TECHNICAL NOTE

Hydrostatic Loading in Bladed

Report No.: 110052-UKBR-T-17, Rev. D
Date: 25/09/2014

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Rev. No.	Date	Reason for Issue
A	2014-09-05	First issue
B	2014-09-25	Updated to DNVGL template
C	2014-10-16	Changed sign convention for vertical position realtive to sea surface z in section 3. Added equation numbers in section 3. Added note to "parallel distributed loading" equation for unsealed members in equation (3-12) Improved diagrams in 3.2 on perpendicular distributed loading. Improved Figure 3-7 showing an element crossing the sea surface.
D	2017-02-02	Added notes on hydrostatics below the mudline in section 3.4

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1 SUMMARY

This document describes the calculation of hydrostatic loading on support structures in Bladed.

The calculation of hydrostatic forces on isolated elements is discussed. Example hand calculations of internal member loads are presented for a monopile tidal turbine.

A summary of the mathematical basis of the element buoyancy calculation is also presented.

2 HYDROSTATICS DEFINITION FOR STRUCTURAL ELEMENTS

Hydrostatic forces are calculated by considering the pressure forces on structural elements in isolation.

Support structure members can be defined as "sealed" or "unsealed". "Sealed" elements can be defined as "flooded" or "unflooded". These terms are defined in this section, illustrated in Figure 2-1, and summarised in Table 2-1.

Sealed vs. Unsealed members

The "sealed" or "unsealed" options represent whether the ends of the members are sealed with a plate. This results in different pressure forces being applied to the elements.

Pressure forces on "sealed" elements:

- Element end pressure forces act on the whole element end cross-sectional area calculated using member outer radius at each end.
- Distributed forces on the element sides act only on the outside surface of the member
- For an element in isolation, the buoyancy force corresponds to the mass of water displaced by metal and the space inside the members.

Pressure forces on "unsealed" elements:

- Element end pressure forces act on the element wall cross-sectional area at each end, calculated using the element radius and thickness.
- Distributed forces on the element sides act on the inside and outside surface of the member
- For an element in isolation, the buoyancy force corresponds to the mass of water displaced by the metal only.

"Unsealed" elements are assumed to be full of water when they are below the water line. In this case, the inertia of water inside the element is accounted for by including additional hydrodynamic added mass, which acts only in a direction perpendicular to the element axis. Note that this added mass is in addition to the added mass included by specifying the hydrodynamic inertia coefficient on each element.

Flooded vs. Unflooded members

"Sealed" elements can be specified as "flooded" or "unflooded". This determines whether the sealed element contains water. For flooded members, the mass of enclosed water is added to the element mass. The pressure forces on "flooded" and "unflooded" elements are identical.

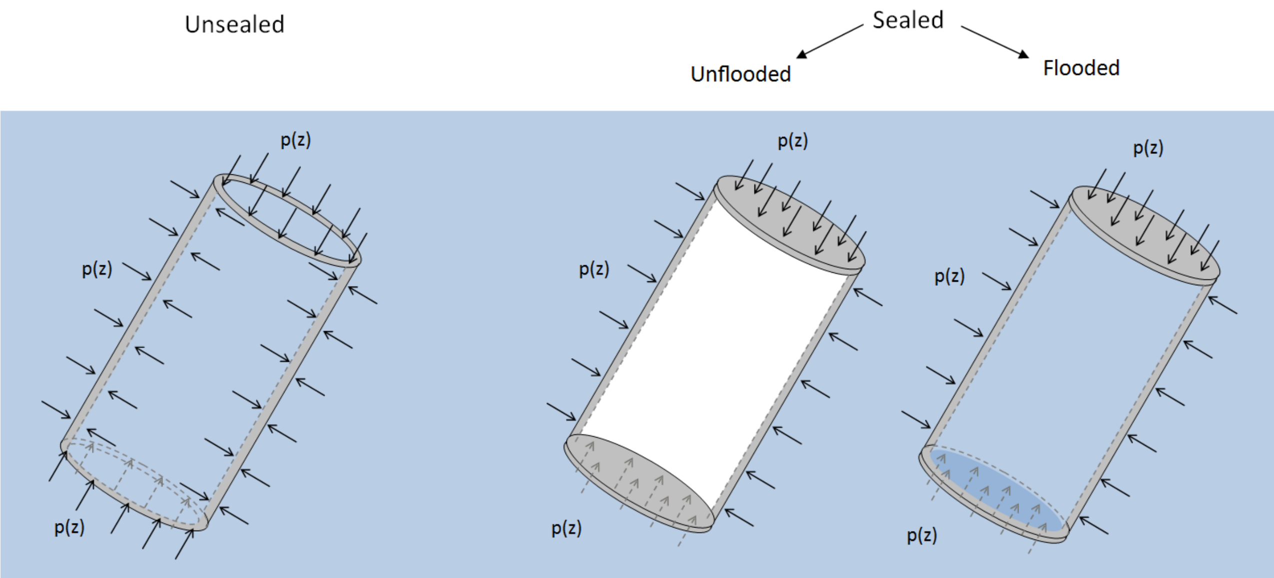

Figure 2-1: Sealed and unsealed structural elements

	Unsealed	Sealed	
		Unflooded	Flooded
End point forces act on	wall area at element end	whole cross-section at element end	
Side wall forces act on	inside and outside of walls	outside wall only	
Extra internal water mass?	Added mass perpendicular to element axis	None	Structural mass of water added to element

Table 2-1: Summary of hydrostatic and water mass assumptions

3 HYDROSTATICS IMPLEMENTATION IN BLADED

This section describes the calculation of hydrostatic loading on structural elements in Bladed. This section is relevant for still water in the steady state; hydrodynamic loads from waves and currents are not discussed.
Each element is treated individually and viewed as a separate entity in water.

