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SPLASH ZONE LIFTING ANALYSIS OF SUBSEA STRUCTURES

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ABSTRACT

The lifting analysis of a subsea structure determines the maximum allowable design sea state in which the structure can be installed safely. Normally, such analysis on the structure at the splash zone governs the expected largest forces in the hoisting system and in turn the allowable sea state since the water particle kinematics is larger in the splash zone.

In this paper, the DNV Recommended Practice for Modelling and Analysis of Marine Operation (DNV-RP-H103, April 2009) is discussed with emphasis on the hydrodynamic coefficients and analysis methodology for the splash zone lifting analysis.

An approach is suggested here to take into account the free surface proximity effect on added mass of flat surfaces in the absence of test results.

Discussions on the following points are also included,

- For structures which show restricted sea state due to large double pendulum motion and consequently high dynamic tension in the crane wire, a solution could be obtained by lowering the sling angles.
- For inertia dominated structures, the drag coefficients should be chosen with caution unless experimental results are available since the drag may induce unrealistic damping in the system.
- For the structural design of large subsea structures, the design DAF for submerged condition should be chosen from a preliminary lifting analysis result. The current industrial practice of using DAF = 2 with respect to the static submerged weight could be increased following the analysis result to optimise the use of the crane capacity by achieving a higher design sea state.
- For lifting analysis of structures with large added mass / submerged weight, modelling of winch speed may represent a worse loading case as compared to the case with zero winch speed in the splash zone.
- For the splash zone analysis, correct modelling of the stiffness of the crane structure along with the wire is important. The assumption that the crane structure is rigid may lead to unrealistic analysis results.

Experimental programmes to obtain further information on the amplitude dependent characters of the hydrodynamic coefficients, the stiffness and the damping of the Crane, the wires etc are furthermore recommended.

INTRODUCTION

A subsea structure encounters a critical phase when it passes through the splash zone.

The DNV recommended practice “Modelling and Analysis of Marine Operations” (DNV-RP-H103) which is published recently has proposed a systematic approach to estimate the dynamic load during installation and to check if the operation can be carried out safely by using proper acceptance criteria.

As a general approach, first a simplified and conservative method is adopted by assuming that the structure is small as compared to the wave length so that the hydrodynamic load can be conservatively estimated at few characteristic points on the structure and be added together to compare with the allowable load limits. This method can be used to estimate the loads due to slamming as well as the loads on partially or fully submerged condition.

But this approach frequently appears to be over conservative for structures with large dimensions/volume and in such cases numerical analysis of the dynamic system is performed using Morison’s model by keeping the structure at a fixed “static” depth of submergence.

The success of numerical analysis mainly depends on the correct input to the model of the hoisting system (the stiffness of the crane, the wire and the damping coefficients), selection of the hydrodynamic coefficients for the structure, method of interpretation /extrapolation of the dynamic analysis results and selection of the acceptance criteria. These are discussed in this paper with respect to the current practice and following DNV-RP-H103.

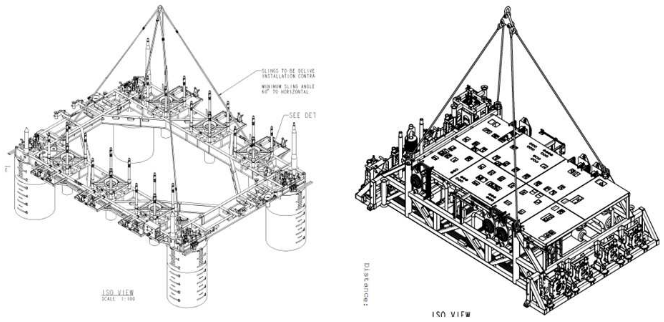


Fig. 1. A Template Foundation (left) and Manifold structure

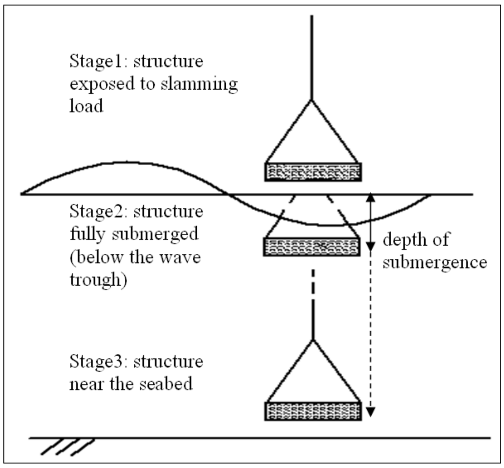


Fig. 2. Different stages of a lifting analysis (lowering through water column)

SELECTION OF HYDRODYNAMIC COEFFICIENTS FOR LIFTING ANALYSIS

Subsea structures fitted with different equipments (for example Fig.1) almost never possess regular solid geometrical shapes and sizes. It is, therefore, the most critical part of a lifting analysis to select the correct hydrodynamic coefficients. For regular shaped objects, recommended coefficients are commonly available in standard textbooks of hydrodynamics, but published model test results on actual subsea structures are rare.

Based on the depth of submergence (ref Fig. 2), DNV[3] uses two different types of hydrodynamic coefficients for lifting analysis; one for the structure passing through the water surface (i.e., the slamming coefficient, related to “Stage 1” of Fig.2), and the other for a fully submerged condition (“Stage 2” of Fig.2). In this paper, the slamming coefficients are not discussed.

DNV[3] recommends that the most accurate method for estimating hydrodynamic coefficients of a 3-dimensional subsea structure with a complex geometry is to carry out model tests. An analysis with CFD programs on a simplified geometry of the structure may also provide good insight on its hydrodynamic behaviour which should be verified with approximate hand calculations or available model test data on similar structures. But these approaches are not widely followed in the industry.

