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GUIDANCE ON STABILITY OF LIFTS

Heavy Lift Exchange Forum

GUIDANCE

Contents

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Introduction

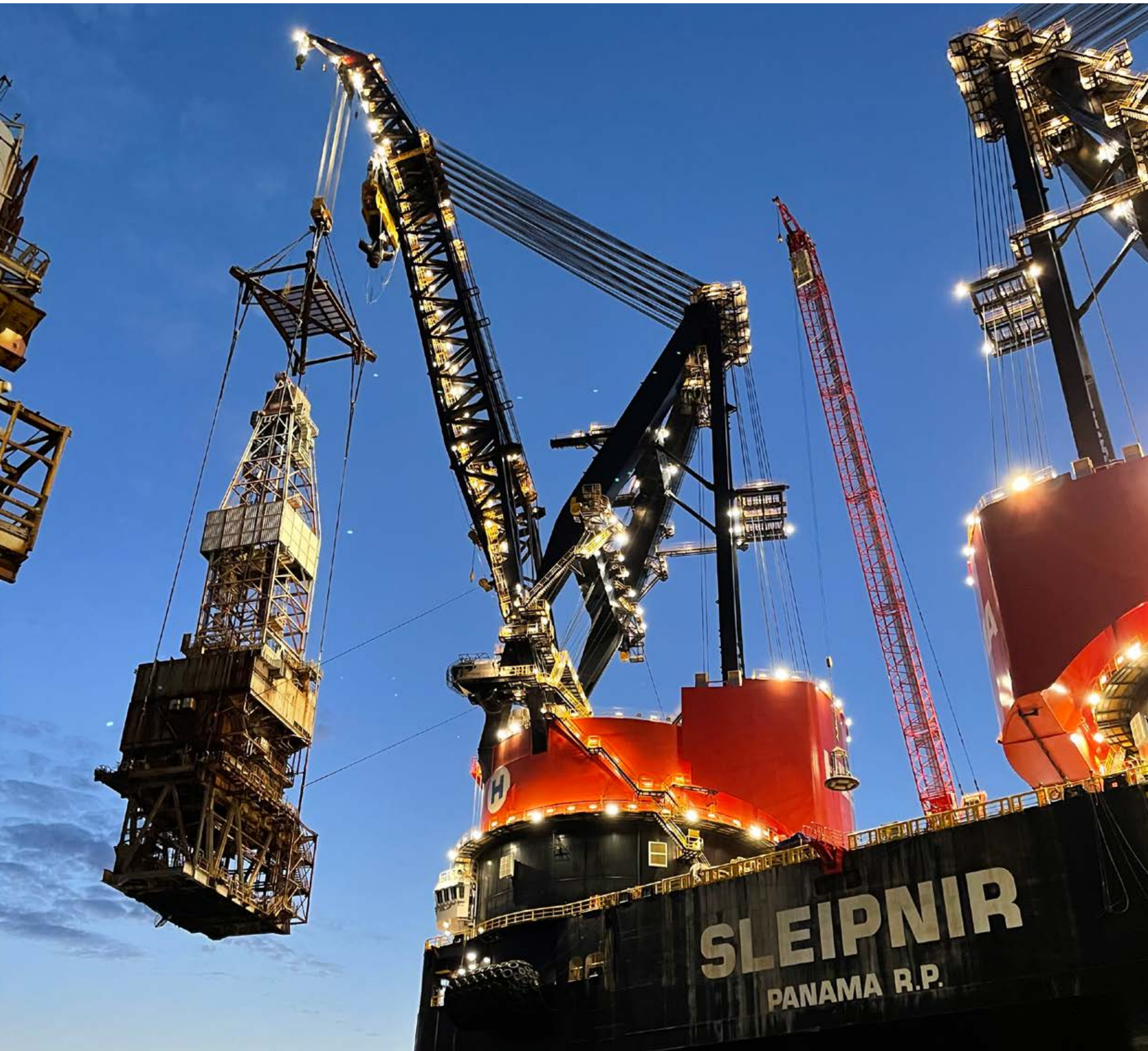
The purpose of this document is to provide an overview of methods to assess the stability of lifting arrangements. It shall allow the reader/user to form a substantiated opinion about the stability of a particular lifting arrangement by using the provided methods and data.

In the sense of this guideline the stability of a lift / lifting arrangement shall be understood as follows:

A stable lift is a lift that remains in a balanced condition, within a safe margin, when subjected to predefined disturbing factors.

This paper contains information about currently available calculation methods, belonging explanations, guidance for assumptions on loads and factors, and background information.

Reasons for issuing this document are the gap in the guideline landscape when it comes to lifting stability and the lack of comprehensive guidance in this matter.



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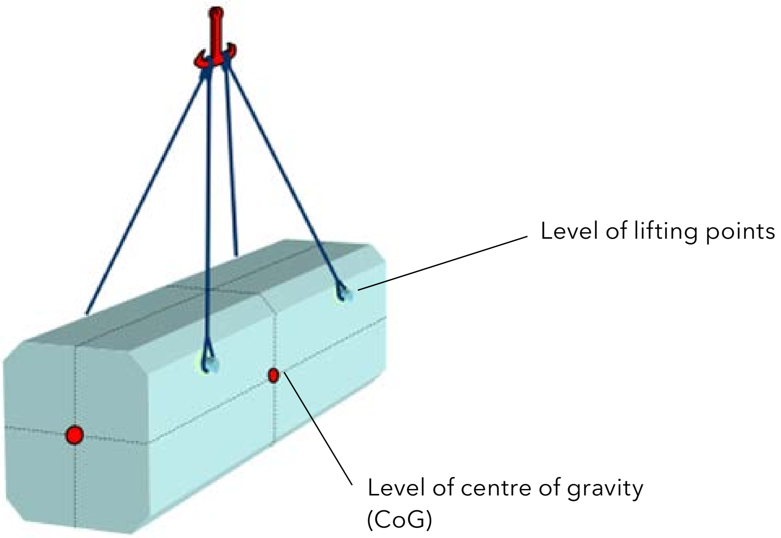
Abbreviations and Definitions

Primary and secondary suspension

FIGURE 1.1

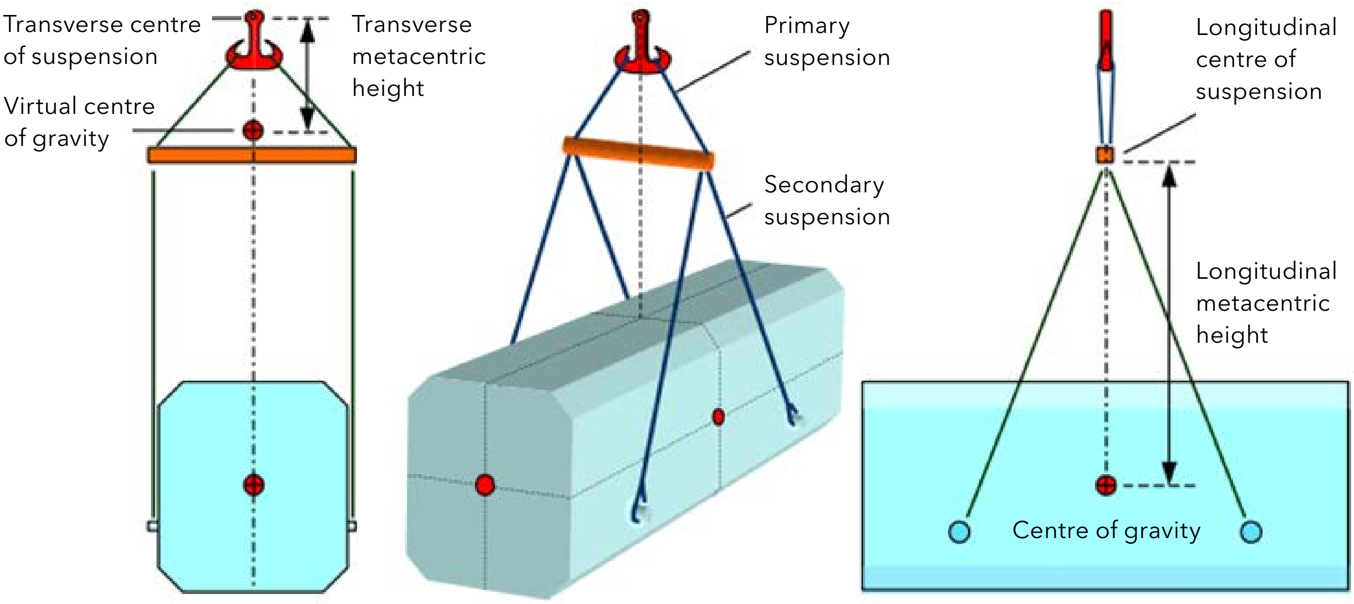
Stable primary suspensions



Definition of rigging components and geometry (Kaps 2013)

FIGURE 1.2

Potentially unstable primary/secondary suspension arrangement



Abbreviations

BFT	Beaufort
CAD	Computer-aided design
CoG	Centre of gravity
FDLP	Friction-dependent lift point
FLP	Fixed lift point
GM	Vessel`s metacentric height
GZ	Uprighting lever-arm
HMPE	High Modular Polyethylene
IMCA	International Maritime Contractors Association
IMO	International Maritime Organization
ISO	International Organization for Standardization
MBL	Minimum Breaking Load
RFQ	Request for Quote
SST	Static Stability Triangle
SWL	Safe Working Load
VCG	Vertical centre of gravity

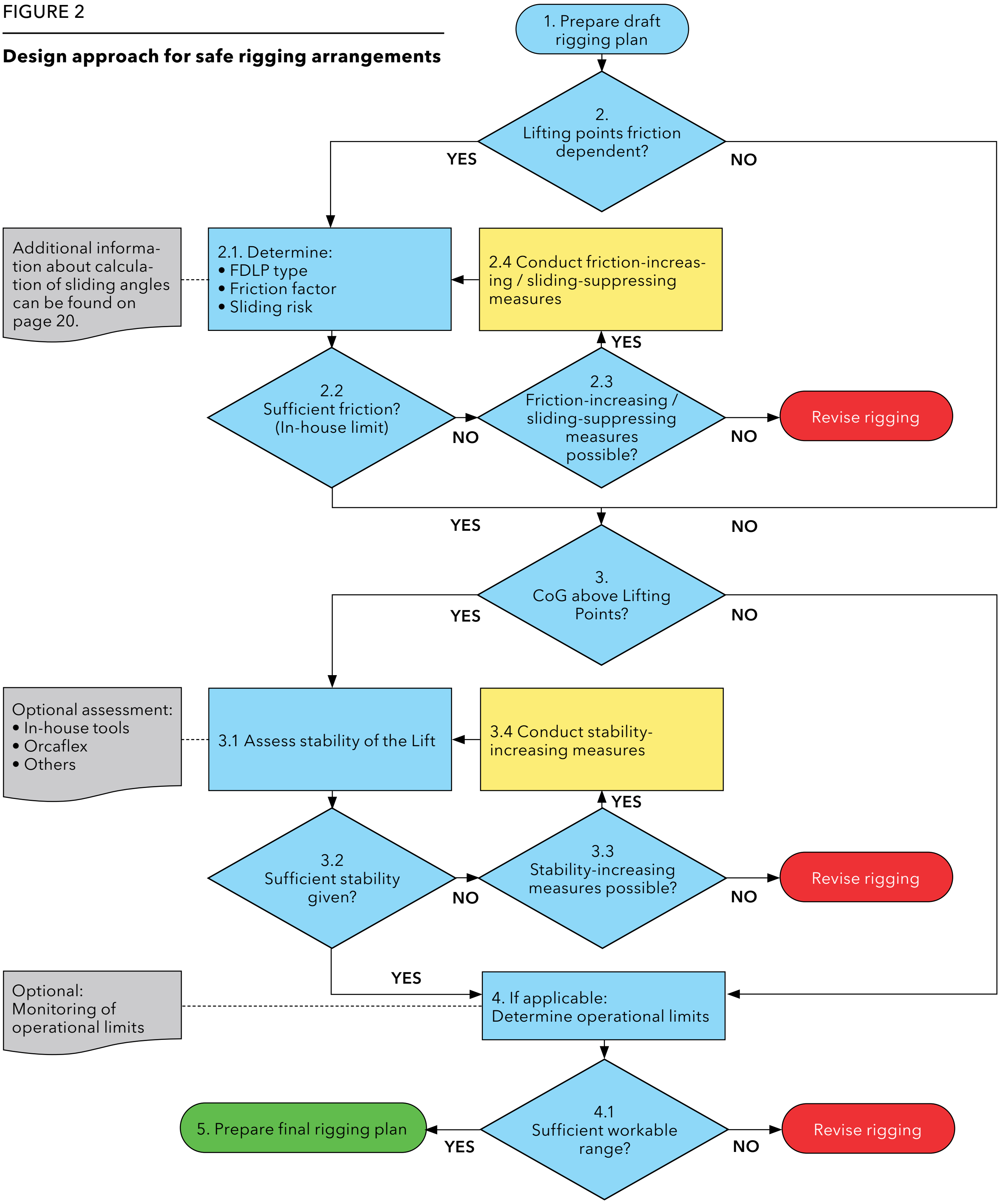
Unless otherwise noted, all units are metric and in accordance with the International System of Units (SI).

