AAS-JAKOBSEN

Challenges in bridge design for the ferry-free E39 project in Norway.

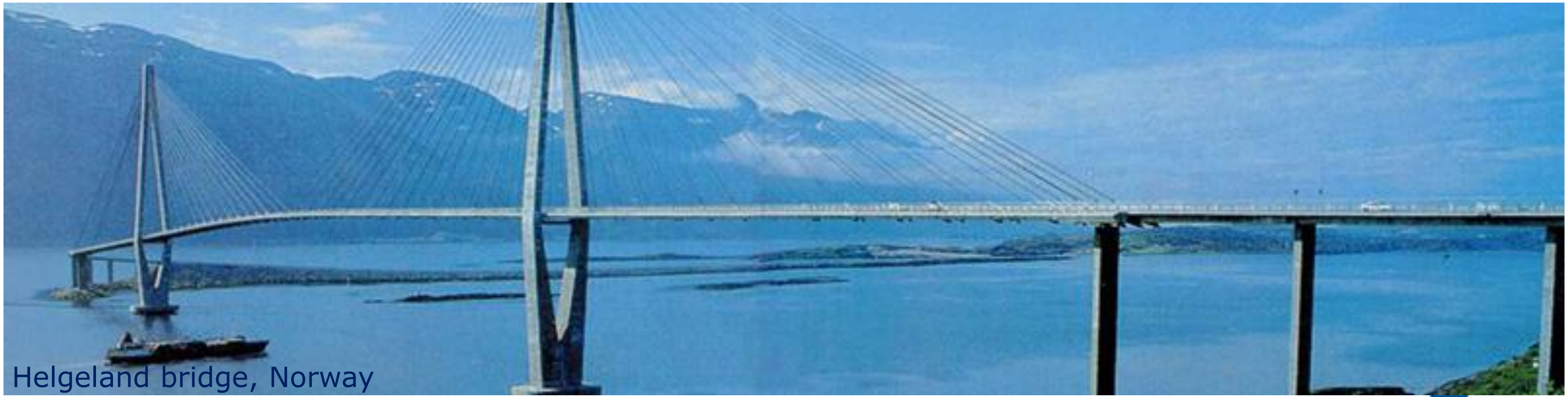
19th of March 2018

Content

Overview of Aas-Jakobsen

The E39 project – bridges

E39 – Challenges and solutions

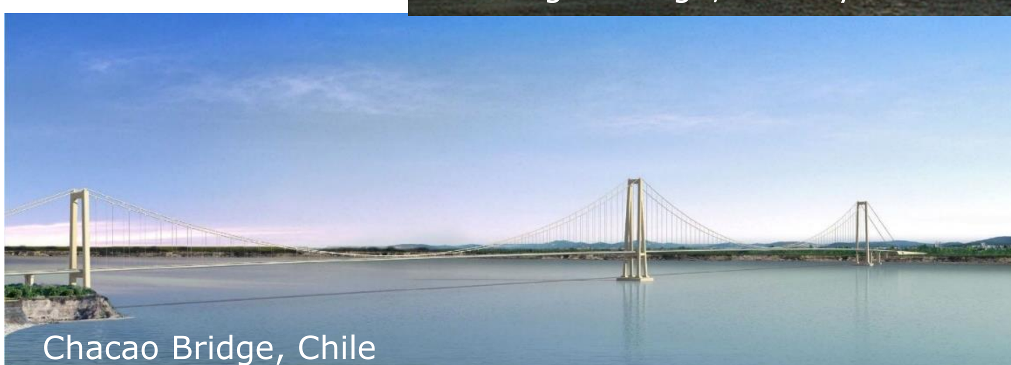


Helgeland bridge, Norway

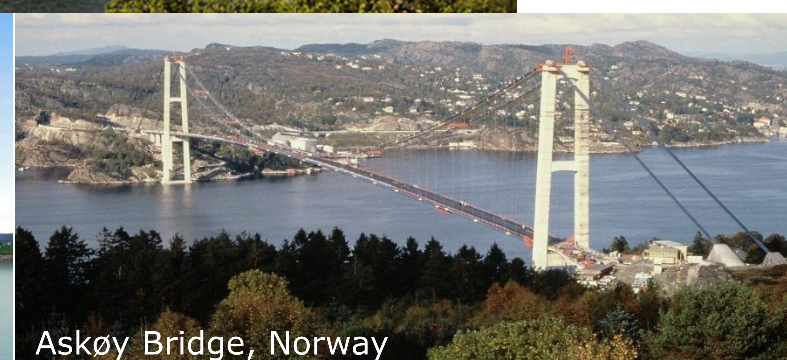
Introduction to Aas-Jakobsen – Bridge department

Bjørnafjorden Bridge, Norway

Hardanger Bridge, Norway



Chacao Bridge, Chile



Askøy Bridge, Norway

Key Data

Highly skilled

5% Ph.D. / 70 % M.Sc.

15 % B.Sc.

Turnover:
600 MNOK / 70M € (16)

Owners: Employees

Main office: Oslo (140), Norway

Trondheim (35), Bangkok (70)

Company structure

Bridge department
Infrastructure department
Building department
Marine department


Stonecutters. HK, checking team


Industrial Ring Road,


Storda and Bømla bridge


Nordhordaland

AAS-JAKOBSEN

Bridge experience

Cantilever

Floating

Network

Suspension

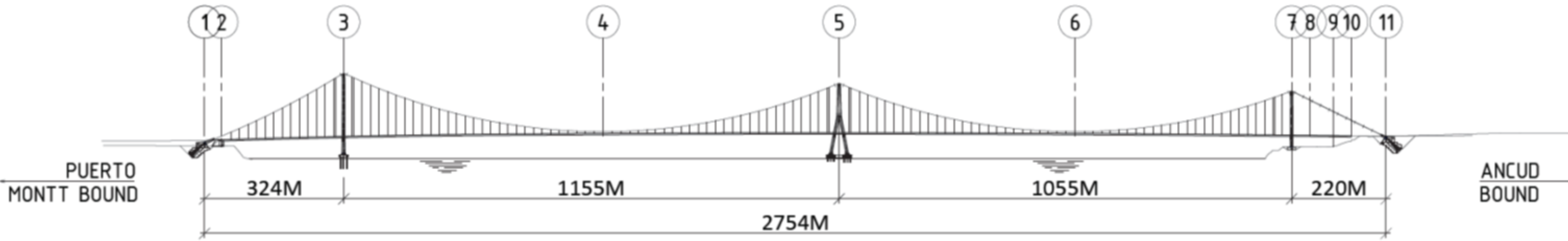
Cable stayed


Raftsundet, Norway

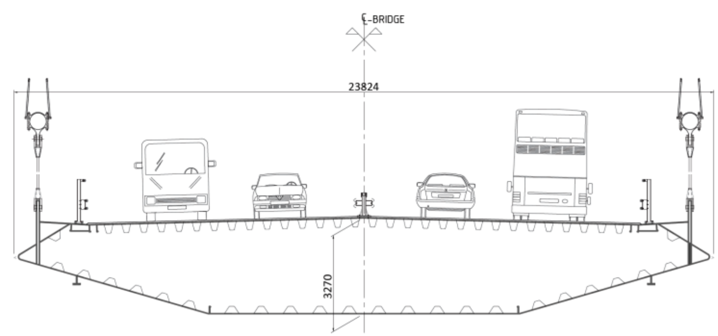

Nordhordalandsbrua, Norway


Brandangersundet, Norway

Chacao bridge - Chile



- Location: Chile
- Spans: 1155m + 1055m
- Pylon height: 157m-199 m
- Girder Dimension: 23.8m x 3.27m.
- Deck elevation: 50m
- U_10min_100y = 42.5 m/s



- Flutter criteria: 63.5 m/s

Canakkale – Independent Design Verification

Main span: 2023m

Total length of bridge deck: 3563m
Approcah bridges: 365m(Europe) + 680m (Asia)

Tower height: 318m

Navigational channel: 1600m x 70m

Design code: Eurocode + lokale krav

Opening: 2023

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The E39 project – and its major bridges

Statens vegvesen

Norwegian Public Roads Administration

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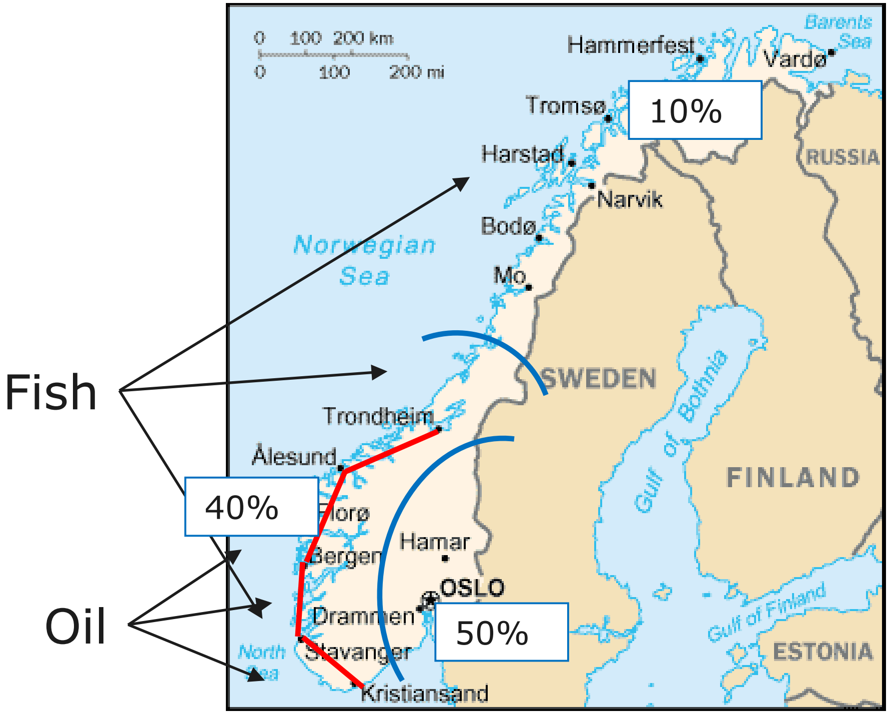
Norway and the E39



E39: 1100km. Today: Ferry, 21h

Ferry-free => 11h ===➔ Save 10h!