Estimation of Hydrodynamic Coefficients for Structures with Complex Geometry

Normally, the recommended hydrodynamic coefficients for the regular geometrical objects, i.e. added mass and drag coefficients (ref Table 6 at the end of this paper) are used to estimate the hydrodynamic coefficients for a structure with complex geometry in such a way that the resulting forces are conservative. The commonly adopted procedure is described below in brief,

- A structure with complex geometry (ref Fig. 1) is normally divided into more than one regular shaped components and the total added mass or drag is taken as the summation of contributions from individual components. For example, cylindrical shaped members (suctions anchors, isolated tubular members etc) are considered to be separated from the part of the structure which is covered by flat surfaces and calculations are done separately.
- The part of the structure covered with flat surface(s) is normally idealized by assuming a 3D box shaped object. Hydrodynamic coefficients for a box in a certain direction is calculated first by considering the 2D surface area perpendicular to that direction as a flat plate and then by modifying it due to the effect of body-extension in the same direction. The DNV recommended practice[3] provides a simplified calculation method for this.
- If the 2D area is irregular in shape, it is split into more than one regular area. If the split areas are sufficiently away from each other, then the total added mass or drag is taken as the summation of the contributions from individual areas. On the other hand, if the areas are close to each other, a single bigger area encompassing all smaller areas are considered to calculate the hydrodynamic properties and the internal gaps between the areas are treated as perforations over the larger area.

Once the coefficients of the structure based on the above approach are estimated, they are then modified due to the effect of the proximity of the structure to the free water surface, perforation, effect of side walls of a moon pool (if applicable), etc.

Effect of perforation, free surface proximity and amplitude of motion on Added mass

Published data on the effect of perforation over hydrodynamic coefficients are rare. Normally the added mass of a perforated object is calculated from the added mass of the same but non-perforated object by multiplying with a reduction factor.

In industry, this reduction factor is widely taken as $e^{-\frac{P}{28}}$ (where P = perforation ratio in %). But experimental results13 show that for cylinders with perforation (eg, suction anchors with open hatches etc) oscillating in the axial direction, this expression may underestimate the resultant added mass. DNV[3] suggests a modified and conservative expression (Ref. Fig. 3, plot of experimental results and recommended reduction factor) by assuming that there is no reduction of added mass for perforation ratio up to 5%.

But in Fig.3, it may also be observed that for some cases, this assumption may become over conservative. Similar observations on the added mass of suction cans with open hatches are also reported in Ref. 5.

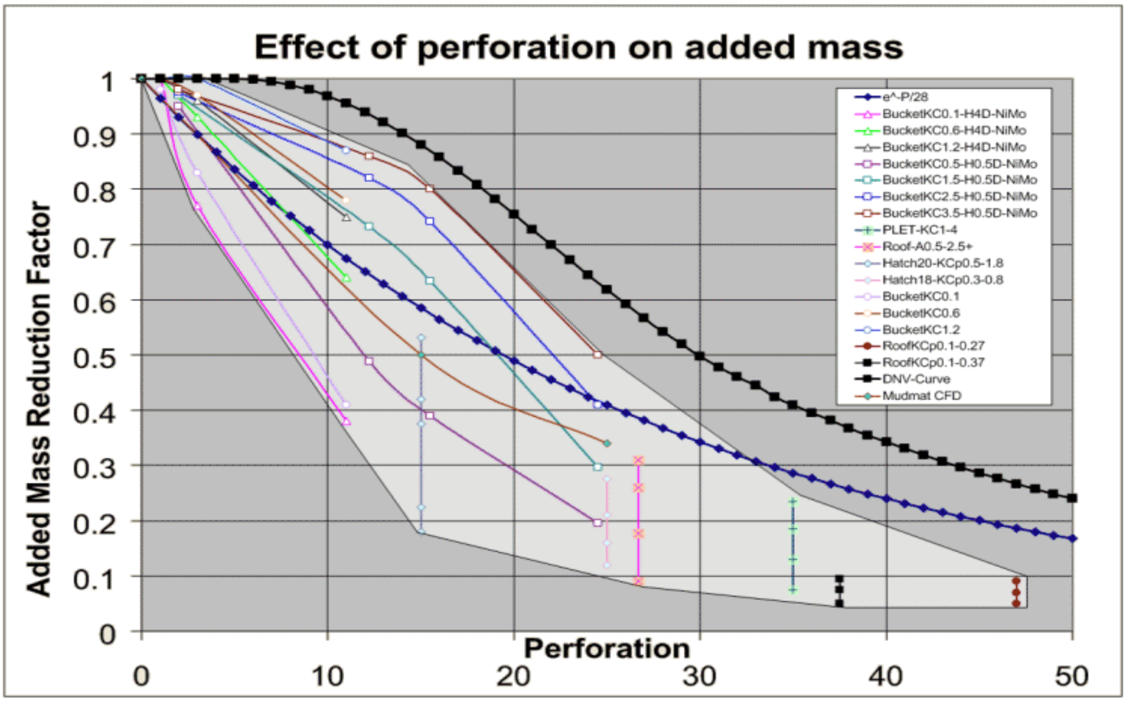
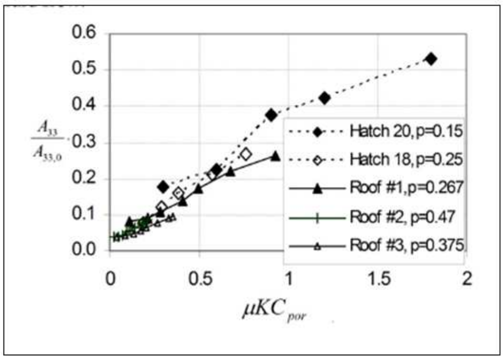