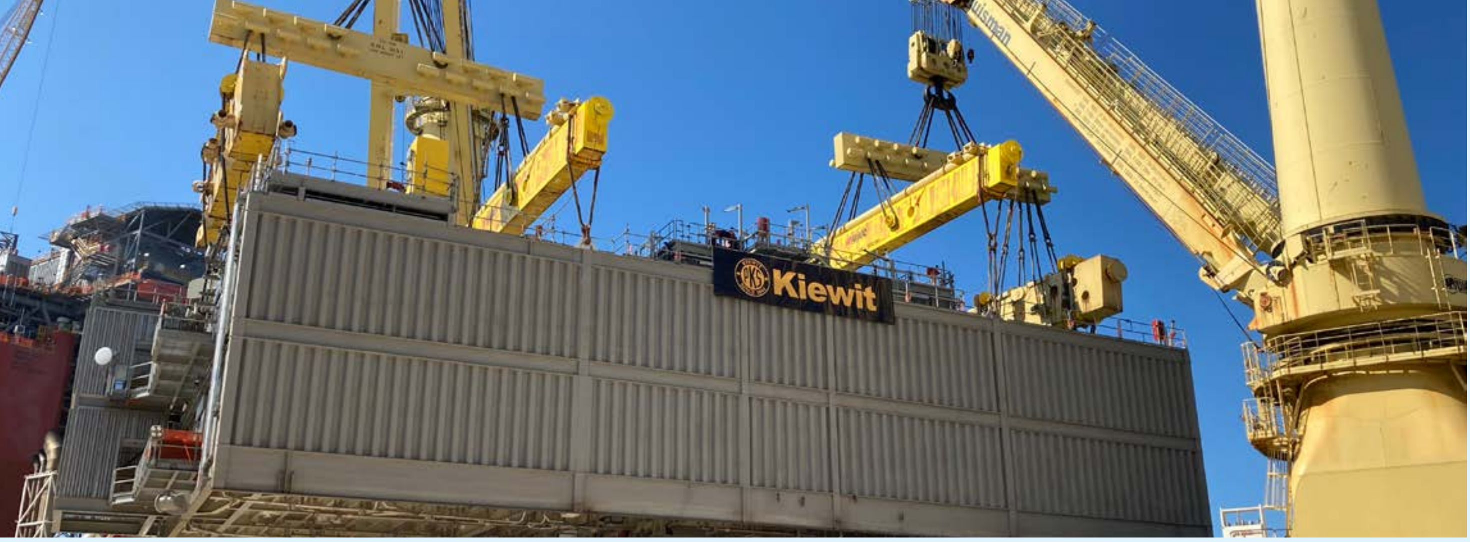
Assessing stability of lifting arrangements

This flowchart gives the user the guidance to assess the lifting stability of a rigging plan. Various check points and information blocks allow the user to review the created rigging plan, determine its suitability, and create a framework of boundary conditions. It should be noted that while various suggestions are given, they are by no means exhaustive. The user should and shall assess the possible variations to the shown parameters. The next sections further clarify the text boxes of the flowchart.

FIGURE 2

Design approach for safe rigging arrangements





Step 1 – Sketch rigging plan

As a first step the user shall make a draft of a rigging plan, assessing the general particulars of a cargo item, such as the overall geometry, CoG location, weight, dimensions and location of lifting points. In the next steps this set-up shall be reviewed.

The initial rigging plan shall be a feasible arrangement based on relevant expertise and experience of the designer. A feasible arrangement is stable, safe to operate, and has an equilibrium state as intended by the designer of the rigging plan. In order to determine feasibility the equilibrium state of the configuration shall be calculated, meaning no motions in the system and all loads and internal moments in equilibrium. If applicable, predefined disturbing factors are included in this assessment. In the equilibrium state without the presence of external loads, the combined CoG of cargo and rigging is vertically in line with the top pivot point of the system, typically the crane hook. Further guidance on the stability checks is given in the section 'Aspects to be considered in the stability assessment' (page 14).

For arrangements with the CoG above the lifting points, reference is made to step 3 of this flowchart. Furthermore, all rigging items shall have sufficient capacity for the maximum factored line loads. The arrangement is deemed feasible when the equilibrium state of the arrangement meets the applicable lifting standards. The following design considerations shall be taken into account:

- Primary rigging:
  - the longer, the more stable
  - suspension angle between 5° and 45° from vertical
- If applicable, secondary rigging:
  - the longer, the less stable
  - suspension angle tilted outwards (Ref. figure 21) increases stability
  - suspension angle tilted inwards (Ref. figure 22) decreases stability
- Preference for fixed lifting points over friction-dependent lifting points. Pad-eyes and trunnions are examples of fixed lifting points. A belly sling arrangement is friction dependent.

- Consider response sensitivity of rigging to external loads like wind, tugger-loads, etc.

Step 2 – Are the lifting points friction-dependent?

2.1 Determine the amount of friction

In case there are friction-dependent lifting points in the arrangement then the amount of friction shall be determined. This depends on the area and shape of the lifted object at the location of each lifting point and the friction coefficient between rigging and lifted object.

The amount of friction can be determined based on the normal load on the contact area, the materials of the lifted object and rigging gear, the surface and shape of the lifted object, and the material and surface conditions (dry, wet, greased, contaminated). It can often be derived from tables but also be determined by tests. The lowest possible friction factor for the given pair of materials shall be considered for the assessment.

The following considerations shall be taken into account:

- Determine friction-dependent lifting point type, for example:
  - Sling around cylindrical cargo
  - Sling around conical cargo
  - Sling around box-shaped cargo
  - Other shapes
  - Flat surfaces (e.g. flat rack)
- Determine friction coefficient:
  - Material combination
  - Surface conditions (roughness, wet/dry)
  - Lubricant type and amount of lubricant on rigging wire
- Determine sliding risk:
  - Sliding angle
  - Tilted slings
  - Presence of obstructions

2.2 Do the lifting points have sufficient friction?

Based on the friction factor and the type of lifting point and its geometry the sliding angle can be determined (see section 'Calculation of sliding and effective inclination angles', page 20). The sliding angle describes at which inclination between sling and cargo surface the lifted cargo starts to slide. It must always be ensured that this angle is not attained during lifting. It must be considered that slings may already have an angle by design of the rigging arrangement which reduces the angle at which the lift becomes unstable due to sliding of a lifting point.

The resulting critical sliding angle shall be used for determining sliding risks of the proposed rigging arrangement. For this risk assessment predefined disturbing factors shall be considered as well to cover the full operational range of the lift. The resulting risks shall be checked against internal company guidelines and project-specific criteria.

An iterative loop could be started to reduce the sliding risk when the system does not comply with the criteria. Additional mitigations, such as increasing the friction or rigging securing measures could be taken, after which the user rechecks the outcome (steps 2.3 and 2.4). The limiting tilt angle can be used as criterion later in the assessment when additional lift influencing parameters are analysed (step 4.1).

If the maximum tilt angle is deemed satisfactory (i.e. smaller than the critical sliding angle) then the user can proceed to the next step. In the worst case, when no suitable set-up can be found with the initial parameters, then an overall design change of the rigging could be required (red box 'Revise rigging').

Step 3 – Is the CoG above the lifting points?

If the CoG is positioned below the lifting points the lift is generally considered stable. The user could then proceed to the next step. But when the CoG is located above the lifting points then the lift can potentially become unstable. This is the case when the CoG is positioned outside the primary suspension and the system cannot find an upright equilibrium state when the lifting operation commences. For more complex configurations with multiple suspensions – i.e. when beams or spreader bars are used – the stability of the arrangement becomes even more complex and requires a careful analysis.

3.1 Assess stability of the lift

Various methods are available to assess the stability of a lift arrangement. An overview and comparison of methods that are widely used in the industry is elaborated in the next section. These methods have in common that the stability of a lift is expressed by a metacentric height, analogous to the GM in evaluating stability of ships. This metacentric height is the vertical distance between the (virtual) CoG of the cargo and the suspension point of the lift – typically the crane hook.

The methods presented here are:

- Visual check of virtual CoG
- Kaps method
- Nikitin method
- Numerical computer simulations

Where applicable, the stability of the lift must be assessed in both longitudinal and transversal plane, e.g. in a configuration with a lifting beam and 2 spreaders, where 2 triangles are created in perpendicular planes.

3.2 Sufficient stability given?

The calculated stability of a lifting arrangement varies between the methods and shall be evaluated against internal company guidelines.

In case there is not sufficient stability the user could opt to introduce stability-increasing measures (steps 3.3 and 3.4). This could be done, for example, by elongating the primary suspension, or tilting the secondary suspension wires outwards (Ref. figure 21). If the reiteration does not result in an acceptable stability of the lift, then the rigging concept should be revised (red box 'Revise rigging').

Step 4 – If applicable, determine and document operational limits

When the arrangement is deemed stable, the operational limits could be defined for performing the lifting operation. Various factors can influence the stability of the lift arrangement, eventually resulting in a potentially unstable condition. Relevant parameters for the operation could be quantified, with the results documented in the operational procedure.

Possible limits to be set:

- CoG envelope
- Tilt limits
- Maximum wind speeds
- Tugger arrangement and loads
- Maximum wave height, period and heading
- Crane motions
- Temperature and visibility

4.1 Sufficient workable range

A final check shall be performed to determine if a sufficiently large workable range is obtained for safe execution of the lifting operation. In case the operational range is deemed unsatisfactory, the rigging plan should be revised (red box 'Revise rigging').

Step 5 – Preparing final rigging plan

The rigging plan, complying with the selected criteria, will be finalized and added to the operational procedure.

Overview and comparison of available methods for stability assessments of lifts

In the following section, four different methods to assess stability in lifts as listed in step 3.1 of the flow chart (Ref. figure 2) will be presented and further explained.

1. Virtual CoG concept

For lifts with a primary suspension only, the stability of a lift corresponds to the vertical distance between the suspension point (i.e. the hook) and the CoG of the lifted object. The approach is analogous to the concept of 'metacentric height' in the initial static stability of ships. This method can be used to assess the stability of lifts with also vertical secondary suspensions. It allows a quick geometrical assessment of the lifting stability.