The hydrostatic forces are split up into applied loads

1. Pressure point forces on each **end** of the element. Applied as point forces on each end of the element.

2. Hydrostatic force from pressure component **parallel** to the element axis on the element surface. This is effectively a pressure integral of the parallel pressure component around the element axis. Applied as a distributed load along the element.

3. Hydrostatic force from pressure component **perpendicular** to the element axis on the element surface. This is effectively a pressure integral of the perpendicular pressure component around the element axis. Applied as a distributed load along the element.

Calculation of each of these components is described in section 3.1 to 3.3
The following notation is used in this section

Symbol	Description
$\boldsymbol{R}$	Radius to element surface at particular point along element
$\boldsymbol{L}$	Length of element
$\hat{\boldsymbol{a}}$	Unit vector pointing along the element axis from end 1 to end 2
$\hat{\boldsymbol{k}}$	Unit vector pointing vertically upwards in global coordinates
$\boldsymbol{z}$	Height of node relative to sea surface (should be a negative value)
$\boldsymbol{A}$	Cross-sectional area of element
$\vec{\boldsymbol{F}}$	Force
$\vec{\boldsymbol{F}}_l$	Force per unit length
$\boldsymbol{\theta}$	Angle to element centre-line (radians)
$\boldsymbol{\rho}$	Density of water (constant)
$\boldsymbol{g}$	Acceleration due to gravity (constant)
$_i$	i =1,2 – at end i of the element

3.1 End Point Forces

Point forces are applied to each element end

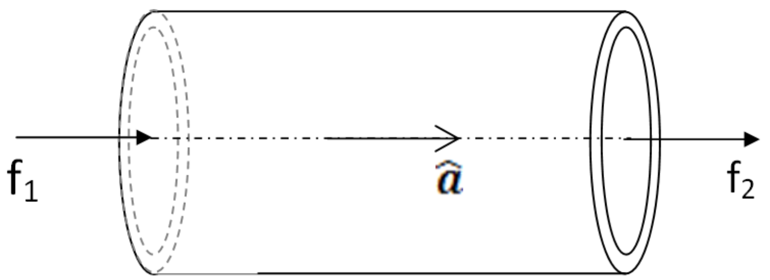

Figure 3-1: End point forces applied to structural elements

The pressure forces on each end are calculated according to:

End 1:

$$\overrightarrow{F_1} = -\rho g z_1 A_1 \hat{\boldsymbol{a}} \tag{3-1}$$

End 2:

$$\overrightarrow{F_2} = \rho g z_2 A_2 \hat{\boldsymbol{a}} \tag{3-2}$$

where

$\hat{\boldsymbol{a}}$ denotes the unit vector along the axis of the "element" coordinate system
A denotes the element end area
z denotes the height of node relative to sea surface (should be a negative value)

Note that if an element is **sealed** then the end area is calculated based on the element outer radius. If the element is **unsealed**, the end area is calculated based on the material cross-section only.

When several members are connected together, these end forces often cancel at the nodes, as illustrated in Figure 3-2.

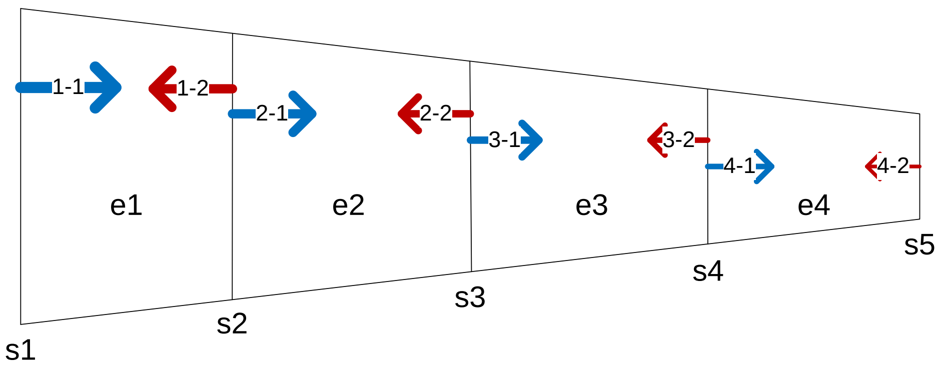

Figure 3-2: Element end forces applied to connected members

3.2 Perpendicular Distributed Loading

Surface pressure integrals are performed to calculate the hydrostatic force per unit length perpendicular to the element axis.

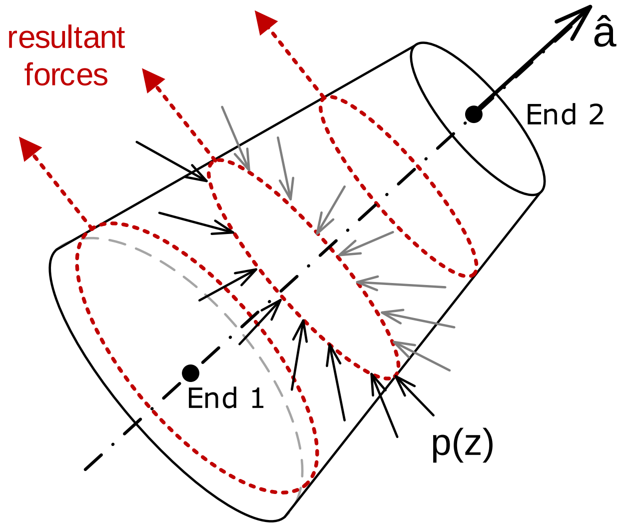

Figure 3-3: Element pressure forces perpendicular to element axis

The pressure integral around the element axis always makes a closed loop and the pressure forces perpendicular to the element axis are in the plane of the loop. As a result, the hydrostatic force per unit length perpendicular to the element axis can be calculated from the cross-sectional area of the element at each point along the element.

