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RELIABILITY IN A SEA OF RISK

Welcome to Day 2

The VMEA Framework in Practice

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Day 2 Agenda

Day 2: 08:00-12:30

08:00 *Arrival*

08:30 Review of day 1

08:45 Case study: Moorings and foundations

09:30 Coffee break

10:00 Case study: Structural component

11:00 Case study: Electrical component

12:00 Summary of Key learning points

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Day 1 Review

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Case Study: Moorings and foundations

Andy Shanks, Project Manager
EMEC

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Contents

- EMEC within RiaSoR
- Foundations
- Moorings
- Design process
- Uncertainty in the design process
- The Safety Factor Issue
- VMEA approach
- EMEC Case study

EMEC within RiaSoR

EMEC focussed on the connection of a device to the seabed – **why?**

- A common feature to every developer on every site
- Often not core to a developers business
- A significant part of the cost of a project
- An area that non-developers can help in progressing and refining

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Foundations for Marine Energy Converters

A range of styles and approaches previously used at EMEC

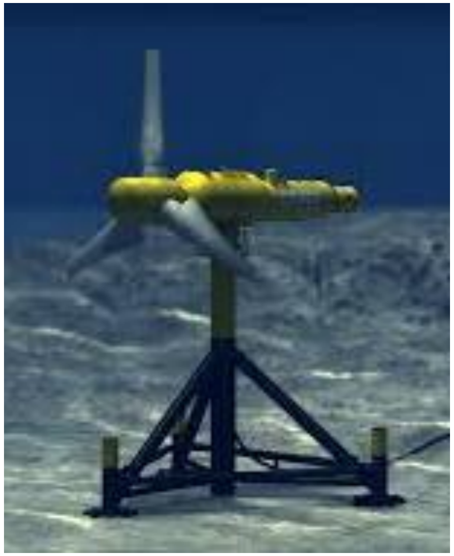
Monopile

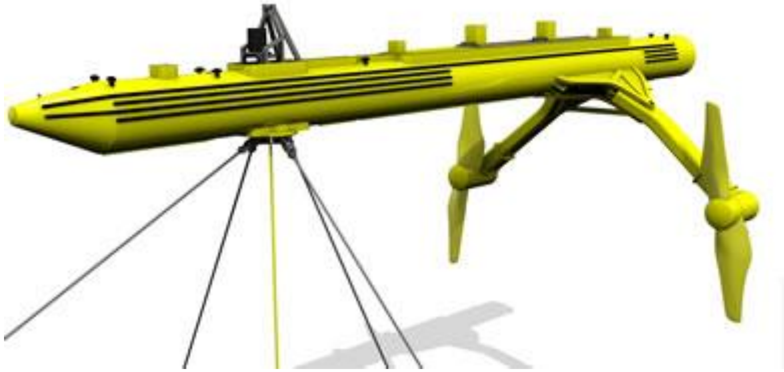
Gravity Tripod

Piled Tripod

A Focus on moorings

There is a general move within the testing underway at EMEC, away from devices fixed to solid foundations, and towards floating devices with moorings.





EMEC case study within RiaSoR <u>focuses on moorings</u>

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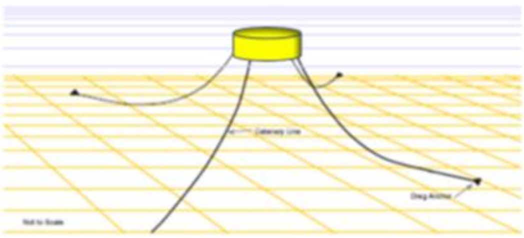
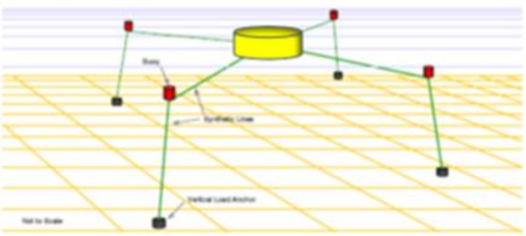
Types of moorings

- Many different styles and compositions, suited to different application and seabed types
- EMEC have seen both various systems used
- Catalogue of mooring types created as part of RiaSOR

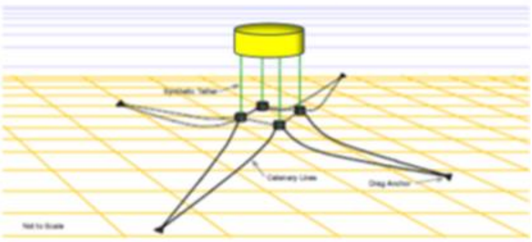
1. Conventional Chain Catenary Mooring



6. Buoy Mooring with Vertical Load Anchors



8. Multi-Tether "Admiralty Type" Mooring



Mooring design process

Inputs
Environmental, operational, equipment

↓

Model
Mooring analysis software (OrcaFlex/Optimoor etc)

↓

Outputs
Spectrum of loads on mooring components, movements and behavior of device

↓

Specifications
Minimum strength of mooring components

↓

Survivability and usability assessment
For mooring component selection

↓

Procurement
For mooring components

Mooring design uncertainty

Uncertainties at each step of the design process

complex and aggressive environments; difficult to measure, and then model accurately

Very variable conditions within deployment sites introduces risk of under or over estimation of forces

New techniques and materials being used, so no data available on rates of wear

The “Safety Factor Issue”

- A high level of uncertainty, leads to high safety factors and over-specified designs
- EMEC intend to develop the understanding of the uncertainties by relating it them to their contribution to the overall safety factor
- Scope for reducing uncertainties and costs through testing and measuring programmes – guided by VMEA analysis

VMEA - a range of solutions

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VMEA (Variation Mode and Effect Analysis)

Product Development

Concept Phase

Basic VMEA
Only limited information is available

- Select among design concepts.
- Choose a design alternative which is robust to variation.

Example:
Evaluate the AC power transmission supply alternatives:
• Hydraulic • Electric • Belt

Use engineering judgment to evaluate the variation sizes by using a simple ranking system.

Conclusions:
Choose Belt alternative.

Design Phase

Enhanced VMEA
More information is available

- Better information on the sources of variation.

Example:
Compare different designs using a Belt.
Judge the sizes of the variation sources and their sensitivity to the failure of the Belt

		Variation size (1-10) σ_i	Sensitivity (1-10) α_i	Variation number $\alpha_i^2\sigma_i^2$
T	Temperature	8	2	256
P	Tension	8	10	6400
Δ	Tolerance	3	1	9
W	Wear	6	8	2304
	Total variation = $\sum_i \alpha_i^2\sigma_i^2$ = 8969			

Result:
Choose a design with low "Total variation"

Detailed Design Phase

Probabilistic VMEA
More detailed information about the structure and the sources of variation

- Assign statistical variances to the different sources.
- Evaluate the physical property, e.g. time to failure.