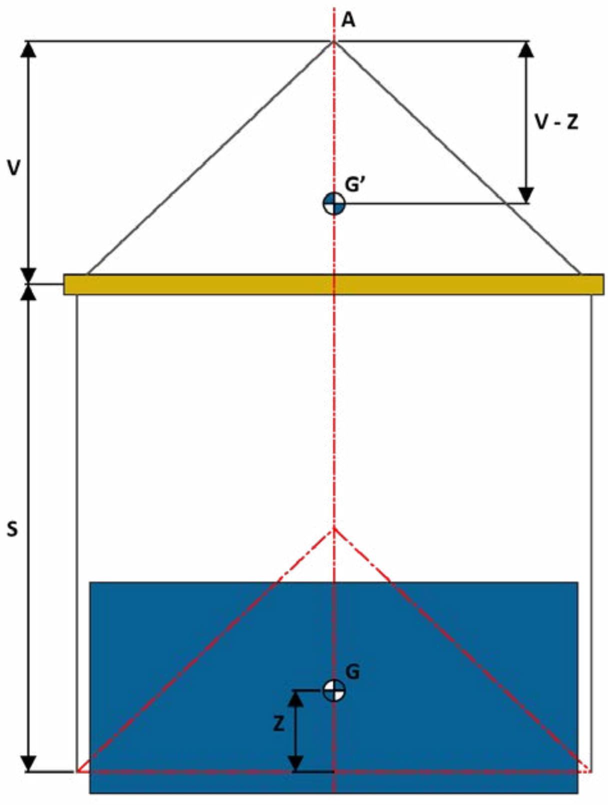
The vertical secondary suspension is not contributing to the lifting stability, therefore the distance s has no impact on it. A lifting arrangement is stable when the vertical distance z (lifting point to CoG) is smaller than the vertical distance v (height of stabilizing triangle). For visualisation a virtual CoG (G') can be introduced by shifting the CoG upwards by the distance s.

The metacentric height can then be calculated as the vertical distance from virtual CoG to pivot point A (v-z). Positive values describe a stable lift; the higher, the more stable. If the distance is negative (i.e. the G' is above the pivot point A) the lift is unstable.

A sophisticated calculation program may give a deeper insight. However, the static results at least show clearly that the primary slings should be made as long as possible while the secondary slings should be as short as possible.

FIGURE 3

Illustation of virtual CoG concept



2. Kaps method

Professor Hermann Kaps has published a paper with a calculation method following the idea of the 'Virtual CoG' concept. Based on a mathematical model, it allows the consideration of additional factors with impact on lifting stability. The stabilizing effect of the self-weight of the primary suspension can be considered as well as the sling angles of the secondary suspension. The method also allows elasticity of slings to be taken into account, and provides an approach for a 2-crane-lift with different rigging arrangements on each crane.

The 'Kaps method' allows quick assessments of the (initial) 'lifting stability' and is comparatively easy to use and well-established in the heavy lift industry.

Addressing potential instability when lift points are below the centre of gravity, the method offers a quantification and solutions for secure lifting of delicate cargo units. Even complex rigging arrangements involving primary and secondary suspensions can be analysed analytically.

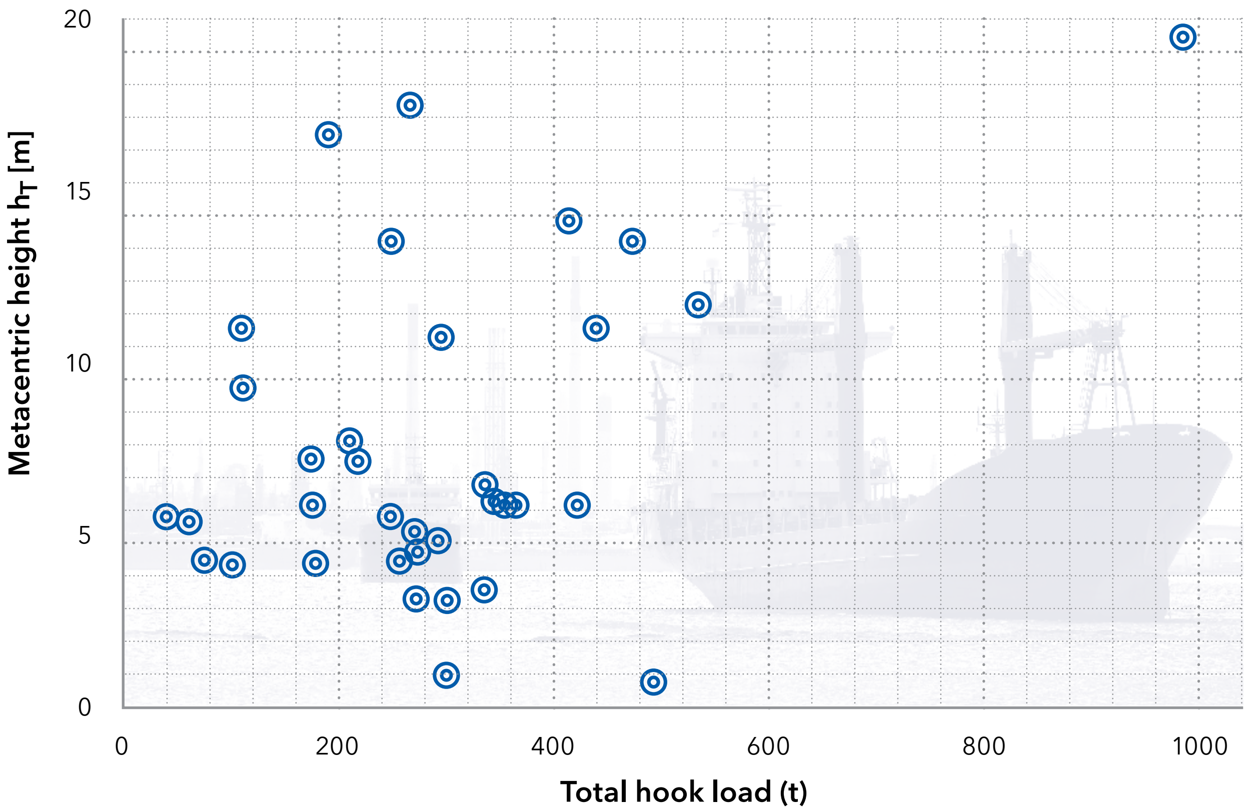
In the following graph, the result of 35 stability calculations based on the Kaps method is shown. It summarizes the metacentric height in metres over the hook load in metric tonnes for various 'best-practice-rigging arrangements'. The graph shows a concentration of metacentric height values in the range of approximately 3 m to 15 m. This shall not be taken as a strict limitation but gives a valid overview of the stability of heavy lifts that were executed successfully and without incidents.

The metacentric height presented in this method is for the primary suspension. In case of parallel secondary suspension, the result is also valid for the lift object / secondary suspension. If gamma > 0, the results are conservative since the lift object will rotate less than the primary suspension. For gamma < 0, however, the opposite is true and the metacentric height calculated according this method is not conservative.

For definition of angle γ refer to Fig. 21 and 22.

FIGURE 4

Metacentric heights of various performed heavy lifts



3. Nikitin method

Doctor Yevgeny Nikitin has published papers on stability of two-chain suspension arrangements (Ref. figure 22). This method uses the classical Lagrange stability concept and calculates an envelope for the CoG in which static and tip-over stability gives a stable equilibrium. This envelope is called the Static Stability Triangle. The vertical distance from the CoG to the top of this triangle is a measure for the response to an overturning moment. The horizontal distance from the CoG to the edge of this triangle is a measure for the amount of overturning moment at which the edge of stability is reached.

For two-chain arrangements with parallel secondary suspensions the results of this method are identical to that of the Kaps method, for non-parallel suspension, however, there are different results.

The static stability triangle calculation method only presents results for the case that the base of the primary suspension is identical to the top of the secondary suspension; when the base of the primary suspension is smaller, the base of the stability triangle will also be smaller. The described method only considers symmetrical arrangements.

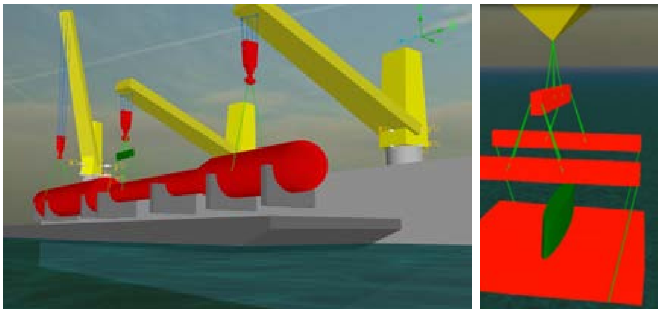
4. Numerical computer simulation – Standard

Specialised software tools (e.g. Orcaflex) allow the assessment of a rigging arrangement considering arbitrary geometries, boundary conditions and physical dependencies, and to expose them to loads like forces (e.g. from wind), accelerations (e.g. from crane motions), deformations (e.g. from elongation of slings), etc.

Usually, particular scenarios that are assumed to be critical or limiting (e.g. lift-off or set down situations), are assessed, and often the calculation model does not only include the rigging arrangement but also the crane and ship. Selected criteria (e.g. max. angle, deformations, loads, as well as lift stability) can be checked.

FIGURE 5

Illustration of a numerical computer simulation in 3D



5. Numerical computer simulations - Extended

An extensive method has been developed by SAL Engineering to allow for a comprehensive assessment of lifting stability that considers all relevant aspects like lift point geometry, friction dependency of lifting points, sensitivity to external forces, stiffness of rigging components and cargo and, at the same time, provides qualitative and quantitative information about failure mechanisms.
The below graph shows the relation between the inclination of a lifted object and the resulting uprighting moment. It is equal to the overturning moment, so illustration at the same time shows the inclination that results from a certain overturning moment.

It is further possible to identify collapse points of the assessed lifting arrangements. The kinks indicate sliding of lifting slings and resulting collapse of the lift. The different lines represent different friction factors for friction-

FIGURE 7

Illustration of lift stability (overturning moment over resulting inclination)

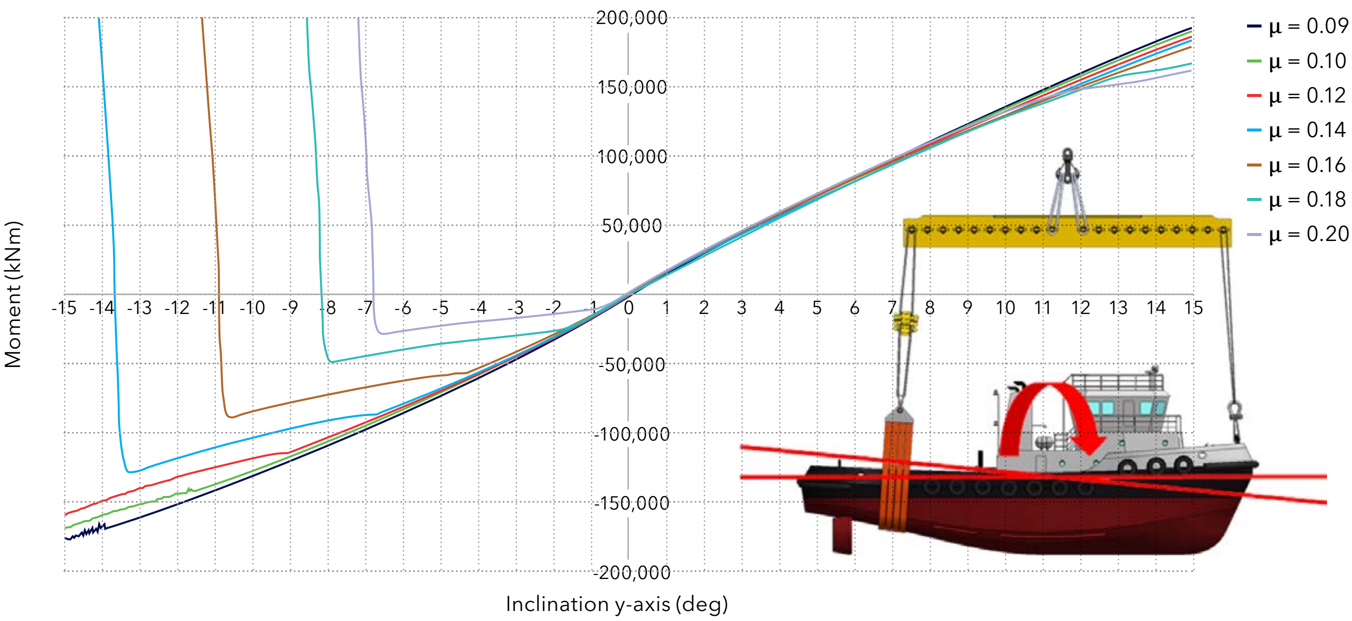
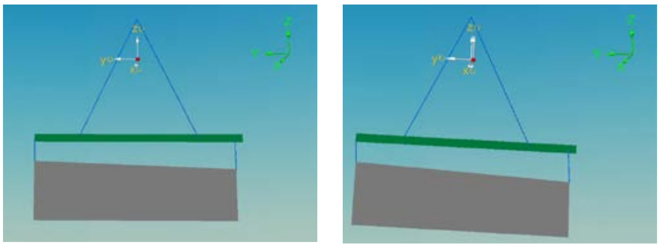


FIGURE 6

Illustration of a numerical computer simulation in 2D



dependent lifting points. Also the effect of the asymmetry of the lifting arrangement is visible.