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E39 – Criteria and challenges

E39 – 1100km highway with speed limit110km/h

7 large fjord crossings

Properties:

- Width: 2-7.5 km
- Depths: 300-1300 m
- Different climate with varying intensity
  - Wave
  - Wind
  - Current
- Some fjords have large vessel traffic
  - Navigational channel needed, typical (dep. on type of vessels)
- Today: low traffic volume, but will increase significantly when E39 is finalized
- Designed for 100y lifetime:
  - Typical mean wind speed at deck level : 40m/s
  - Gust speed: 54 m/s
  - Some of the floating concepts shall withstand 10m high buildings.

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Bridge crossings – summary (Fjord width and depth)

Fjordkryssingane

(Breidde og djupn)

Halsafjorden, 2 km, 5-600 m

Romsdalsfjorden, 15,5 km Undersjøisk tunnel 350 MUH + 1,6 km bru, 5-600 m

Sulafjorden, 3,8 km, 500 m

Vartdalsfjorden, 2,1 km, 600 m

Nordfjorden, 1,4 km, 500 m

Sognefjorden, 3,7 km, 1250 m

Bjørnafjorden, 5 km, 5-600 m

Langenuen, 1,3 km, 500 m

Boknafjorden, Rogfast undersjøisk tunnel på 27 km, 390 MUH

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E39 – Boknafjorden (Rogfast)

27km long tunnel. Twin tube with profile T10.5.
Estimated cost 16.8 billion NOK

Rated as the most profitable infra structure project in Norway
Approved in Parliament in May 2017

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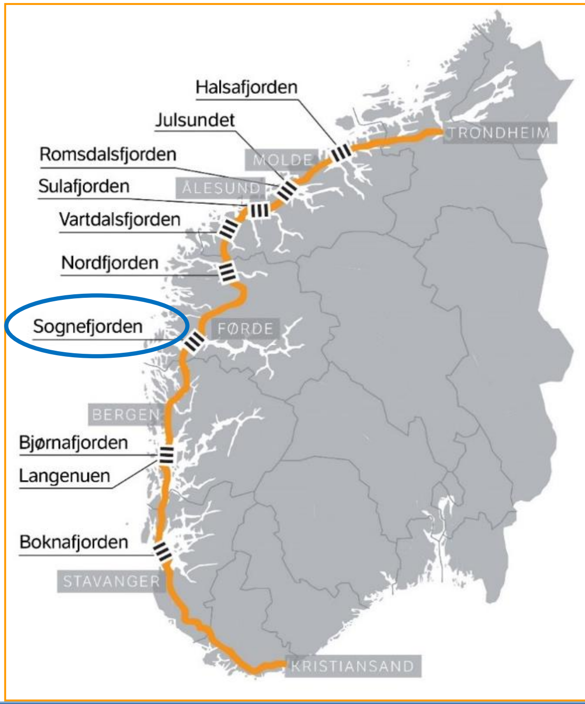
E39 – Langenuen (Hordfast)

- Suspension bridge with main span of approx. 1600m
- Bridge needed to access Bjørnafjorden
- Currently investigating concepts. Tech Status unknown.

E39 – Bjørnafjorden (Hordfast)

E39 Sognefjorden

- Fjord width 3800m. 1300m deep fjord. Difficult to cross.
- Project in concept phase.
- If built it will most likely be the last large bridge structure on E39



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E39 - Nordfjorden

- Concept most likely Suspension bridge. Main span 1600m

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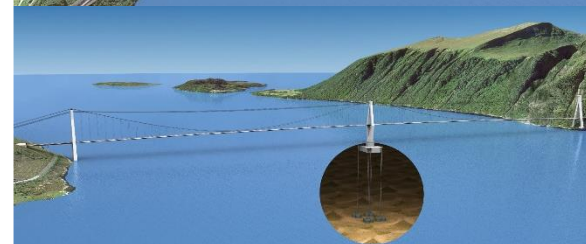
E39 – Vartdalsfjorden (Hafast)



This bridge is needed to access Sulafjorden.

Concept development onging:

- Suspension brdige: Main span: 2250m. Double deck
- TLP
- Floating

Wind and wave measurements ongoing

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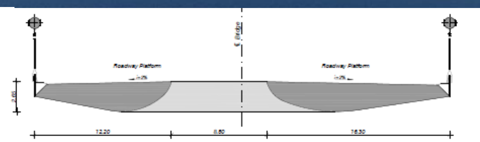
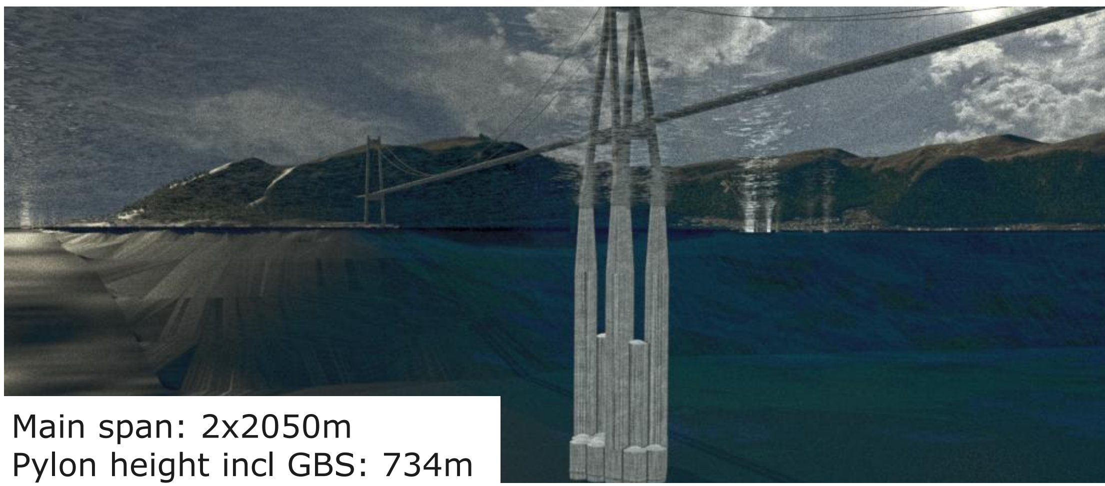
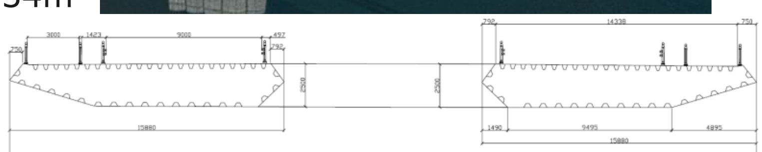
E39 - Sulafjorden – several concepts. Here, two is shown. (Hafast)

Main span: 2800m
Pylon height: 400m
Twin-box: 12+9+16m





Main span: 2x2050m
Pylon height incl GBS: 734m
Depth: 450m
Twin-box: 16+11+16m



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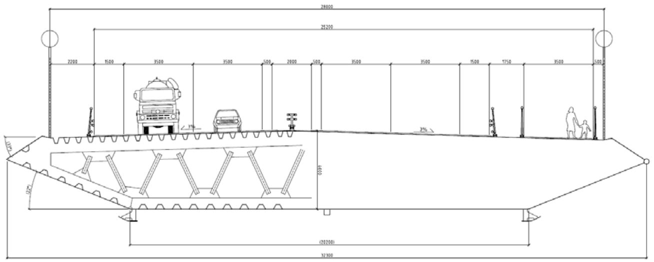
E39 Julsundet / Romsdalsfjorden (Møreaksen)



Suspension bridge crossing Julsundet.

Main span: ca1625m

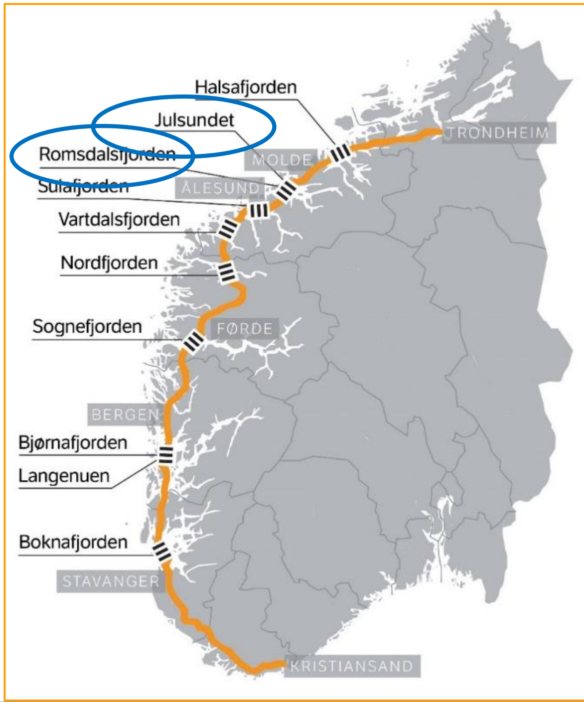
Bridge girder: ca 32m x 4m

15km tunnel under Romsdalsfjorden

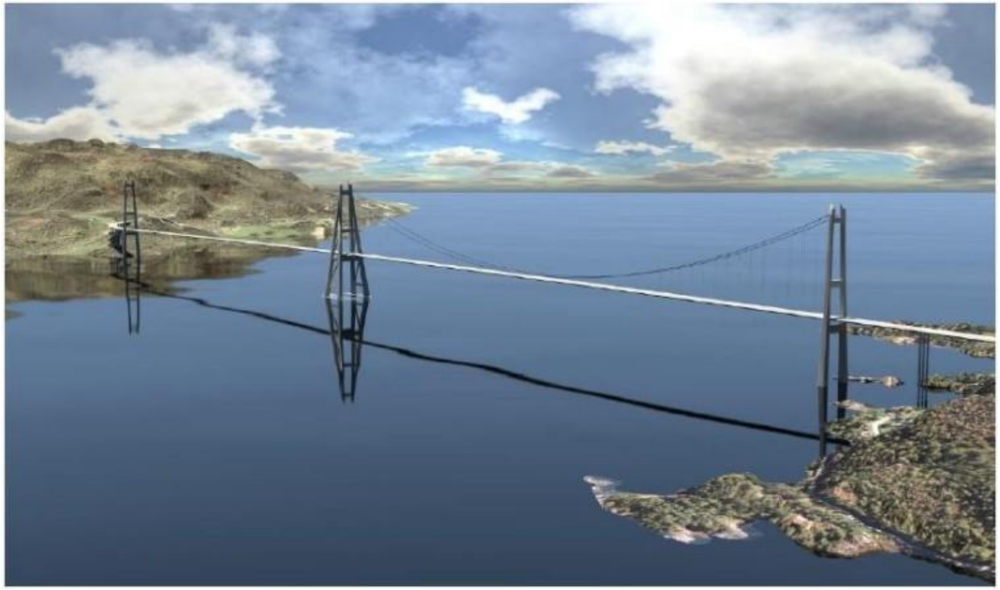
Estimated cost for project 16 billion NOK