This force can then be scaled so that it is zero when the element axis is vertical and equal to the full volume buoyancy when the element axis is horizontal. The direction of the force is perpendicular to the element axis, in the most vertical direction. This direction can be calculated with a vector triple product, as shown below, where $\vec{k}$ is a unit vector pointing vertically upwards and $\vec{a}$ is the element axis. This vector $\vec{a}\times(\vec{k}\times\vec{a})$ lies in a vertial plane.

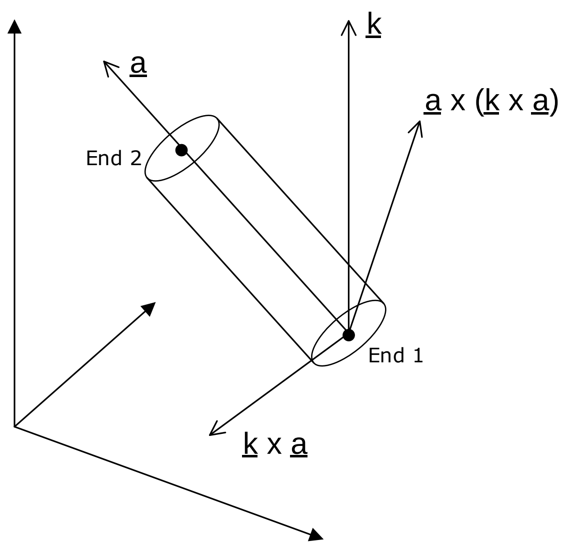

Figure 3-4: Calculation of the direction of buoyancy force

At any point along the element, the force per unit length is given by

$$\vec{F_l} = \rho g A(\vec{a}\times\vec{k}\times\vec{a}) \tag{3-3}$$

Note that if an element is **sealed** then the area A is calculated based on the element outer radius. If the element is **unsealed**, the area A is calculated based on the material cross-section only.

The per-unit-length forces are calculated at each end. For example, for a sealed member

At end 1:

$$\vec{F_{l1}} = \rho g \pi R_1^2(\vec{a}\times\vec{k}\times\vec{a}) \tag{3-4}$$

At end 2:

$$\vec{F_{l2}} = \rho g \pi R_2^2(\vec{a}\times\vec{k}\times\vec{a}) \tag{3-5}$$

The distributed pressure force is then applied to the structure assuming a linear variation in load between the load at each end. This is a slight approximation as the loading actually changes quadratically along the element.

3.3 Parallel Distributed Loading

The pressure forces parallel to the element axis is can be calculated from the projected area when looking along the element axis.

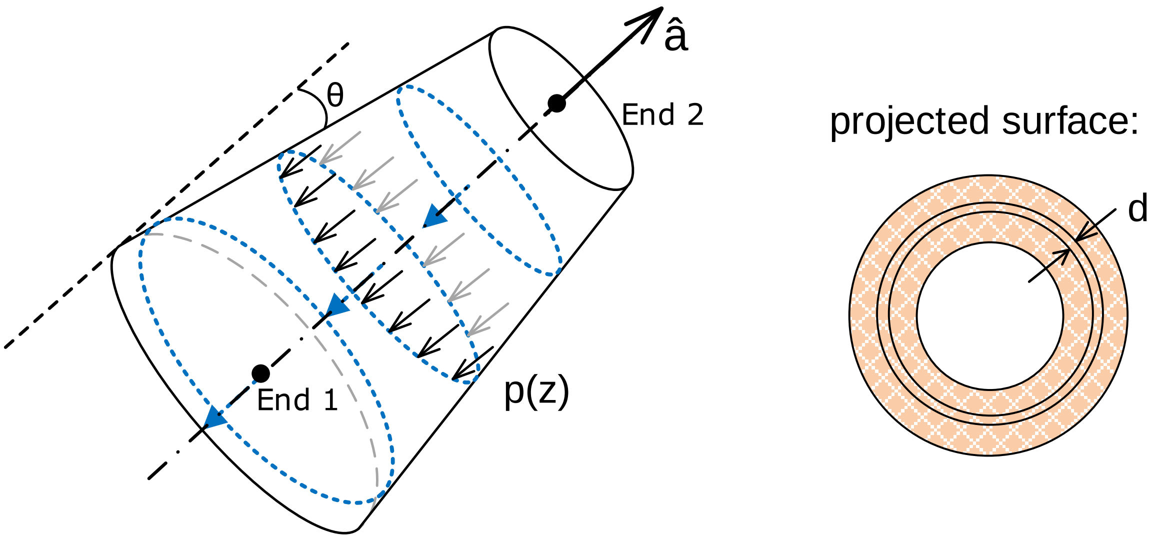

Figure 3-5: Element pressure forces parallel to element axis

If the element is **sealed**, it is only necessary to calculate a force per unit length from pressure on the outer wall. Consider the surface as a series of rings, each one with a circumference of $2\pi r$. The length of an element along the element axis, dl, is related to the segment dr as shown in Figure 3-6.

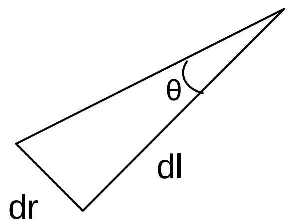

Figure 3-6: Relationship between dr and dl

The force (from End 1 to End 2) on a length dl of element at an arbitrary point is:

$$\begin{aligned}\overrightarrow{\boldsymbol{F_{dl}}} &= 2\pi r\, dr(-\rho g z)\vec{\boldsymbol{a}} \\ &= 2\pi r\, dL\frac{dr}{dL}(-\rho g z)\vec{\boldsymbol{a}}\end{aligned} \tag{3-6}$$

where $\frac{dr}{dL} = \frac{R_2 - R_1}{L}$ is the change of radius per unit length.