The assessment of lifting arrangements with this method is time-consuming and requires specialised software tools (e.g. Orcaflex) and specific expertise. Its application is therefore only reasonable for lifting operations that are knowingly critical, and a high engineering effort is justified.

Comparison of methods and recommended areas of application

Methods described under 1. (Virtual CoG). and 2. (Kaps) allow the evaluation of the initial stability of the lift only. They do not provide information about the behaviour of the lift when external forces are applied or the CoG is off-set, nor do they allow conclusions about potential failure mechanisms. The Method described under 3 (Nikitin). gives insight on the stability against overturning of two-chain suspensions. It provides the initial stability as well as a range of stability measured by a maximum allowed tilting angle. Nevertheless the Kaps-method is broadly used within the industry. A direct comparison with the also analytical but more complex approach by Nikitin is given in the Appendix. The methods described under 4 and 5 require a numerical simulation.

The below table provides an overview of the introduced methods.

TABLE 1

Comparison of methods

	Virtual CoG concept	Kaps method	Nikitin method	Numerical computer simulation - Standard	Numerical computer simulation - Extended
Approach	Graphical	Analytical Excel-based solution available	Analytical Can be automated	Numerical Simulation software needed	Numerical Simulation software needed
Complexity	Low	Medium	Medium	High	High
Time effort	Low	Low	Low	Medium	High
Accuracy	Low (but for most cases sufficient)	Medium	High	High (for specific cases and conditions)	High
Range	Initial stability only	Initial stability only*	Gives initial stability and range of static stability	Stability for defined conditions	Stability for all angles
External forces	Cannot be considered	Cannot be considered*	Cannot be considered	Can be considered	Can be considered
Lifting points	'fixed' only	'fixed' only	'fixed' only	Characteristics can be considered	Characteristics can be considered
	Does not consider stabilising effect of lifting beam weight as well as sling angles of secondary suspension.	Gives metacentric height for primary suspension, no info on range of stability. Only considers symmetric arrangement.	Only considers symmetric arrangement. Base of primary suspension needs to be identical to top of secondary suspension.	Efforts for postprocessing and documentation only as much as needed. Ultimate failure mechanism not of interest.	High efforts on post-processing to produce GZ-curves and to identify failure mechanisms and points.

*analytical assessment based on Kaps method theoretically possible but not developed yet (June 2024).

Aspects to be considered in the stability assessment

A stable lift is a lift that remains in a balanced condition, within a safe margin, when subjected to predefined disturbing factors.

Disturbing factors may include:

- Wind
- Rigging length tolerance
- Steering line forces
- Crane movement
- CoG shift
- Vessel motions
- Friction at the lifting points

The following subchapters highlight an assortment of disturbing factors and present a way to incorporate them into the calculations for rigging stability assessment.

External forces from wind

For every heavy lift, the wind is an important factor for the safety of the operation. Mostly, maximum acceptable limits of the wind speed are set by either experiences or stipulated recommendations. For the analysis of the influence on the stability of lifts, multiple analytical formulas can be used to determine forces acting on the lifted structure, as well as resulting tilt angles of the suspended rigging arrangement.

Wind speed and vertical wind profile

The wind speed information is always related to a reference level above the ground level, usually 10 metres. On this basis, the distribution of wind speed with increasing height may be estimated by means of the so-called logarithmic wind profile with the equation:

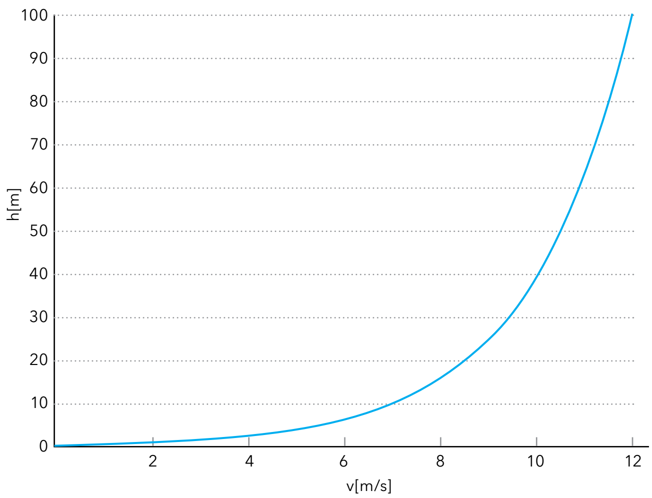
$$v(z) = v_r \cdot \left(\frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_r}{z_0}\right)} \right) \quad [m/s]$$

$v(z)$ = wind speed in level z above the ground [m/s]
v_r = wind speed in the reference level zr above the ground [m/s]
z = actual level above the ground [m]
z_r = reference level above the ground [m]
z_0 = level above the ground for v = zero [m]

The value of z_0 depends on the unevenness of the ground environment. For a moderately built-up port area a figure of z_0 = 0.4 may be used.

FIGURE 8

Wind profile for v_r=7 m/s with z_0=0.4 m and z_r=10 m



Windforce determination

For obtaining the force F acting on a body under the blow of the wind a well-known equation is used.

$$F = A \cdot c \cdot \left(\frac{p}{2}\right) \cdot v^2 \ [N]$$

A = affected area, or the projection perpendicular to the wind direction [m²]
c = coefficient of resistance (Reference is made to values given in literature)
More information may be found in DNV-RP-C205 – Environmental conditions and environmental loads
ρ = density of air [kg/m³], temperature dependent, 1.25 kg/m³ may normally be assumed
v = wind speed [m/s]

For determination of wind area A, a common simplified approach is to use the full projected area without any openings. If perforated wind areas behind each other are affected by wind, the shielding effects should be considered case-by-case.

For the consideration of wind effects, the hanging load should be assumed to be in the highest crane position. This is generally the position where the bottom of the unit hangs above the hatch coaming or the hatch covers of the vessel.

The total wind force acting on a cargo unit is obtained by adding the forces acting on horizontal sections of, for example, 5 metres height, for which the wind speed is taken individually from the above described wind profile. The formula for the total wind force reads:

$$F_W = 0.001 \cdot \sum_{i=1}^{n} (0.5 \cdot A_i \cdot c_i \cdot p \cdot v_i^2) \ v_i^2$$

The height of the common centre of wind attack z_W above the bottom of the cargo unit is obtained by:

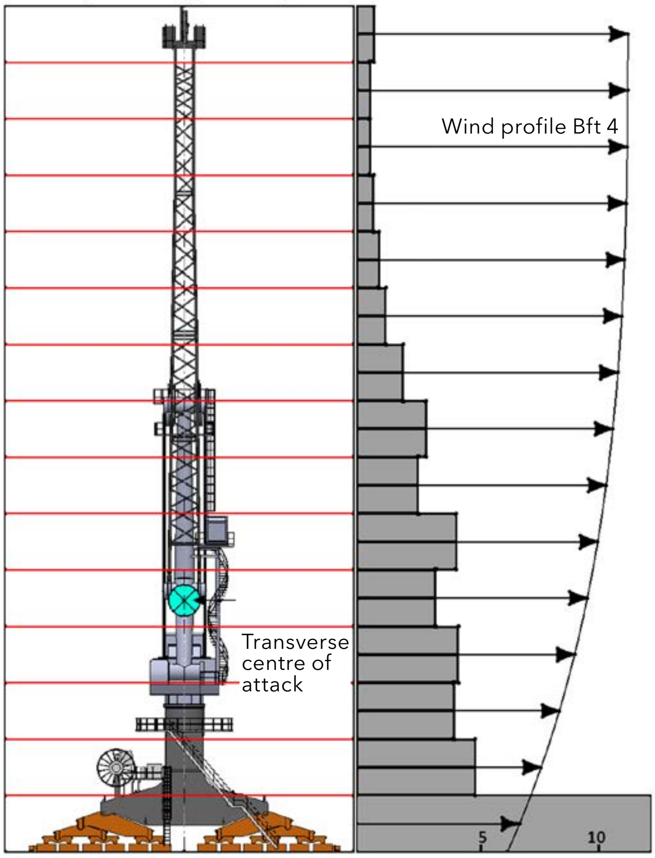
$$z_W = \frac{\sum_{i=1}^{n} (0.5 \cdot A_i \cdot c_i \cdot p \cdot v_i^2 \cdot z_i)}{\sum_{i=1}^{n} (0.5 \cdot A_i \cdot c_i \cdot p \cdot v_i^2)} \quad [m]$$

This calculation is conveniently carried out by a spreadsheet program. Alternatively, the wind area and centre of wind attack can be determined by CAD programs or similar.

It should be noted that the centre of wind-force attack is normally not identical with the VCG or the geometrical centre of an object. For such cases, the centre of windforce attack should be calculated.

FIGURE 9

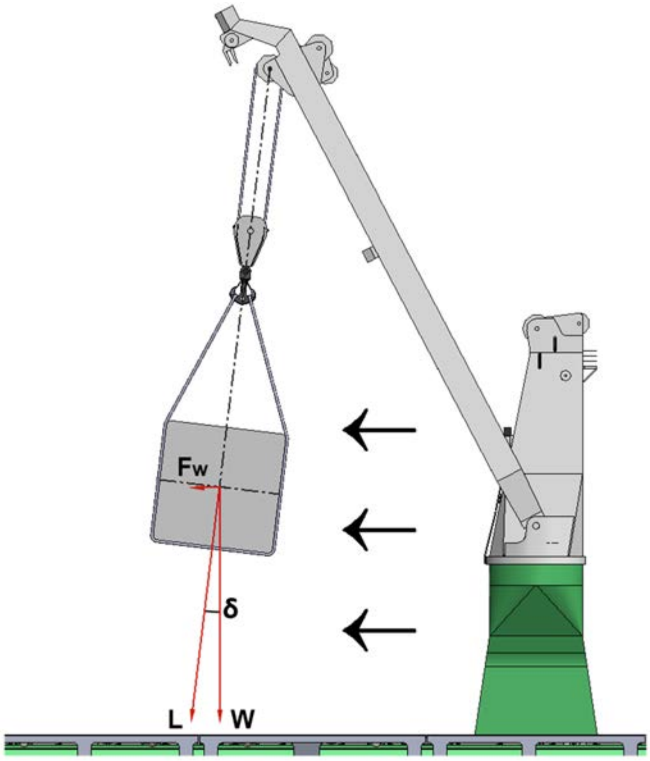
Example of compilation of wind force and centre of attack



Transverse view Area

FIGURE 10

Single crane lift, inclination of angle δ



Effects of wind attack

Wind force to a hanging cargo unit has the following static effects:

When handling a cargo unit with only one ship's crane there will be a slightly inclined pull on the lifting tackle and a negligible increase of the hook-load.

When handling with two cranes there will be also an inclined pull, but also a re-distribution of hook-loads caused by the component of the wind in the plane through both crane tops.

When handling with two cranes it may be that the cargo reaches high up between the two crane tops. It may then happen that the point of common wind attack is far above the centre of gravity of the cargo unit or even above the centre of suspension of the rigging arrangement. In such a situation the component of the wind, which is perpendicular to the plane through both crane tops, will create an additional tilting of the suspension.

Effects on single-hook lifts

The inclination of the tackle in Figure 10 is obtained by:

$$\delta = \arctan\left(\frac{F_W}{W}\right)$$

The force L in the tackle is increased against the weight W to:

$$L = \sqrt{(F_W{}^2 + W^2)}$$

Under the assumption that the wind force F_W attacks at the level of the centre of gravity of the cargo unit, the suspension arrangement will be tilted by the angle δ.