Fig. 3. Effect of perforation (in percentage) on added mass, taken from DNV-RP-H103[3]

From the plot of Fig. 3, it can be observed that the DNV's recommendation on the added mass of perforated objects can be used for cylindrical structures if test results on similar objects are not available. On the other hand, for structures with flat surfaces, the reduction factor $e^{-\frac{P}{28}}$ appears to be conservative. In fact, the added mass of a perforated object is also dependent on its motion amplitude (ref. Fig. 4)[11] and for large flat perforated structures (e.g. roof hatches etc) it can be significantly lower than the value estimated by using the reduction factor $e^{-\frac{P}{28}}$.

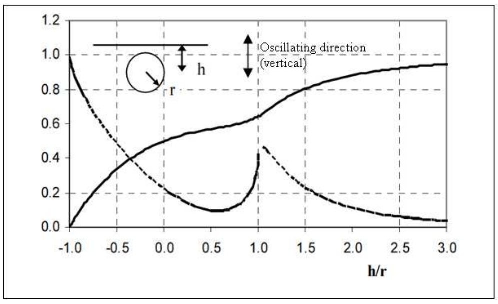
The proximity of an object to the free water surface also affects its added mass. Fig. 5 presents this effect for a cylinder[3] (applicable for spools etc) which shows that fully developed added mass should be applied when the top surface of the structure is at a depth greater than the radius of the cylinder (i.e., $h/r \geq 2$). The use of high values of the added mass may introduce excessive conservatism in the analysis if the structure is too close to the surface where the water particle kinematics is larger in magnitude.

In case of rectangular plates, the recommended hydrodynamic coefficients (as presented in DNV-RP-H103) indicate that added mass effect is equivalent to two half-cylinders of water; on the top and on the bottom surfaces of the plate respectively. *It is here suggested to extend this as an assumption* for the added mass over a flat plate close to the free water surface as presented in Fig.6 where the developed added mass is taken as the available volume of the water-cylinder depending on the depth of submergence. Any effect from the presence of waves is here ignored. In the absence of available experimental results, this approach can be used in the analysis through a sensitivity check on the depth of submergence of the structure so that the maximum dynamic load in the hoisting system is obtained.



Legends:
p = perforation ratio ($0 < p < 1$)
A_{33} = added mass of perforated structure
$A_{33,0}$ = added mass of non-perforated structure
μ = discharge coefficient, defined by Molin (2001)
KC_{por} = porous Keulegan-Carpenter number = $\frac{z}{D}\frac{(1-p)}{2\mu p^2}$, where, z = oscillation amplitude, D = typical dimension perpendicular to direction of oscillation

Fig. 4. Effect of amplitude of motion on added mass of perforated structure (taken from DNV-RP-H103) [3,11]



ω = frequency of motion, $\to \infty$
a_{33} = added mass in the vertical direction
solid line: $a_{33} / \rho\pi r^2$,
dotted line: $(da_{33} / dh) / \rho\pi r^2$

Fig. 5. Added mass of a cylinder near the free surface (taken from DNV-RP-H103)[3]

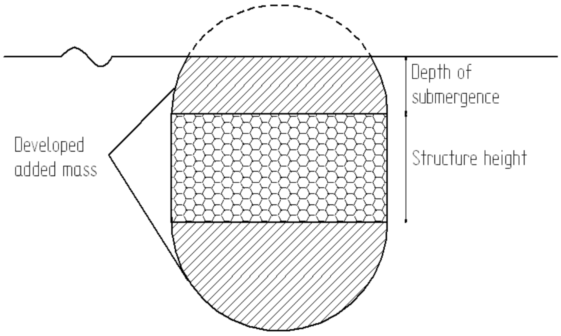


Fig. 6. Suggested assumption of the added mass on a flat surface of a structure near the free surface, any effect from wavy surface is ignored

Drag coefficients for unsteady flow

The recommended drag coefficients for the regular shaped objects in *steady flow* are commonly available (ref. Table 6) and are used in analysis. But these values may not be applicable for splash zone analysis where the flow is *unsteady* in nature. The test results of cylindrical objects show that the drag coefficient increases significantly when the object undergoes oscillatory motion (Fig. 7)[13]. DNV[3] recommends that for subsea structures with complex geometry, the CD value could be up to 4 to 8 if wake wash out effects are ignored. In the absence of adequate experimental results, it is suggested that drag coefficients may be applied as twice the steady state values in lifting analyses.

However for large structures whose hydrodynamic is inertia dominated, higher drag coefficients should be used with caution since it may induce unrealistic damping (refer section EFFECT OF LARGE DRAG COEFFICIENTS ON THE INERTIA DOMINATED STRUCTURES) in the simulation of the motion.

The correct selection of hydrodynamic coefficients is always a challenge to the engineer since a large gulf exists between the available information and the target application. A user should pay attention to the range of valid extension of the available test results and review associated risk by comparing with previous experiences.