Note that this means that the force acting from End 1 to End 2 is positive when $R_2 > R_1$, and negative when $R_2 < R_1$.

The force per unit length is therefore given by

$$\overrightarrow{\boldsymbol{F_l}} = 2\pi r\ \frac{dr}{dL}(-\rho g z)\vec{\boldsymbol{a}} \tag{3-7}$$

The forces per unit length at each end are given by the following expressions:

$$\overrightarrow{\boldsymbol{F_{l1}}} = 2\pi R_1 \frac{dR}{dL}(-\rho g z_1)\vec{\boldsymbol{a}} \tag{3-8}$$

$$\overrightarrow{\boldsymbol{F_{l2}}} = 2\pi R_2 \frac{dR}{dL}(-\rho g z_2)\vec{\boldsymbol{a}} \tag{3-9}$$

This distributed pressure force is applied to the structure assuming a linear variation in load between the load at each end. In this case, there is indeed a linear variation in force.

If the element is **unsealed**, then the contribution must also be added from the inner wall, so:

$$\overrightarrow{\boldsymbol{F_l}} = \left[2\pi r\ \frac{dr}{dL}(-\rho g z(l))\vec{\boldsymbol{a}}\right] - \left[2\pi(r-t)\ \frac{d(r-t)}{dL}(-\rho g z(l))\vec{\boldsymbol{a}}\right] \tag{3-10}$$

Noting that

$$\frac{d(r-t)}{dL} = \frac{(R_2 - t_2) - (R_1 - t_1)}{L} = \frac{dr}{dL} - \frac{dt}{dL} \tag{3-11}$$

The force expression simplifies to

$$\begin{aligned}\overrightarrow{\boldsymbol{F_l}} &= 2\pi\big(-\rho g z(l)\big)\left[r\frac{dr}{dL} - (r-t)\left(\frac{dr}{dL} - \frac{dt}{dL}\right)\right]\vec{\boldsymbol{a}} \\ &= 2\pi\big(-\rho g z(l)\big)\left[t\frac{dr}{dL} + (r-t)\frac{dt}{dL}\right]\vec{\boldsymbol{a}}\end{aligned} \tag{3-12}$$

Note that Bladed assumes that the $\frac{dt}{dL}$ term is small, so this term is not included.

3.4 Elements crossing the sea surface or sea bed

For members that cross the sea-surface, hydrostatic forces are only applied to the part of the element that is submerged, as illustrated in Figure 3-7. The dotted line shows the distance along the element that hydrostatic forces are applied. This location is determined as the intersection of the sea-surface and the element axis.

Hydrostatic forces are applied below the mud-line (i.e. it is assumed that the pile is surrounded by saturated soil).

For all member types, hydrodynamic added mass is not included on members below the mudline. This means that unsealed members below the water line do not include any enclosed water mass.

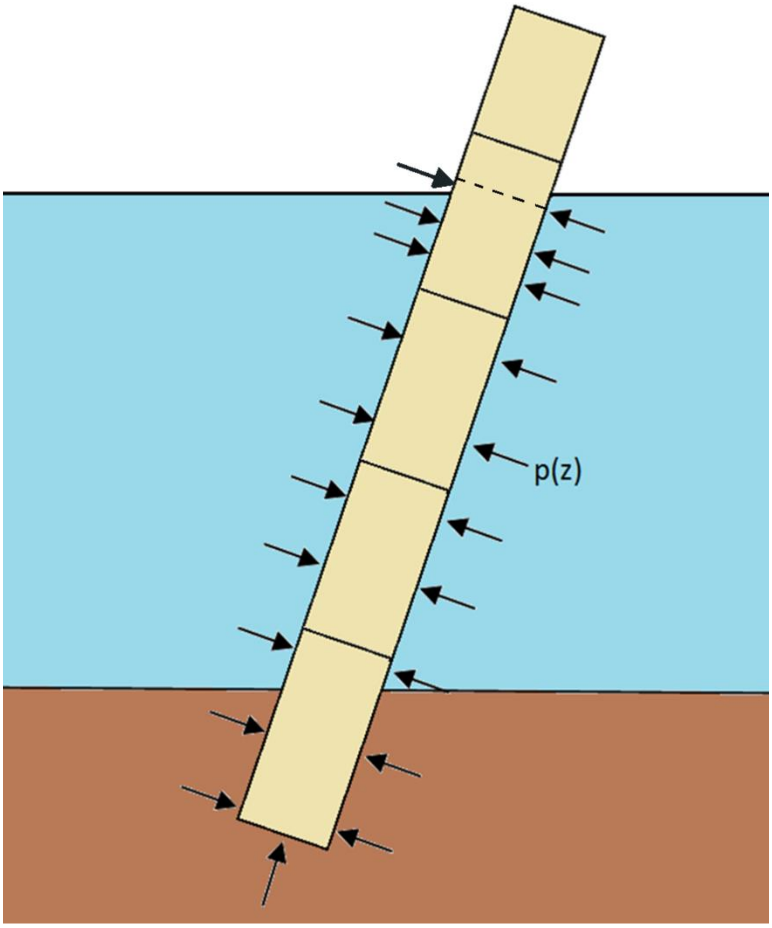

Figure 3-7: Pressure forces on members crossing the sea surface or sea bed

4 TIDAL TURBINE CASE STUDY

Figure 4-1 shows a typical tidal turbine support structure and nacelle definition, where the nacelle and monopile support structure are both defined using structural elements.