External forces from tugger winch or steering line

One of the points differentiates a single lift from a tandem lift is lack of manouevrability of the suspended load. While during "tandem lift" operations the cargo can be easily controlled by 2 cranes, single lift operations need additional method to prevent undesired movements of the cargo. The most effective method is using tugger lines.

Tugger lines are steel or HMPE wires which are rolled on the winch and during single lift operations they are connected either directly to the cargo or to the lifting beam. Usually heavy lift vessels have cranes equipped with tugger winches, but in some cases they can also be placed on dedicated positions on the vessel. Positioning of tugger winches on deck can be an advantage as the position of the winch can be chosen in a way to have better control of the cargo during the whole operation, while the tuggers on the crane are fixed.

The purpose of tugger lines is to control the suspended load. They are not only used to steer the cargo in a desired direction, but also to reduce the swinging motion of the cargo created by the movements of the crane and vessel (swell), or by an external force such as wind. The tugger lines act as a damper, preventing the movement of the cargo by pulling the wires with a winch.

Using tugger lines needs to be done cautiously as possible hazards could occur. Applying extreme pulling force to a suspended load could result in a CoG shift, possibly decreasing the lifting stability. Extreme loads result in a tilted rigging, possibly decreasing on tugger wires during offshore operations have resulted in snapping of the wires.

Lifting operations need to be properly planned, with an understanding of which possible loads will arise on tugger lines. Positioning of the winches needs to be done while avoiding the creation of undesirable angles on the wires, which could increase the wire tension. The risk of a wire snap can be prevented by using constant tension tuggers. These tuggers are set to a constant tension. The wire is automatically released when the tension in the wire increases, while the winch tensions the wire when it becomes slack.

Slings

Sling length tolerance and stiffness and effect on stability

Uncertainty in sling length can result in increase of tilt of the lifted object. Tilt in turn can bring the lifted object closer to the edge of stability. Therefore, sling length tolerances need to be taken into account for lift arrangements that are close to the stability limit.

New slings

Fabrication length tolerance for new-built cable-laid wire rope products can be found in IMCA LR008 M179. This document states that the length tolerance on slings and grommets is +/- 1.5 d (where d is the sling/grommet diameter), and the difference in length between sling/grommets of matched pairs does not exceed 0.5 d.

Fabrication length tolerance for high-performance fibre slings should be discussed at the time of RFQ (at specific load, combined with specific hardware, pre-stretched) reference is made to IMCA LR009 M237.

Existing slings

Length tolerance for existing slings or grommets might need to be considered depending on the amount of use of the sling/grommet since the last length measurement.

Sling stiffness

Sling/grommet stiffness can also influence the tilt of the lifted object, especially when slings are not loaded equally (not elongated to the same extent).

For critical cases, a properly documented sling/grommet stiffness (E-modulus) or a conservative (low) E-modulus should be applied/assumed. For steel slings/grommets, the default stiffnesses indicated in DNV-ST-N001 Sec. 16.2.6, and shown in the table below, may normally be applied.

TABLE 2

Typical sling stiffness

Type of sling	Area [mm²]	Stiffness EA [N]
Single laid wire rope sling	$\frac{\pi}{4}d^2$	$80{,}000\frac{\pi}{4}d^2$
Cable-laid wire rope sling	$\frac{\pi}{4}d^2$	$25{,}000\frac{\pi}{4}d^2$
Cable-laid wire rope grommet	$\frac{\pi}{2}d^2$	$25{,}000\frac{\pi}{2}d^2$

The deflection of the lifted object (angular rotation) at the lift point location alters the angle between the sling and the bearing surface and can influence the stability of the friction-based lift points.

This effect may be relevant for long and slender cargo with small stiffness.

Belt materials

The contact material of a sling determines the static friction coefficient and thus, the maximum allowable tilt and/or sliding angle (equivalent to a maximum allowable lateral force at the lift point) of a given rigging arrangement. For different sling and sling protection materials, the respective static friction coefficient can vary significantly. Reliable information might be given by the manufacturer of slings. Special caution is required when using greased steel wire grommets because the friction coefficient cannot be reliably determined and approaches zero. For synthetic slings, a non-representative test shows static friction factors ranging from 0.03 to 0.15 depending on sling force, belt material, cargo coatings, temperature and wet/dry/dirty condition. In doubt, a low-end value of the range shall be chosen.

Friction-dependent lift points (FDLP) vs. fixed lift points (FLP)

As soon as the failure point of a lift point depends on the friction between lifting equipment and cargo, or between lifting equipment components, it is a 'friction-dependent lift point'. It must be noted that the friction is needed to keep the lifting equipment in its intended position. The lifting force itself is not transferred by friction (at least not in the heavy lift sector).

A typical friction-dependent lift point is a sling, slung around an object.

In cases where the friction between lifting equipment and cargo has no influence on the failure point or the capacity of the lifting equipment to stay in its position it is a 'fixed lifting point'.

A typical 'fixed lifting point' is a pad-eye with a shackle. The rigging arrangement can be attached to the lifted object by means of various types of connections. Basically, these connections can be categorized as either fixed or friction-dependent lifting points.

Fixed lifting points mounted on lifted objects physically restrain the attached rigging from any translations. Only rotations are allowed between lifting point and rigging. Typical examples are shackles through pad-eyes mounted on cargo. Or grommets around trunnions or hubs.

Friction-dependent lifting points do not have physical constraints with respect to shifting of rigging. The stability of the rigging solely depends on the static friction between cargo and rigging. For example, this is the case when using lifting beams to support cargo during lifting operations. Or lifting belts applied under cargo, as typically used when lifting floating equipment such as yachts and tugs. The friction force depends on the cargo shape, the types of material, the roughness of the two surfaces, and the presence of intermediate lubricant layers (i.e. dry/wet surface).

Types of lifting points

Fixed lift points

In the case of fixed lift points, the accuracy of the location is high (within 10 to 15 mm from planned location). It is common practice to predefine the lift point location on lift and/or fabrication drawings. During and after fabrication or installation of the lift points it is highly recommended to perform inspections to confirm the as-built/as-installed locations (accuracy within 1 mm). Any inaccuracies can be measured, and it is possible to adopt the lift arrangement if required.

Friction-dependent lift points

With respect to friction-dependent lift points there are some items which should be taken into account.

To install the rigging at the exact required location as prescribed by the lift plan can be cumbersome, especially with heavy and stiff slings. Therefore, an offset can quite easily be observed. To avoid large offsets/inaccuracies, it is recommended to indicate lift point locations on the object itself.

When a friction-dependent lift point is used, and the sling is planned to be perpendicular to the bearing surface, sliding of the sling will occur when friction is overcome due to tilt of the lift object. Due to this, the lift point location will alter and, in some cases, might not find a new equilibrium position that stops the sliding (unstable lift).

When a friction-dependent lift point is used and the sling is not planned to be perpendicular to the bearing surface, friction is then required to keep the sling in the planned location. The friction needs to be sufficient to resist the above load and take the load from possible tilt.

Other aspects to be considered

Lift point location

The actual lift point location can have an influence on the stability of lift, depending on the type of lift point.

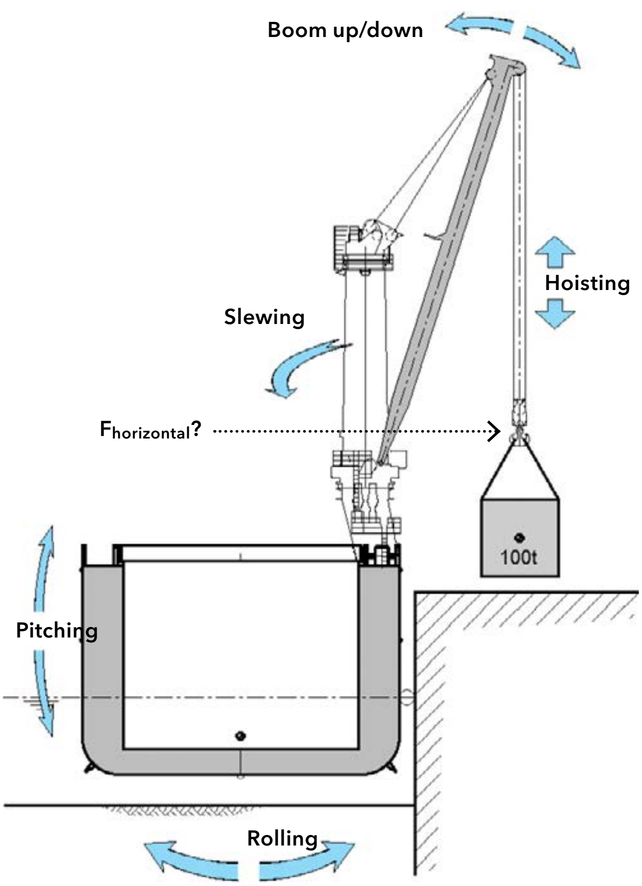
CoG position

The position of the CoG is essential information for designing a rigging arrangement and assessing its stability. However, despite its importance, the CoG position is afflicted with inaccuracies that can be significant – especially for complex structures. Often, therefore, an envelope is given, describing the most extreme possible/expected positions of the CoG. While the CoG position in the lateral plane can be determined by weighing the structure, it is not practically possible to measure the vertical position of the CoG. It is recommendable to choose the highest and therefore most unfavourable CoG position for the stability assessment.

Furthermore, it must be considered that liquids with free surfaces inside the lifted cargo, e.g. fuel or water tanks, can cause a shift of the CoG (usually to the wrong direction...).

FIGURE 11

Vessel and crane motions



Dynamic effects

Vessel motions

- Pitching
- Rolling

Crane movements

- Slewing
- Booming up and down
- Hoisting

For stability of the lift, the effect of the horizontal loads resulting from all these movements needs to be considered.

For the crane movement, the hoisting up/down will not have an effect on the stability of the lift unless there is a tandem lift. This can be overcome with the tilt factor described by DNV. Both the slewing and booming up/down movements can be translated into accelerations from which a horizontal force component can be calculated. For the movement of the ship, it seems more complicated. If the pendulum time of the lifted object is larger compared to the pendulum time of the ship's movement it will increase the motion of the lifted object. This needs to be investigated with a dynamic analysis software.

Final remark

The figures for inclinations and sling loads can be negligibly small but shall not obscure the fact that in reality, excessively higher values may occur for short periods. Short-term unsteadiness of wind may produce oscillations of the suspension with amplitudes exceeding the static figures by factor 1.5 or more, easily. Wind gusts of BFT 5, which may come within a BFT 4 steady wind, may increase these figures even further. Another effect may be the build-up of oscillations by resonance between the coupled mechanical systems of vessel, crane tackle, suspension arrangement, and cargo unit. Thus, it will be wise to at least double the result figures for using them in a risk assessment.

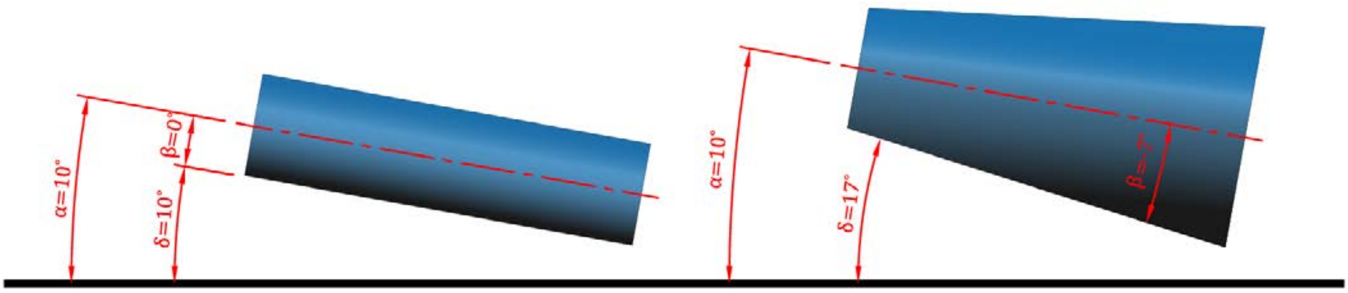
Calculation of sliding and effective inclination angles

The sliding angle is a useful property of a lifting arrangement with friction-dependent lift points (FDLP). It describes, at which inclination α of the lifted cargo it starts to slide. It depends on the friction factor of the materials in use, but also on the shape of the contact surface. For instance, the effective inclination angle of a belly-slung cylindrical object is significantly different for a conical section.

