



IALA GUIDELINE

G1099 THE HYDROSTATIC DESIGN OF BUOYS

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1. PURPOSE

The purpose of this Guideline is to provide information on the calculation of buoy stability for new buoy designs and for establishing the impact of the installation of new equipment on existing buoys. Methods of measuring these parameters on existing buoys are also explained.

2. SCOPE

This Guideline provides information on those aspects of buoy design that effect the buoyancy and stability of the buoy. The Guideline *G1066 The Design of Floating Aid to Navigation Moorings* [1] should be consulted when loads due to wind and tidal effects are being considered. It is recommended that a standard textbook on naval architecture should be consulted if the reader is not familiar with basic ship stability calculations.

The aspects of buoy design discussed in this Guideline provide the basis for designing a buoy from first principles but can also be used when considering mounting different superstructures and new equipment on existing buoys or operating existing buoys in different mooring environments.

3. INTRODUCTION

This Guideline provides information on the hydrostatic performance of conventional buoys (skirt, tailtube, ballasted spar) moored with conventional moorings (as described in Guideline *G1066* [1]). Some of the buoy types are illustrated in Figure 1.

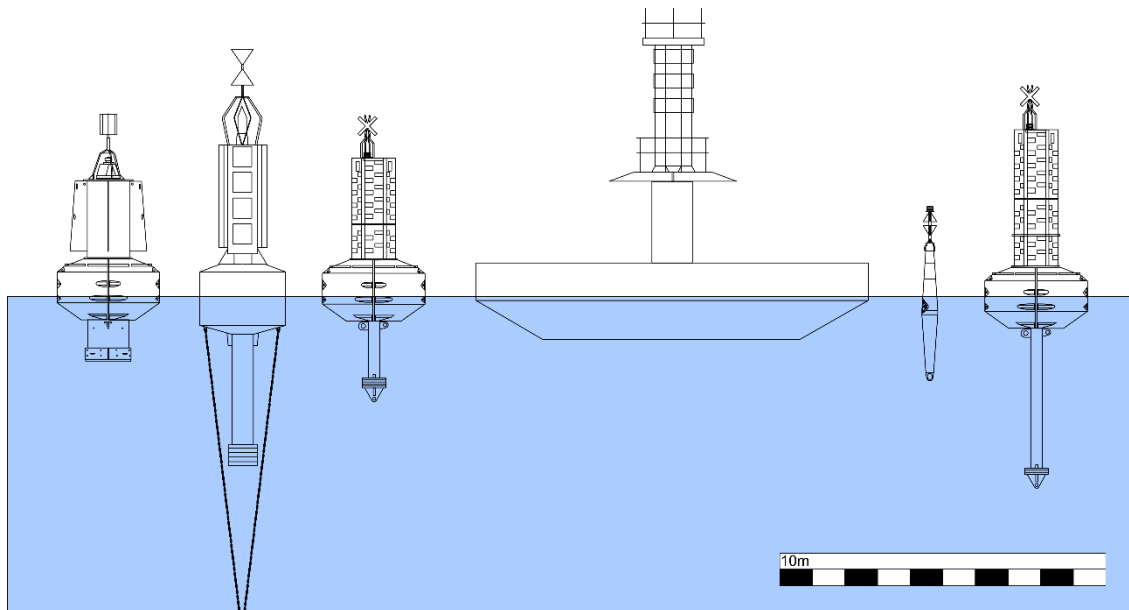


Figure 1 Buoy types (left to right: skirt, deep tail tube, short tail tube, LANBY, ballasted spar, tail tube with single mooring attachment)

The illustrations used in the Guideline are those of a tailtube buoy used in the French service. However, the principles and processes described apply to all freely floating buoys with external or internal ballast.

The stability of articulated beacons and spar buoys depends on the mooring providing sufficient vertical force to maintain the buoy in an upright position. Details of such calculations are not included. However, the information provided on displacement and centre of buoyancy are relevant to these buoy types.

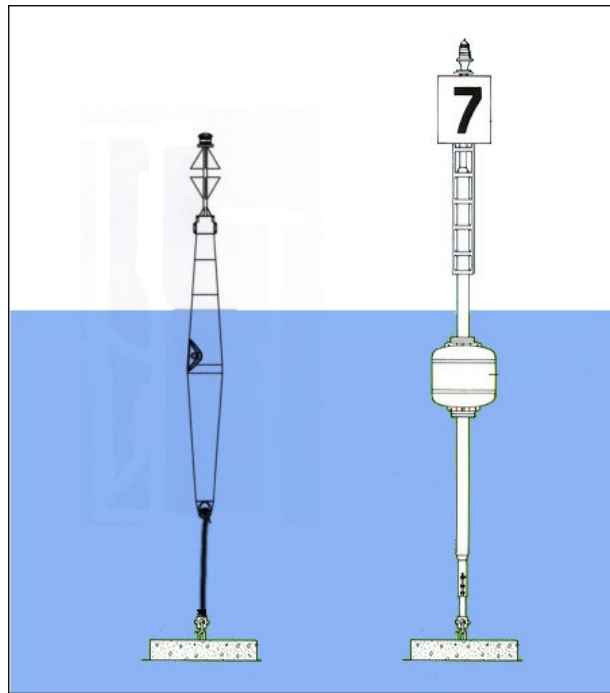


Figure 2 Spar buoy, articulated beacon

The size of the buoy and hence the size of the daymark will depend on the daytime range at which the buoy must be visible and the height of the daymark or tower will depend on the focal plane height that is required for the light or for aerial systems (see *NAVGUIDE* [2] and *Guideline G1094 Daymarks for Aids to Navigation* [3]).

4. BUOYANCY

Buoyancy is the upward vertical force provided by the immersed part of the buoy displacing a volume of water.

It is vital that the buoy will retain sufficient reserve buoyancy for all weather conditions and that the AtoN will remain effective in most weather conditions. There must be sufficient buoyancy to support the entire weight of the buoy and the moorings. If it is anticipated that maintenance personnel will work on the buoy afloat then the buoy must have sufficient reserve buoyancy and stability for this to be safely carried out. The size and hence the weight of the buoy will depend on the navigational requirements and the local environmental conditions.

In the case of buoys with several watertight compartments an authority may require the buoys to remain afloat with one or more sections of the float damaged, and no longer buoyant. Floatation calculations should then be made with the reduced number of buoyant compartments.

When there are wind forces and/or tidal flow forces acting on the buoy then these will increase the loads in the mooring and more buoyancy will be required to support the added mooring loads (See [1]).

If low temperatures are expected estimates of the weight of ice on deck and superstructure should be included in calculations. Ice forces, due to the freezing of the water surrounding the buoy, are not considered in the following calculations.

Waves will have some effect on the mooring loads and hence buoyancy requirements. Wave effects are extremely complex. However, if the waves are not breaking then the buoy will follow the water surface and there will be some increase in the buoyancy requirements in order to cope with the wave drift.

5. STABILITY

Stability measures the ability of the buoy to remain upright so that the AtoN will remain effective in most operating conditions. There are two aspects of stability that will be incorporated in the buoy design. These are form stability and weight stability.