The sealed nacelle is defined using sealed, unflooded members. The monopile is defined using unsealed members. The nacelle attachment point has been defined as the top of member 3 as shown.

This section will discuss how the axial load varies in the monopile, in particular at the sealed-unsealed interface between members 2 and 3.

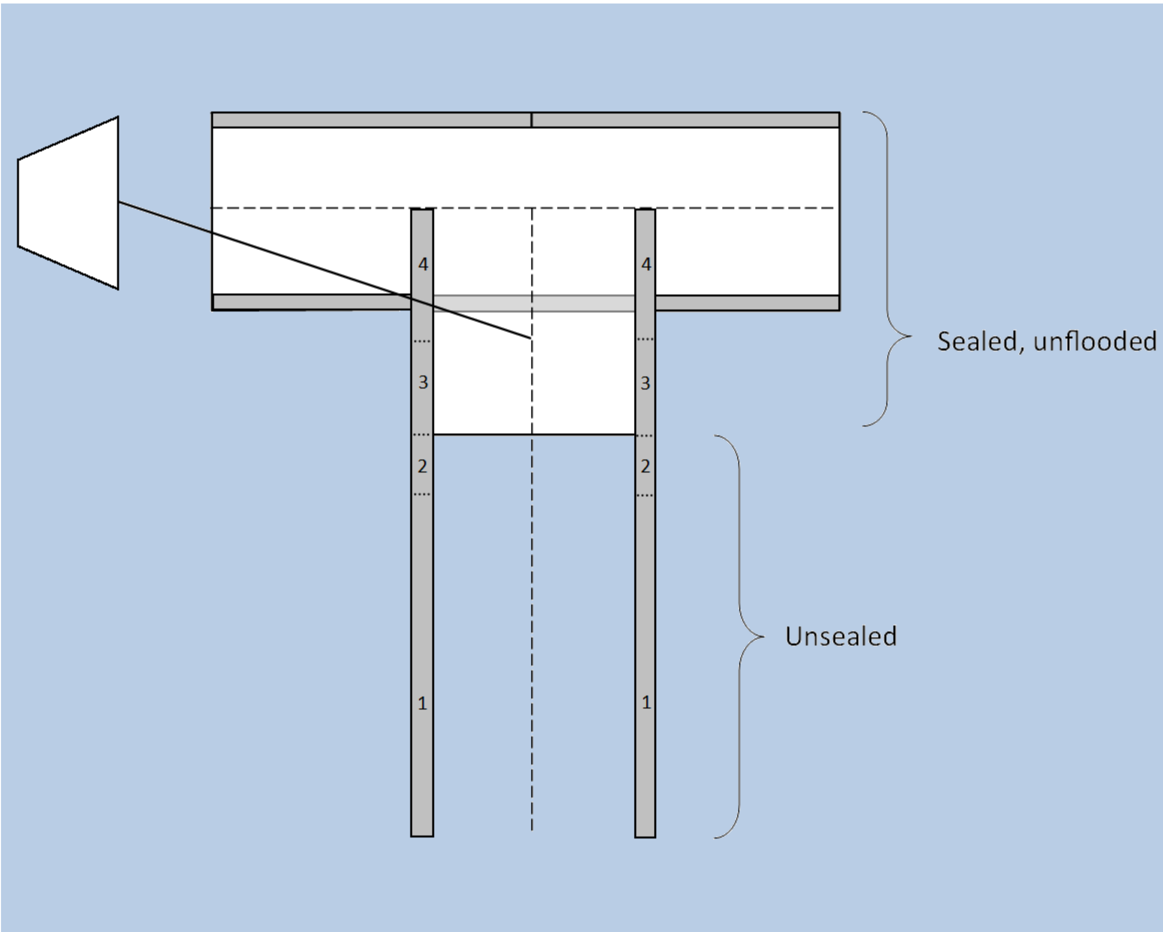

Figure 4-1: Tidal turbine system with sealed nacelle and unsealed tower

4.1 Step change in load at sealed-unsealed interface

The pressure forces acting on the end of members 2 and 3 are illustrated in Figure 4-2.

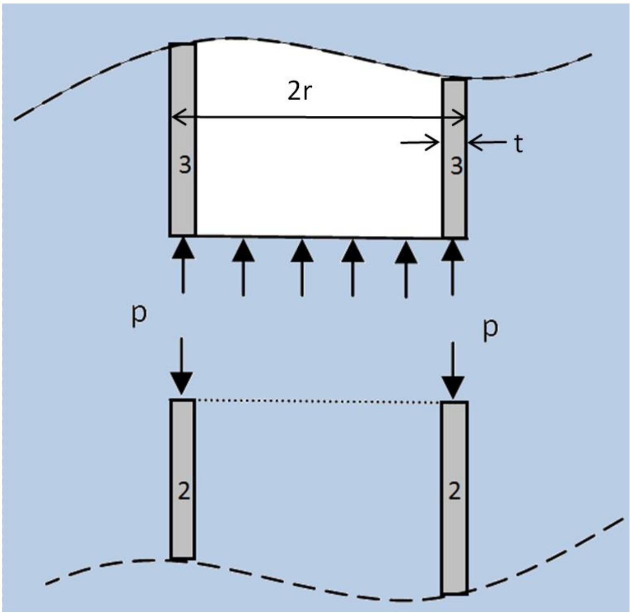

Figure 4-2: Pressure forces acting at the sealed-unsealed interface

Assuming an equal element wall area at the ends of member 2 and 3, the pressure forces on the walls will cancel out. The pressure force acting on the sealed end of member 3 will therefore cause a discontinuity in the axial load on either side of this interface.