Figure 12 illustrates how the effective inclination angle δ for a cylindrical cargo is equal to its tilt angle α. For conical or uneven cargoes, the effective inclination angle is dependent on the tilt angle α but also on the cone/surface angle β. It can also be seen that the effective inclination angle can be significantly higher than the object tilt α - or can even have a different sign to the tilt angle α for certain cone/surface angles β. The following given formulas can be used to calculate theoretical sliding angles for standard cases. It must be kept in mind that friction coefficients can vary significantly; assumptions should be made conservatively.

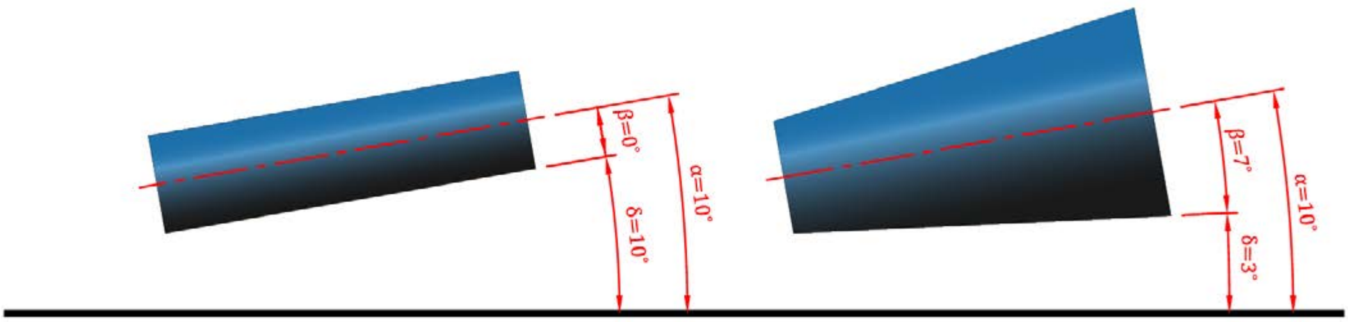
FIGURE 12

Inclination angles for cylindrical and conical objects



$$\delta = \alpha - \beta$$
$$\delta = 10° - 0°$$
$$\delta = 10°$$

$$\delta = \alpha - \beta$$
$$\delta = 10° - (-7°)$$
$$\delta = 17°$$



α = tilt angle
β = cone/surface angle
δ = Effective inclination angle

$$\delta = \alpha - \beta$$
$$\delta = 10° - 0°$$
$$\delta = 10°$$

$$\delta = \alpha - \beta$$
$$\delta = 10° - 7°$$
$$\delta = 3°$$

Flat top

FIGURE 13

Lifting arrangement of a box on a flat rack

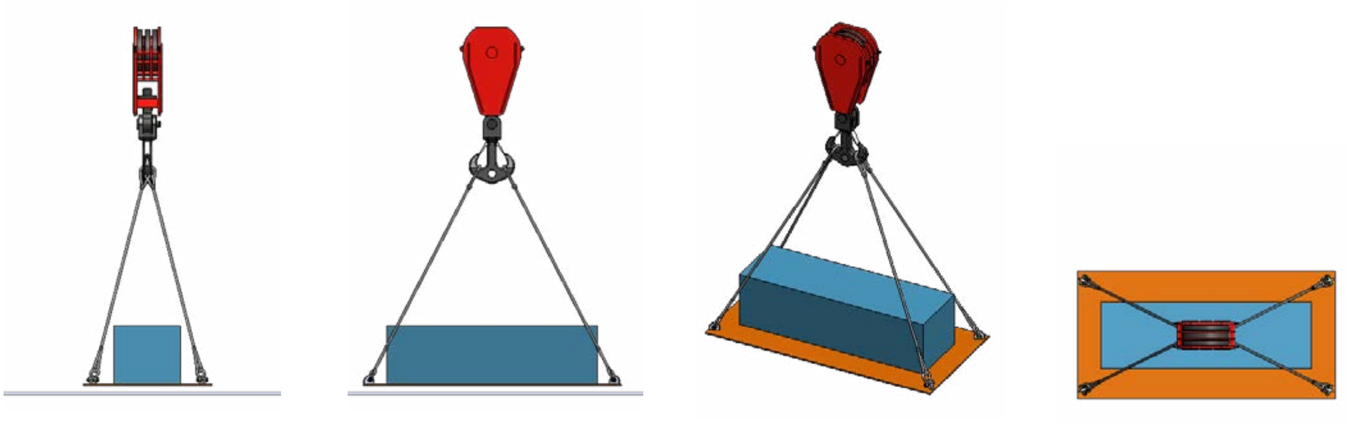
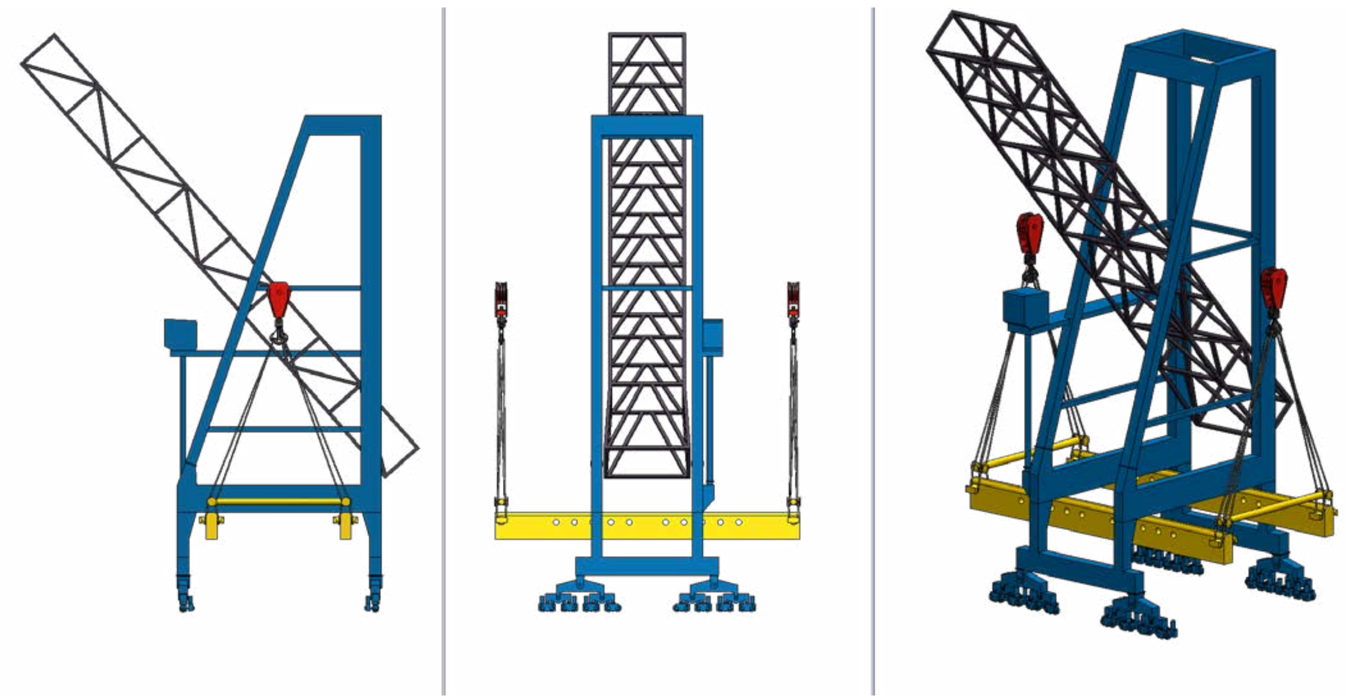


FIGURE 14

Lifting arrangement of a crane



Sliding occurs if the downhill force is larger than the friction force in normal direction.

With
m = mass [t]
g = gravitational acceleration to 9.81 [m/s²]
μ = friction coefficient [-] (depending on surfaces of cargo and the material of supporting structure)

The formula results to:

$$m \cdot g \cdot \sin(\alpha) > m \cdot g \cdot \mu \cdot \cos(\alpha)$$

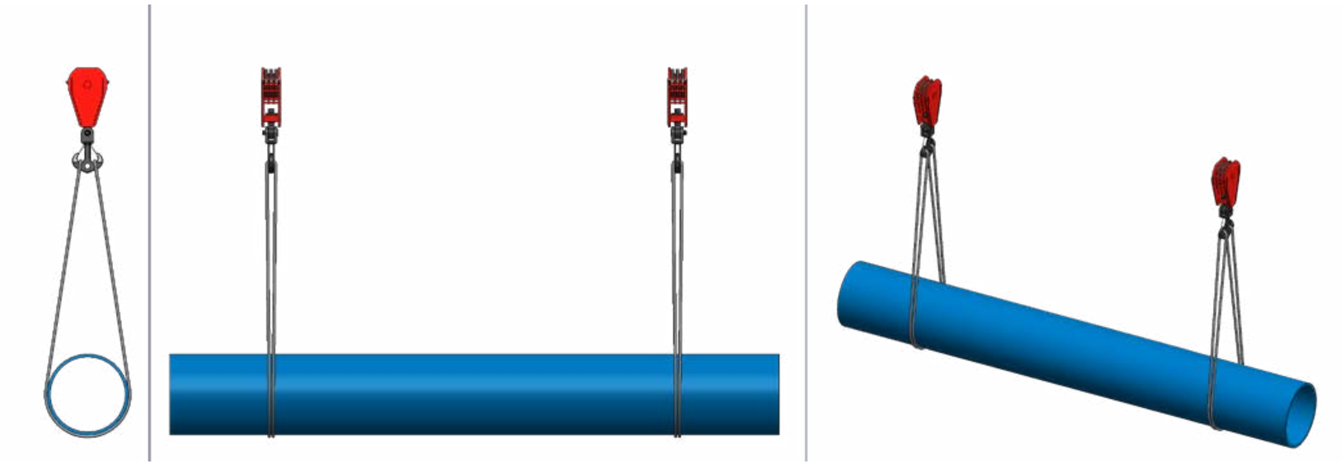
The maximum inclination below which sliding of the cargo does not occur is determined by:

$$\alpha_{\max} = \arctan(\mu)$$

Cylindrical

FIGURE 15

Cylindrical pile in tandem lift



For the lifting stability of a cylindrical object, the geometry of the object needs to be considered as the friction force is dependent on the wrap-around angle γ of the sling around the object. The wrap around angle is determined by the addition of the sling angle ϕ where the sling is in full contact with the cylinder. With the angle of contact usually being 90°, the formula appears as:

$$\gamma = (90\,° + \phi) \cdot 2$$

Furthermore, the wrap around angle is translated into the arc length l, which is needed to calculate the total load in the slings.

$$l = \frac{U}{360} \cdot \gamma$$

For the total load it is necessary to additionally determine the line load, which consists of the sling load divided by the cargo diameter. The total load is assumed to be equally divided into the 4 slings. The sling load is calculated as known with the mass, gravitational acceleration and the sling angle. With the mentioned components, the formula for the sling load F_S, the line load F_L and total load F_T for each hook of a tandem lift result to:

$$F_S = \frac{\frac{F_G}{4}}{\cos(\phi)}$$

$$F_L = \frac{2 \cdot F_S}{d}$$

$$F_T = F_L \cdot l$$

The friction force is then calculated by multiplying the total load with the friction coefficient as well as the inclination, which results in the formula:

$$F_{R,i} = F_T \cdot \mu_i \cdot \cos(\alpha)$$

The force is then compared to the downhill force, as sliding will not occur if the friction force is larger than the downhill force. The downhill force is calculated in the same manner as for the previous case. Finally, the maximum inclination angle below which sliding does not occur is determined by:

$$\alpha_{max,i} = \arctan\left(\frac{F_{R,i}}{F_G}\right)$$

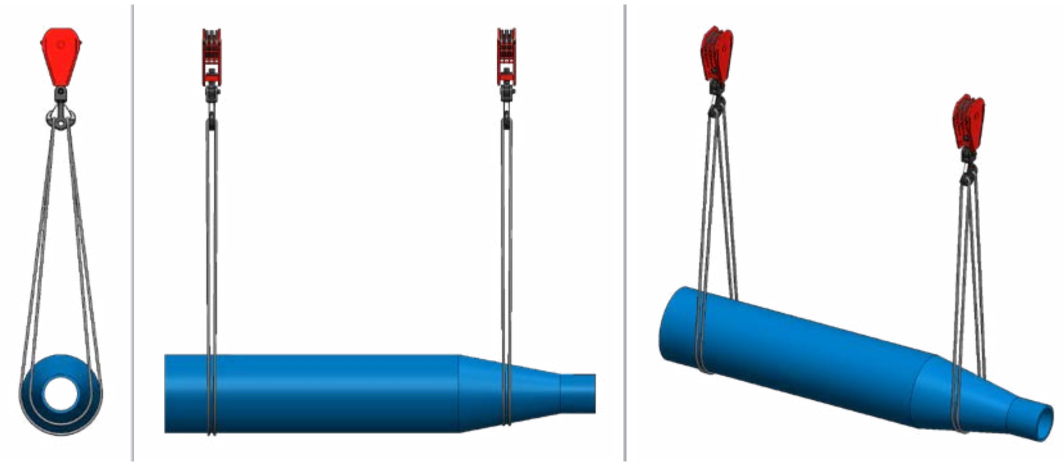
Overall, the stability is at risk if the inclination angle is larger that just one of the maximum inclination angles derived from the slings. Similarly, sliding occurs if the normal force is larger than only one of the resulting friction forces between cargo and sling.