Form stability is the stability provided by the shape of the immersed part of the buoy. In a normal cylindrical buoy the greater the diameter of the buoy the more stable it will be. An extreme example of this is the LANBY buoy which has a shallow 13-meter diameter “dish” like body. Due to its large diameter this body provides considerable stability in most situations, however in extreme conditions even this large buoy can capsize and will then be stable in an inverted position.

The centre of gravity of the buoy being in a position such that it tends to right the buoy provides weight stability. The deep tailtube buoy provides an example of this type. The ballast on the base of the tailtube provides righting forces.

Static stability calculations evaluate the combined effects of form stability and weight stability.

6. DEFINITION - UNITS – NOTATION

All units are shown according to SI-System.

6.1. MOVEMENT OF A BUOY

The following Figure 3 illustrates the various movements of a buoy. These are the definitions used in naval architecture. The horizontal centreline of a ship would correspond to the direction of the water flow past the buoy.

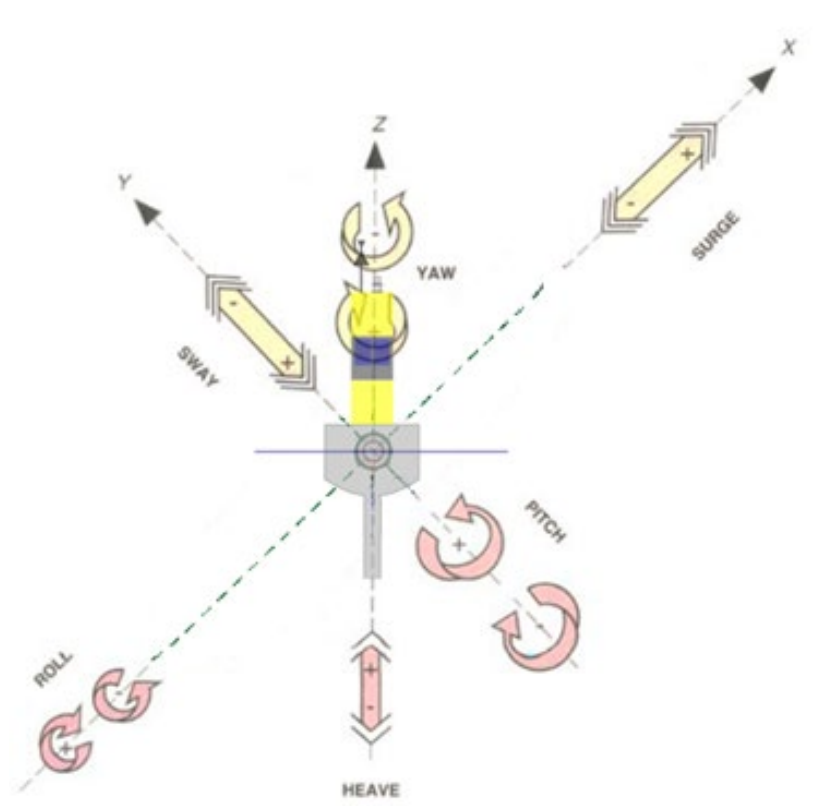


Figure 3 Description of movement of a buoy (from IALA Guideline G1065)

6.2. VOLUME

The body of the buoy forms a closed volume that provides the buoyancy of the buoy when immersed in water. The total volume is defined as V (m^3).

6.3. WATERLINE

The waterline WL_i is the horizontal line between the submerged part of the buoy and the emerged part of the buoy.

6.4. DIAMETER OF THE WATERLINE

The diameter of the waterline D (m) is the diameter of the buoy body measured at the waterline.

6.5. WATER PLANE AREA

When the buoy is in upright position, then the water plane is usually circular. Water plane area WP (m^2) is the area of the section of the float formed by the waterline.

Note:

The area of any tube passing through the float and open to the surrounding water must be subtracted from the area of the water plane.

6.6. INERTIA OF WATER PLANE

Inertia of water plane I_f (m^4) is the moment of inertia of the water plane about the axis of the centre of water plane O . It characterizes the energy needed to rotate the surface around an axis as the buoy is displaced from the vertical.

$$\text{e.g. } I^f = \frac{1}{64} \cdot \pi \cdot D^4 \text{ for circular surfaces}$$

Equation 1 Inertia of water plane

6.7. WEIGHT

Weight W is the vertical force (N) of gravity downwards, applied on the buoy. This is the summation of the mass of all the individual components multiplied by acceleration of gravity g .

$$W = m_b \cdot g = \sum_i m_i \cdot g$$

Equation 2 Weight of a buoy

where

- m_b mass of the buoy in kg
- m_i mass of each component in kg
- g acceleration of gravity in m/s^2

6.8. BUOYANCY

Buoyancy V_B (m³) is the volume of the submerged part of the buoy limited by the waterline. The buoyancy includes the body (float) and other immersed components such as skirt, mooring eyes, tailtube, external ballast etc.

6.9. DISPLACEMENT

Displacement Δ (kg) is the total volume displaced (V_B) by the buoy multiplied by the density of water.

$$\Delta = V_B \cdot \rho$$

Equation 3 Displacement of a floating buoy

where

ρ density of water in kg/m³ (see values in 6.13)

6.10. RESERVE BUOYANCY

Reserve buoyancy R (m³) is the enclosed volume of the buoy that is above the waterline. It is often expressed as a percentage of the total volume.

$$V = R + V_B$$

Equation 4 Reserve buoyancy

6.11. CENTRE OF BUOYANCY

Centre of Buoyancy B is the centroid of the displaced volume of water. It is the application point of the buoyancy forces. The position of the centroid varies with loads, roll, draft and other movements of the buoy.

6.12. BUOYANT FORCE

The buoyant force F_B (N) is the vertical force applied to the submerged portion of the buoy, due to the displacement of water.

Definition

An immersed body in a fluid undergoes a vertical force F_B directed upwards (and opposite to the weight of the displaced fluid). This is equal to the displacement Δ of the floating body (see 6.9).

