is an outrigger caisson design that can be installed with a jack-up drilling unit. It would have application as a satellite platform structure.

Use of these minimum-cost platform and caisson designs would enable development of marginal fields in Cook Inlet that heretofore could not be developed because the high cost of mobilizing and demobilizing heavy lifting equipment to and from Cook Inlet would make development uneconomic.

Considering the range of designs which have been proposed in non-ice areas, the braced caisson and the jacket structure can be set aside because of the interference of the bracing members with the flow of ice around the structure and the vulnerability of bracing members to high local loads. Guyed structures can be eliminated for the same reason. Note that for jack-ups the use of cylindrical legs in ice is demonstrated here rather than the conventional triangular braced legs which are most commonly used in ice-free environments. Some of the minimal structures shown below also have conical sections at the waterline. However, cones are difficult to integrate with jacket column legs for obvious reasons.

EXAMPLES OF EXISTING INSTALLATIONS

Figure 1 gives examples of some structures which have already been built in first-year ice environments. Four of these are oil production platforms, one is a mooring structure and one is a lighthouse (for comparison purposes). The reason for reviewing these installations is to establish representative examples for the dynamic analysis which follows.

Cooke Inlet Monopod (Case a)

Cooke Inlet, Alaska represents the first instance of the installation of offshore oil and gas platforms in ice-covered waters. Although the region is subarctic, the Inlet can develop substantial first-year ice formations. Ice floes vary in extent from medium to large and are usually less then 0.6 m thick, although the design ice thickness in this instance was 1.8 m. Ice floe velocities are high, and may be up to 3.0 m/s. The monopod platform shown in Figure 1a was installed in 1966, and has a single central steel column of 8.7-m diameter. The structure is anchored by 32 piles each 90 cm in diameter, driven to 30 m penetration. From a dynamic analysis carried out by Blumberg and Strader (1969) it was estimated that the natural frequency of the structure at the first mode shape was 1.2 Hz.

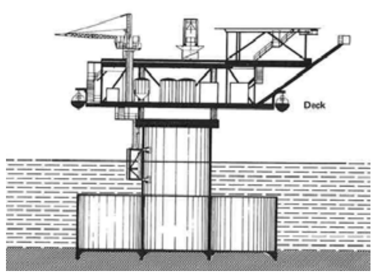
GBS Platform, Baltic Sea (Case b)

The Schwedeneck-See oilfield was the first offshore oilfield developed in German waters and the first field in the Baltic Sea (Klatt et al, 1988). For military restrictions and environmental protection reasons two unmanned platforms were designed to be remotely controlled from a shore station some 13 km from the platform locations. The platforms were designed for 0.6 m level ice and 4.0-m deep ridges. The most favourable concept was deemed to be a concrete gravity substructure and a steel truss superstructure. The diameter of the central column is 13 m, and the overall width of the base caisson is 38 m (Figure 1b). The concrete substructures were built in a dry-dock and then towed into deeper water where they were completed to final height.

GBS Lighthouse, Baltic Sea (Case c)

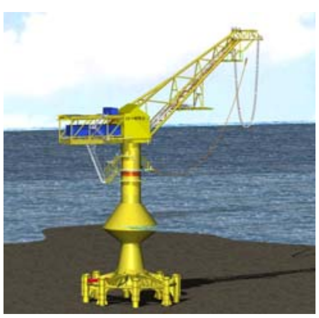
Coastal structures in northern and central European waters must also be designed to withstand the loads caused by moving ice. The structure discussed here is the Swedish lighthouse Norströmsgrund located about 60 km off Luleå in the Gulf of Bothnia (Fransson and Lundqvist, 2006). The lighthouse is a cylindrical concrete GBS with a diameter of 7.6 m at the water line. (Figure 1c). Ice thicknesses in this area of the Gulf are typically 40 to 60 cm in the northern part. Rafted ice can occur. Maximum ice pressures measured were in the order of 1.5 MPa.

a) Cooke Inlet Monopod
(Blumberg and Strader, 1969)



b) Baltic Sea GBS
(Klatt et al., 1988)

c) Gulf of Bothnia Lighthouse
(Fransson and Lundqvist, 2006)



d) Sakhalin Mooring Tower
(Ottolini and Kind, 2007)

e) Bohai Sea Monopod
(Shi et al, 2007)

f) Cook Inlet Multileg Platform
(Visser, 2005)