With γ = wrap-around angle [°]
ϕ = sling angle [°] e.g. of primary rigging directly on the hook
μ_i = friction coefficient for the sling i of the rigging [-]
α = inclination angle [°]
$\alpha_{max,i}$ = maximum inclination angle for sling i [°]
d = pipe diameter [m]
F_G = weight force [kN]
F_L = line load [kN/m]
F_T = total load [kN]
l = arc length [m]
U = circumference [m] U= π*d

Conical

FIGURE 16

Partly conically shaped pile in tandem lift



In case of a conical section within a cylindrical object as shown in Figure 16, the cone angle is subtracted from the tilt angle according to the nomenclature in the beginning of chapter. (see figure 12). Hereby, the resulting inclination angle results to:

$$\delta = \alpha - \beta$$

The maximum inclination angle $\alpha_{max,i}$ is again calculated as mentioned previously. Additionally, the maximum sliding angle for the section i is determined by subtracting the cone angle from the maximum inclination angle.

$$\delta_{\mathrm{max,i}} = \alpha_{\mathrm{max,i}} - \beta$$

Sliding then occurs if one of the sections maximum sliding angles are exceeded:

$$\alpha > \alpha_{\mathrm{max,1}} \quad \text{or} \quad \alpha_{\mathrm{max,2}}$$

Friction forces are determined by multiplying the total force with the friction coefficient of the section and the inclination angle, which, when inserting the new angle α, results to:

$$\mathrm{F_{R,i}} = \mathrm{F_T} \cdot \mu_{\mathrm{i}} \cdot \cos(\alpha)$$

Respectively, this procedure is applied to the downhill force, resulting in the following formula:

$$\mathrm{F_H} = m \cdot \mathrm{g} \cdot \sin(\alpha)$$

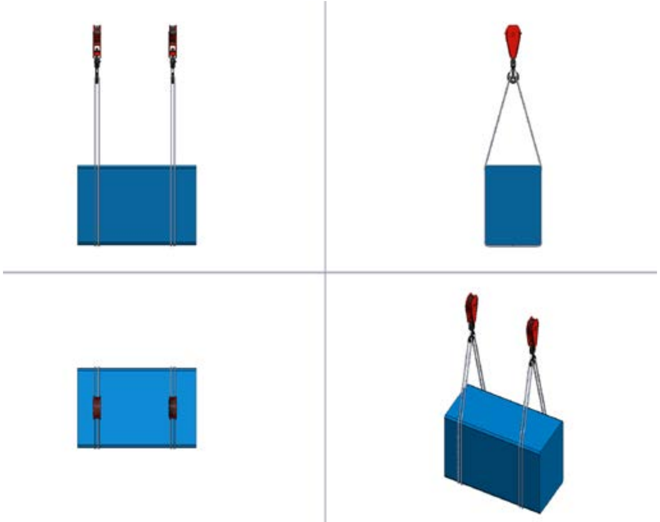
Again, sliding occurs if the downhill force is greater than the frictions force of either section 1 or 2:

$$\mathrm{F_H} > \mathrm{F_{R,1}} \quad \text{or} \quad \mathrm{F_{R,2}}$$

Box

FIGURE 17

Box in belly slings in a tandem lift



The forces in the slings are calculated by including the contact length between the sling and the object lc which is defined by:

$$l_C = 2 \cdot h + b$$

When using a spreader bar, h=0 should be considered. For small angles ϕ, the effect of friction on the sides of a box becomes small. This should be considered by assuming h=0. The line load and the sling load are calculated as follows:

$$F = \frac{2 \cdot F_S}{b} \qquad F_S = \frac{F_G}{4}$$

So that the total load results in the line load multiplied by the length:

$$F_T = F_L \cdot l_C$$

The friction force is then calculated with the friction coefficient dependent on the surface material of the object and the slings:

$$F_{R,i} = F_T \cdot \mu_i \cdot \cos(\alpha)$$

Following the calculations, the forces of friction and downhill are compared. Sliding occurs if one of the friction forces from the slings is smaller than the downhill force F_H.

$$F_H > F_{R,1} \quad \text{or} \quad F_{R,2}$$

The maximum inclination angle is calculated with the help of the friction forces and the force resulting from the cargo load:

$$\alpha_{max,i} = \arctan\left(\frac{F_{R,i}}{F_G}\right)$$

For the determination of sliding depending on the inclination angle the max. inclination angles for each sling are then compared to actual inclination angle. Sliding does occur if one of the maximum angles is exceeded.

$$\alpha > \alpha_{max,1} \quad \text{or} \quad \alpha_{max,2}$$

With h = height of the object [m]
b = breadth/width of the object [m]
l_c = contact length [m]

Other (hull shapes)

For other cases, e.g. hull shapes, no analytical formula applies.

FIGURE 18

Ship in belly slings

Calculation examples

Calculation example 1.1: Comparison of Virtual CoG method and Kaps method

FIGURE 19

Example rigging with vertical secondary suspension

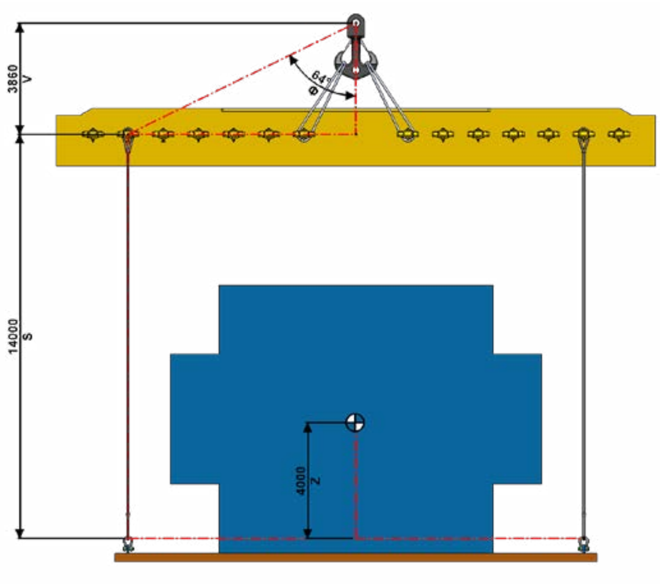
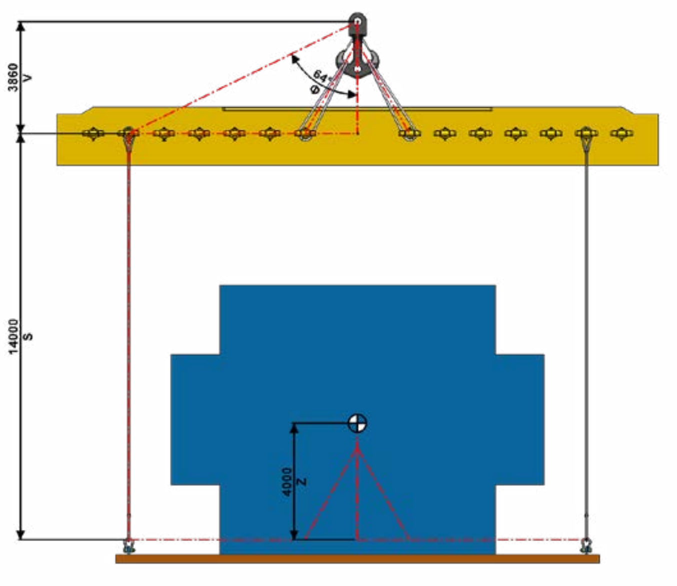


FIGURE 20

Example rigging with vertical secondary suspension and Virtual-CoG-triangle



In the following a comparison of the virtual CoG method and the Kaps method is shown. To illustrate the risk of relying on only one method (Virtual CoG method as the easiest one) a rigging is chosen, where one method shows sufficient stability while the other does not. The reason for that lies in certain assumptions and simplifications that are made and result in a neglect of geometrical details, which influence the stability calculations.

The rigging shown above is checked for lifting stability with both methods for the following values.

Symbol	Value
v	3.86 m
s	14.00 m
z	4.00 m
Φ	64 °
γ	0 °
Mass cargo mc	250 t
Mass traverse mT	50 t

The Virtual CoG concept uses only the primary rigging height v and the CoG height z to calculate the metacentric height of the rigging arrangement. The length and angle of the secondary rigging, as well as the cargo and traverse masses, are neglected. The following figure 20 illustrates the 'projection' of the primary rigging onto the baseline of the lifting points. As a rule-of-thumb, the Virtual CoG method classifies a rigging arrangement as stable when the CoG is located within the red triangle.

The effect of these simplifications becomes clear in the following comparison.

Results of Virtual CoG method

The calculation of the metacentric height with the Virtual CoG method results in a negative value of:

$$h = v - z = 3.86\ m - 4.00\ m = -0.14\ m$$

which leads to the conclusion to not lift the cargo with this rigging.

Results of Kaps method

The calculation with the Kaps method gives:

$$h = s \cdot (1 - c) + \nu \cdot \left(1 + \frac{m_T}{m_C}\right) - z \cdot \left(1 - \frac{c \cdot s \cdot \tan\gamma}{\nu \cdot \tan\varphi + s \cdot \tan\gamma}\right) = 0.63\ \mathrm{m}$$

with

$$c = \cos^2\gamma - \left(1 + \left(\frac{m_T}{m_C}\right) \cdot \frac{\sin\gamma \cdot \cos\gamma}{\tan\varphi}\right)$$

which leads to the conclusion that the lift potentially can be done.

Results after conducting stability-increasing measures

If one wants to follow the recommended measures to increase the lifting stability, the easiest way is to increase the secondary sling angle by rigging the secondary slings closer to the centre of the suspension. This results in an increased γ, a decreased φ, and a negligible decrease of *s* (due to the increase of γ) which is illustrated in following figure.

The small change in the rigging arrangement leads to the following values:

Symbol	Value
v	3.86 m
s	13.95 m
z	4.00 m
Φ	60 °
γ	5 °
Mass cargo *mc*	250 t
Mass traverse *mT*	50 t

This results in an increased metacentric height of h = 2.15m without changing any components of the rigging arrangement, calculated with the Kaps method. The Virtual CoG method cannot be used for an inclined secondary rigging.