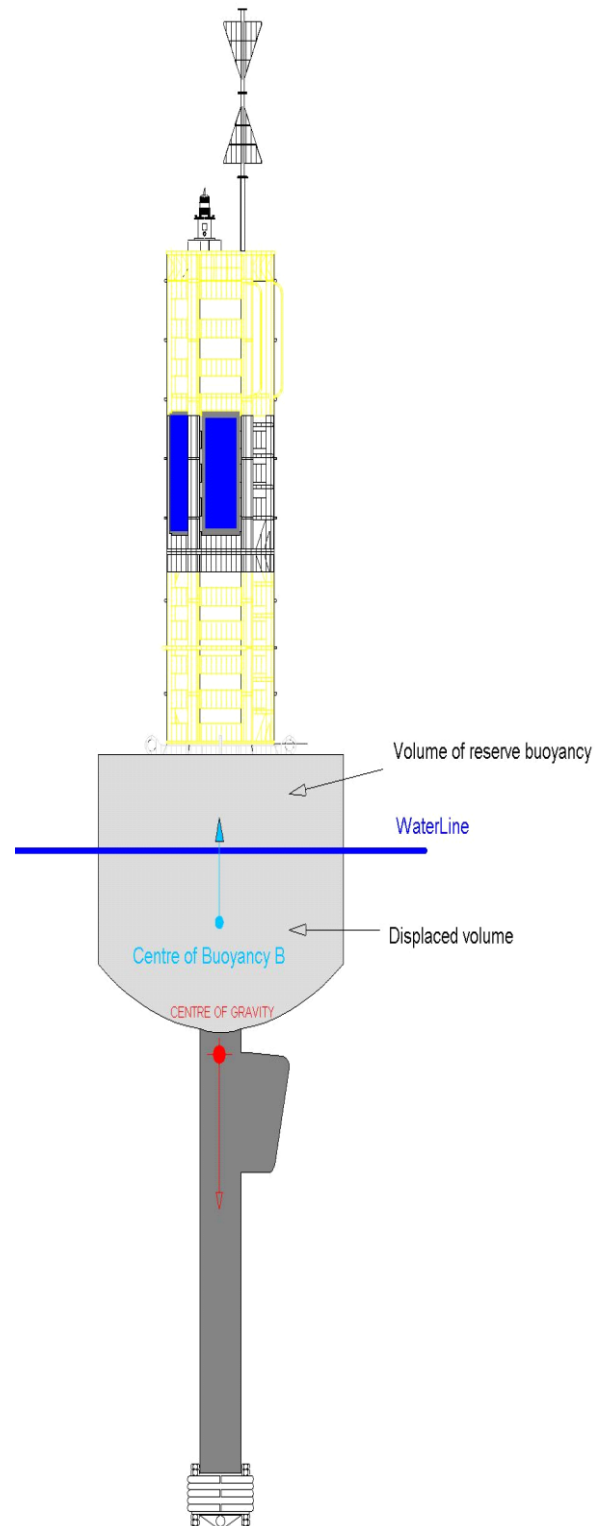


Figure 4 Centre of buoyancy

$$F_B = V_B \cdot \rho \cdot g$$

Equation 5 Buoyant force

6.13. DENSITY OF WATER

Density of water ρ depends on mainly

- Temperature
- Salinity

Typically, we retain the average values of density of seawater ρ

- North Atlantic seas at 1025 kg / m³.
- Mediterranean Sea at 1028 kg/ m³.
- Estuary waters from 1000 kg/ m³ to 1015 kg/ m³.

6.14. CENTRE OF GRAVITY

The centre of gravity G is the application point of overall weight W .

7. CALCULATIONS

The starting point for the calculations will be a detailed drawing of the buoy along with details of all the equipment to be mounted on it. The weight budget of the buoy will then be a summation of all these components. The mass of steel work, aluminium fabrications, plastic mouldings etc. can be calculated, but it is recommended that checks be made by weighing components, where this is practical.

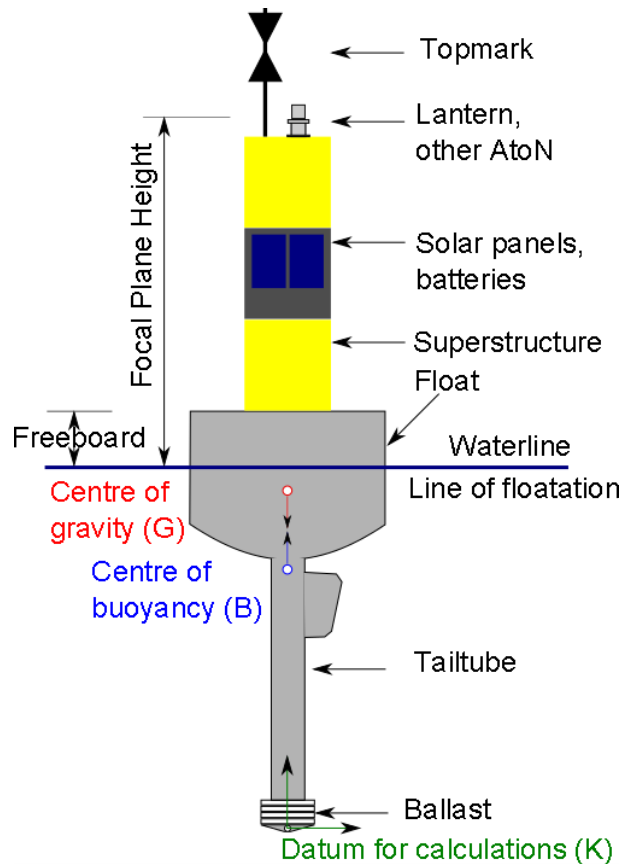


Figure 5 Centre of gravity of a buoy

7.1. CENTRE OF GRAVITY

The centre of mass, usually referred to as the centre of gravity (G), can then be established by summing the moments of each component about a chosen origin (K). As buoys are usually largely symmetrical about their vertical axis it is only necessary to take the moments in the vertical (X) axis. The origin is usually taken as the base line of the keel or skirt of the buoy. The moments are then always positive. The summation of the moments is divided by the total mass and the result is the vertical distance of the centre of gravity above the origin. All this information is usually included in the weight budget (example in annex A).

7.2. CENTRE OF BUOYANCY

The Centre of Buoyancy (B) is the centroid of the immersed volume of the buoy. It should be noted that this changes with the depth of immersion of the buoy and the angle of heel.

To calculate the position of the centre of buoyancy, the moments of the volumes of all the immersed components about the origin (same as used for Centre of Gravity) can be summed and the centre of buoyancy calculated (example in annex B).

7.3. STABILITY

WL ₀	initial waterline
WL ₁	heeled waterline
G	centre of gravity
B ₀	initial centre of Buoyancy
B ₁	heeled centre of Buoyancy
M	metacentre
GM	metacentric height
BM	metacentric radius

With the total mass (m), centre of buoyancy (B) and centre of gravity (G) being established the metacentric height (GM) can be calculated. The metacentric height provides a measurement of the righting moment of the centre of mass of the buoy relative to the centre of buoyancy.

For calculation of stability, it is usual to consider the buoy as a free floating body, i.e. without the moorings. This will usually represent the worst stability case. For small buoys the mooring may be vital for stability and the mooring weight will then have to be included in stability calculations. The weight of the mooring varies with water level and wave variations.