Figure 1: Examples of Minimal Platforms in Ice

Arctic Tower Loading Unit (Case d)

In 2005 Bluewater Energy Services completed the Arctic Tower Loading Unit (TLU) for the Sakhalin I, DeKastri Oil Export Terminal (Figure 1d). The structure was designed and delivered by Bluewater Energy Services BV for Exxon Neftegas Ltd. (Ottolini and Kind, 2007). The TLU is designed to moor a dedicated 110,000 DWT tanker all year round in ice conditions with thicknesses up to 0.55 m - the structure itself is able to resist level floes up to 1.5 m thick. The structure is piled into the seabed and has a rotating head which ensures that the tankers can weathervane freely and take up the position of least resistance to the prevailing weather.

Bohai Sea Monopod (Case e)

An intensive study into the ice interaction problems experienced in the Bohai bay, China, resulted in the design of a new ice-resistant platform (JZ20-2NW) shown in Figure 1e. The most significant ice related problems experienced were those of ice-induced vibrations (Shi et al, 2007). The thickness of ice sheets in vicinity of the platform are relatively low, generally from 5 to 20 cm, but wind-driven ice sheet velocities can be up to 1 m/s. The natural frequencies of most Bohai Bay structures is in the area of 1-3 Hz, and this has always caused concern when compared to observed crushing load frequencies. Recent experience in by Dalian University researchers suggested that the use of ice breaking cones might reduce vibration problems, and the final design of the structure featured a cylindrical leg of diameter 3.5 m, a cone angle of 60º and a maximum cone waterline diameter of 6.0 m.

Cook Inlet "Jackup" (Case f)

Strictly speaking, the platform shown in Figure 1f is not a jackup (although it was raised and lowered on its foundation piles during its installation). However, the column diameters and spacing are fairly close to those of a conventional jackup in any case. The platform project was completed by Forest Oil Corporation in 2000 at a fraction of the cost of a conventional platform, thereby allowing exploration and subsequent development of a hitherto noncommercial oil field discovery dating back to 1969 (Visser, 2005). The 900-ton tower section has four 4.3-m diameter vertical legs at 21.3 x 24.6 m spacing. The 1,500-ton deck structure is a space truss spanning between the legs. The structure is designed for the 100-year ice condition similar to the design loads used for the existing Cook Inlet platforms. The Osprey platform is innovative in several areas, (1) using the Cook Inlet tidal action for installation, (2) the self erecting feature, (3) the floating "float-over" mating and (4), the capability to be relocated.

Table 1: Outline Description of Specific Minimal Platform Installations

Case	a	b	c	d	e	f
Type	GBS	GBS	monopod	monopod	monopod	multileg
Location	Baltic Sea, Germany	Gulf of Bothnia	offshore Sakhalin	Cook Inlet, Alaska	Bohai Sea, China	Cook Inlet, Alaska
water depth, m	16	n/a	21.5	20.0	n/a	13.7[3]
leg diameter, m (cylinder)	13	7.2	6.5[1]	8.7	3.5	4.3
leg spacing, m	---	---	---	---	---	21.3 x 24.6
waterline diameter, m (cone)	---	---	14.4	---	6.0	---
cone angle (from hor.)	---	---	53	---	60	---
max. level ice thickness, m	0.6	0.6	1.5[2]	1.8	n/a	1.1[2]
topside weight, tonnes	1,100	n/a	n/a	n/a	n/a	2,900
substructure weight, tonnes	8,400	n/a	n/a	n/a	n/a	

[1] At top of cone

[2] 100-year design ice thickness

[3] Extreme high water +7.4 m, extreme low water -1.8 m

SELECTION OF MINIMAL PLATFORMS FOR ANALYSIS

Three cases have been chosen to demonstrate the structural performance of the different types of minimal structures which have been constructed in the past, with particular consideration of the provisions of the new ISO19906 standard, and the most recent research in ice-induced vibrations. The three cases, respectively denoted as Case A, B and C are depicted in Figure 2. Case A is that of a gravity-base structure which may or may not have a conical section at the waterline and case B represents a monopod structure with a piled foundation. The third example, Case C, is that of 4-leg jackup platform. In the comparative analysis which follows we assume a constant water depth of 20 m and a 0.75 m ice cover. Additional assumed ice parameter values are taken from ISO19906. Thus, we use an ice density of 900 kg/m^3, an ice strength coefficient of 2.8, a flexural strength of 0.5 MPa, a Young's modulus of 4 GPa and Poisson's ratio of 0.3.