The axial load change across this interface will be equal to

$$\begin{aligned}\delta F_{axial} &= p * \pi(r-t)^2 \\ &= \rho g z \ * \pi(r-t)^2\end{aligned} \tag{4-1}$$

Inserting some example data

z = 30 m
ρ = 1025 km/m^3
r = 1.5 m
t = 0.04 m

$$\text{Change in axial load} = 2.02 \text{ MN}$$

Clearly a large load difference can be seen in the adjacent members either side of the sealed – unsealed interface.

4.2 Calculating axial load in monopile

In this section, it is discussed how to calculate the axial load in the monopile of the tidal turbine.

First, a simple way to calculate the hydrostatic force on the sealed members is presented. This hydrostatic force is then used to calculate the total axial force at two locations in the monopile.

4.2.1 Nacelle hydrostatic force calculation

If the nacelle was completely surrounded by water (Figure 4-3), then the buoyancy force could be calculated just by considering the nacelle volume.

$$\text{Hydrostatic force } = \rho g * (\text{nacelle volume}) \tag{4-2}$$

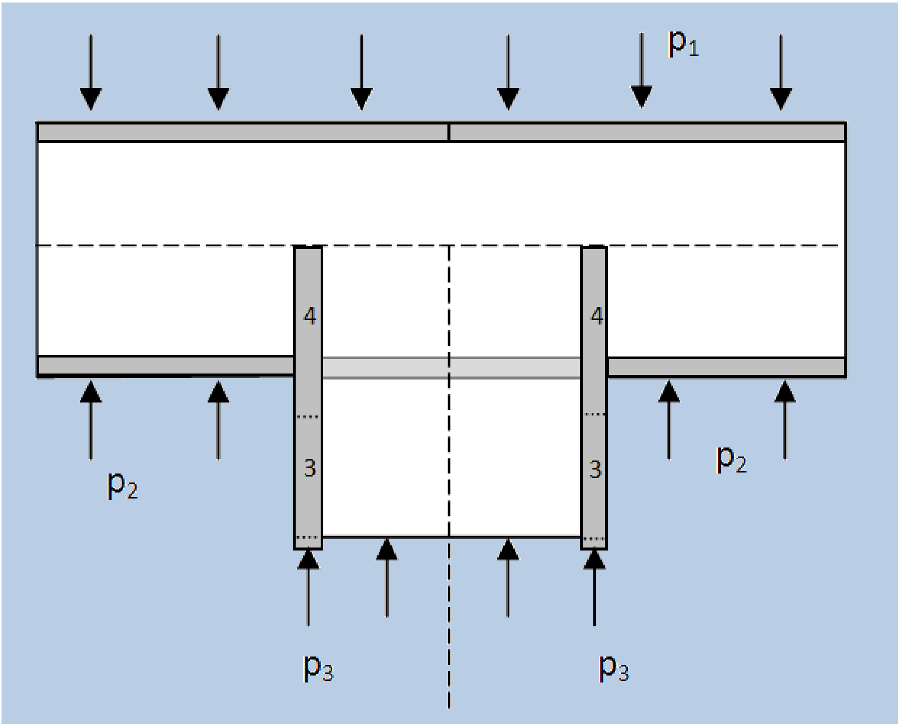

Figure 4-3: Nacelle surrounded completely by water

However, for the real structure, there is no water on the underside of member 3. This means that there isn't a complete pressure integral around the sealed members as illustrated in Figure 4-4.

The resultant vertical hydrostatic force <u>on the sealed members</u> can be most easily calculated by considering the area that is *not* surrounded by water, and the total nacelle volume.

$$\begin{aligned}&\text{Hydrostatic force on sealed members}\\&\qquad = \rho g * [\text{nacelle volume} - Z_{\text{M3End1}} * \pi(r^2 - (r-t)^2)]\end{aligned} \tag{4-3}$$