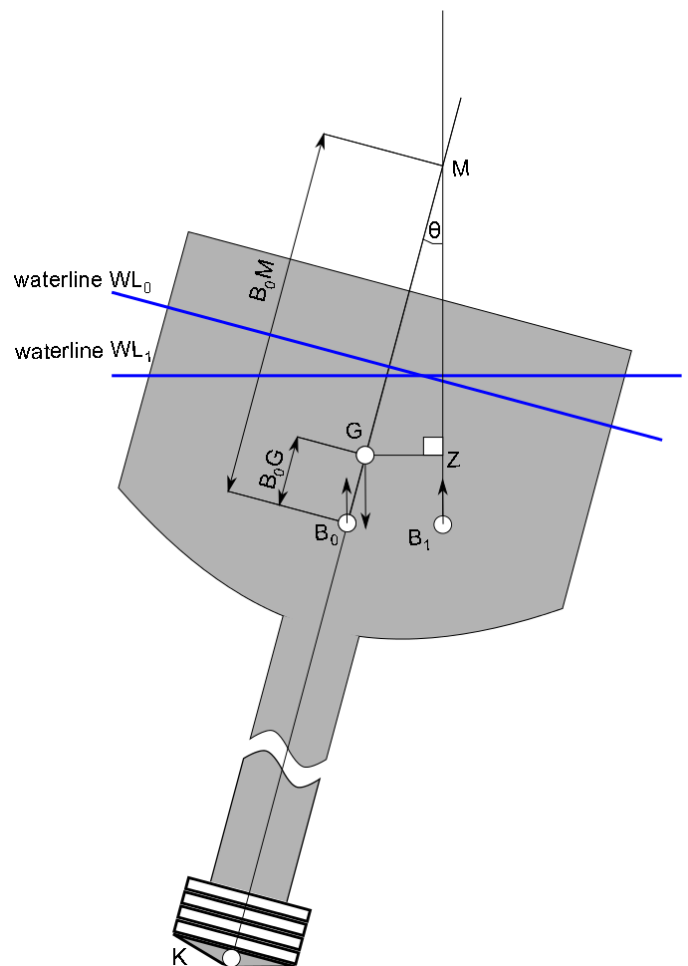


Figure 6 Metacentric height

7.4. METACENTRIC HEIGHT

GM (see Figure 6) is the metacentric height and BM is the metacentric radius. For small angles of heel the metacentric radius defines the motion of the centre of buoyancy (B) about the metacentre (M). When the angle of heel is small, M is the intersection point of the line B_0G and the vertical line passing through B_1 .

If metacentric height (GM) is positive, when the buoy is heeled it will return back to its upright position. If it is negative, then in most cases any displacement of the buoy will result in heeling further and tending to capsize.

To increase the metacentric height either the body diameter will have to be increased or, more usually, the centre of gravity (G) will have to be lowered. This can be accomplished by:

- increasing the weight of the ballast and/or placing it lower down;
- reducing the weight of the superstructure and equipment or placing them lower down.

The ideal value for the metacentric height is difficult to define. A guide of 10% of the body diameter was quoted for standard steel buoys (3 metre diameter) but this is thought to be rather small for light weight plastic buoys.

Table 1 Examples for metacentric height of plastic buoys used by various administrations

Diameter / m	Metacentric height / m	Administration
1.80	0.65	NL
2.30	0.40	F
2.45	0.50	F
2.60	0.95	NL
2.65	0.60	F
3.00	1.10	NL

If it is planned for maintenance personnel to climb the buoy superstructure then a value of the metacentric height and consequent angle of heel should be calculated with the estimated weight of personnel at the highest working point on the superstructure. This will confirm if the metacentric height remains positive in this situation i.e. the buoy remains stable with personnel on board.

7.5. MASS BUDGET AND POSITION OF THE CENTRE OF GRAVITY (G)

Before starting the calculation of stability the mass and centre of gravity must be calculated by summing all the masses of the components and equipment on the buoy and the position of the centre of gravity can then be determined.

Then we obtain the total mass m_b of the buoy and the vertical position of the centre of gravity (G) (example in 0).

7.6. DISPLACED VOLUME

The displaced volume V_B , can be calculated as follows:

The total sum of all forces is zero.

$$\sum F = 0$$

For static equilibrium the weight of the buoy minus the buoyancy is zero.

$$W - F_B = 0$$

$$(m_b \cdot g) - (V_B \cdot \rho \cdot g) = 0$$

$$V_B = \frac{m_b}{\rho}$$

Equation 6 Displaced volume

7.7. VERIFICATION OF THE BUOYANCY

This calculation ensures that the buoy does not sink. The volume of the buoyancy must be less than the total volume of the buoy.

$$V_B < V$$

The difference between V and V_B is the reserve buoyancy. This allows us to estimate the additional load that the buoy can support.

For the buoy to remain afloat the buoyancy reserve volume needs to be positive ($R_b > 0$).

7.8. POSITION OF THE CENTRE OF BUOYANCY

From the amount of buoyancy and centre of buoyancy of the float and each other immersed part of the buoy, we calculate the position of the centre of buoyancy B (example in annex B).

Note:

Most 3D-CAD drawing systems provide centres of volume of defined shapes.

7.9. RIGHTING ARM

At equilibrium the initial waterline is WL_0 . The centre of buoyancy is B_0 .

The buoy is heeled to an angle θ relative to its equilibrium position and it floats on a new waterline WL_1 . The centre of buoyancy moves from B_0 to B_1 .

M is the intersection point of the line ($B_0 G$) and the vertical line passing through B_1 . The point M is called metacentre.

The distance ($B_0 M$) is called metacentric radius.

The distance (GM) is called metacentric height.

For the angle of heel θ a righting moment noted RM occurs, such as:

$$RM = m_b \cdot g \cdot GZ$$

GZ is the righting arm

In the right angle triangle GZM :

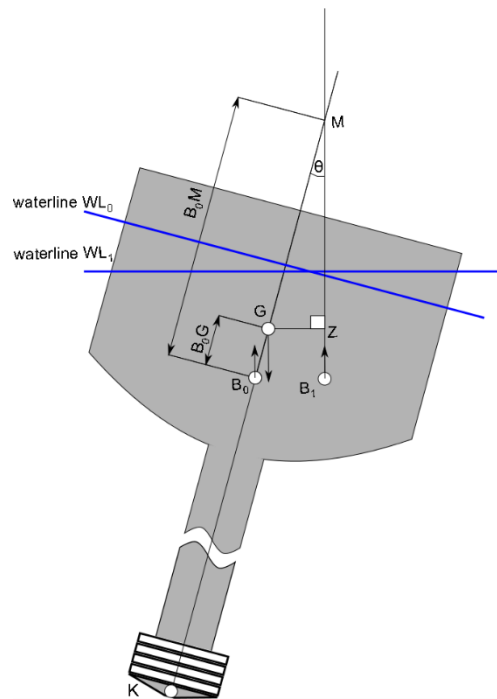


Figure 7 Metacentric height

$$GZ = GM \cdot \sin \theta \quad \text{then}$$

$$GZ = (B_0M - B_0G) \cdot \sin \theta$$

therefore:

$$RM = W \cdot (B_0M - B_0G) \cdot \sin \theta$$

Equation 7 *Righting moment*

Stability Condition

For the buoy to be stable GM must be positive and M must always be above G.

7.10. ANGLE OF HEEL

The angle of heel θ that the buoy may assume in wind and current conditions can be calculated either from the wind and current loading information provided in Guideline *G1066* [1] or other sources of wind and current loads. It is not practical to estimate the extreme loads due to moving ice.