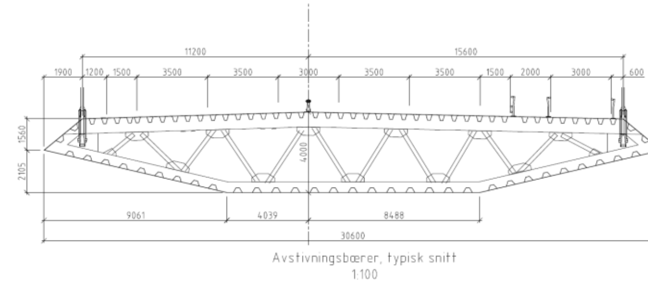
NPRA has concluded on the design.

Wind measurements at site ongoing.



E39 Halsafjorden





Multispan suspension bridge, same principles as Bjørnafjorden.

Main span: 2x1200m

Navigational channel: 55m+
Water depth: approx. 500m

Bridge girder: approx. 30m x 4m

Wind and wave measurements at site ongoing
Concept development currently ongoing

Statens vegvesen

Norwegian Public Roads Administration

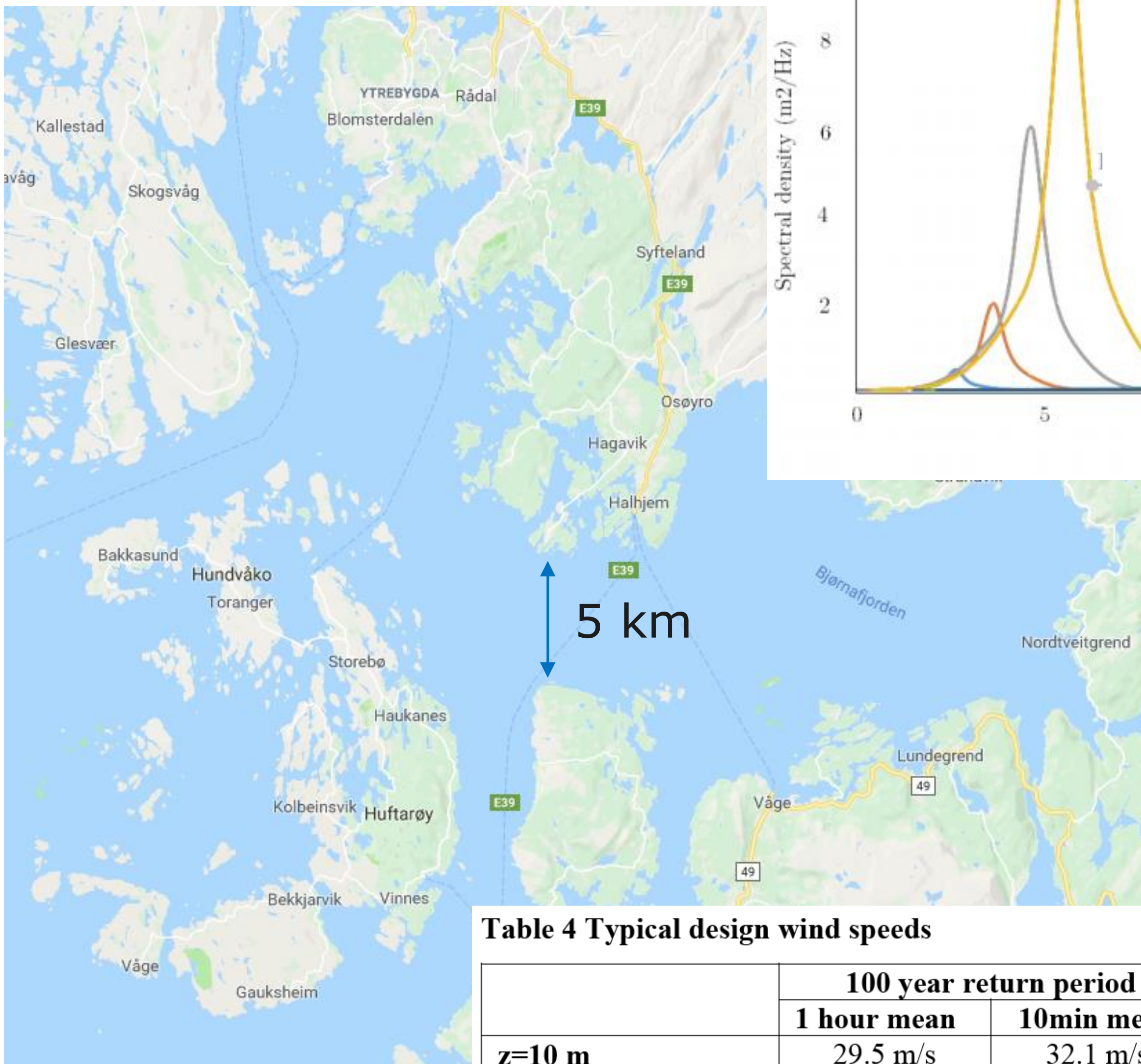
Bjørnafjorden concepts

Multiconsult AAS-JAKOBSEN AkerSolutions

mossmaritime NGI JOHS HOLT Norconsult RAMBØLL

COWI DR. TECHN. OLAV OLSEN PLAN ARKITEKTER

Bjørnafjorden



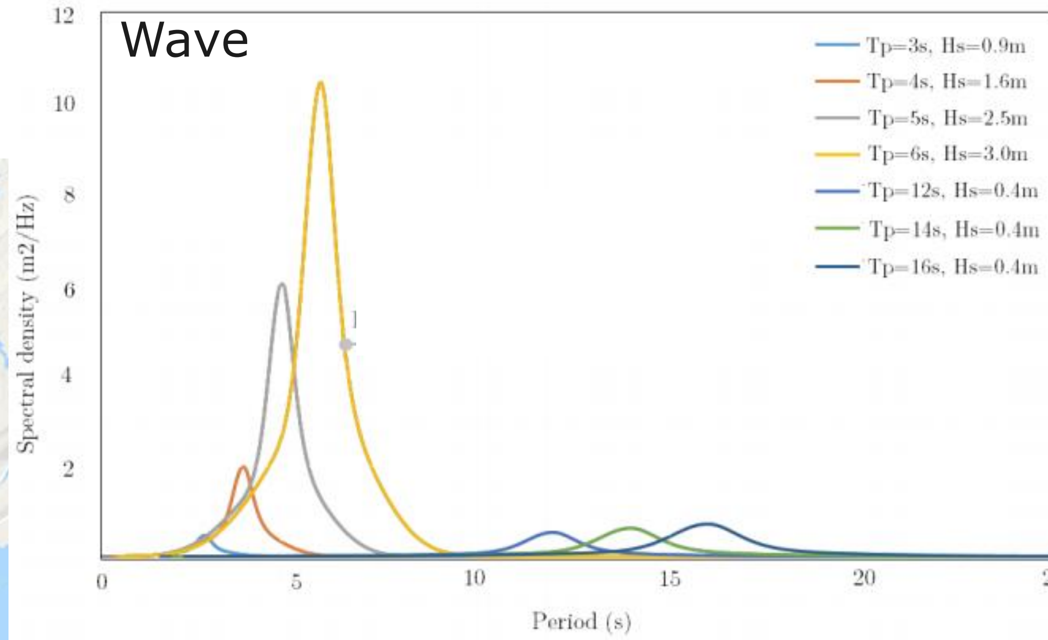


Table 4 Typical design wind speeds

	100 year return period	
	1 hour mean	10min mean
z=10 m	29.5 m/s	32.1 m/s
z=60 m (deck level)	37.2 m/s	40.5 m/s
z=200 m (pylon top)	43.1 m/s	46.9 m/s

Typical environmental loads

Typical weather window for inst. in North sea: H_s < 2.5m

Wind at deck level (1 hour mean):

1y: 27.1 m/s

100y : 37.2 m/s I_u = 14 % (Parallell: 17% - 30%)

Wind driven wave:

1y : H_s : 0.8 – 1.5 m / T_p = 4.0 – 5.3 s

100y: H_s : 1.5 – 2.8 m / T_p = 5.0 – 6.6 s

Swell:

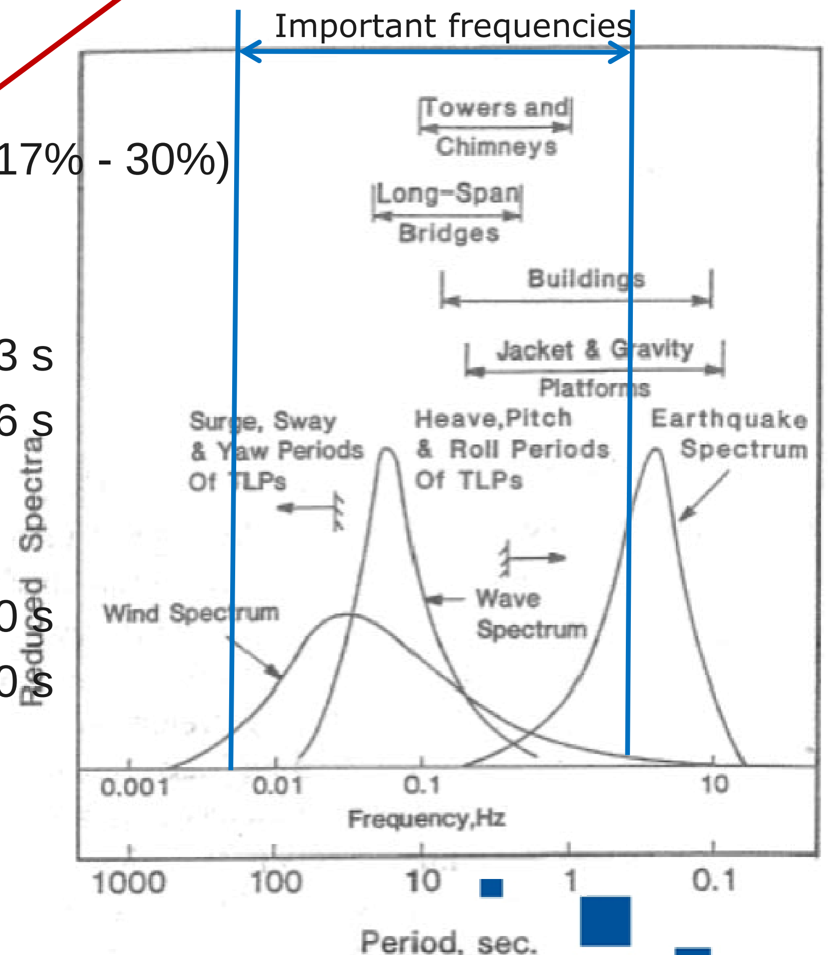
1y : H_s : 0.18 – 0.26 m / T_p = 6 – 20 s

100y: H_s : 0.28 – 0.40 m / T_p = 6 – 20 s

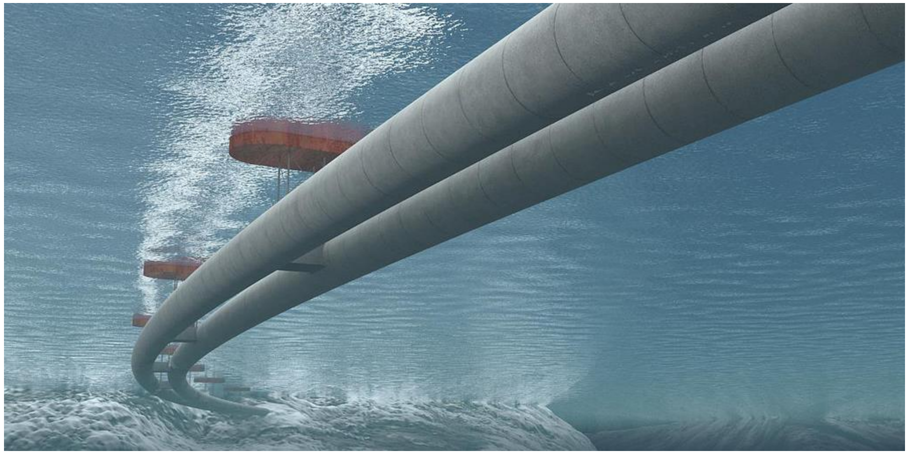
Current (0-15m):

1y: 1.00 m/s

100y: 1.40 m/s



Bjørnafjorden – The concepts



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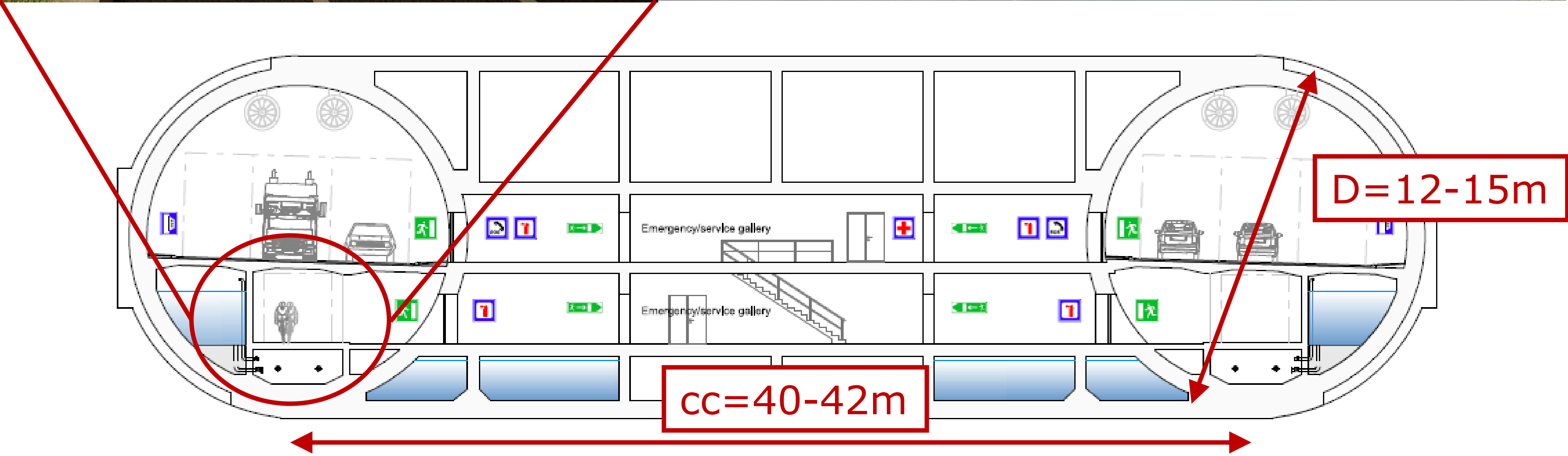
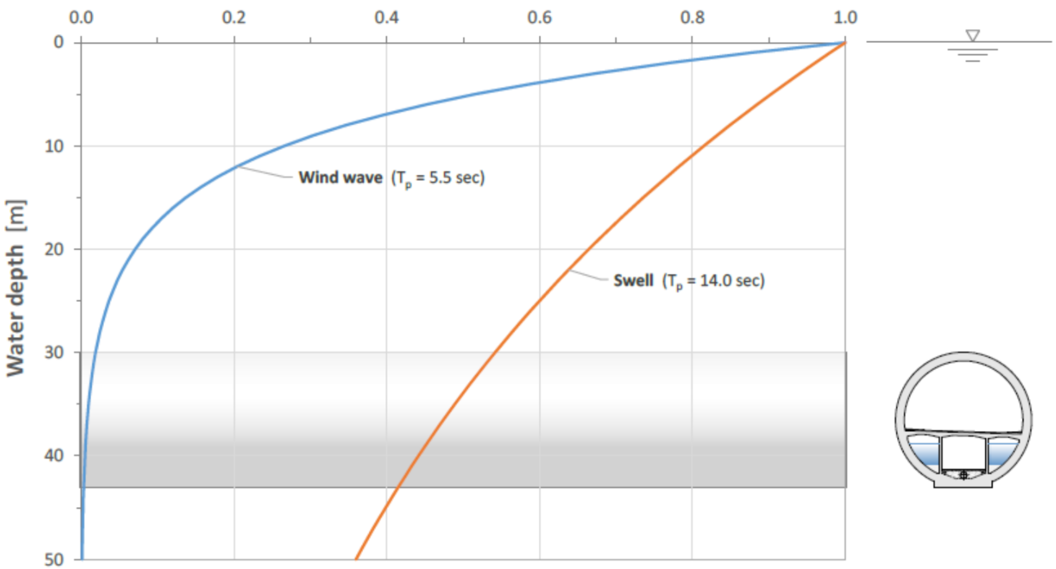
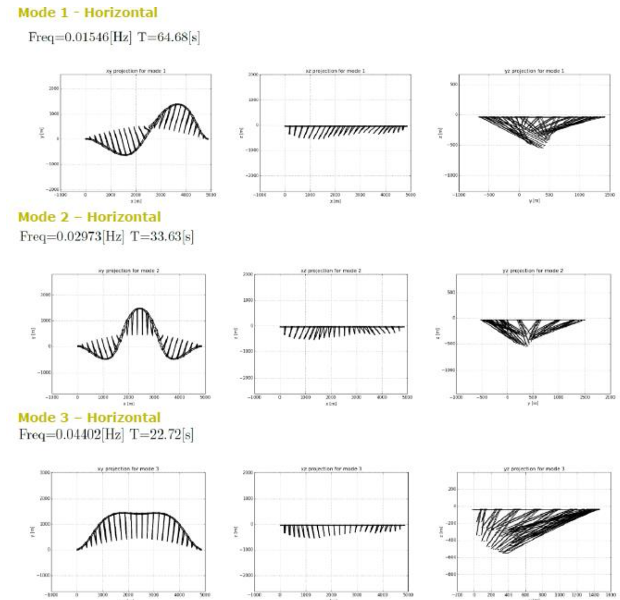
The Submerged Floating Bridge