Example:
Evaluate the variation in life, N, of the most attractive design.

$$\ln(N) = f(T, P, \Delta, W) = f(x_1, x_2, x_3, x_4)$$

$$c_i = \frac{\partial_i f}{\partial x_i}, \quad \tau_i^2 = Var(x_i)$$

		Variation size τ_i	Sensitivity c_i	Variation $c_i^2\tau_i^2$
T	Temperature	0.28	1.1	0.09
P	Tension	0.22	3.8	0.70
Δ	Tolerance	0.08	0.5	0.002
W	Wear	0.16	3.4	0.30
	Var(ln(N))= $\sum_i c_i^2\tau_i^2$ = 1.09			

Result:
Uncertainty in predicted life of the Belt.
To improve the reliability, it would be most efficient to Improve the Tension properties.

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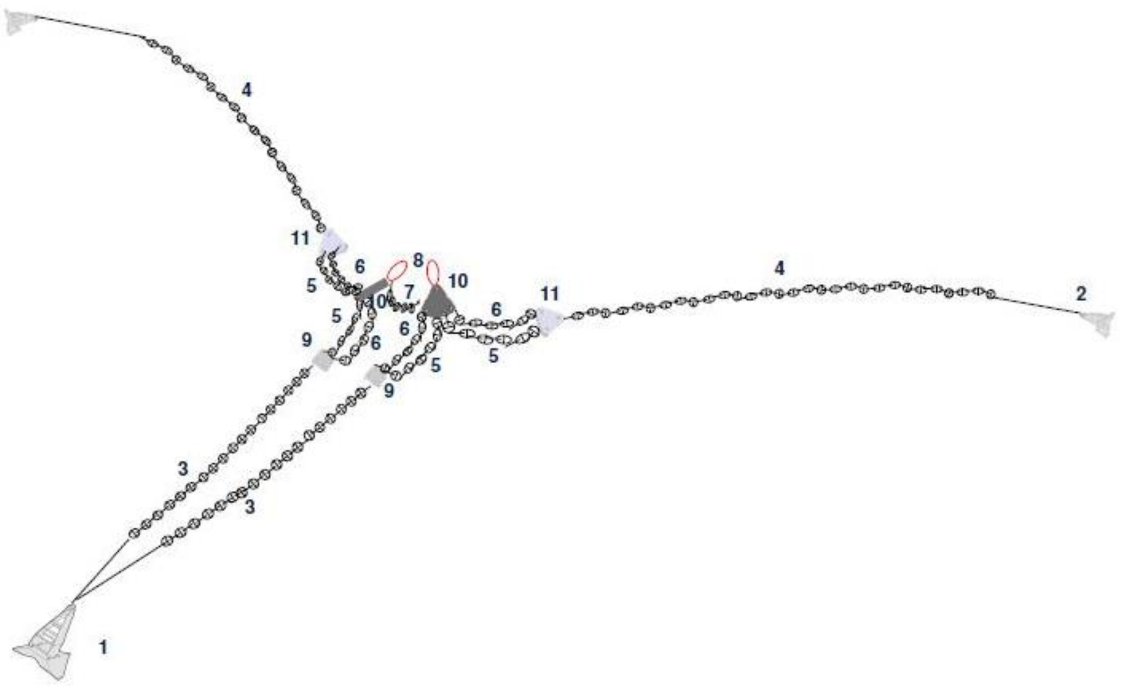
Pelamis Case Study

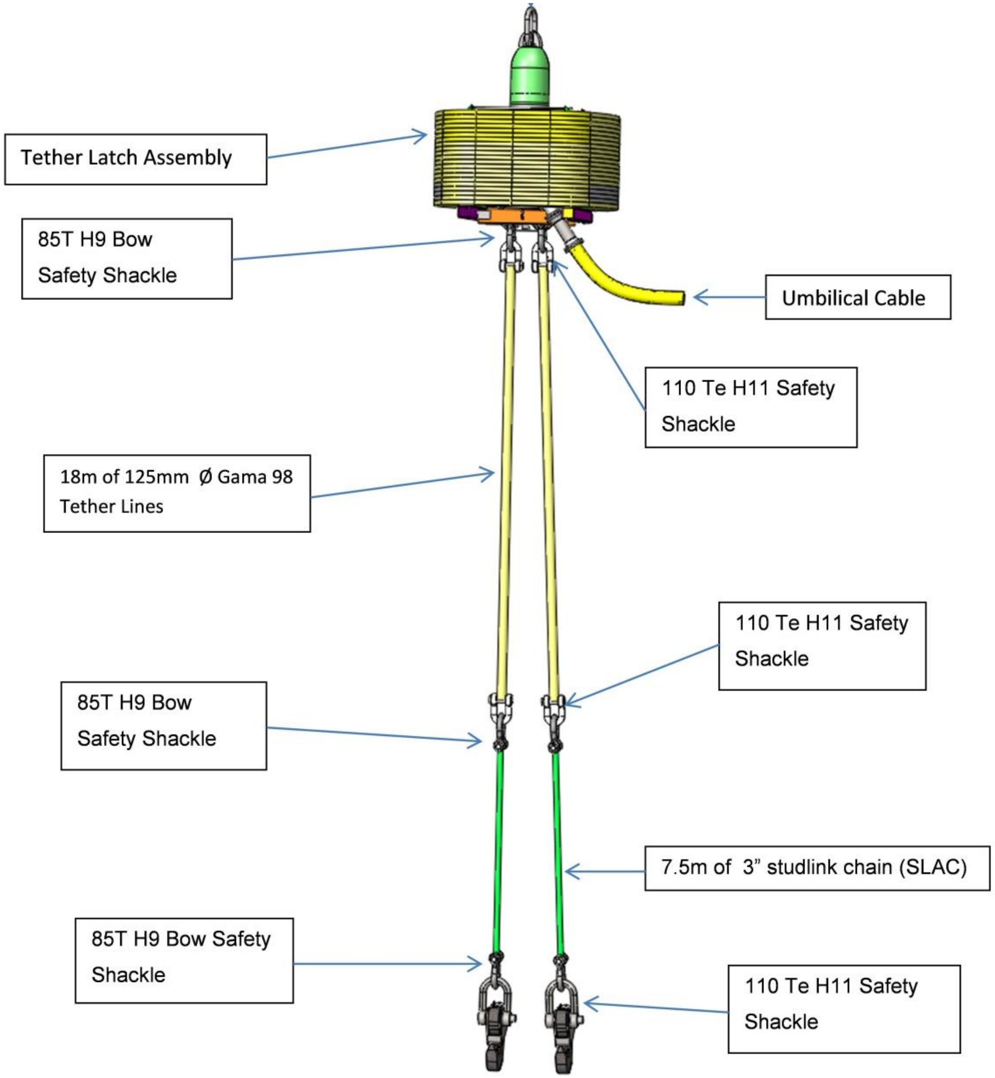
Pelamis P2001 device, in position at EMEC test site

Pelamis moorings



The bulk of the Pelamis P2001 mooring system was comprised of an “Admiralty type mooring pattern”, using drag/embedment anchors, ground chain, and (not shown) clump weights

Pelamis moorings

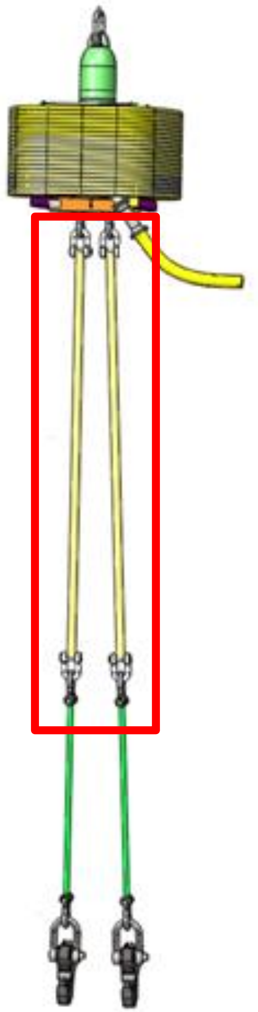


The connection between the ground chain and the device was formed using several bespoke items including chain hooks, tethers, and a midwater buoy that combined mechanical with electrical connections, as well as some more standard components and shackles.