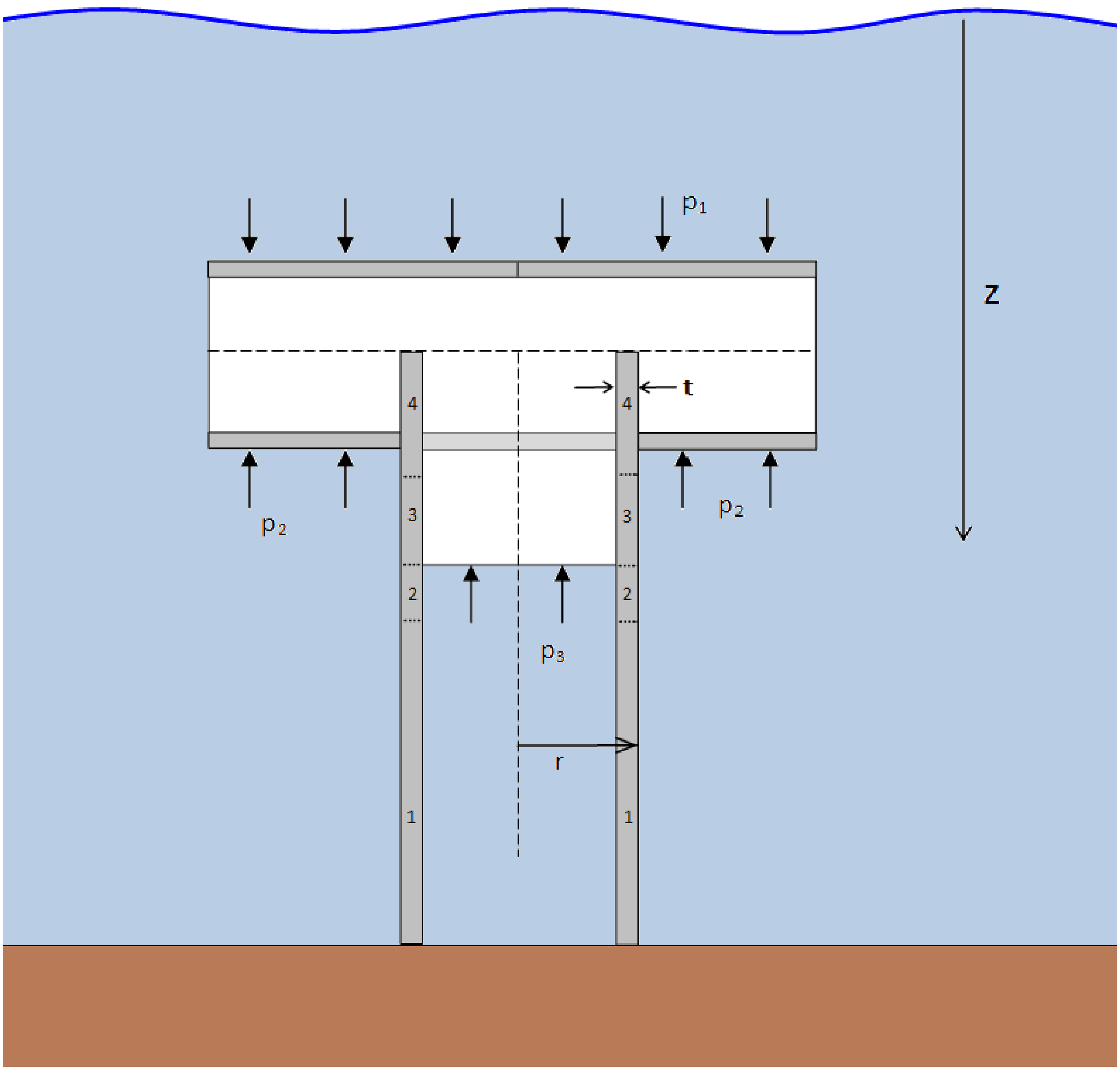

Figure 4-4: Nacelle and support structure hydrostatic pressure

4.2.2 Axial force in monopile

The axial force in the monopile can be derived by considering free body diagrams either side of the sealed-unsealed interface.

4.2.2.1 Axial force in Member 2

To calculate the load in Member 2, consider the free body diagram in Figure 4-5.

Note that there is pressure on the whole underside of the nacelle assembly except for the steel area of Member 2.