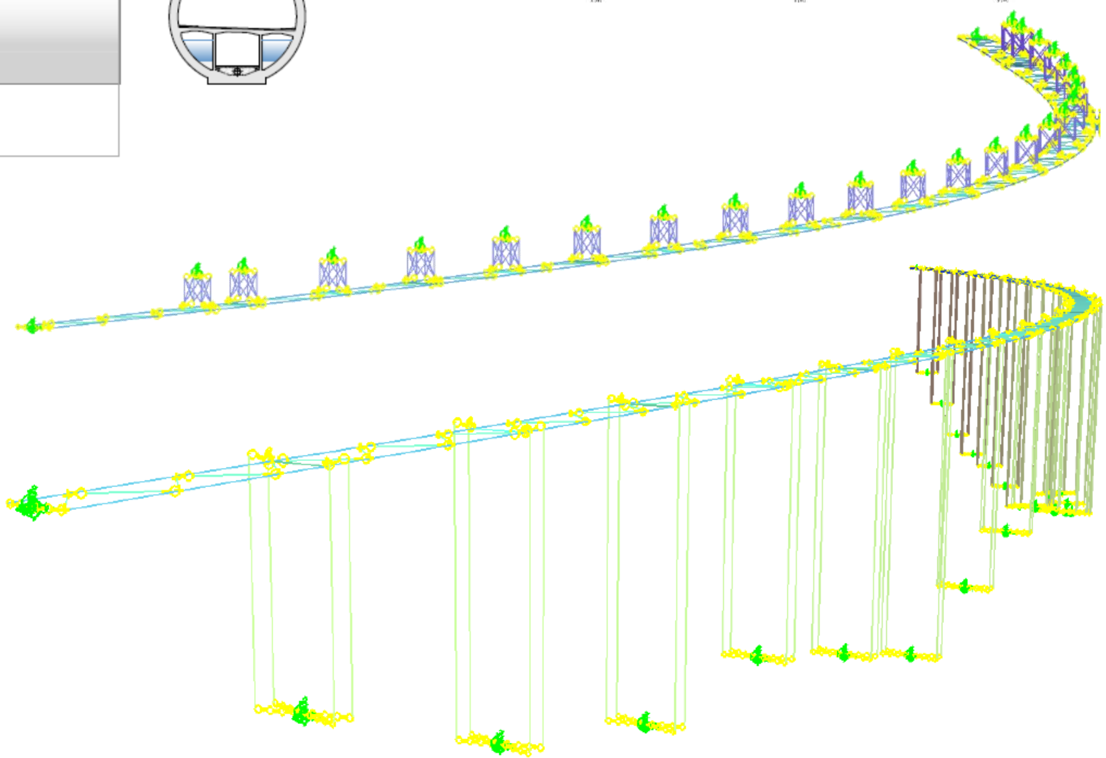
The submerged floating bridge



Key technical aspects







Vibration periods:

Tether supp.: T=64 s and lower

Pontoon supp.: T=69 s and lower

Vert. motion in SLS < 0.05m/s^2

Hori. motion in SLS < 0.10 m/s^2

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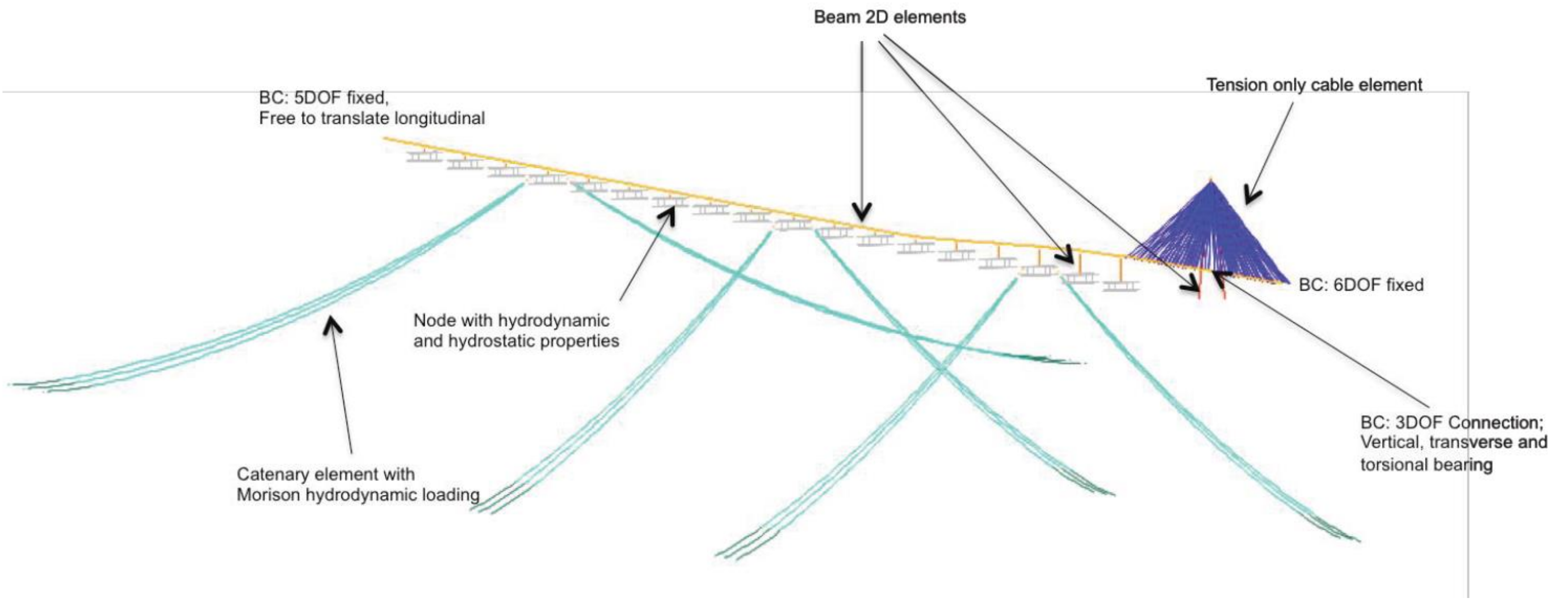
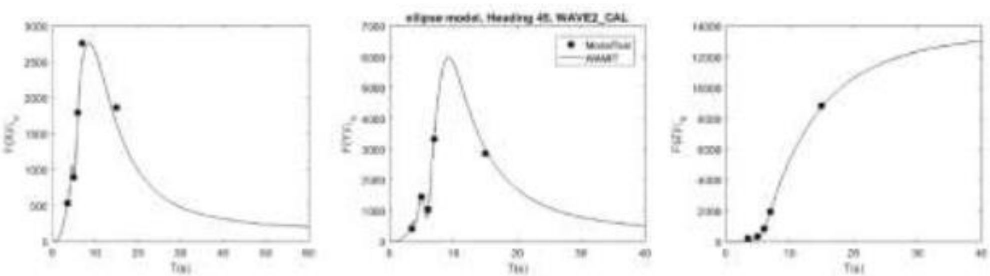
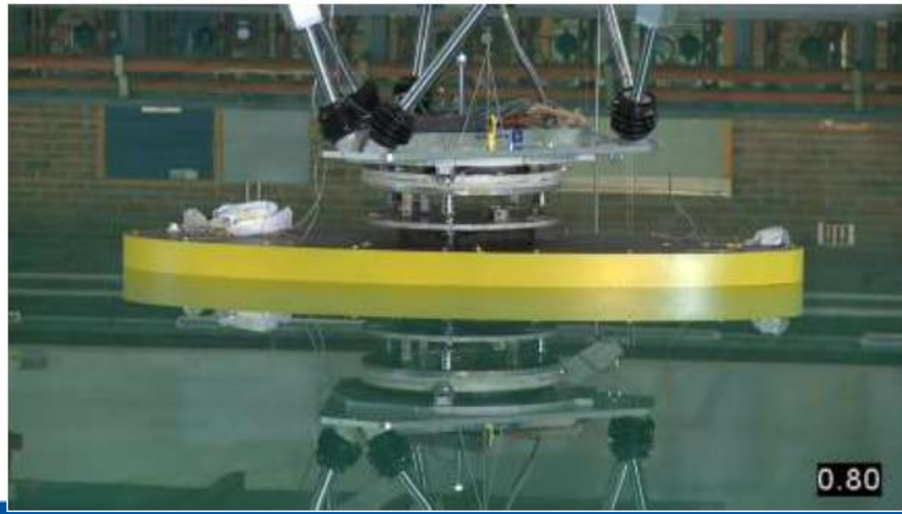
The Floating Bridges