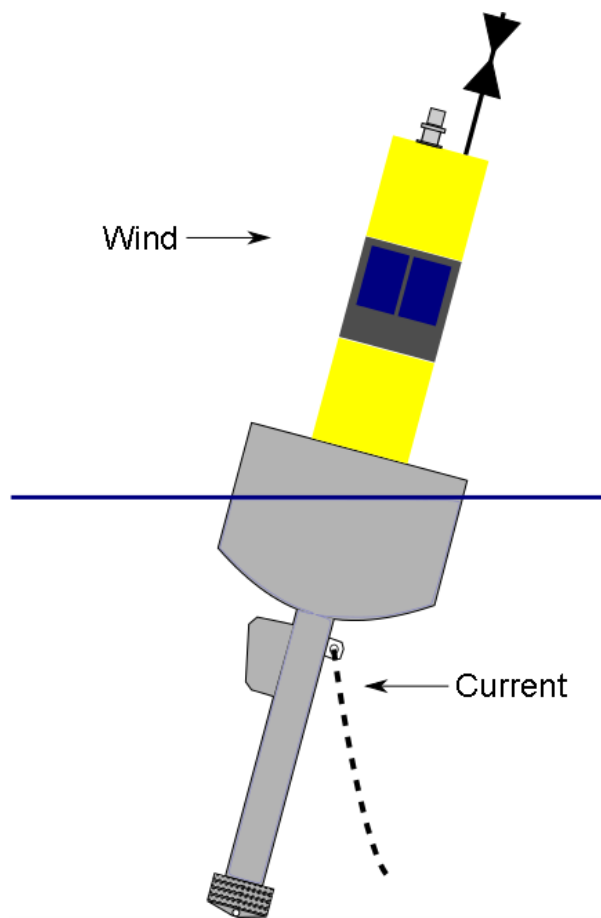


Figure 8 *Angle of heel*

The moment of the area of the buoy which is subject to wind load, about the point of mooring attachment and the moment of the submerged area of the buoy subject to current load, about the mooring attachment can be summed and the resulting heel angle calculated. The worst case is usually assumed when the moments produced by the current and wind forces are both trying to heel the buoy in the same direction. The direction of heel due to current flow will depend on the area of the immersed parts of the buoy that are situated above and below the mooring eye.

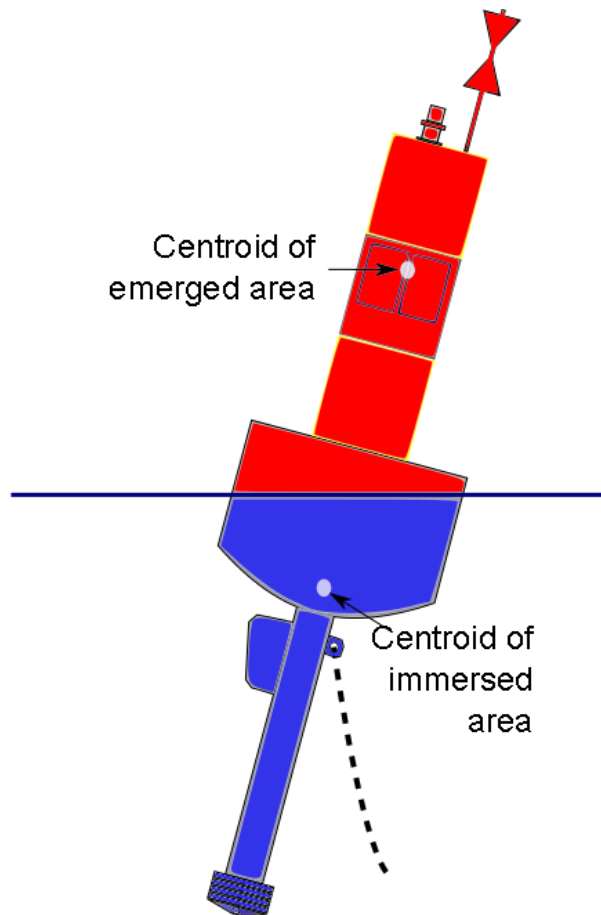


Figure 9 Areas of wind- and water forces

The buoy is restrained by the mooring and will pivot about the point of attachment of the mooring (mooring eye). In Figure 9 the force of the wind will act on the area of the buoy above the waterline, shaded red. The force will act about the centroid of this area. Current forces on the submerged area of the buoy (blue) will act about the centroid of the submerged area. Moments are taken about the mooring eye(s). Water forces acting on the buoy include current (tidal or stream), wind generated surface current and wave drift.

$$\text{wind drag [N]} = \text{wind force [N/m}^2\text{]} \cdot \text{emerged projected area [m}^2\text{]}$$

$$\text{water drag [N]} = \text{water force [N/m}^2\text{]} \cdot \text{immersed projected area [m}^2\text{]}$$

The wind drag moment [Nm] is calculated by multiplying the wind drag [N] by the distance from the centroid of emerged area to the mooring attachment point [m].

The water drag moment [Nm] is calculated by multiplying the water drag [N] by the distance from the centroid of immersed area to the mooring attachment point [m].

Moments are taken as positive, if the buoy tends to rotate in a clockwise direction about the mooring point and negative if anticlockwise. The sum of these moments about the mooring point provides a value for the overturning moment.

$$\tan(\theta) = \frac{\text{overturning moment [Nm]}}{\text{weight [N]} \cdot GM[m]}$$

Equation 8 Angle of heel (valid for angles of less than 10°)

This formula is only valid for small angles of heel (less than ten degrees). These heeling calculations will provide a guide to the angle the buoy will attain due to the given wind and current forces. However, as the angle of heel increases the calculated result will become less accurate as the effective shape and projected area of the buoy body will change.

If a buoy is to be used in a particular current flow situation, these calculations can be also used to evaluate the position of mooring eyes or mooring attachment if the buoy has several mooring attachment positions.

Note:

For the model of buoy shown in these diagrams where the mooring attachment is away from the centre line the heeling moment due to the mooring forces being applied at a distance from the buoy centre line (the arm) will need to be added to the calculations.

When angle of heel is being considered it should be noted that the anticipated maximum angle of heel should not exceed half the vertical divergence (FWHM) of the lantern.

8. PRACTICAL MEASUREMENTS

The practical measurement of weight, freeboard and metacentric height may be of particular value when considering alterations or the installation of new equipment to existing buoys for which design drawings and calculations are not available.

Practical measurements can also be useful to confirm calculated values of Centre of Gravity.

8.1. CENTRE OF GRAVITY

Assuming that a crane capable of lifting the assembled buoy is available then the centre of gravity position can be confirmed by suspending the buoy from one lifting eye that is away from the centre line (see). The buoy must hang freely and not be restrained by any handling lines. The centre of gravity will then be at the intersection of the line of suspension with the central axis of the buoy. This can be conveniently recorded with a digital photograph or measured with an inclinometer on the buoy.

8.2. ROLL PERIOD

The natural roll frequency can be estimated by displacing the buoy and timing the roll period. The buoy must be floating freely and then displaced as far as is practical in one direction and then released. Timing is started when the buoy reaches its maximum roll angle in the opposite direction and timing stopped when the buoy returns to this maximum roll position. Time can be measured over two or three complete roll cycles to find the average roll period. Roll period measurement can be easily carried out from a video recording of the rolling buoy. Acceleration sensors installed on the buoy will also provide accurate information. An example can be found in annex C.