This case study focussed on investigating the more unique sections, as they were comparatively unproven in the sector, leading to greater uncertainty as to their wear rates, and life expectancy

Pelamis uncertainties

- The uncertainty within the wear rate of the tether is only one variable in a larger array of unknowns, which is the building blocks of the basic VMEA



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Basic VMEA (1)

	Input		Results		
Modelling uncertainties	Sensitivity	Uncertainty	Uncertainty	VRPN	Proportion
Model detail of device	5	6	30	900	7
Model detail of mooring/foundation	3	6	18	324	2
Accuracy of modelling environmental data - wave	7	6	42	1764	13
Accuracy of modelling environmental data - wind	2	4	8	64	0
Accuracy of modelling environmental data - tide	3	5	15	225	2
Seabed conditions, and seabed stability	4	3	12	144	1
Design uncertainties					
Interation between moorings/foundation and seabed	4	8	32	1024	8
Ultimate loads seen by device (100 year storm)	5	8	40	1600	12
Fatigue loads seen by device (20 year working life at rated power)	5	9	45	2025	15
Measured metocean data not representative due to short sample period	1	5	5	25	0
Measured metocean data not representative due to distance from final site	4	7	28	784	6
In operation uncertainties					
Failure rate of surface connections and midwater shackles	6	7	42	1764	13
Failure rate of long term mooring shackles on seabed	2	7	14	196	1
Failure rate of bespoke tethers	7	7	49	2401	18
			380	13240	100

Example of Basic VMEA upon Pelamis moorings

Basic VMEA (2)

	Input		Results		
Modelling uncertainties	Sensitivity	Uncertainty	Uncertainty	VRPN	Proportion
Model detail of device	5	6	30	900	7
Model detail of mooring/foundation	3	6	18	324	2
Accuracy of modelling environmental data - wave	7	6	42	1764	13
Accuracy of modelling envi	2	4	8	64	0
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Measured metocean data not representative c to short sample period				25	0
Measured metocean data not representative c to distance from final site	4	7	28	784	6
In operation uncertainties					
Failure rate of surface connections and midwater shackles	6	7	42	1764	13
Failure rate of long term mooring shackles on seabed	2	7	14	196	1
Failure rate of bespoke tethers	7	7	49	2401	18
			380	13240	100

The level of impact on safety factor that each line item has.

The uncertainty in measurement/modelling of each line item

Explanation of Basic VMEA inputs

Basic VMEA (3)

	Input		Results		
Modelling uncertainties	Sensitivity	Uncertainty	Uncertainty	VRPN	Proportion
Model detail of device	5	6	30	900	7
Model detail of mooring/foundation	3	6	18	324	2
Accuracy of modelling environmental data - wave	7	6	42	1764	13
Accuracy of modelling environmental data - wind	2	4	8	64	0
Accuracy of modelling environmental data - tide	3	5	15	225	2
Seabed conditions, and seabed stability	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Design uncertainties					
Interation between moorings/foundation and seabed	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ultimate loads seen by device (100 year storm)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Fatigue loads seen by device (20 year working life at rated power)	[illegible]	[illegible]	[illegible]	[illegible]	15
Measured metocean data not representative du[illegible] to short sample period	[illegible]	[illegible]	[illegible]	[illegible]	0
Measured metocean data not representative due to distance from final site	4	7	28	784	6
In operation uncertainties					
Failure rate of surface connections and midwater shackles	6	7	42	1764	13
Failure rate of long term mooring shackles on seabed	2	7	14	196	1
Failure rate of bespoke tethers	7	7	49	2401	18
			380	13240	100

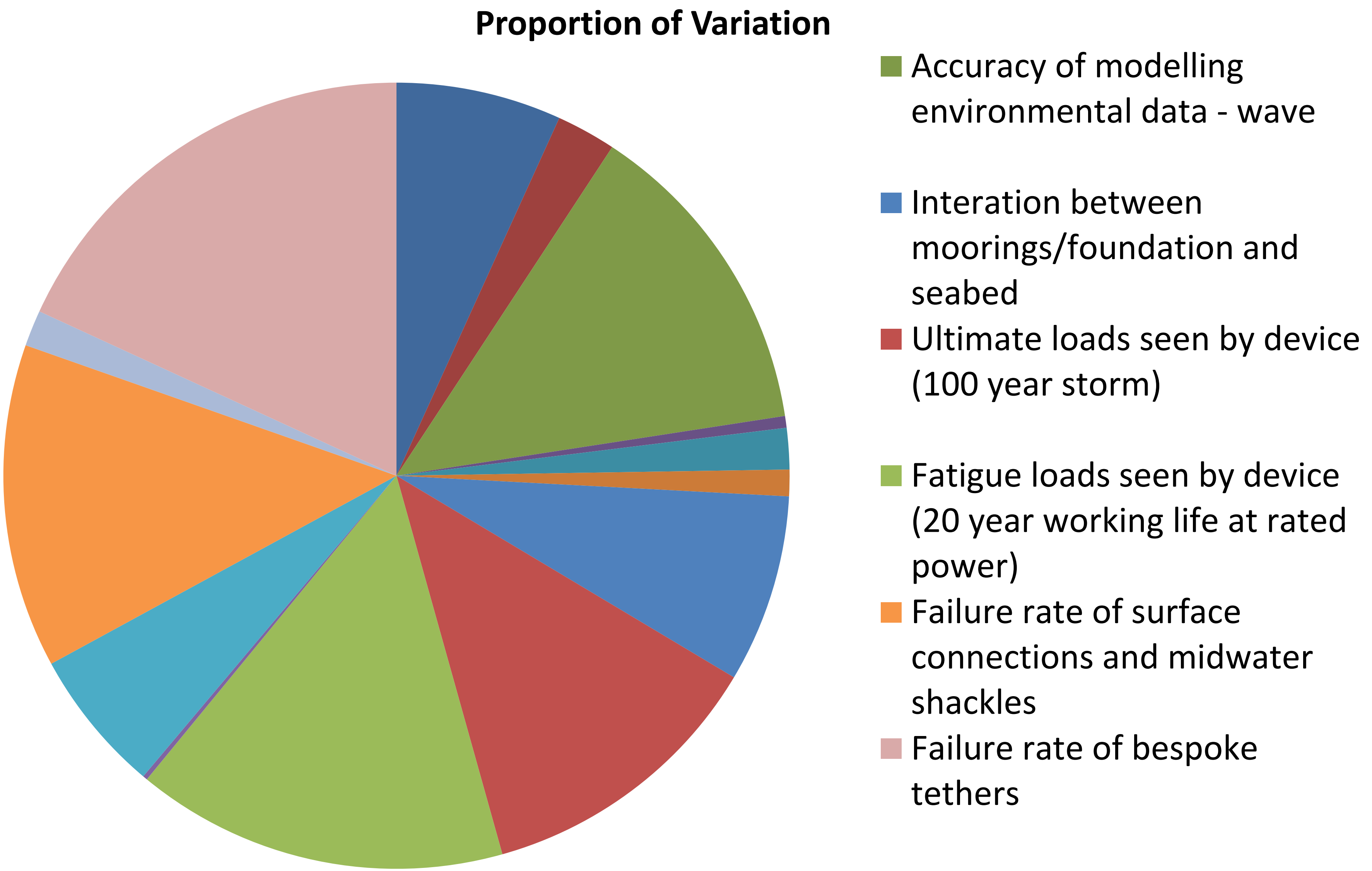
The combination of the input sensitivity and the input uncertainty. Gives a weighted uncertainty, showing how important it is to the overall design