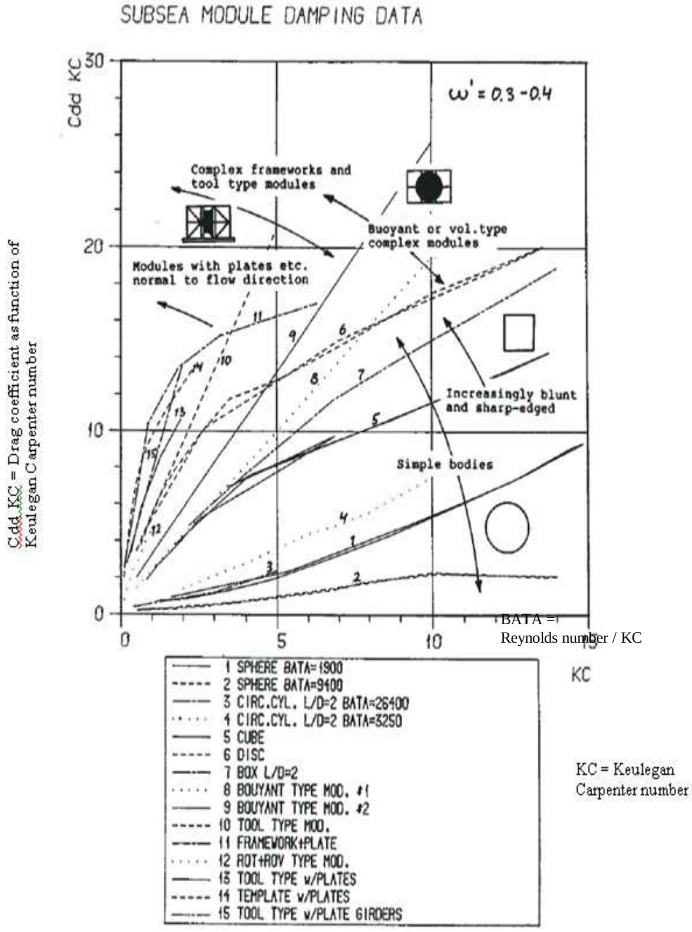


Fig. 7. Summary on the subsea module hydrodynamic data (Øristland, 1989[13])

SELECTION OF ACCEPTANCE CRITERIA

The acceptance criteria for an installation analysis (allowable load in the crane wire including any dynamic effects) guarantee that the hoisting system is not adversely affected by the possible maximum load in the crane wire. The allowable maximum load in the crane wire is defined as the smaller value of the crane capacity (at the radius of deployment) and the structure's design capacity whereas the allowable minimum load should preferably be above zero. DNV[3] recommends 10% of static submerged weight of structure as the minimum allowable tension so that slack in slings never occurs. The reason for not allowing slack slings is to avoid any case of snap load (i.e., peak load that may occur after slack) in the hoisting system.

In case slack sling occurrence is unavoidable, DNV[3] recommends a conservative approach to estimate snap load assuming that the structure is falling with a constant velocity and is stopped by the hoisting system.

A time domain analysis, on the other hand, also could be employed to estimate the snap load for the design purpose provided the model inputs are accurate enough and the time step in simulation is carefully chosen to reflect the system behaviour correctly. In general, a system with higher stiffness provides a higher snap load due to smaller time of impact, i.e., a stiffer model in the numerical analysis should provide a conservative estimation of the snap load. It is suggested that a sensitivity study should be undertaken to analyze the effects of uncertainties in the hoisting system's stiffness values.

It may be noted that if the snap load is high, slings made of softer materials (e.g. nylon) may be used to reduce the overall stiffness of the hoisting system and thus lessen the magnitude of the impact load.

NUMERICAL ANALYSIS METHODOLOGY

The simplified method of analysis as outlined in DNV[3] could be sufficient for small structures to get a reasonably good sea state. But for larger structures, this approach may appear to be conservative and numerical analysis by using commercial packages like MACSI, SIMO etc becomes inevitable. The general approach to perform the numerical analysis for lifting of a structure in a fully submerged condition is described below in brief.

- Model the geometric and the hydrodynamic properties of the structure following its drawings and the weight report as much as practicable.
- Analysis with regular waves may be used as a preliminary approach. DNV[3] suggests that a sea state of H_s (significant wave height) can be checked by using a regular wave of wave height H = 1.8 x H_s. The corresponding range of Tp to be checked is given as $8.9\sqrt{\frac{H_s}{g}} \le T_z \le 13$, Tz = zero crossing time period (can be taken as wave period in case of regular wave[3]), g = acceleration due to gravity. Note that the same document can be referred to get a relation between Tp and Tz.
- A sensitivity study should be carried out using regular waves at the depth of submergence, the wind sea heading angle to the vessel (target heading ± 15°, ref DNV[3]), the swell heading angle (swell along with the wind sea and swell from the beam sea), total weight of the structure (including or excluding the weight contingency) and the winch speed (if considered necessary).
  The duration of the simulation with the regular waves should be sufficient enough to include few wave crests.
- The sensitivity study results are used to screen out the critical configuration(s) and sea state(s) which may need further analysis with random waves to arrive at more accurate design sea state values.
- For random wave analysis, choose a suitable wave spectrum based on the metocean data of the site. Guidelines given in DNV-RP-H103[3] may be followed in absence of any site specific information.
- Choose the simulation duration following the actual duration of the operation. It may be suggested to use 30 min as simulation duration if the winch speed is not modelled since in actual operation, the structure passes through splash zone without any stop.
- For each sea states, it is suggested here to run 10 random samples each of 30 minutes simulation duration and the average of the maximum values from the 10 samples may be taken as the expected extreme values which can be compared with the acceptance criteria.

Sometime due to the nature of the operation, it is needed to consider longer simulation duration. In such cases the overall time consumption for the numerical analysis may be reduced by running shorter simulation duration and extrapolating the output statistically to the longer duration.