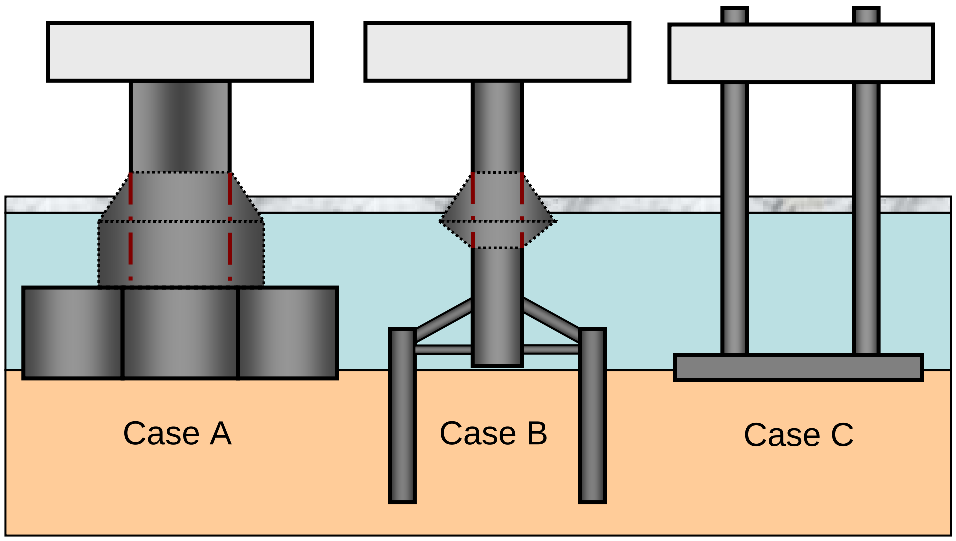


Figure 2: Sketches of Case Studies

The application of "ice cones" is not included here as many studies and field measurements have demonstrated the effectiveness of these cones in reducing static ice loads. This paper will concentrate primarily on the static and dynamic performance of cylindrical structures in ice.

ANALYSIS OF STATIC LOADS FOR MINIMAL PLATFORM CONCEPTS

Only an outline of the approach to static ice loads is given here. The ISO19906 standard is used throughout, and should be referred to for more detailed explanations of the loading algorithms.

Data obtained from full-scale measurements in Cook Inlet, the Beaufort Sea, the Baltic Sea and Bohai Sea have been used in ISO19906 to determine upper bound ice pressure values for scenarios where first-year or multi-year ice acts against a vertical structure. The formulation for peak crushing loads (ISO19906, Section A.8.2.4.3) on a vertical cylinder applies for rigid structures with aspect ratios $w/h > 2$, where the waterline displacement, obtained as a static response to the representative ice action, is typically less than 10 mm, and where the ice velocity is less than 0.1 m/s.

ANALYSIS OF DYNAMIC RESPONSE FOR MINIMAL PLATFORM CONCEPTS

In the dynamic analysis, cases A, B and C are modelled using an effective beam as shown in Figure 3. The beam is assumed to perform planar vibrations according to the Euler Bernoulli model. The top and bottom masses are assumed point like and reflect the inertial properties of the topside and the substructure, respectively.

Interaction of the submerged part of the structure with water, which is assumed quiescent, is accounted for according to the Morison's equation. The drag-related term in the latter is linearized using the harmonic balance method.