The percentage of the total uncertainty that each line item represents.

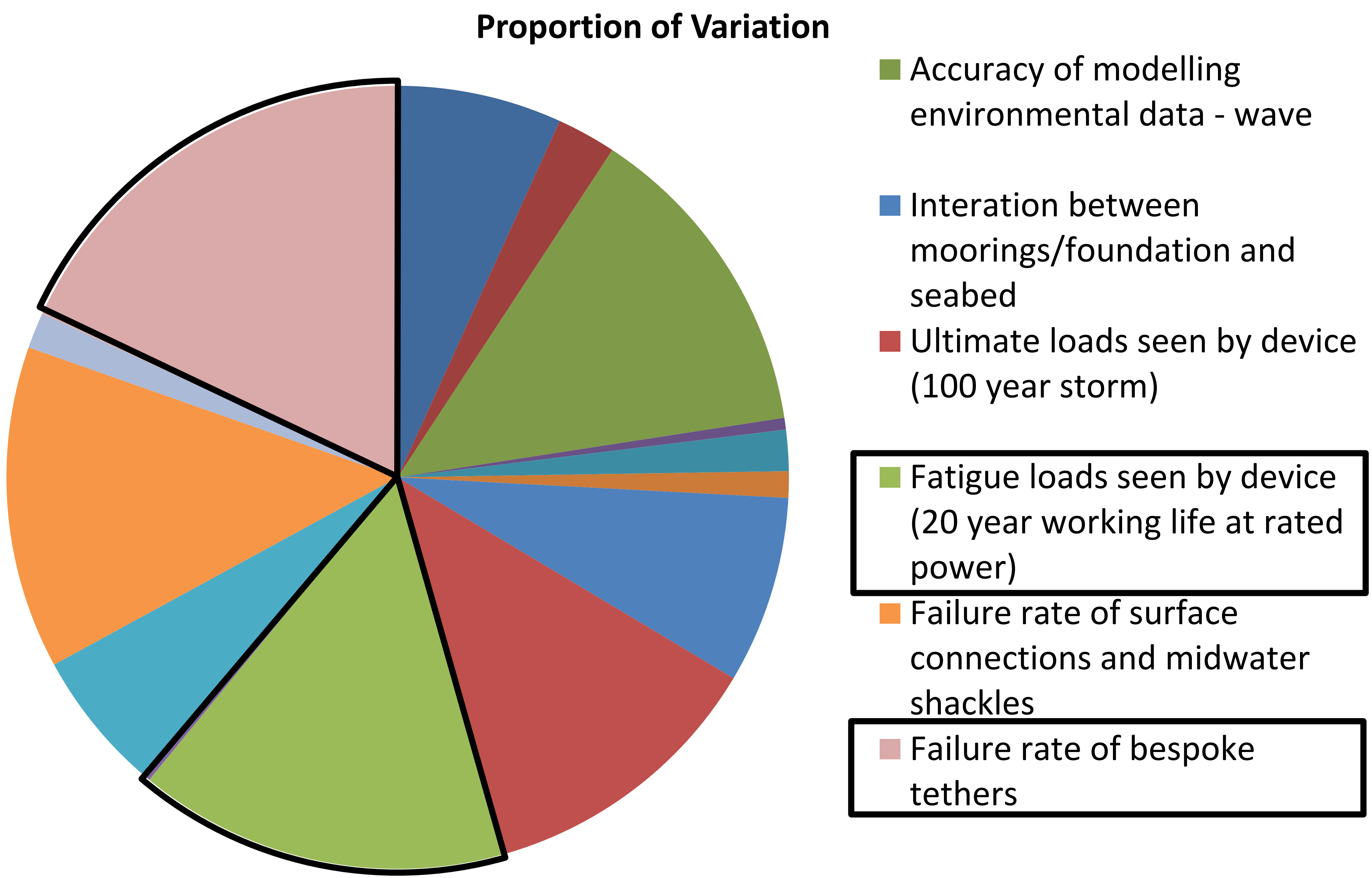
Second order weighting

Explanation of Basic VMEA outputs

Basic VMEA (4)


Proportion of Variation
Accuracy of modelling environmental data - wave
Interation between moorings/foundation and seabed
Ultimate loads seen by device (100 year storm)
Fatigue loads seen by device (20 year working life at rated power)
Failure rate of surface connections and midwater shackles
Failure rate of bespoke tethers

Basic VMEA (5)


Proportion of Variation
Accuracy of modelling environmental data - wave
Interation between moorings/foundation and seabed
Ultimate loads seen by device (100 year storm)
Fatigue loads seen by device (20 year working life at rated power)
Failure rate of surface connections and midwater shackles
Failure rate of bespoke tethers

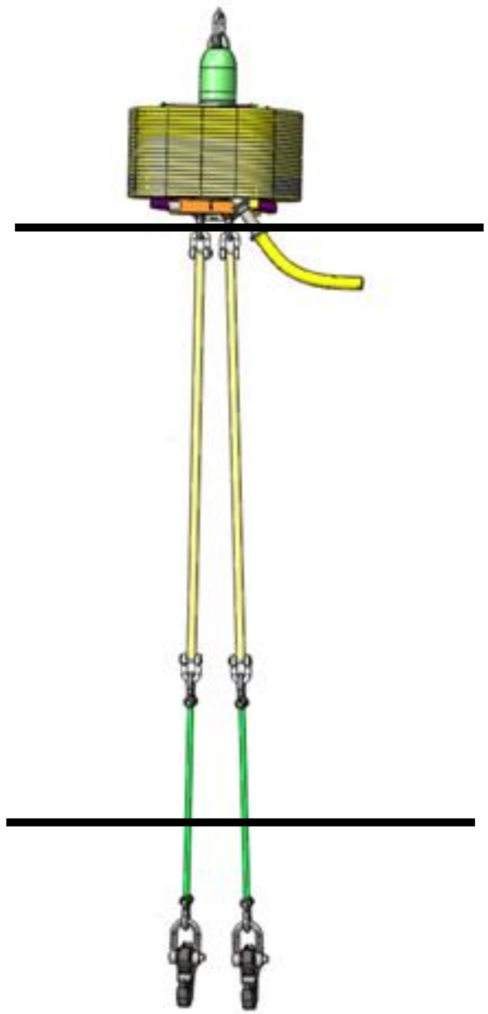
Basic VMEA (6)