Floating bridge – End Anchored and Side Anchored

Side anchored - modelling







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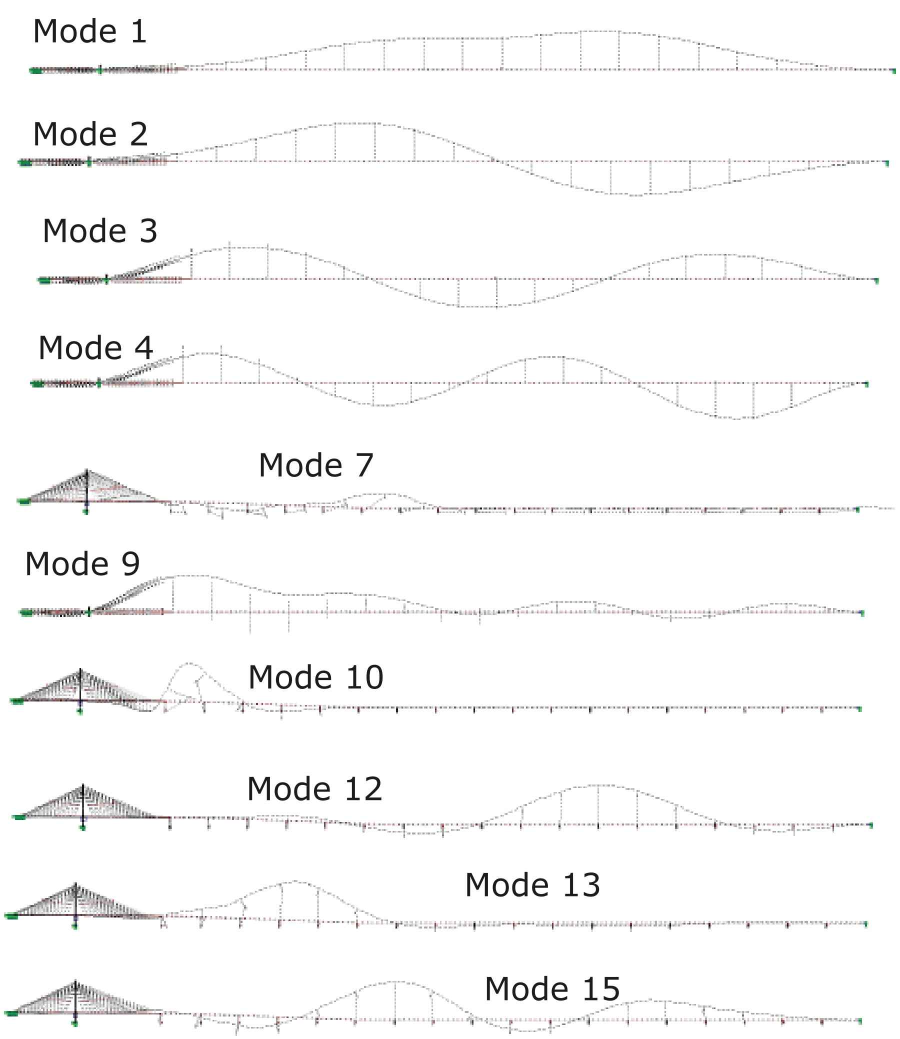
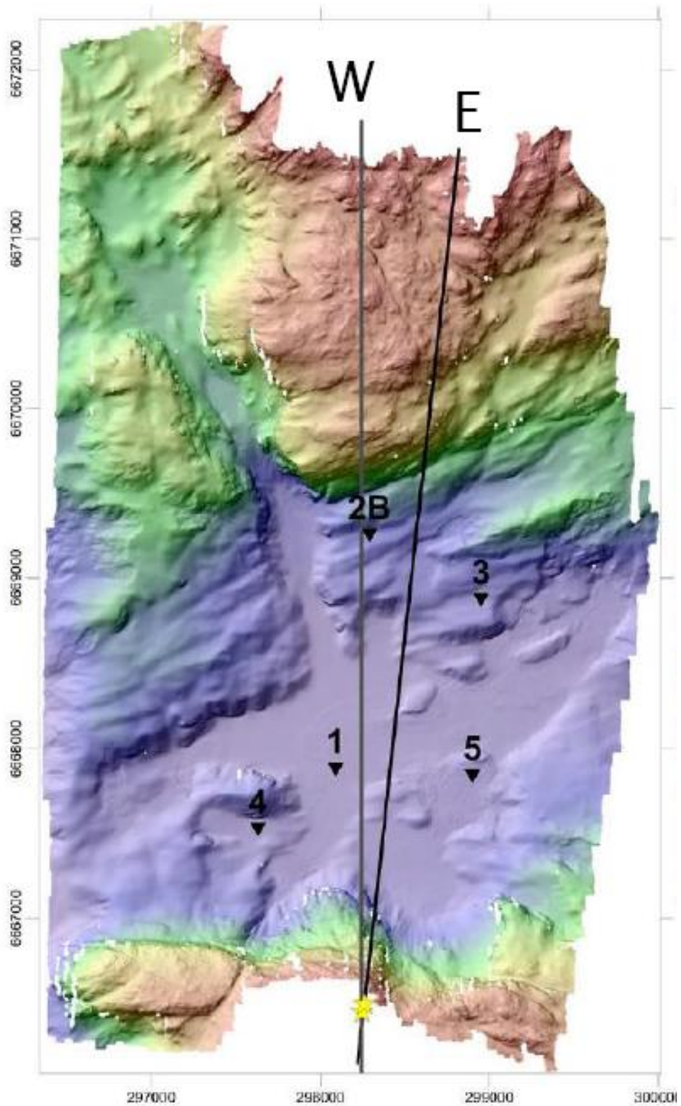
Side anchored – vibration modes

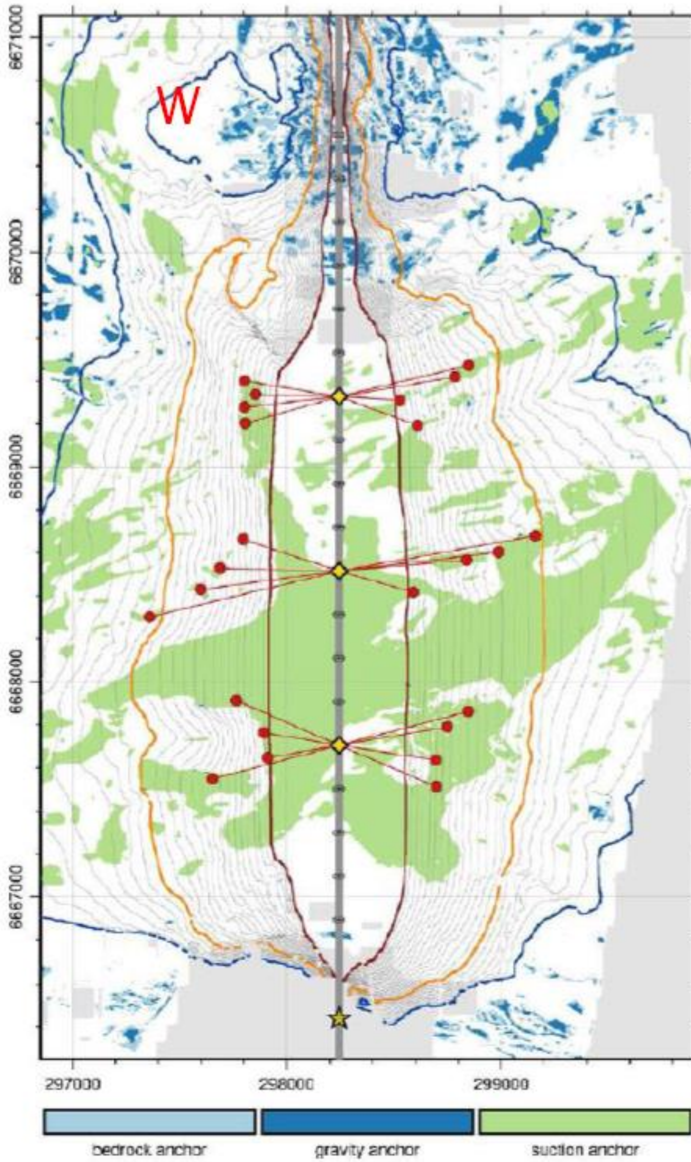


Eigen modes calculated including hydrodynamic added mass are given in th

Mode	Period [s]	Frequenzy [Hz]	X [%]	Y [%]	Z [%]	RX [%]	RY [%]
1	78.25	0.0128	0	100	0	0	0
2	71.21	0.0140	0	100	0	0	0
3	40.78	0.0245	0	99	0	0	0
4	32.48	0.0308	0	99	0	1	0
5	23.44	0.0427	0	98	0	2	0
6	17.69	0.0565	0	97	0	3	0
7	14.09	0.0710	97	0	3	0	0
8	14.09	0.0710	0	82	0	17	0
9	13.06	0.0766	0	37	0	63	0
10	11.45	0.0873	35	0	63	0	2
11	11.32	0.0884	0	14	0	86	0
12	10.92	0.0916	0	0	100	0	0
13	10.89	0.0918	2	0	98	0	0
14	10.88	0.0919	0	90	0	9	0
15	10.87	0.0920	1	0	98	0	0
16	10.87	0.0920	0	0	100	0	0
17	10.84	0.0922	1	0	99	0	0
18	10.76	0.0930	9	0	90	0	1
19	10.66	0.0938	3	0	97	0	1
20	10.50	0.0952	8	0	91	0	1
21	10.32	0.0969	5	0	94	0	1
22	10.02	0.0998	7	0	92	0	1

Side anchored – location of anchors





End anchored - optimization

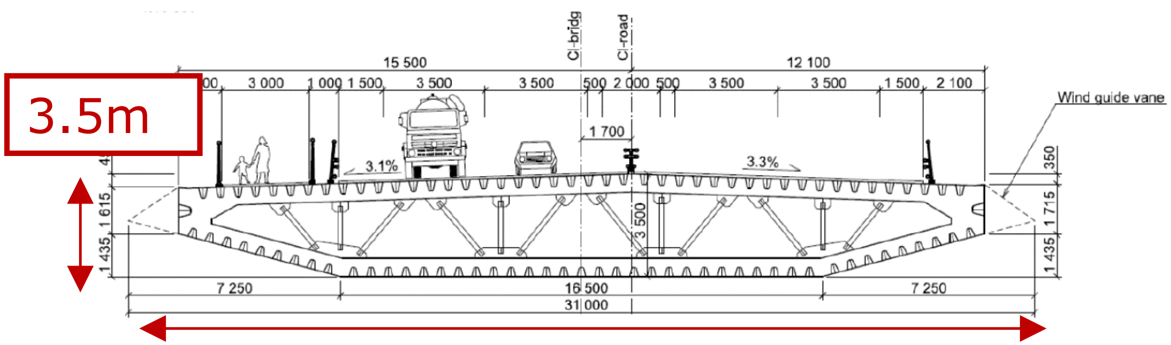
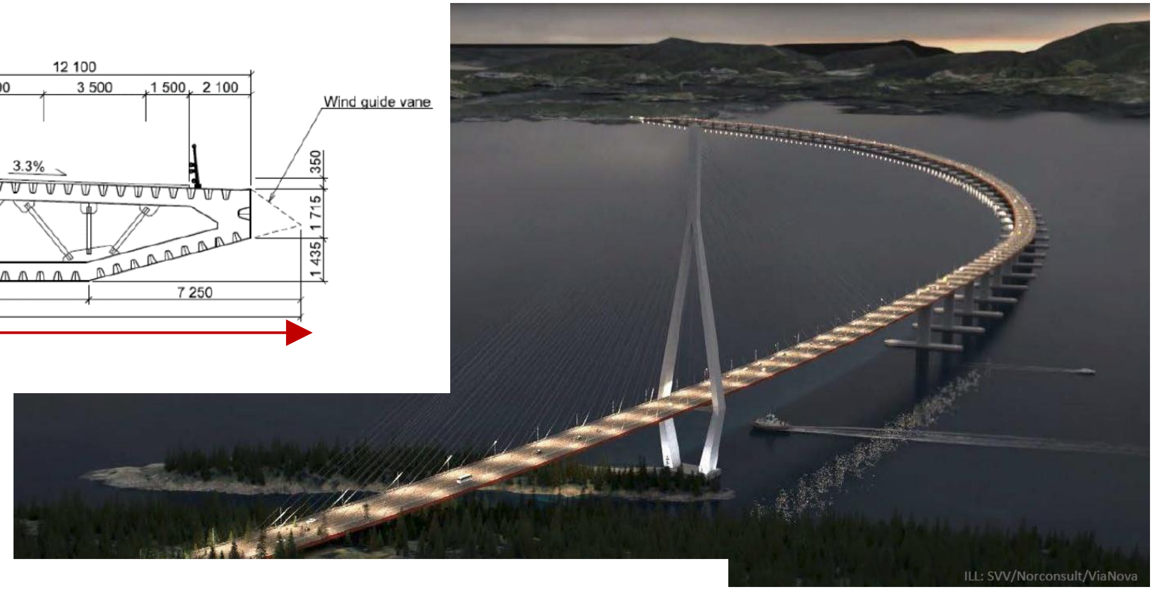