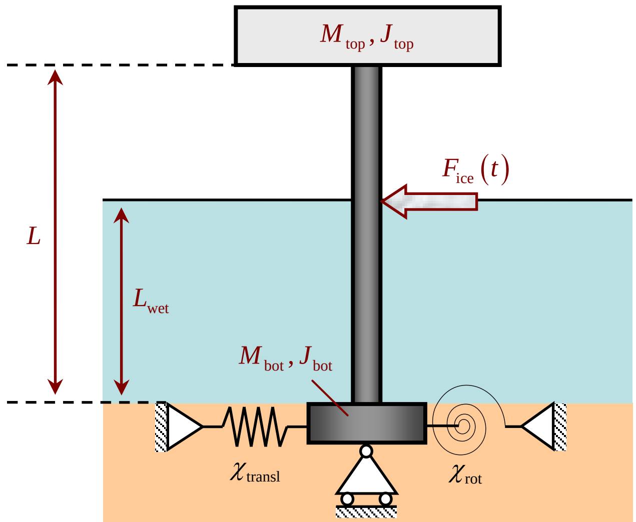


Figure 3: Effective model used in dynamic analysis

The dynamic interaction with the sea bed is accounted for by means of effective rotational and translational springs. The dynamic stiffnesses χ_{transl} and χ_{rot} of these springs are complex-valued functions of the (i) soil parameters; (ii) foundation geometry and (iii) frequency of vibration of the structure. To estimate the dynamic stiffnesses we assume for case A and case C that the minimal platforms are founded on rigid disks that are located on top of the sea bottom. The foundations of the platforms are considered as disks located on top of a homogeneous half-space so that we may apply the single cone model developed by Wolf (Wolf, 1998). For case A we thus assume 1 large disk, while case C is modelled having 4 separate footings, i.e. 1 footing per leg. For case B, we approximate the pile foundation by a single rigid cylinder embedded in the half-space, by assuming that the soil bounded by the piles is moving together with the piles. The applicable model is the so-called double cone model. The applied simplistic foundations for cases A, B and C are depicted in Figure 4.

Applying the cone model (Wolf, 1998), the dynamic stiffnesses of the foundations in cases A, B and C can be expressed as:

$$\chi_{transl} = K_{transl} \times \left(k_{transl}(\Omega) + \mathrm{i}\Omega c_{transl}(\Omega)\right), \qquad \chi_{rot} = K_{rot} \times \left(k_{rot}(\Omega) + \mathrm{i}\Omega c_{rot}(\Omega)\right), \tag{1}$$

where K_{transl} and K_{rot} are the so-called static stiffnesses, which are given as:

$$K_{transl} = \frac{8Gr_0}{2-\nu}\left(1+\frac{e}{r_0}\right), \quad K_{rot} = \frac{8Gr_0^{\ 3}}{3(1-\nu)}\left(1+2.3\frac{e}{r_0}+0.58\left(\frac{e}{r_0}\right)^3\right) \tag{2}$$

Here, G and ν are respectively the shear modulus and Poisson's ratio of the soil, r_0 is the radius of the circular foundation base and e is the embedment of the considered foundation.

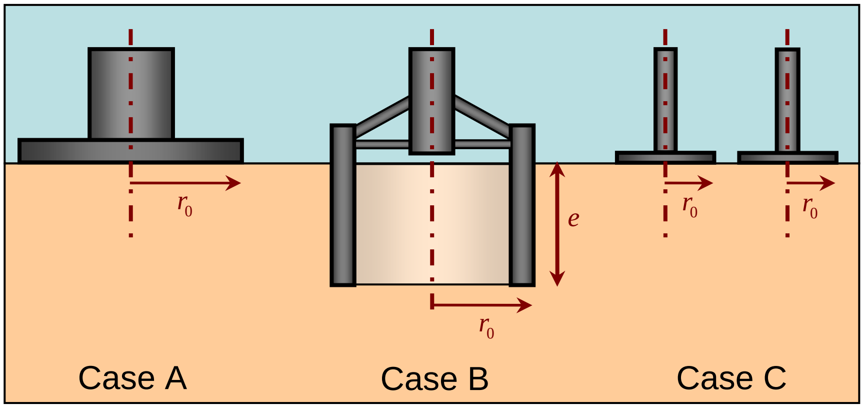


Figure 4: Schematization of soil-structure interaction

The frequency dependent parts of the dynamic stiffnesses χ_{transl} and χ_{rot} in equations (2) depend on the dimensionless frequency Ω, which is related to the angular frequency ω of structural vibrations as $\Omega = \omega r_0 / c_T$, where c_T is the shear wave speed. The dimensionless dynamic stiffness coefficients $k_{\text{transl,rot}}(\Omega)$ and the dimensionless dynamic damping coefficients $c_{\text{transl,rot}}(\Omega)$ in equations (2) are given as:

$$k_{\text{transl}}(\Omega) = 1, \quad k_{\text{rot}}(\Omega) = 1 - \frac{1}{3}\frac{1}{\left(\dfrac{16}{9\pi(1-\nu)\Omega}\right)^2 + 1} - \frac{9\pi}{80}(1-\nu)\left(\nu - \frac{1}{3}\right)\Omega^2 \tag{3}$$

$$c_{\text{transl}}(\Omega) = \frac{\pi}{8}(2-\nu), \quad c_{\text{rot}}(\Omega) = \frac{3\pi}{16}\frac{1-\nu}{\left(\dfrac{32}{18\pi(1-\nu)\Omega}\right)^2 + 1} \tag{4}$$