	Input		Results		
Modelling uncertainties	Sensitivity	Uncertainty	Uncertainty	VRPN	Proportion
Model detail of device	5	6	30	900	7
Model detail of mooring/foundation	3	6	18	324	2
Accuracy of modelling environmental data - wave	7	6	42	1764	13
Accuracy of modelling environmental data - wind	2	4	8	64	0
Accu					
Seab					
Desi					
Interaction between moorings/foundation and seabed	4	8	32	1024	8
Ultimate loads seen by device (100 year storm)	5	8	40	1600	12
Fatigue loads seen by device (20 year working life at rated power)	5	9	45	2025	15
Measured metocean data not representative due to short sample period	1	5	5	25	0
Measured metocean data not representative due to distance from final site	4	7	28	784	6
In operation uncertainties					
Failure rate of surface connections and midwater shackles	6	7	42	1764	13
Failure rate of long term mooring shackles on seabed	2	7	14	196	1
Failure rate of bespoke tethers	7	7	49	2401	18
			380	13240	100

Chosen improvement areas: Condition monitoring of deployed moorings, with a focus on bespoke tethers, surface connections, and midwater shackles

Reducing uncertainty through break testing of decommissioned moorings

Case Study results



Tethers and shackles out for detailed investigation, leading to a final break test – results to follow!

Further work

Moving from basic VMEA towards probabilistic VMEA

Detailed dissection of a design process extracting actual safety factors

Not captured within RiaSoR, but included in the scope of work for RiaSoR 2

Beehive! Discuss…

What do you think are the main reliability issues for moorings?

Which areas would you like to see more work done on?

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Coffee Break

09:30 – 10:00

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Case Study: Structural component

Thomas Svensson, PhD

SP Technical Research Institute of Sweden

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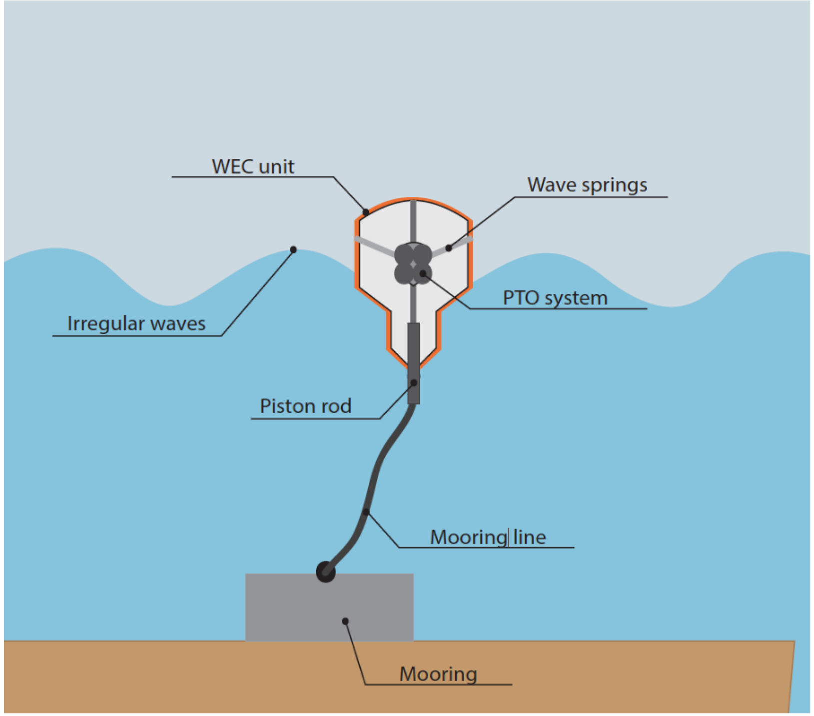
Fatigue strength for a piston rod



We study the fatigue strength of a ***piston rod*** that is subjected to both tensile and bending induced stresses transforming buoy movements to the mooring line.

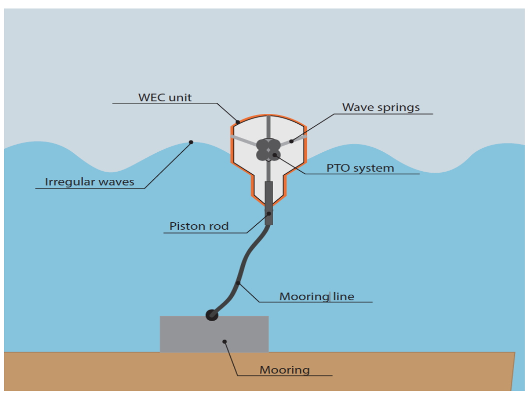
The main engineering tools in this application are

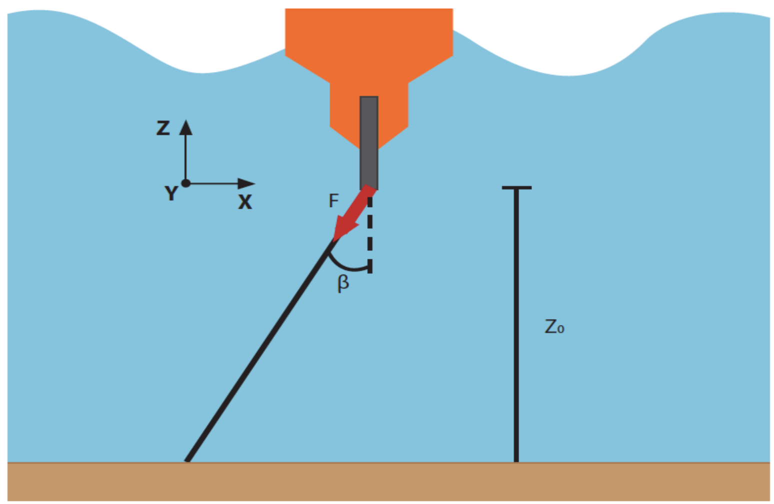
1. a hydrodynamic numerical tool,
2. a finite element numerical tool, and
3. a fatigue model.