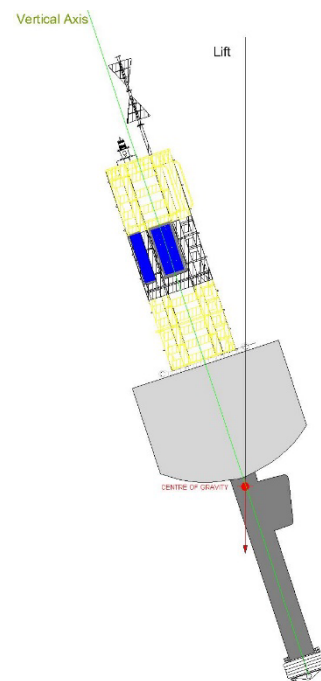


Figure 10 A buoy lifted at an off-centre lifting point

The amplitude (angle) of heel should not exceed 10° / 15° from one side to the other side. The test can be repeated with some of the moorings suspended from the buoy's mooring eyes, when some of the effects of changing in roll frequency due to mooring weight will be demonstrated. The natural roll period is given by the following.

$$T = 2\pi \sqrt{\frac{J(1+k)}{m_b \cdot g \cdot GM}}$$

Equation 9 Natural roll period

where

- T roll period in seconds
- J moment of inertia of the buoy about the axis through the centre of gravity in kg*m²
- k added mass coefficient (which can vary from 0.1 up to 1, depending on the float shape and the type of skirt or tailtube)
- m_b mass of the buoy in kg
- g acceleration due to gravity in m/s²
- GM metacentric height in m

The state of the buoy should be consistent for m and GM.

The added mass coefficient (k) accounts for the amount of boundary water that moves with the buoy. Note that the mass of the mooring line is neglected in the above formula. Moreover, remind that this formula is valid only for small angles and static position of the buoy.

8.3. WATERLINE

When the freeboard is known the effects of adding the mooring loads to the buoy can be easily calculated and the effective freeboard in service conditions estimated.

If suitable calm water facilities are available, along with a crane capable of lifting the buoy, then floatation trials can be carried out. The draft can be measured and the line of floatation and hence the freeboard confirmed.

At this stage weights can be placed on the deck of the buoy, possibly those to be used for the inclining experiment. These are placed on opposite sides of the superstructure so that the buoy remains floating in an upright position. The weights should be of sufficient size to sink the buoy by a significant amount. The displacement (kg) per mm immersion can then be established (or calculations confirmed). This should be carried out with two or more sets of weights to ensure accuracy of the results.

Note:

The line of floatation will vary depending on the density of water the buoy is floating in (see 6.13).

8.4. METACENTRIC HEIGHT

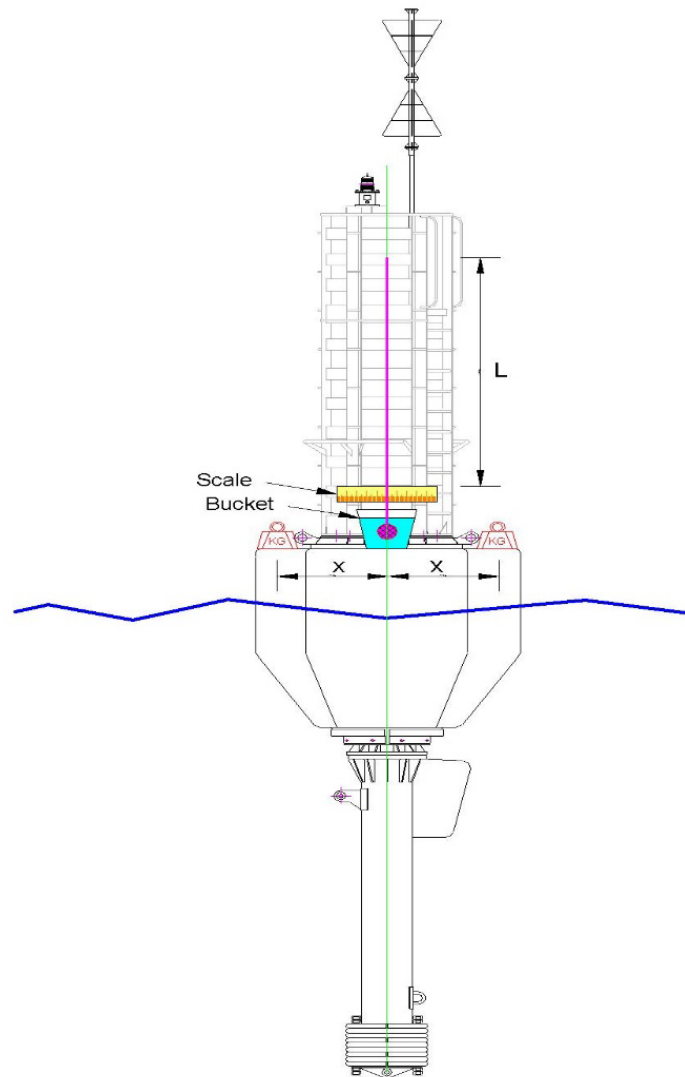


Figure 11 Measuring the metacentric height

Weights will be required that can be placed at the outboard edge of the buoy's deck to heel the buoy. The angle of heel can then be measured and used to calculate the metacentric height. Several weights should be used to heel the buoy first one way and then the other. The angle of heel may be measured with a pendulum (see Figure 11) on the buoy. The movement of the pendulum can be measured with a horizontal scale.

$$\tan(\theta) = \frac{\text{horizontal displacement}}{\text{length of pendulum}}$$

The angle could also be measured with an inclinometer or by photographing the buoy with a horizontal or vertical reference line in the background.

The metacentric height should be calculated with several different inclining weights.

The buoy mooring lines must be completely slack and no foreign weights or personnel must be allowed on the buoy during the inclining test.

$$GM = \frac{\text{weight on deck} \cdot \text{distance} \times}{\text{weight} \cdot \tan(\text{angle of heel})}$$

Equation 10 metacentric height (for small heel angles less than 5°) (m)

This is valid for small heel angles (less than five degrees) and the measurements must be carried out in flat water. These calculated values should all be similar and an average may be taken.

If the pendulum is used the mass of the pendulum is usually immersed in a container of water to damp the motion of the pendulum.

If the photographic method is used the photos must be taken from a direction perpendicular to the plane of heel of the buoy.

8.5. TOWING TRIALS

When the buoy is to be used in fast current or river situations towing trials can be carried out to evaluate the buoy's performance in moving water. The buoy can be towed from its mooring point(s) with a ballast weight in the towline that is sufficient to maintain a downward slope in the line from the buoy to the weight.

The towing speed can be recorded from instruments of the towing vessel. The angle of heel can be conveniently estimated from digital photographs or taken from sensors on the buoy.

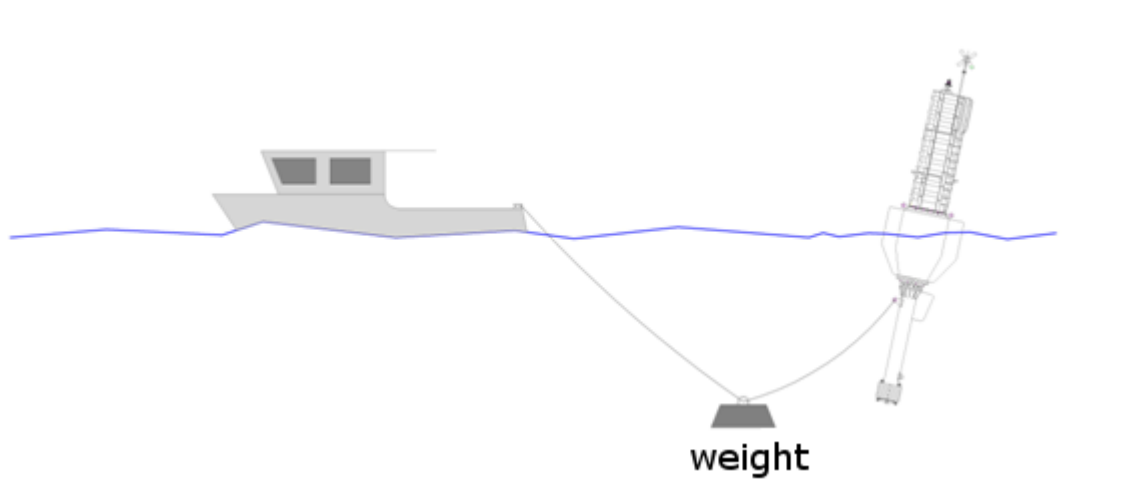


Figure 12 Towing trials

Alternatively the propeller wash from a large vessel pushing against the quay can be used to produce a steady flow of water past a moored buoy.