The usage of two different methods can lead to drastically different results, as the following table shows:

Method used	Metacentric height	Stable?
Virtual CoG	-0.14m	No
Kaps	0.63m	Yes, but might be fragile
Kaps with stability-increasing measures	2.15m	Yes

Calculation example 1.2: Comparison of Kaps method and Nikitin method

As presented the usage of different methods can lead to significantly different results. Thus, the Kaps method will also be compared to the Nikitin method. For the calculation the following rigging is introduced.

The values taken for the comparison can be obtained from following table.

FIGURE 21

Example rigging with outwards-inclined secondary suspension

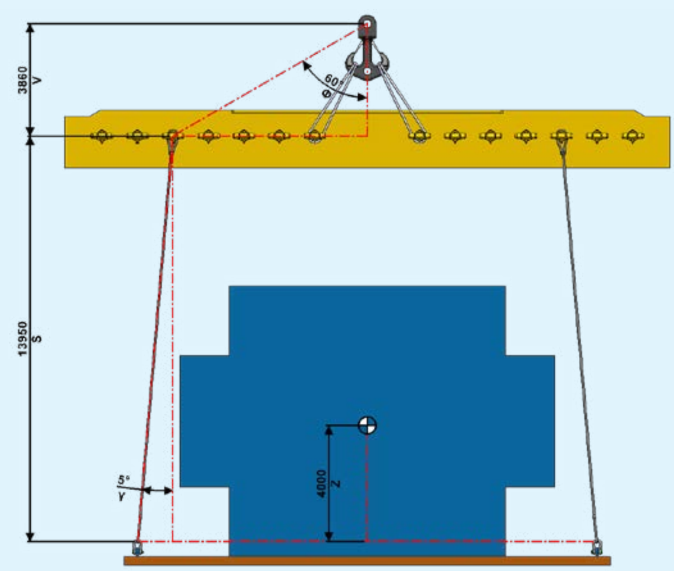
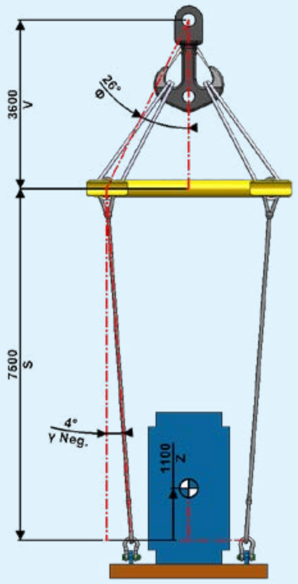


FIGURE 22

Example rigging for inwards-inclined secondary suspension comparing the Kaps and Nikitin methods



Symbol	Value		
Case	I	II	III
v	3.60 m	3.60 m	3.60 m
s	7.50 m	7.50 m	7.50 m
z	1.10 m	1.10 m	1.10 m
Φ	26 °	26 °	26 °
γ	0 °	4 °	-4 °
Mass cargo mc	60 t	60 t	60 t
Mass traverse mT	2 t	2 t	2 t

In general, there are three different cases regarding the secondary suspension that must be evaluated. These are

- Case I:
  straight secondary suspensions with γ = 0 °, outwards
- Case II:
  inclined secondary suspensions with γ > 0 °, and inwards
- Case III:
  inclined secondary suspensions with γ < 0 °.

For Case I the reduction of the vertical distance s caused by the inclination γ is small and neglectable.

Vertical secondary suspensions
Case I: $\gamma = 0°$

For the calculation with the Kaps method, the metacentric height is calculated as before and results in:

$$h = s \cdot (1 - c) + v \cdot \left(1 + \frac{m_T}{m_C}\right) - z \cdot \left(1 - \frac{c \cdot s \cdot \tan\,\gamma}{v \cdot \tan\,\varphi + s \cdot \tan\,\gamma}\right) = 2.62\ m$$

with

$$c = \cos^2\,\gamma - \left(1 + \frac{m_T}{m_C}\right) \cdot \frac{\sin\,\gamma \cdot \cos\,\gamma}{\tan\varphi}$$

The calculation with the Nikitin method requires few more formulas and results in the three values αm – overturning angle of the rigging arrangement, zm – height of the SST, and ym – width of the SST at the given CoG. Analogously to the Kaps method, the distance $zm - zCoG$ between the height of the SST and the height of the CoG is equivalent to the metacentric height h and represents a measure for the response of the system to a disturbance. The formulas are:

$$AB = 2 \cdot v \cdot \tan(\varphi) = 3.51\ m$$

Where AB is the distance between the suspension point (usually the crane hook swivel point) and the primary lift point on the traverse.

The metacentric height h is equal to the result from the Kaps method:

$$h = z_m - z_{CoG} = 3.72\ m - 1.10\ m = 2.62\ m$$

The metacentric height h is equal to the result from the Kaps method:

$$z_m = \left(\frac{m_t}{m_c} + 1\right) \cdot v = 3.72\ m$$

$$y_m = \frac{AB}{2} \cdot \left(1 - \frac{z}{v \cdot \left(\frac{m_t}{m_c} + 1\right)}\right) = 1.23\ m$$

$$\alpha_m = \arctan\left(\frac{y_m}{v \cdot \left(\frac{m_t}{m_c} + 1\right) - z}\right) = 25.3°$$

Outwards inclined secondary suspensions
Case II: $\gamma > 0°$

For the calculation with the Kaps method, the metacentric height is calculated as before and results in:

$$h = s \cdot (1 - c) + v \cdot \left(1 + \frac{m_T}{m_C}\right) - z \cdot \left(1 - \frac{c \cdot s \cdot \tan\gamma}{v \cdot \tan\varphi + s \cdot \tan\gamma}\right) = 3.97\ m$$

The calculation with the Nikitin method again requires additional formulas and results in the following:

$$z_m = \frac{CD}{2} \cdot \tan(\theta_2) = 6.17\ m$$

$$y_m = \left(1 - \frac{z}{z_m}\right) \cdot \frac{CD}{2} = 1.87\ m$$

$$\alpha_m = \arctan\left(\frac{\tan(\varphi)}{\frac{m_t}{m_c} + 1}\right) = 25.3°$$

with:

$$CD = AB + 2 \cdot r \cdot \sin(\gamma) = 4.56\ m$$

$$AB = 2 \cdot v \cdot tan(\varphi) = 3.51\ m$$

$$r = \frac{s}{\cos(\gamma)} = 7.52\ m$$

$$\theta_2 = \theta_{21} + \theta_{22} = 19.4° + 50.3° = 69.7°$$

$$\theta_{21} = \frac{\pi}{4} - \frac{\alpha_{m2}}{2} + \arctan\left(\frac{AB - r}{\mathrm{AB} + \mathrm{r}} \cdot \frac{1}{\tan\left(\frac{\alpha_{m2}}{2} + \frac{\pi}{4}\right)}\right) = 19.4°$$

$$\theta_{22} = 2 \cdot \arctan\left(\frac{m_\theta}{F_\theta - r}\right) = 50.3°$$

$$\alpha_{m2} = \arctan\left(\frac{\tan(\varphi)}{\frac{m_t}{m_c} + 1}\right) = 25.3°$$

$$m_\theta = \sqrt{\frac{(F_\theta - CB) \cdot (F_\theta - r) \cdot (F_\theta - CD)}{F_\theta}} = 1.56\ m$$

$$F_\theta = 0.5 \cdot (\mathrm{CB} + \mathrm{r} + \mathrm{CD}) = 10.82\ m$$

$$CB = AB \cdot \frac{\cos(\alpha_{m2})}{\sin(\theta_{21})} = 9.56\ m$$

The distance $zm - zCoG$ = 6.17 m − 1.10 m = 5.07 m is for outwards inclined secondary suspensions higher than the metacentric height h of the Kaps method with h = 3.97 m. This means the Nikitin method indicates a more 'robust' system regarding disturbances. Or one could say the Kaps method is here the more conservative approach.

Inwards inclined secondary suspensions
Case III: $\gamma < 0°$

For the calculation with the Kaps method, the metacentric height is calculated as before:

$$h = s \cdot (1 - c) + v \cdot \left(1 + \frac{m_T}{m_C}\right) - z \cdot \left(1 - \frac{c \cdot s \cdot \tan\gamma}{v \cdot \tan\varphi + s \cdot \tan\gamma}\right) = 1.02\ m$$

The calculation with the Nikitin method now requires an additional differentiation for the conditions $\chi > \varphi$ or $\chi < \varphi$. For the given example the condition $\chi > \varphi$ is true and therefore Case III-b gives the results for zm, ym and αm.

Case III-a:
$\gamma < 0°$ and $\chi < \varphi$

Again, additional formulas are used as per following:

$$z_m = \frac{CD}{2} \cdot \tan(\theta)$$

$$y_m = \left(1 - \frac{z}{z_m}\right) \cdot \frac{CD}{2}$$

$$\alpha_m = \frac{\pi}{4} - \frac{\varepsilon}{2} + \arctan\left(\frac{ER - v}{ER + v} \cdot \frac{1}{\tan\left(\frac{\varepsilon}{2} + \frac{\pi}{4}\right)}\right)$$

with:

$$CD = AB + 2 \cdot r \cdot \sin(\gamma)$$

$$AB = 2 \cdot v \cdot ta\,n(\varphi)$$

$$r = \frac{s}{\cos(\gamma)}$$

$$F_\chi = 0.5 \cdot (AB + 2 \cdot r + CD)$$

$$m_\chi = \sqrt{\frac{(F_\chi - AB) \cdot (F_\chi - r) \cdot (F_\chi - CD - r)}{F_\chi}}$$

$$\chi = 2 \cdot arctan\left(\frac{m_\chi}{(F_\chi - CD - r)}\right) - \frac{\pi}{2} = 35.6° > \varphi = 26°$$

$$\omega = 2 \cdot \arctan\left(\frac{m_\chi}{F_\chi - r}\right)$$

$$\varepsilon = \frac{\pi}{4} - \frac{\chi}{2} + \mathrm{arcta\,n}\left(\frac{r - 0.5 \cdot AB}{r + 0.5 \cdot AB} \cdot \frac{1}{\tan\left(\frac{\chi}{2} + \frac{\pi}{4}\right)}\right)$$

$$ER = \frac{r \cdot \mathrm{co\,s}(\chi)}{\left(1 + \frac{m_t}{m_c}\right) \cdot \sin(\varepsilon)}$$

$$\theta = \pi - (\alpha_m + \varphi) - \left(\omega + \left(\frac{\pi}{2} - \varphi\right)\right)$$

Case III-b:
$\gamma < 0°$ and $\chi > \varphi$

For the condition $\chi > \varphi$ (as given in this example) the same formulas:

$$z_m = \frac{CD}{2} \cdot \tan(\theta_2) = 1.42\ m$$

$$y_m = \left(1 - \frac{z}{z_m}\right) \cdot \frac{CD}{2} = 0.28\ m$$

$$\alpha_m = \arctan\left(\frac{\tan(\varphi)}{\frac{m_t}{m_c} + 1}\right) = 25.3°$$

The distance $zm - zCoG$ = 1.42 m − 1.10 m = 0.32 m is for inwards inclined secondary suspensions lower than the metacentric height h of the Kaps method with h = 1.02 m. This means the Nikitin method indicates a much less 'robust' system regarding disturbances. The Kaps method is here the much less conservative approach.

As the above results indicate, the Kaps method seems to underestimate the stability of rigging arrangements with outwards inclined secondary suspensions. On the other hand, it overestimates the stability of rigging arrangements with inwards inclined secondary suspensions. In the respective case, the more conservative approach should be used, or results should be double-checked with the other method. For vertical secondary suspensions both methods yield identical results.

References

Stability of cargo suspension arrangements
Prof. Capt. Hermann Kaps (2013)

DNV-ST-N001 (2023-December)
Marine operations and marine warranty

DNV-RP-C205 (2021-September)
Environmental conditions and environmental loads

IMCA LR008 M179 (2019-April)
Guidance on the manufacture and safe use of cable-laid slings and grommets

IMCA LR009 M237 (2024-February)
Guidance on the selection, safe use and inspection of high performance fibre slings used for engineered lifts

Static and Tip-over Stability Analysis of Tow-Chain Suspension Arrangements for Large-Scale Cargo Operations, Yevgeny V. Nikitin, WMU Journal of Maritime Affairs vol 13, pages 101-126 (2014)

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