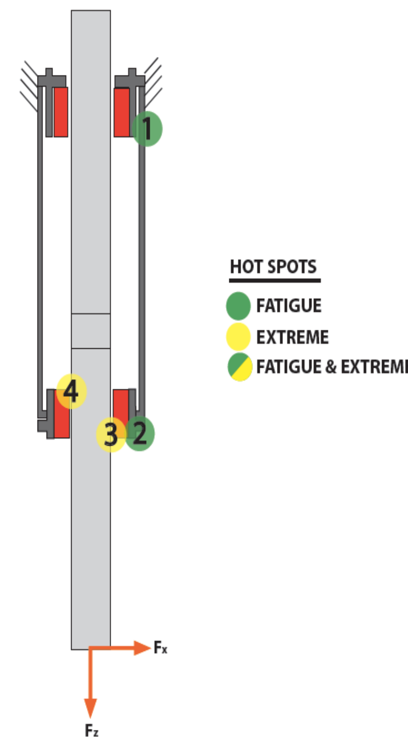
Strength calculation, overview

standard tools | Hydrodynamic model data reduction | FEM model | Wöhler curve + corrections

Waves → ***Hs Tp*** → ***Fx, Fz*** → ***von Mises stresses*** → ***fatigue strength***







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Uncertainty sources

Waves ⟶ *Hs/Tp* — standard tools

Relevance of Hf, Tp.
Measurement uncertainties
Statistical uncertainty
Possible sampling error
Site variation

Hf/Tp ⟶ Fx,Fz — hydrodynamic model

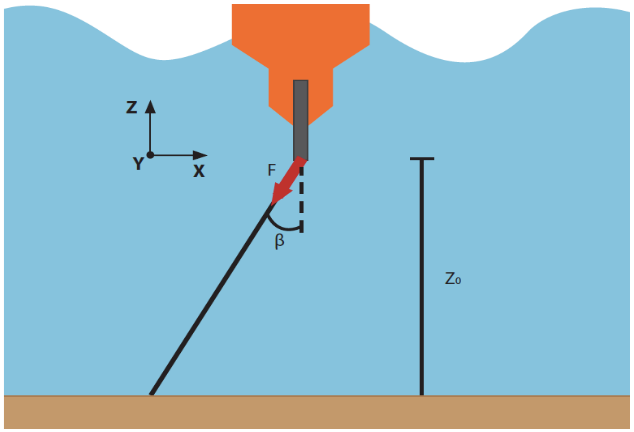
Possible model errors
Initial conditions
Marine growth
Data reduction bias

Fx, Fz ⟶ von Mises stresses — FEM model

Possible FEM-model errors

von Mises stresses ⟶ *fatigue strength* — Wöhler curve

Relevance of von Mises stress
Fatigue scatter
Statistical uncertainty
Wöhler curve relevance
Corrosion adjustment error
Peripheral distr. correction error
Palmgren-Miner rule for damage accumulation

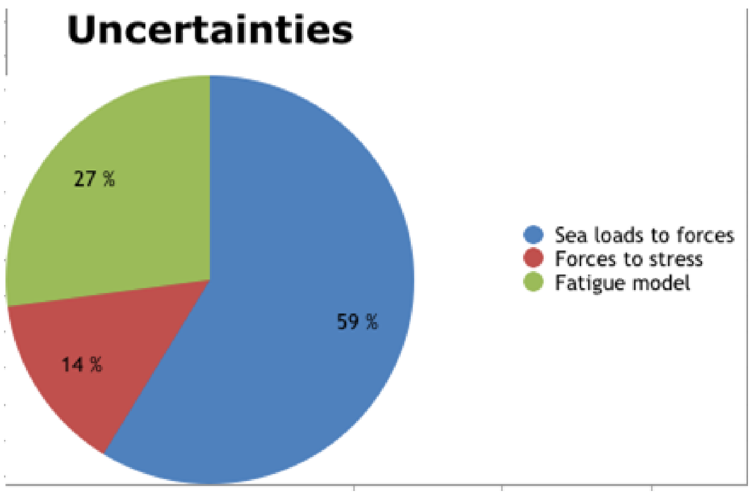


An initial assessment, a basic VMEA

A meeting at the developers office worked out a basic VMEA.

The dominating uncertainties were identified:

1. Uncertainty in the design (connection solution)
2. Model error in hydrodynamic model
3. Variation between sites
4. Influence of threads (stress intensity factor)



Input			Result		
Uncertainty components	Sensitivity (1-10)	Variation (1-10)	Resulting variation Variation	Variation contribution VRPN	Portion
Sea loads to forces					
- Estimation of sea states	5	3	15	225	2 %
- Variation within site	5	2	10	100	1 %
- Variation between sites	5	7	35	1225	12 %
- Neglected loads (wave direction, current, ...)	2	4	8	64	1 %
- Model error, calculation	5	8	40	1600	16 %
- Marine growth (increase loads?)	5	4	20	400	4 %
- Connection (flexible?)	7	7	49	2401	23 %
- System degeneration (may increase forces)	0	3	0	0	0 %
Total Sea loads to forces			**78**	**6015**	59 %
Forces to stress					
- FEM, stiffness	5	3	15	225	2 %
- FEM, simplified model	5	6	30	900	9 %
- FEM, mesh	5	2	10	100	1 %
- Position (low-mid-high)	5	3	15	225	2 %
- Model simplifications	0	5	0	0	0 %
Total Forces to stress			**38**	**1450**	14 %
Fatigue model					
- Fatigue strength, scatter	5	3	15	225	2 %
- Fatigue strength, uncertainty	5	6	30	900	9 %
- Wöhler slope	2	5	10	100	1 %
- multiaxial effects	2	5	10	100	1 %
- stress intensity factor	5	7	35	1225	12 %
- Equivalent load sequence	5	3	15	225	2 %
Total Fatigue model			**53**	**2775**	27 %
Total uncertainty			**101**	**10240**	100 %

Next step, extend to enhanced VMEA

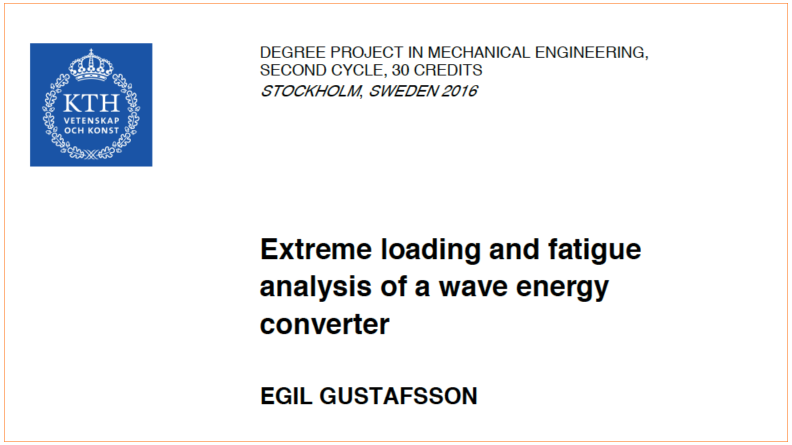
The Basic VMEA only gives a qualitative picture but no information of safety limits.

The Basic VMEA indicates which are the dominating uncertainty sources.
In order to find proper safety limits, these sources must be ***physically quantified***, which is the aim with the ***enhanced VMEA***.

We lack detailed knowledge about all components in the life assessments, but use a recent master thesis as a starting point.

In the thesis, the fatigue life of the piston rod has been studied.