Table 2: Parameters used in Dynamic Calculations

Case	A	B	C (per leg)
Outer diameter (m)	12	6	4
Inner diameter (m)	11	5.88	3.92
Wall thickness (mm)	500	60	40
Material density (kg m^{-3})	2400	7850	7850
Young’s modulus (GPa)	30	200	200
Effective length L (m)	27	35	35
Submerged effective length L_{wet} (m)	12	20	20
Top mass M_{top} (t)	1100	1100	1100/4=275
Top mass moment of inertia J_{top} (t m^2)	57200	57200	57200/4=14300
Bottom mass M_{bot} (t)	8400	0	0
Bottom mass moment of inertia J_{bot} (t m^2)	437000	0	0
Effective foundation radius r_0 (m)	20	15	8
Effective foundation radius e (m)	0	20	0
Shear modulus of soil G (GPa)	150	150	150
Effective Poisson’s ratio of soil ν	0.4	0.4	0.4
Speed of shear waves in soil c_T (m s^{-1})	300	300	300

Calculations are performed using parameters specified in Table 2. First the frequency response function (FRF) is calculated as the normalized (by the static deflection) ratio of the amplitude of the top displacement to the amplitude of a harmonic force applied at the water level. This function allows the identification of both the resonance frequencies and the corresponding damping ratios.

The FRF calculated in accordance with Table 2 for Case A is shown in Figure 5a. One can see that the first two resonance frequencies are found at $f_1^A \approx 4.71\,\text{Hz}$ and $f_2^A \approx 22.69\,\text{Hz}$. The corresponding damping ratios can be found from the graph (using the quality factor approach) as $\varsigma_1^A \approx 0.013$ and $\varsigma_2^A \approx 0.0046$. Note that these values for the damping ratios definitely underestimate the actual damping as no account was taken of the material damping in the soil and in the platform itself.