Figure 2-2 Chosen general cross-section



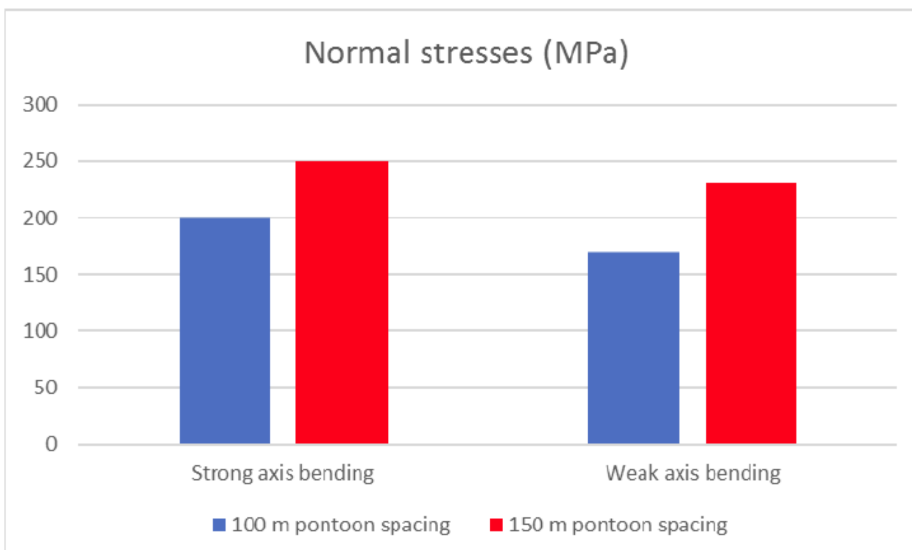


Figure 2-3 Stresses from wind sea for two different pontoon spacings

End anchored - optimization

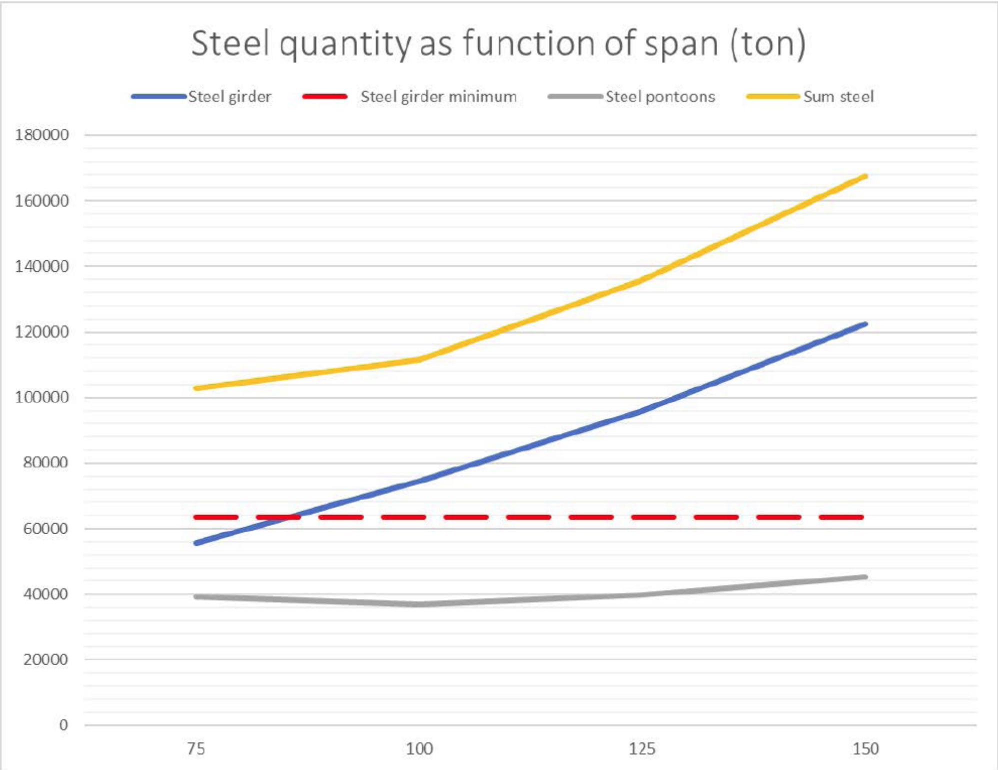
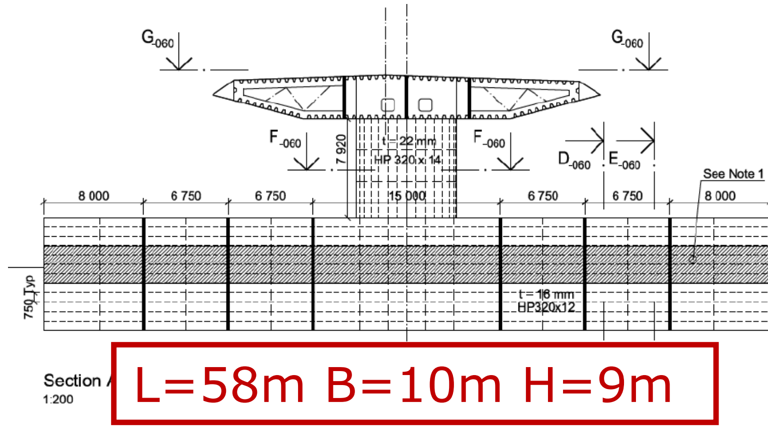
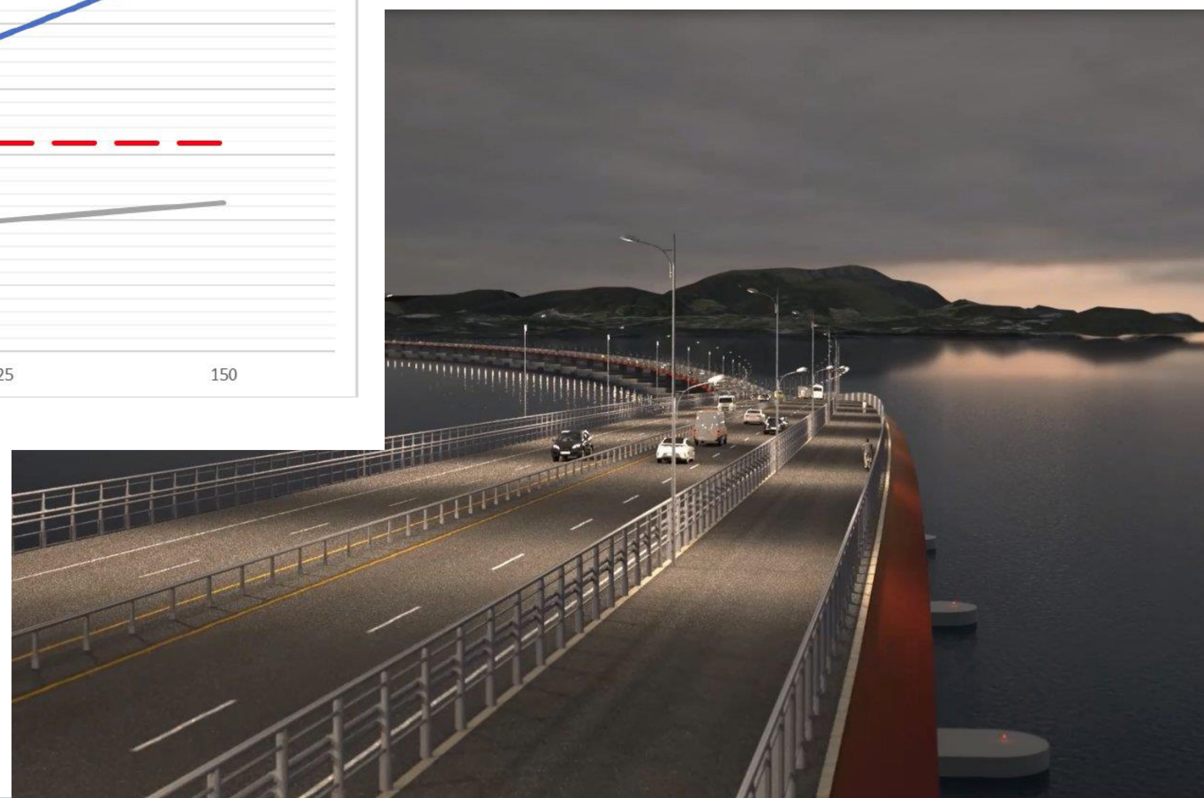