The study is based on a ***specific solution*** for the connection to the mooring line and performed by using an in-house program for the hydrodynamics and a commercial Finite Element program for both stress analysis and fatigue calculations.


DEGREE PROJECT IN MECHANICAL ENGINEERING,
SECOND CYCLE, 30 CREDITS
STOCKHOLM, SWEDEN 2016

Extreme loading and fatigue analysis of a wave energy converter

EGIL GUSTAFSSON

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An enhanced VMEA

Input						Result		
Uncertainty components	scatter	uncert.	Sensitivity coefficient c	t-correction factor t	standard deviation s	Scatter	Unce	
Strength								
Scatter	x		1.000	1.0	0.250	0.250		
Fatigue strength specification		x	3.000	1.0	0.120			
Adjustment uncertainty CA/VA		x	1.000	1.0	0.100			
Mean value influence		x	1.000	1.0	0.100			
Total Strength uncertainty						**0.250**		
Load								
Model error in hydrodynamic model.		x	3.000	1.0	0.087			
Variation within sites	x		3.000	1.0	0.012	0.036		
Marine growth		x	3.000	1.0	0.029			
Variation between sites	x		3.000	1.0	0.120	0.360		
Simplification in the Finite Element Method		x	3.000	1.0	0.029			
Total Load uncertainty						**0.362**		
Total uncertainty						**0.440**	**0.483**	**0.653**

1. Define a target function
2. List uncertainty components
3. Quantify their uncertainty by means of standard deviations
4. Find their sensitivity to the actual target function
5. Evaluate a proper safety factor

Reliability Evaluation

Input		Result	
Median life (days)	640	Safety factor	0,88
Target life (days)	730		

Result (log-scale)	
Life	6,46
Target life	6,59
Distance	-0,13

Evaluation - Extra safely factor			
		Variation safety factor	2,92
Required extra safety factor	2	Extra safety factor	0,30

Variation dist.	1,07
Extra dist.	-1,20

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The actual target function

The target for this equipment is that the life should exceed two years in service.

We then choose the target function

$$\ln(N_{nom}) - \ln(N_{target})$$

that for a reliable structure should fulfil

$$\ln(N_{nom}) - \ln(N_{target}) > \delta_S + \delta_E$$

The extra safety distance δ_E is chosen to be 0.7 in this case (*a factor* 2)

The statistical safety distance δ_S is found by studying all possible uncertainty sources in the life prediction.

Reliability Evaluation

Input		Result	
Median life (days)	640	Safety factor	0,88
Target life (days)	730		

Result (log-scale)	
Life	6,46
Target life	6,59
Distance	-0,13

Evaluation - Extra safely factor			
		Variation safety factor	2,92
Required extra safety factor	2	Extra safety factor	0,30

Variation dist.	1,07
Extra dist.	-1,20

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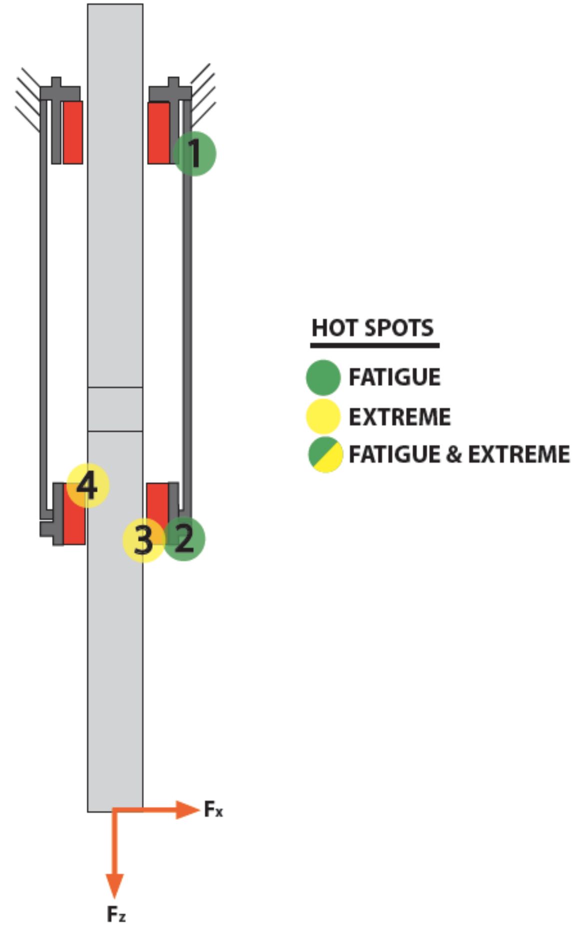
Find a relevant Wöhler curve

Two hot spots are identified. At both these locations the component is threaded, which is ***not modelled*** in the FEM solution.

In order to adjust for that, we have found experimental results for threaded bolts subjected to combined bending and tensile stress. However, the material is different and therefore, the transformation from pure material to threads is quite uncertain.



International Journal of Fatigue 72 (2015) 102–108

Contents lists available at ScienceDirect

International Journal of Fatigue

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Experimental characterization of the bending fatigue strength of threaded fasteners

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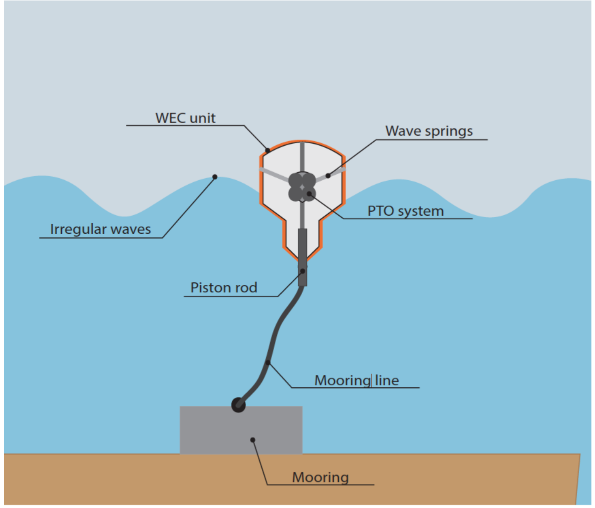
Circumferential distribution

The immediate calculated damage is probably exaggerated because of an expected circumferential distribution of stress.

Namely, the buoy may be assumed to rotate randomly between the load cycles. This means that at a certain circumferential point the severity of a specific bending load cycle is only $\cos\alpha \cdot F_a$, i.e. the amplitude of the cycle is reduced by the angle to the specific wave direction.



Assuming now that the angle is random in time and uniformly distributed, then the expected severity of a specific load cycle is

$$\frac{1}{\pi}\int_{-\pi/2}^{\pi/2} \cos\alpha \cdot F_a d\alpha = 0.64F_a$$

Since this is true for each load cycle, it means that the whole spectrum of cycles should be reduced by the factor 0.64 and the life be elongated by approximately a factor 4.

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RELIABILITY IN A SEA OF RISK

Quantify uncertainties and sensitivities 1

Input						Result		
Uncertainty components	scatter	uncert.	Sensitivity coefficient c	t-correction factor t	standard deviation s	Scatter	Uncertainty	Total
Strength								
Scatter	x		1.000	1.0	0.250	0.250		

From the illustration of the experimental result for threaded fasteners the standard deviation for the ***scatter*** can be estimated to 25% in life.