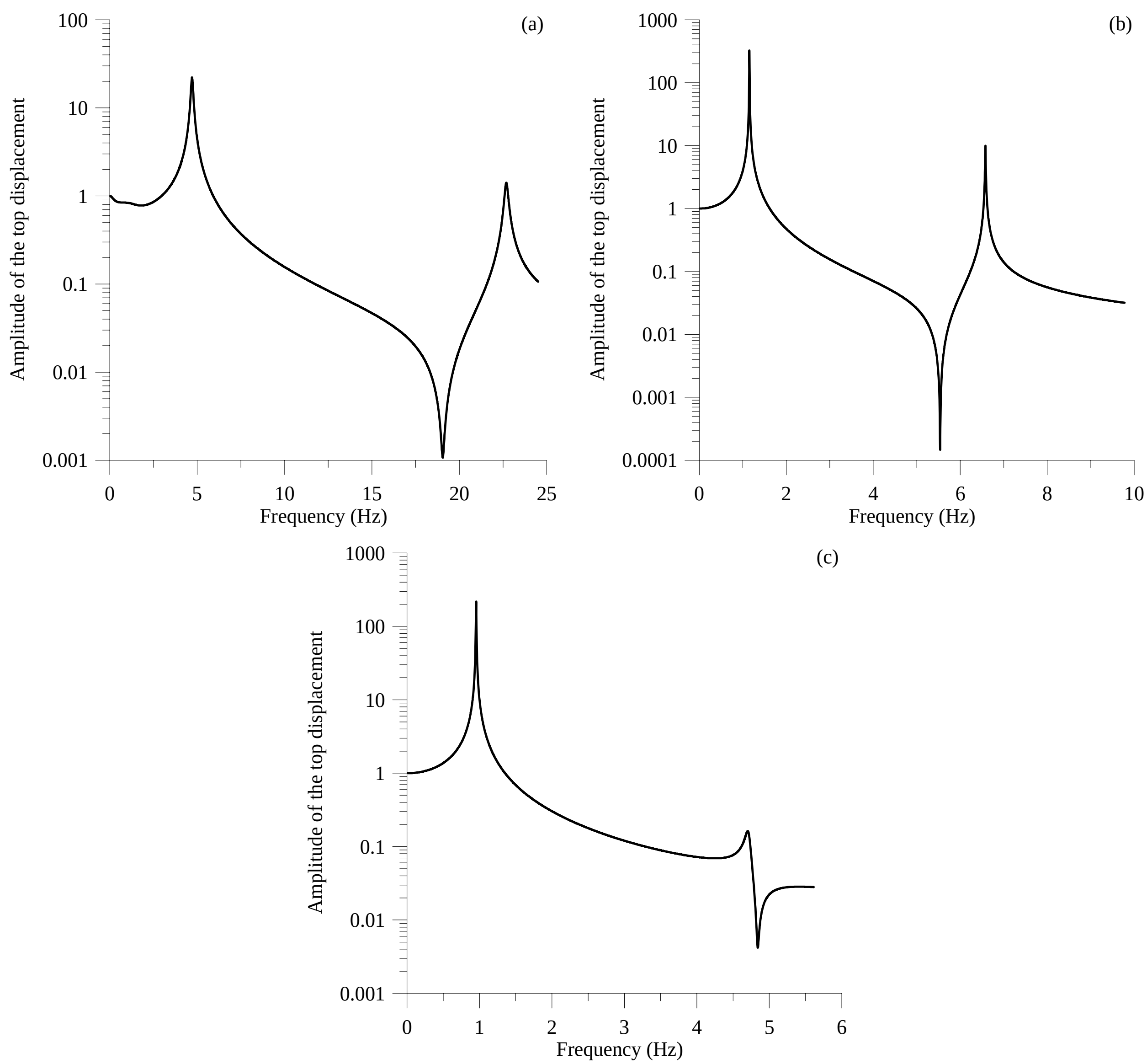


Figure 5: Frequency response functions for Cases A, B and C

The FRFs for Cases B and C are shown in Figures 5b and 5c, respectively. Note that the scales of the horizontal axis are different in the figures. From Figures 5b it can be concluded that the first two natural frequencies for case B are $f_1^B \approx 1.15\,\mathrm{Hz}$ and $f_2^B \approx 6.58\,\mathrm{Hz}$, whereas the corresponding damping ratios are $\varsigma_1^B \approx 0.0014$ and $\varsigma_2^B \approx 0.0007$. Figure 5c shows that the first natural frequency and the corresponding damping ratio can be estimated as $f_1^C \approx 0.95\,\mathrm{Hz}$ and $\varsigma_1^C \approx 0.0022$. Obviously, the hydrodynamic damping and the radiation damping in the soil provide a very small rate of dissipation to the structure.

Below, the potential response is checked of the model-structures A, B and C to the ice loading in the regime of frequency lock-in. According to the ISO19906, an SDOF approximation of each of these structures is subjected to a saw-tooth periodic loading with the period equal to the first natural period of the structure. This loading is described in the Chapter “Susceptibility to frequency lock-in” of the ISO. Essentially, the following equation is solved:

$$\ddot{x} + 2\varsigma\omega\dot{x} + \omega^2 x = F(t)/m \tag{5}$$

The parameters of the effective SDOFs used in the calculation of the response of the structures are summarized in Table 3 along with the characteristics of the force (given in terms of the ISO19906). The last two rows of the table show the corresponding static deflection and the amplitude of vibration in the lock-in regime, both having been calculated at the waterline. The effective parameters of the SDOF are identified in the following classical manner. First, the static stiffness of the structure is computed at the waterline. Then, using the natural frequencies found in the analysis above, the effective mass is calculated by dividing the static stiffness by the squared angular frequency. Finally, the damping ratio is assumed as the sum of the above identified damping ratios for the first mode and a somewhat arbitrarily chosen value of 0.02 (2% of the critical) that is supposed to represent the damping mechanisms that are not accounted for in the calculations above.