The foundation structure of Fig. 1 is analysed and the time series of the crane wire tension for a single random simulation is used to present Fig. 8 where two commonly used methods of extrapolation (namely, Rayleigh and Weibull distributions) are fitted to the probability of maxima values of the crane wire tension.

It is evident from the figure that the Weibull's distribution provides a better fit for extrapolating the splash zone analysis results. The Skewness and Kurtosis values (ref. statistical parameters in Fig. 8) show that for this example the time series of the crane wire tension is non-Gaussian (For Gaussian distribution, skewness = 0, kurtosis = 0). The number of random samples (N) required to achieve the desired accuracy in estimating the expected extreme value may be checked by using the central limit theorem as $N = \left(\frac{C}{C_T}\right)^2$, where, C_T = target coefficient of variation (suggested value is 10-15%), C = coefficient of variation of the expected extreme values for N samples. As recommended before, N = 10 provides a good start.

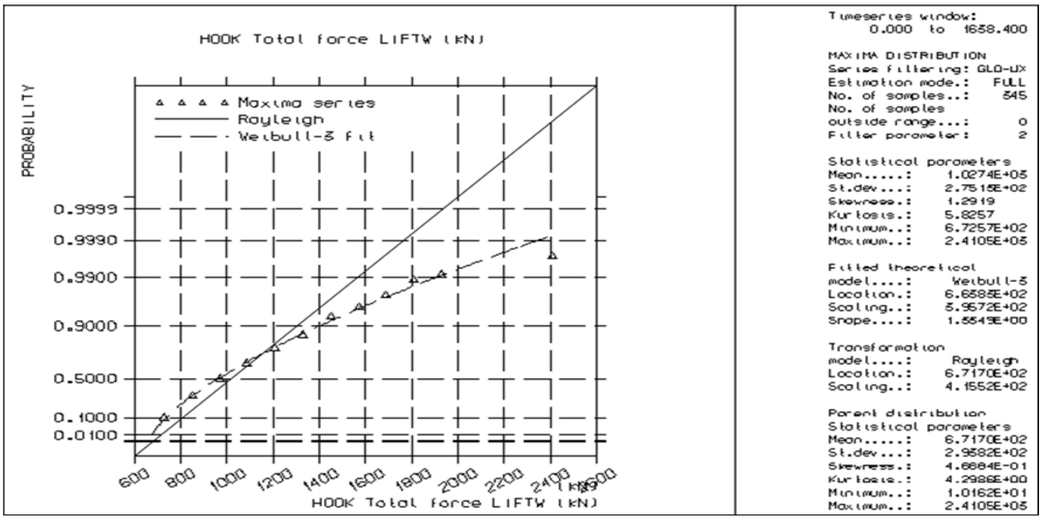


Fig. 8. An example of fitting of Rayleigh and Weibul-3 distributions to the splash zone analysis results (time series of tension in the crane wire)

EFFECT OF LARGE DRAG COEFFICIENTS ON INERTIA DOMINATED STRUCTURES

Following the Morison's model, the dynamic equation of a lifted object at the splash zone can be written as,

$$m\ddot{x}+c\dot{x}+kx=\underbrace{\rho V_1\ddot{w}\;+\;C_A\rho V_2(\ddot{w}-\ddot{x})}_{\text{Inertia force}}\;+\;\underbrace{C_D\rho(\text{drag area})|\dot{w}-\dot{x}|(\dot{w}-\dot{x})}_{\text{Drag force}}\quad\ldots 1$$

Where, m = mass of the object, c = system damping, k = stiffness, ρ = density of water,

C_A = added mass coefficients, C_D = quadratic drag coefficients

V_1 = volume for Froude-Krylov force calculation, V_2 = volume for added mass calculation

$\ddot{w}, \dot{w}$ = water particle acceleration and velocity respectively

$\ddot{x}, \dot{x}$ = structure acceleration and velocity respectively.

Removing the inertia force due to the structure's acceleration and taking $V_1 = V_2$, the excitation force in Eq.1 becomes,

$$F(t)=(1+C_A)\rho V\ddot{w}\;+\;C_D\rho(\text{drag area})|\dot{w}-\dot{x}|(\dot{w}-\dot{x})\quad\ldots 2$$

For structures with large added mass and / or large entrapped volume, the hydrodynamic force is dominated by the inertia force term. The expression for the drag term indicates that depending on the relative velocities of the structure and the water particles, the drag may become a source of damping in the simulation. This means that in the numerical analysis of large volume structures, an increase in the drag coefficient may reduce the resulting maximum dynamic force in the crane wire due to the damping effect.

The methodology as described in the previous sections is employed and six cases with different drag coefficients are studied. The base case (case 1) comprises the steady state drag coefficients as presented in DNV[3] (ref Table 6) while in the other cases (case 2 to 6), multiples of the steady state drag coefficient values are used. The results are presented in Table 1.

The overall effect is the reduction in the dynamic tension of the crane wire which can be observed in the standard deviation values as well as the maximum and the minimum wire tension values. A comparison of the vertical velocity of the structure (at the top of a suction can) and the relative velocity between the structure and the water particles at the same point as obtained from the results of case 6 is presented in Fig.11 which shows that they are almost out of phase, i.e., the drag force is acting against the structure's change of momentum.

Similar observation on the role of drag related to burst type response is reported in Ref. 9.

Hence it is suggested that unless detailed experimental results on similar objects are available, a sensitivity study should be carried out for lifting analysis of large structure to understand the role of the drag coefficient. This will be useful to avoid unrealistic analysis.