This is a rough estimate rounded upwards to account for uncertainty and the t-correction factor is then kept at unity.

The standard deviation is estimated in percentage life which has a one-to-one sensitivity to log life.

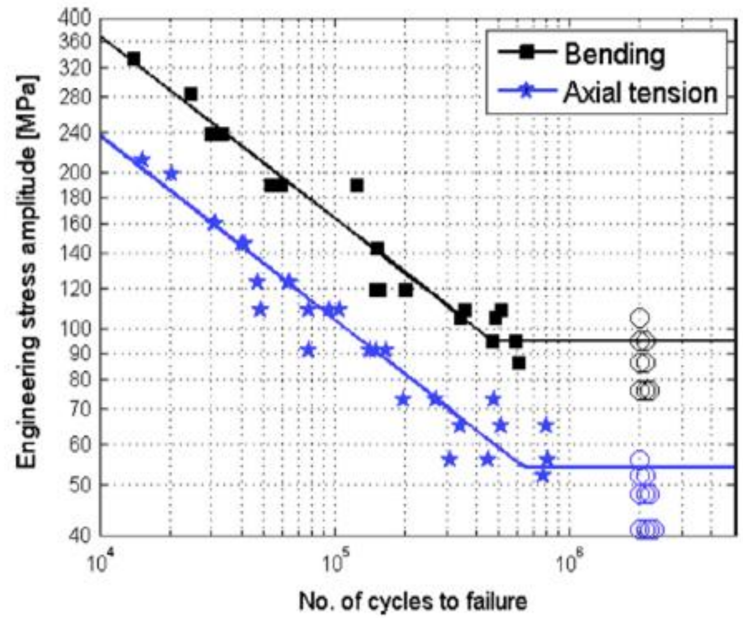

Fig. 10. Wöhler diagram showing the fatigue strength of M14/10.9 bolts, each marker corresponds to a tested specimen and run-outs are marked with circles.

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Quantify uncertainties and sensitivities 2

Input						Result		
Uncertainty components	scatter	uncert.	Sensitivity coefficient c	t-correction factor t	standard deviation s	Scatter	Uncertainty	Total
Strength								
Scatter	x		1.000	1.0	0.250	0.250		
Fatigue strength specification		x	3.000	1.0	0.120		0.360	

The nominal fatigue strength has here been estimated from another material than the actual and has been adjusted with respect to a few apparent differences. These adjustments are assumed to introduce at most 20% error in strength.

$$\frac{0.2}{\sqrt{3}} = 0.12$$

The strength is related to fatigue life through the Wöhler curve with slope 3, which gives the actual sensitivity coefficient.

$$N = \alpha \cdot \Delta\sigma^{-3}$$

$$\ln N = \ln\alpha - 3 \cdot \ln\Delta\sigma$$

$$\frac{\partial \ln N}{\partial \ln\Delta\sigma} = -3$$

Quantify uncertainties and sensitivities 3

Input						Result		
Uncertainty components	scatter	uncert.	Sensitivity coefficient c	t-correction factor t	standard deviation s	Scatter	Uncertainty	Total
Strength								
Scatter	x		1.000	1.0	0.250	0.250		
Fatigue strength specification		x	3.000	1.0	0.120		0.360	
Adjustment uncertainty CA/VA		x	1.000	1.0	0.100		0.100	
Mean value influence		x	1.000	1.0	0.100		0.100	
Total Strength uncertainty						**0.250**	**0.387**	**0.461**

Possible model error introduced by using the Palmgren-Miner cumulative damage accumulation law is judged to be 17% in life

$$\frac{0.17}{\sqrt{3}} = 0.1$$

Possible model error due to mean value influence is also judged to be 17% in life

$$\frac{0.17}{\sqrt{3}} = 0.1$$

Quantify uncertainties and sensitivities 4

Total Strength uncertainty						**0.250**	**0.387**	**0.461**
Load								
Model error in hydrodynamic model.		x	3.000	1.0	0.087		0.261	
Variation within sites	x		3.000	1.0	0.012	0.036		
Marine growth		x	3.000	1.0	0.029		0.087	
Variation between sites	x		3.000	1.0	0.120	0.360		
Simplification in the Finite Element Method		x	3.000	1.0	0.029		0.087	
Total Load uncertainty						**0.362**	**0.289**	**0.463**

The hydrodynamic model is not calibrated and is assumed to contain errors up to 15% in output force.

$$\frac{0.15}{\sqrt{3}} = 0.087$$

Variation in wave forces between sites and within site are estimated from experience to 20% and 2%, respectively, possible influence from marine growth to at most 5% and errors due to simplifications in the Finite Element analysis to 5%.

$$\frac{0.20}{\sqrt{3}} = 0.12 \qquad \frac{0.02}{\sqrt{3}} = 0.012$$

$$\frac{0.05}{\sqrt{3}} = 0.029 \qquad \frac{0.05}{\sqrt{3}} = 0.029$$

All these estimates have been done with respect to force giving the senstivity coefficient 3 from the actual Wöhler curve.

$$N = \alpha \cdot \Delta\sigma^{-3}$$

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Evaluate the reliability

Input		
Uncertainty components	scatter	uncert.
Strength		
Scatter	x	
Fatigue strength specification		x
Adjustment uncertainty CA/VA		x
Mean value influence		x
Total Strength uncertainty		
Load		
Model error in hydrodynamic model.		x
Variation within sites	x	
Marine growth		x
Variation between sites	x	
Simplification in the Finite Element Method		x
Total Load uncertainty		
Total uncertainty		

The estimated nominal life is 640 days

The target life is two years, 730 days

The ***actual*** safety factor is:

The total uncertainty evaluation demands a statistical safety distance,

which corresponds to the statistical safety factor,

$$\ln 640 = 6.46$$

$$\ln 730 = 6.59$$

$$\frac{640}{730} = 0.88$$

$$1.64 \cdot 0.653 = 1.07$$

$$e^{1.64 \cdot 0.653} = 2.92$$

Reliability Evaluation

Input		Result	
Median life (days)	640	Safety factor	0,88
Target life (days)	730		

Result (log-scale)	
Life	6,46
Target life	6,59
Distance	-0,13

Evaluation - Extra safely factor			
		Variation safety factor	2,92
Required extra safety factor	2	Extra safety factor	0,30

Variation dist.	1,07
Extra dist.	-1,20

The actual extra safety factor is

$$\frac{0.88}{2.92} = 0.30$$

Next step for the actual design…

…Redesign! The analysed preliminary solution is not satisfactory.

- Reduce uncertainties
- Find a more relevant strength specification
- Measure in service for calibration of the hydrodynamic model
- Refine the finite element analysis
- Specify severities of a limited number of sites

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Why VMEA?

Flexible tool that can be used from the initial design phase with limited access to data to full system analysis

Framework is generic, **simple** and applicable regardless of design and product

It identifies the critical points and the weakest links

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Thank you!

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