Table 3: Effective parameters and results for the lock-in regime

Case	A	B	C (per leg)
Angular frequency ω (rad s-1)	29.6	7.23	5.98
Effective stiffness (MN m^{-1})	3243.5	172.8	3.92
Effective mass (t)	3704	3307	904.7
Effective damping ratio (-)	0.033	0.021	0.022
Peak value of the force $F_{\max}$ (MN)	17.9	10.0	7.1
Double amplitude of the force ΔF (MN)	9	0.31	0.06
Mean value of the deflection at waterline (cm)	0.4	5.7	21.9
Amplitude of vibration at waterline (cm)	1.32	1.32	1.32

CONCLUSIONS

The deflection analysis shows that only the GBS satisfies the limitation for ISO static load calculations, where the waterline displacement (measured as a static response to representative ice actions) should be less than 10 mm. Strictly speaking the ISO formulae should not be used for more slender steel structures where this requirement is not met, even if a limiting slenderness ratio of 2 can be achieved. Calculations for "ice cones" demonstrate that the reduction in static load levels is substantial, possibly as high as 80%, but at the cost of increased structural weight and inflexibility with respect to variations in water level.

An effective dynamical model has been developed for the types of minimal offshore platforms described here. This model consists of a single vertical beam with a top mass and accounts for the dynamic soil-structure and water-structure interaction. The soil reaction has been modelled using effective rotational and translational springs whose stiffness is complex-valued and frequency dependent. The interaction with water has been accounted for employing the Morrison's formulae. Using the developed effective model, the natural frequencies and effective modal parameters have been derived for three platforms chosen for case studies. These parameters have then been used to identify the stationary response of these platforms to level ice in the regime of frequency lock-in according to the ISO19906 recommendations. In the dynamic analysis, all platforms have been assumed to be vertical as the current codes for the dynamic loads on conical structures seem to be immature.

The results of the dynamic analysis are quite striking. It has been shown in this paper that the amplitudes of the stationary ice-induced vibrations of all three platforms are almost equal to each other. This result can hardly be expected given the large differences in the parameters of the platforms. Alerted by that, the authors have checked the obtained results analytically and have found that, indeed, if one follows the recommendations of ISO 19906, the amplitude of vibrations in the regime of frequency lock-in will be found to depend on the modal damping ratio only. Most probably, this means that the recommendations of ISO 19906 in its part related to the response of vertical structures to level ice in the regime of frequency lock-in should not be used.

REFERENCES

Albaugh, E. K. et al., 2001. 2001 Worldwide Survey of Minimal Offshore Fixed Platforms and Decks for Marginal Fields. Offshore Magazine, Vol. 61, Issue 1, January 2001.

Blumberg, R., and Strader, N.R., 1969. Dynamic analysis of offshore structures. Offshore Technology Conference, Houston, Texas. Vol. 2, p. 107-126.

Dunn, C. et al., 2009. Minimal Structures for Marginal Fields in Offshore Nova Scotia. Paper OTC20241, Offshore Tech. Conf., Houston, Texas.

Fransson, L. and Lundqvist, J-E. (2006). A Statistical Approach to Extreme Ice Loads on Lighthouse Norströmsgrund, Proceedings of OMAE2006, 25th Int. Conf. on Offshore Mech. and Arctic Eng. Hamburg, Germany.

Klatt, H.J. et al.,1988. Design and Operation of Two Remote Controlled Platforms in the Baltic Sea, West Germany. Paper SPE 17624, SPE Int. Meeting on Pet. Eng., Tianjin, China.

Ottolini, P.G.M. and Kind, G.J., 2007. Single Point Mooring Towers for Arctic Conditions, Proceedings of the 7th RAO/CIS Offshore Conf., St Petersburg, Russia.

Shi, Z. et al., 2007. A New Ice Resistant Oil Platform in Bohai Bay. POAC-07

Visser, R.C., 2005. Minimum Platform Designs – Cook Inlet Alaska, Paper SPE 93437, SPE Western Regional Meeting, Irvine, California, April 2005.

WS Atkins Limited, 2002. Comparative Evaluation of Minimum Structures and Jackets. Offshore Technology Report 2001/062, Health and Safety Executive, Norwich, UK.

Wolf, J.P., 1998. Simple Physical Models for Foundation Dynamics. Developments in Geotechnical Engineering, Vol. 83, pp. 1-70, Elsevier, 1998.