Table 1 Variation in the crane wire tension due to change in the drag coefficients

Case	Drag coefficient	Parameters of the time series of the Crane wire tension			
		Mean (kN)	Standard deviation (kN)	Maximum (kN)	Minimum (kN)
1	0.78*	1391	290	2574.3	412.5
2	1.5 x 0.78		267.6	2552	436.6
3	2 x 0.78		261	2534	457
4	2.5 x 0.78		255	2516	475.6
5	3 x 0.78		249.7	2500	493.7
6	4 x 0.78		240	2468.5	527.9

*based on the steady state drag coefficients following DNV[3] (as represented in Table 6)

A sensitivity analysis is carried out to study this effect on the foundation structure of Fig.1 which is having the following major properties,

Mass of the structure in air	:	183 Te
Submerged weight	:	1419 kN (144.7 Te)
Overall dimensions (X, Y, Z)	:	20m x 20m x 8m
Diameter of suction cans (4 off)	:	Ø4m, (Length 7.0 m)
Total vertical added mass	:	150 Te
Total entrapped water	:	360 Te
Ratio of (added mass + entr vol)/sub wt	:	3.57
Software used	:	SIMO (performs time domain simulations)

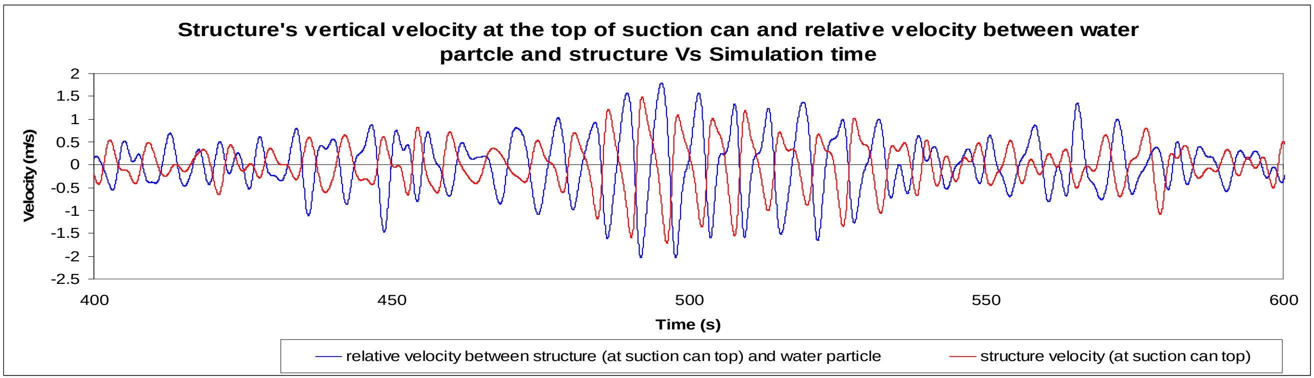


Fig. 9. A stretch of the time series showing the structure's vertical velocity at CAN top is larger than water particle velocity at the same location indicating role of drag as damping

EFFECT OF SLING ANGLE

A structure lifted by a crane is normally idealized by a simple pendulum model which works well as long as the mass of the crane hook is small as compared to the mass of the lifted structure.

But cases where the mass of the hook block is considerable (for e.g., for a crane of 400 Te capacity, the mass of the hook could be 10 Te), a 3D double pendulum model is more suitable for the analysis. Such numerical models of large and heavy subsea structures often show the double pendulum mode of oscillation in the splash zone as shown in Fig.10.

Several studies have been carried out on double pendulum mode of vibration of an object lifted by a crane (such as, Ref. 6, 12) and it has been established that the distance between the hook and the COG of the structure (or the length of the rigging) affects the natural frequency of the double pendulum mode[6] which consequently can affect the dynamic load experienced by the crane wire.

Table 2 Variation of maximum crane wire tension due to change in length of slings

Sling angle	Parameters of the time series of the crane wire tension				
	Distance (SL 1 /SL2) between structure COG and hook (m)	Mean (kN)	Standard deviation (kN)	Max (kN)	Min (kN)
45°	8.9	1391	199	2230	727
50°	10.6		216	2329	698
55°	12.7		248	2447	575
60°	15.4		290	2574	412
65°	19.1		308	2600	256

A detailed analytical approach for such systems is not attempted in this paper, but a sensitivity study on this effect is carried out with the structure of Fig.1 for different "hook-structure distances" (HS1, HS2 in Fig.10) which is achieved by changing the sling angles.

The results are presented in Table 2 which indicates that for some structures, adjusting the sling angle may be a good option to reduce the dynamic tension in the crane wire and to allow working at higher sea states.

The disadvantage of this approach is that it will influence the required design strength of the structure since it will need a stronger structure to withstand the horizontal component of the sling tension.

SELECTION OF DAF FOR THE STRUCTURAL DESIGN

The effect of the DAF (Dynamic Amplification Factor) value used in the structural design for the submerged condition loading cases becomes evident when the maximum allowable hook load is governed by the strength of the structure instead of the crane capacity at the operating crane radius. The DAF for submerged condition is defined as,

$$DAF = \frac{static\ \ submerged\ \ wt\ +\ downward\ \ dynamic\ \ load\ \ amplitude}{static\ \ submerged\ \ wt}$$

If it is assumed that the dynamic load amplitude in the upward and the downward directions are same, then DAF = 2 will mean corresponding slack in the slings when the load acts upward. This assumption forms the basis of using DAF = 2 as the limiting value for the structural designs in industry since slack in slings are considered to be unacceptable. But it is well known that in irregular sea states, the dynamic load amplitude in the downward direction is larger in magnitude than in the upward direction. This means when slack in slings occurs in reality, the DAF value may actually be greater than 2. The same can be observed in the sensitivity study results on the structure of Fig.1 (submerged weight of 1391 kN) as presented in Table 3.