These towing trials will also provide an indication of the buoy's riding performance in moving water. Some buoys will sway or yaw or roll when subject to critical water velocities.

9. STABILITY AT SMALL ANGLES OF HEEL

For small angles of heel B follows a circle centred at M with a radius BM (metacentric radius).

GM and KM are calculated in the following formulae:

$$GM = KM - KG$$

$$KM = KB_0 + B_0M$$

B_0M is calculated using the following formula that incorporates the Inertia of the water plane (see 6.6).

$$B_0M = \frac{I_f}{V_B}$$

The metacentric height is calculated as follows.

$$GM = (KB_0 + B_0M) - KG$$

Equation 11 Metacentric height

where the first part is the form stability and the second part is the mass stability.

9.1. MASS STABILITY AND FORM STABILITY

To improve the stability, we can modify either the mass stability or the form stability.

If form stability is increased, BM distance increases.

To increase mass stability, GM must be increased by lowering G.

10. INTRODUCTION TO DYNAMIC STABILITY

Each buoy has natural periods of roll and heave.

When the buoy is floating oscillations to each side of the equilibrium position result from an external force. These oscillations are damped over time due to the viscosity of water.

Knowledge of the natural roll period of the buoy allows the estimation of the value of the metacentric height and also an estimation of the behaviour of the buoy in the wave fields corresponding to the mooring site.

Resonance is the tendency of the buoy to oscillate at greater amplitude at some wave periods rather than others.

- sea wind wave period of < 5 seconds, irregular small waves, rare case of resonance;
- transitional phase swell periods of between 5 and 10 seconds, rare case of resonance;
- oceanic swell swell period > 10 seconds, regular waves, increased occurrence resonance.

A large value for the metacentric height will result in the buoy returning rapidly to the upright position in a quick motion (small roll period). A small metacentric height will result in a slow oscillation motion (long roll period), possibly with excessive displacement from the vertical.

The effectiveness of the visual AtoN on the buoy will depend on these being clearly visible. If the buoy has a rapid or jerky motion then it will be difficult to clearly recognize the daymark or the light character. A slow and steady rolling motion is therefore preferred, however the extent of the rolling must not be excessive.

11. STUDY OF STABILITY CURVES (RIGHTING ARM CURVES)

Stability is the ability of the buoy to return to an upright position when external actions such as wind, waves and current have displaced it. Stability is considered adequate if the buoy retains this capacity in all situations.

Factors that may affect the stability are the:

- loading of the buoy;
- presence of overturning moments due to external forces.

Stability can be studied via the curve of righting arm.

It is usual to produce two curves, one without mooring and one with the mooring suspended vertically beneath the buoy.

Method:

At each angle of heel θ the value of the righting arm GZ can be determined.

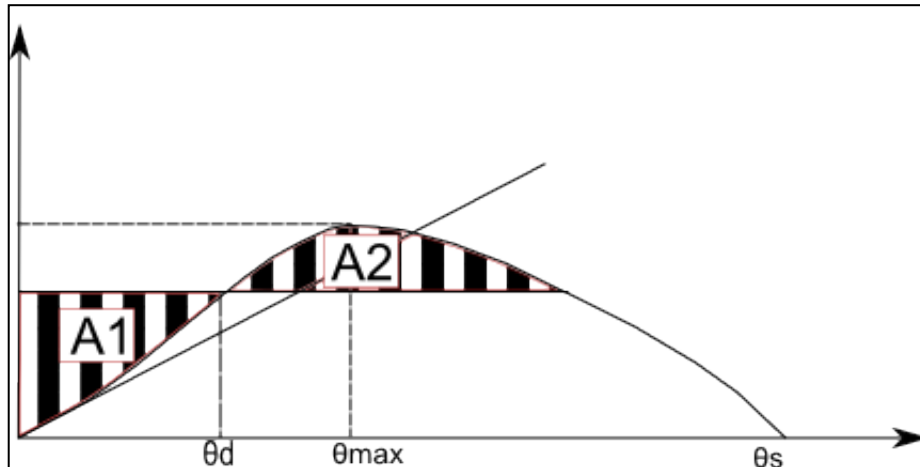


Figure 13 GZ-curve

Analysis of the curve:

The total area under the curve of stability is the stability reserve or the amount of righting energy.

Slope of the curve:

The initial slope of the curve is the value of the modulus GM of the initial stability.

Limit angle of dynamic stability (θ_d):

Angle for which the areas $A1$ and $A2$ are equal.

At that angle the restoring energy (area $A2$) equals the heeling energy (area $A1$).

There is a danger of capsizing beyond this angle for external loads acting dynamically on the buoy.

Limiting angle of static stability (θ_{max}):

The angle θ_{max} is the peak of the curve. It is the maximum angle of stability.

Limit angle of static capsizing (θ_s):

This angle (θ_s) is the point where righting arm disappears and static capsizing occurs.

Beyond this angle the righting moment becomes negative and a prompt capsizing occurs.

12. STABILITY SAFETY CHECK

The stability curve is difficult to produce by manual calculation because the water plane shape of the buoy will change as the buoy heels (except for buoys with spherical bodies).

A simple safety evaluation can be carried out by calculating the overturning moments at 90° heel. This assumes the buoy is knocked down horizontally by wind or waves. It is proposed that this calculation is carried out without considering the effects of moorings, as this will represent the most extreme stability case.

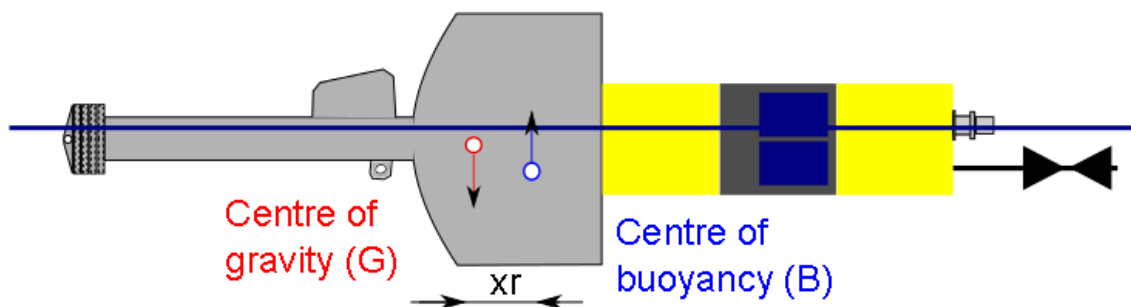


Figure 14 Buoy in horizontal position

The centre of gravity G remains in the same position as in the original calculations. The displaced volume of the buoy is also the same as originally calculated; however, this is now provided by the new immersed section of the buoy body, parts of the tail tube and possibly part of the superstructure. The buoyant element of the superstructure may be significant if the superstructure is enclosed. The horizontal position of this new centre of buoyancy B is calculated and the relative positions of G and B will show if the buoy will tend to right or to capsize.