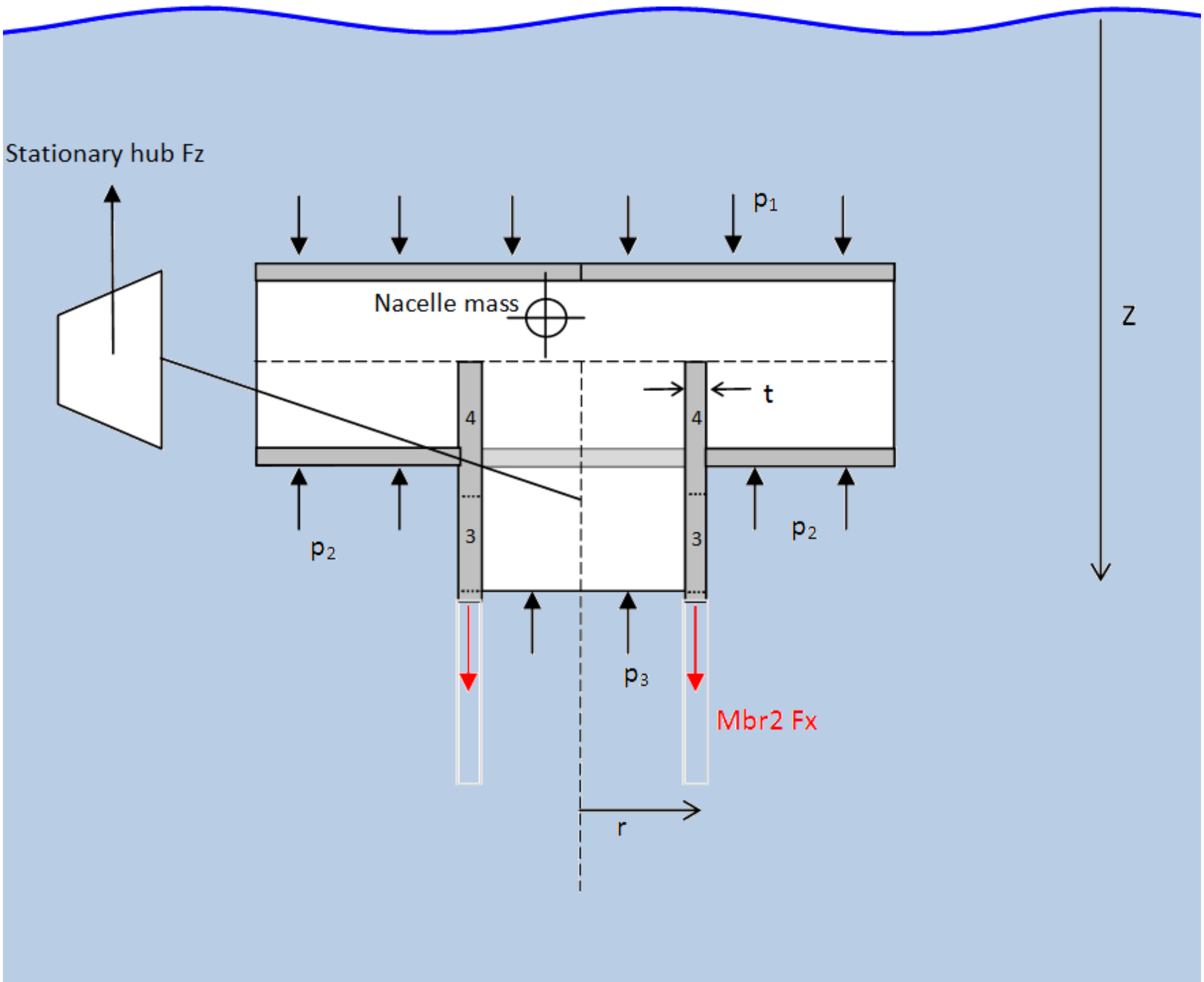

Figure 4-5: Free body diagram to calculate load in Mbr2

By equilibrium, the axial force in Member 2 is calculated

$$\mathrm{Fx}_{\mathrm{M2}} = \rho\mathrm{g}(\mathrm{nac\ vol} - \mathrm{Z}_{\mathrm{M2E2}} * \pi(r^2 - (r-t)^2)) - \mathrm{g} * \mathrm{nac\ mass} + \mathrm{Stat\ Hub\ Fz} \qquad (4\text{-}4)$$

4.2.2.2 Axial force in Member 3

To calculate the load in Member 3 End 1, consider the free body diagram in Figure 4-6.

Note that there is pressure on the whole underside of the nacelle assembly except for the whole cross-sectional area of Member 3.

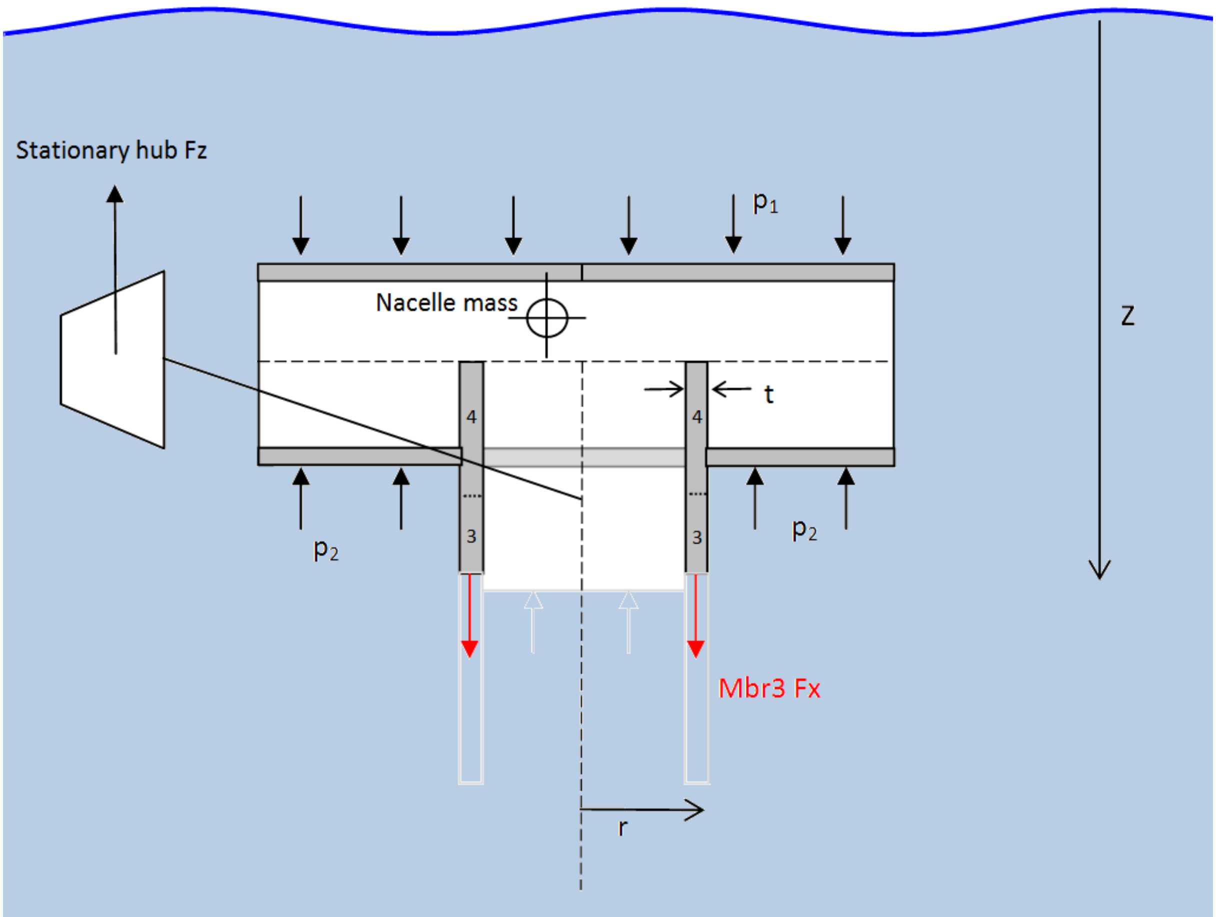

Figure 4-6: Free body diagram to calculate load in Mbr3

By equilibrium, the axial force in Member 3 is calculated.

$$Fx_{M3} = \rho g(\text{nac vol} - Z_{M3E1} * \pi\, r^2) - g * \text{nac mass} + \text{Stat Hub Fz} \qquad (4\text{-}5)$$

4.2.2.3 Change in load over sealed – unsealed interface

The difference in the load at Member 2 and Member 3 can be calculated subtracting equations (4-4) and (4-5).

$$\text{Change in axial load} = \rho g * Z_{M2E2} * \pi(r - t)^2 \qquad (4\text{-}6)$$

Note that this result is identical to that in equation (4-1).