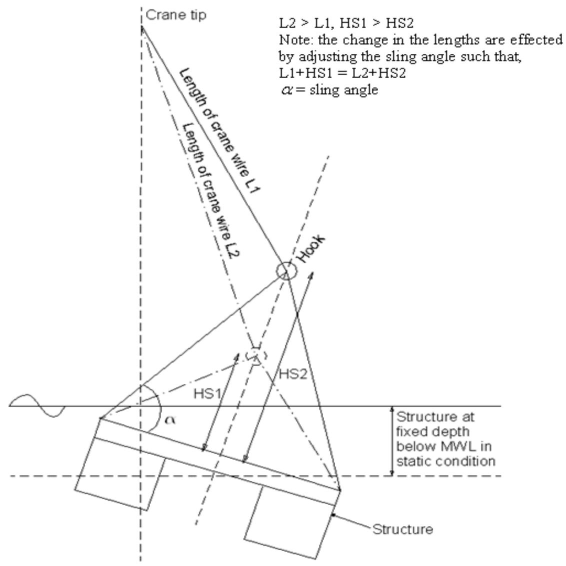


Fig. 10. Double pendulum motion of subsea structure in splash zone

The results of Table 3 indicate that if the design strength of the structure is limited by a DAF = 2, then the maximum allowable design sea state will be H_s=2.2m while a still higher sea state could be achieved provided a higher DAF is considered for the structural design.

Hence, it is here suggested, that for large subsea structures the DAF value for the structural design should be chosen from a preliminary lifting analysis result which may help to optimize the design sea state.

Table 3 Variation of maximum and minimum crane wire tension at different sea states

H_s (Tp 7s)	Parameters of parent series				Parameters of maxima and minima			
	Mean (kN)	Max (kN)	DAF	Min (kN)	Mean of max (kN)	St div of max (kN)	Mean of min (kN)	St div of min (kN)
2.2	1391	2683	2.06	327	1783.5	228.1	1001	197
2.4		2759	2.12	261	1797	238	988	210
2.6		2838	2.2	197	1819	254	965	224
2.8		2921	2.25	153	1843	271	943	240
3.0		3022	2.32	114*	1866	287	921	255

*indicates slack in the crane wire. Slack criterion is taken as 10% of the static submerged

EFFECT OF MODELLING OF THE WINCH SPEED

As mentioned earlier, the common industrial practice to carry out the lifting analysis involves numerical modelling of the hoisting system keeping the length of the crane wire fixed (i.e., no winch speed) assuming that the simulation with no winch speed will provide a conservative estimation of the loads in the splash zone. This assumption may not be true always for structures with large submerged weight or large added mass. The same is reflected in the results of sensitivity studies carried out on two structures as presented in Table 4.

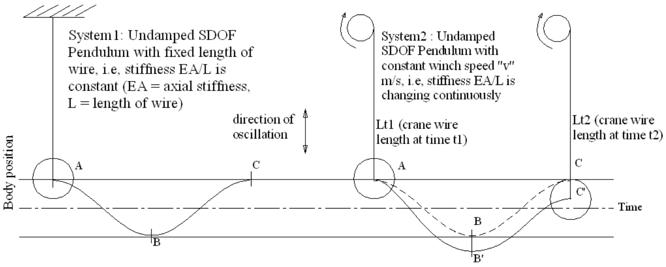


Fig. 11. An oscillating system without and with winch velocity

The primary effect of applying the winch speed is that it changes the body's mean position and the hoisting stiffness continuously. A detailed study on behaviour of such nonlinear hoisting system is not attempted in this paper.

The simplified models of the two undamped SDOF systems (system1 – without winch speed, system2 – with winch speed) are shown in Fig.11. It is known that for system1, the total energy in the gravitational field is constant and equals to *mass* × *acceleration due to gravity* × *distance AB* in Fig.10 (i.e., equivalent to the distance AB since mass and acceleration are constant). But with the winch speed (system2), the oscillating body may actually acquire larger energy from gravity (equivalent to distance AB´, since mass and acceleration are constant) and may consequently induce larger tension in the crane wire. This case is possible for structures with large submerged weight and smaller hydrodynamic coefficients (i.e., structures with large pick-up acceleration from the crest position) as can be observed in the sensitivity results of "Str1" in Table 4.

On the other hand, if the submerged weight of the structure is small and hydrodynamic coefficients are large (i.e., structures with small pick-up acceleration from the crest position), the release of the crane wire (from length L1 to L2 in Fig.11) may increase the chance of getting slack in the slings. The sensitivity result of "Str2" in Table 4 shows this possibility.

The authors didn't come across any published test result on the effect of the lowering speed in the lifting analysis. Hence it is here suggested that for such analysis of large subsea structures, sensitivity checks should be performed with and without winch speed to identify the most critical load case for the detailed analysis.