The righting arm GZ is now xr. The value of the righting moment will be:

$$RM = m \cdot g \cdot GZ = m \cdot g \cdot (xr)$$

Equation 12 Righting moment for buoy in horizontal position

13. DEFINITIONS

The definitions of terms used in this Guideline can be found in the *International Dictionary of Marine Aids to Navigation* (IALA Dictionary) at <http://www.iala-aism.org/wiki/dictionary> and were checked as correct at the time of going to print. Where conflict arises, the IALA Dictionary should be considered as the authoritative source of definitions used in IALA documents.

14. REFERENCES

- [1] IALA. Guideline G1066 The Design of Floating Aid to Navigation Moorings.
- [2] IALA. NAVGUIDE Marine Aids to Navigation Manual
- [3] IALA. Guideline G1094 Daymarks for Aids to Navigation.

ANNEX A DETERMINATION OF CENTRE OF GRAVITY G FOR COMPONENTS OF A BUOY

Table 2 Determination of the centre of gravity for components of a buoy

Aluminum superstructure	Quantity	Total mass [kg]	G above base of super-structure [mm]	Moment [kg mm]
Flanging bottom		52,5	14	756
Standard fixing flange	1	50,0	10	500
Gussets	6	2,0	103	207
Gussets under ladder	2	0,5	103	49
Central structure		162,4	1 541	250 344
Vertical amounts	6	80,0	1 660	132 800
Grips	36	5,0	1 660	8 300
Fixed cladding plates	33	30,0	1 540	46 185
6 mm cladding plates	5	9,0	120	1 080
Removable cladding plates	2	2,0	700	1 388
Ladder bars	7	4,0	1 020	4 080
Handrail	1	8,0	1 000	8 000
Top handrail	1	4,0	1 931	7 724
Floor cladding plates	5	7,0	2 040	14 280
Cladding plates near floor, side steps	1	0,5	2 050	934
Aluminium floor	1	9,0	2 110	18 990
Nameplate	2	4,0	1 650	6 584
Upper parts		18,0	3 149	56 763
Stringers for ladder	2	5,0	2 722	13 608
Upper ring	1	5,0	3 300	16 500
Top plate for light base	1	6,0	3 300	19 887
Light base	1	2,0	3 384	6 768
Support for Day mark		7,0	3 484	24 234
Aluminium pipe	1	3,0	2 825	8 475

Aluminum superstructure	Quantity	Total mass [kg]	G above base of super-structure [mm]	Moment [kg mm]
Carbon pipe	1	2,0	3 800	7 600
Connection plate	1	0,5	3 825	1 740
Support flange for D Mark	1	0,5	4 300	2 150
Gussets for flange 35x35	4	0,50	4 283	2 142
Flange pipe	1	0,5	4 255	2 128
Miscellaneous bolts		10,0	2 050	20 500
Welds		10,0	1 500	15 000
TOTAL		260	1 414	367 597

The height of the centre of gravity G from the datum is $367,597 / 260 = 1,414$ mm.

Table 3 Determination of centre of gravity G of the buoy: steel buoy + aluminium superstructure

	Total mass [kg]	G above keel [mm]	Moment [kg mm]
Topmark	10	9 170	91 700
Aluminium superstructure	260	7 320	1 903 200
Equipment	100	7 120	712 000
Insulation plate for steel / aluminium	5	5 815	29 075
Steel float	2 870	4 305	12 355 350
Tailtube	1 105	2 455	2 712 775
Ballast	650	120	78 000
Total mass	5 000		17 882 100

The height of the centre of gravity G of the buoy is from the datum K
 $17,882,100 / 5,000 = 3,576$ mm.

ANNEX B DETERMINATION OF CENTRE OF BUOYANCY B OF A STEEL BUOY

Table 4 Determination of the centre of buoyancy of a steel buoy

Components	Volumes [liter]	Buoyancy [kg] with water density of 1,026 kg/l	G above the datum K [mm]	Moment [kg mm]
Float cylindrical part	3 231	3 315	5 439	18 030 285
Float truncated part	1 267	1 300	4 756	6 182 800
Bolts	5	5	4 055	20 275
Connecting flange	24	25	4 146	103 650
Ring on cone	3	3	4 760	14 280
Tailtube	195	200	2 454	490 800
Ballast bolts	2	2	238	476
Ballast	146	150	165	24 750
TOTAL	4 874	5 000		24 867 316

The height of the centre of buoyancy B for the buoy from the datum K is
 $24,867,316 / 5,000 = 4,973 \text{ mm}$

The diameter of the buoy is 2.65m.

The volume of the buoy is 4.874m^3 .

B_0K is 4.973m

KG is 3.576m

B_0M is calculated:

$$B_0M = \frac{I_f}{V_B} = \frac{1}{64} \cdot \pi \cdot D^4 \cdot \frac{1}{V_B} = 0.497 \text{ m}$$

GM is calculated:

$$GM = KM - KG = B_0M + B_0K - KG = 0.497\text{m} + 4.973\text{m} - 3.576\text{m} = 1.894\text{m}$$

ANNEX C EXAMPLES OF ROLL PERIODS OF DIFFERENT BUOY TYPES

Table 5 Examples of roll periods for steel buoys


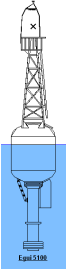

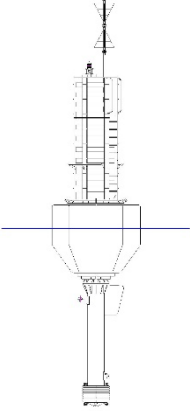
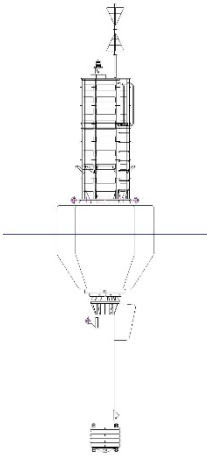
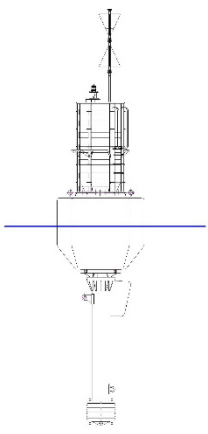
Steel buoys			
Volume	7.50 m ³	12 m ³	26 m ³
Mass	5 000 kg	9 500 kg	15 000 kg
Natural roll period	5.80 seconds	7 seconds	7 seconds

Table 6 Examples of roll periods for modular plastic buoys

Modular plastic buoys	A8L	B6L	C5L
Ballast 650 kg			
Volume	9 m ³	7 m ³	6 m ³
Mass	3 650 kg	3 400 kg	3 150 kg
Natural roll period	4.85 seconds	4.70 seconds	4.20 seconds