ON THE STIFFNESS AND DAMPING VALUES TO BE USED IN THE MODEL

It is always a great challenge for an engineer to use the correct input for the stiffness and the damping of the hoisting system. The stiffness value used for modelling the system should include the stiffness of the crane wire, the crane structure or any other associated components[3] and since they are all normally connected in series, the equivalent system stiffness can be computed as[3],

$$\frac{1}{K_{equivalent}} = \frac{1}{K_{Crane\ \ Structure}} + \frac{1}{K_{Wire\ \ rope}} + \frac{1}{K_{Others}} \qquad \ldots 3$$

Table 4 Effect of winch speed in the crane wire tension on two different structures

Case	Sub wt (kN)	Added mass (Te)	Winch speed (m/s)	Parameters of the time series of the crane wire tension: Mean of tension (kN)	Standard deviation (kN)	Max (kN)	Min (kN)
Str1	2766	198	0.0	2811	101	3373	2374
			0.1	2580	296	3545	1530
			0.2	2564	279	3493	1569
Str2	1390	545	0.0	1391	345.8	2813	223
			0.1	1383	392.5	2758	142
			0.2	1372	444.6	2798	27*

* indicates slack in the crane wire. Slack criterion is taken as 10% of the static submerged

Normally the crane stiffness is ignored by assuming it to be rigid as compared to the stiffness of the crane wire (EA/L) which works well if the operating depth is large (i.e., L is large). But for the splash zone, the length of the wire is smaller and so the stiffness of the wire could be close to the stiffness of the crane structure which makes the assumption invalid.

The example in Table 5 (taken from an existing offshore mast crane of 400 Te capacity) is used to explain the range of the effect that could be experienced by including the crane stiffness in the model. From the data, it is clear that for this particular crane, the assumption of infinitely stiffer crane structure can not be used for the splash zone analysis and dramatic change in the result may be observed by incorporating the crane stiffness since it will affect the system's natural frequency.

Similarly, the damping value of the crane wire is an important input to the model which may affect the result significantly. The damping of the wire ropes is normally much larger than the solid rods due to the internal friction between the wire-strands and modelling of small damping may produce unrealistic results. The authors have experienced that the manufacturers of the crane or the wire rope seldom include the stiffness values of their product in the catalogues and the damping values are never mentioned.

It may be noted that the manufacturer (or the owner) of the cranes and the wires conduct routine tests on their product (or assets). It is here recommended that such testing procedures should also include a methodology to extract the stiffness and the damping values of the cranes and the wires which could provide a reliable data base to the analysis engineers.

Table 5 Effect of Crane Stiffness in the Equivalent Stiffness for Splash Zone Analysis

Crane wire length, L	Axial Stiffness, EA	Stiffness of wire, EA/L	Crane stiffness	Equivalent stiffness
55 m (splash zone)	430000* kN	7818 kN/m	5300* kN/m	3158 kN/m
355 m (near seabed)		1211 kN/m		986 kN/m

*input from crane manufacturer's manual, **subjected to change with the crane radius

CONCLUSIONS AND RECOMMENDATIONS

The challenges in the lifting analysis has been developed very fast in the recent years mainly by the installation of larger and heavier subsea structures than before and by the utilization of more sophisticated tools to model and analyze the hoisting system.

It is concluded that the DNV-RP-H103 provides an excellent basis for the lifting analysis by summarising the state-of-the-art on the hydrodynamic coefficients and the time domain analysis methodology.

It is strongly recommended that more model tests need to be conducted to understand the amplitude dependent character of the added mass and the drag coefficients for structures with complex geometries and large added mass / entrapped water.

For numerical modelling of the hoisting system, a multibody model (i.e., modelling the structure, the hook etc) is more realistic as compared to a simple pendulum model.

It is recommended that before the structural design is carried out, a preliminary lifting analysis should be performed to choose the DAF value (for the structural design) and the sling angles so that the installation sea state can be optimised.

The industry lacks available information when it comes to the stiffness and the damping values of the crane structure and the wires. It is suggested that the routine tests performed on the cranes and the wires should be extended such that the stiffness and the damping values may be extracted from the test results.

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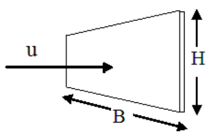
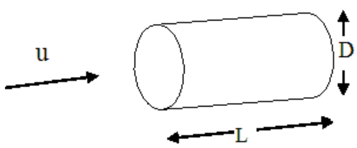
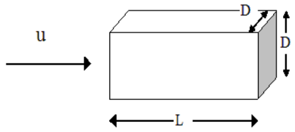
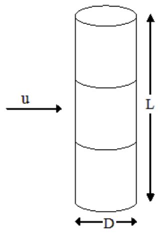
Table 6 Drag coefficients for regular shaped objects in steady flow following DNV-RP-H103[3], $C_{DS} = \kappa C_{DS}^{\infty}$

κ is the reduction factor due to finite length. C_{DS}^{∞} is the 2D steady drag coefficient.

Geometry	*Dimensions*	C_{DS}
Rectangular plate normal to flow direction  	B/H 1 5 10 ∞	 1.16 1.20 1.50 1.90 $R_e > 10^3$
Circular cylinder. Axis parallel to flow.  	L/D 0 1 2 4 7	 1.12 0.91 0.85 0.87 0.99 $R_e > 10^3$

<table>
<tr>
<td>Square rod parallel to flow

</td>
<td>L/D
1.0
1.5
2.0
2.5
3.0
4.0
5.0</td>
<td colspan="2">
1.15
0.97
0.87
0.90
0.93
0.95
0.95
$R_e = 1.7x10^5$</td>
</tr>
<tr>
<td rowspan="2">Circular cylinder normal to flow.

</td>
<td>L/D</td>
<td>Sub critical flow
$R_e < 10^5$</td>
<td>Supercritical flow
$R_e > 5x10^5$</td>
</tr>
<tr>
<td>
2
5
10
20
40
50
100</td>
<td>κ
0.58
0.62
0.68
0.74
0.82
0.87
0.98</td>
<td>κ
0.80
0.80
0.82
0.90
0.98
0.99
1.00</td>
</tr>
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