Figure 2-4 Estimated steel weight as function of span length





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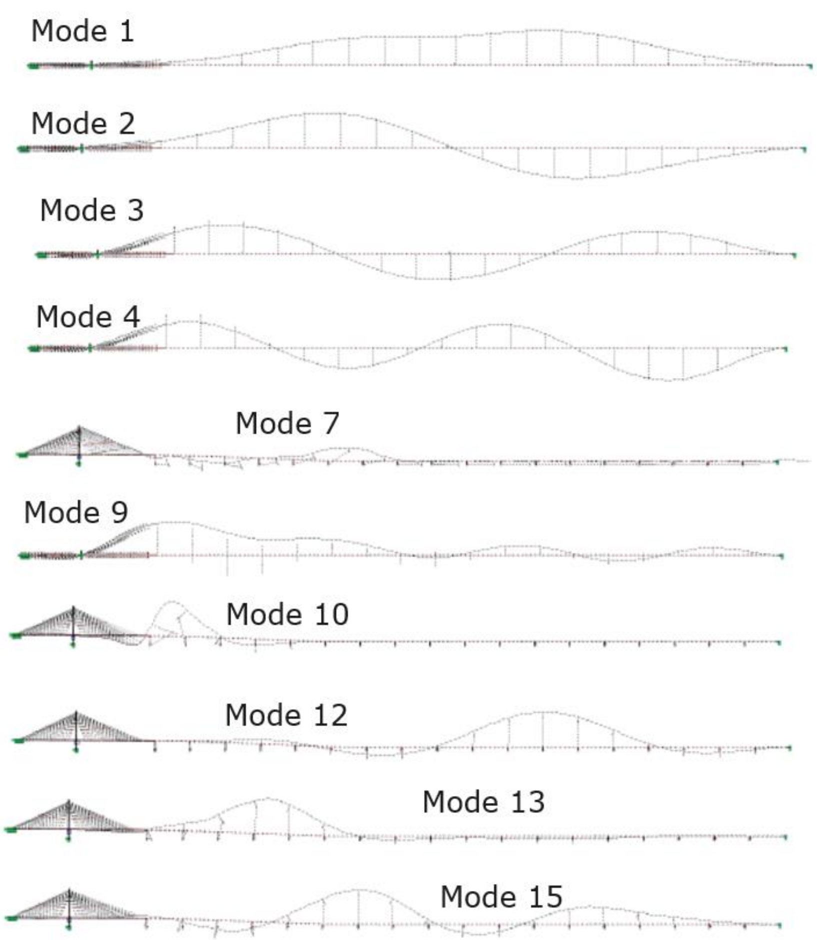
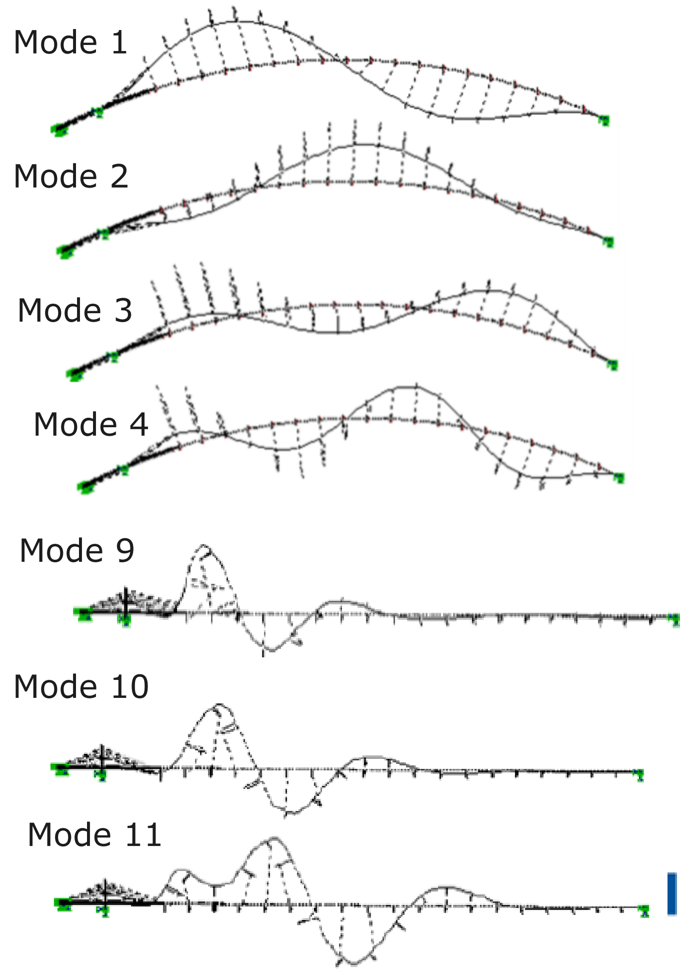
Mode comparison – Side vs End anchored

Side anchored: T= 78s and down



End anchored: T= 48s and down



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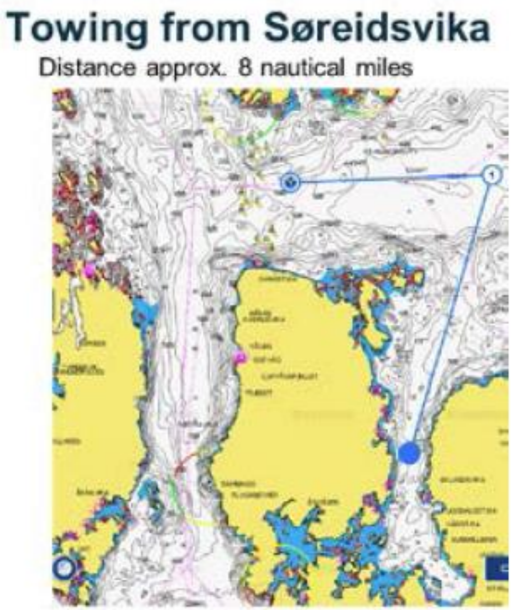
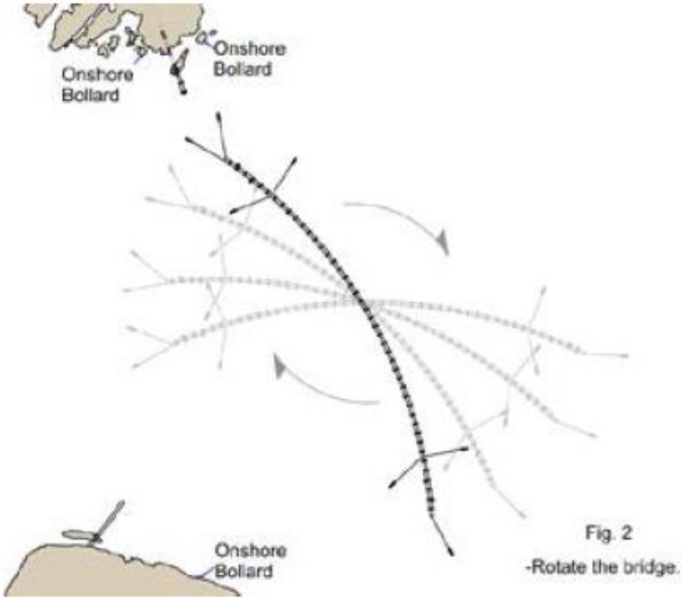
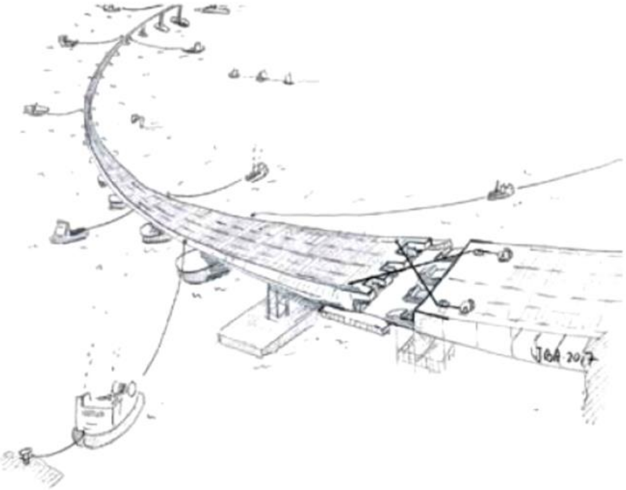
Installation example







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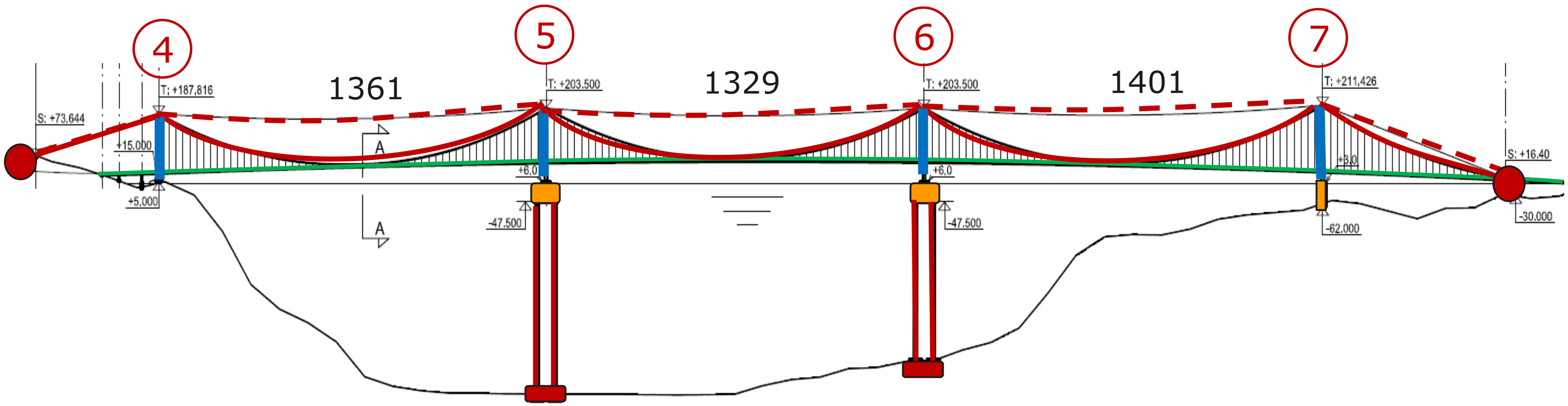
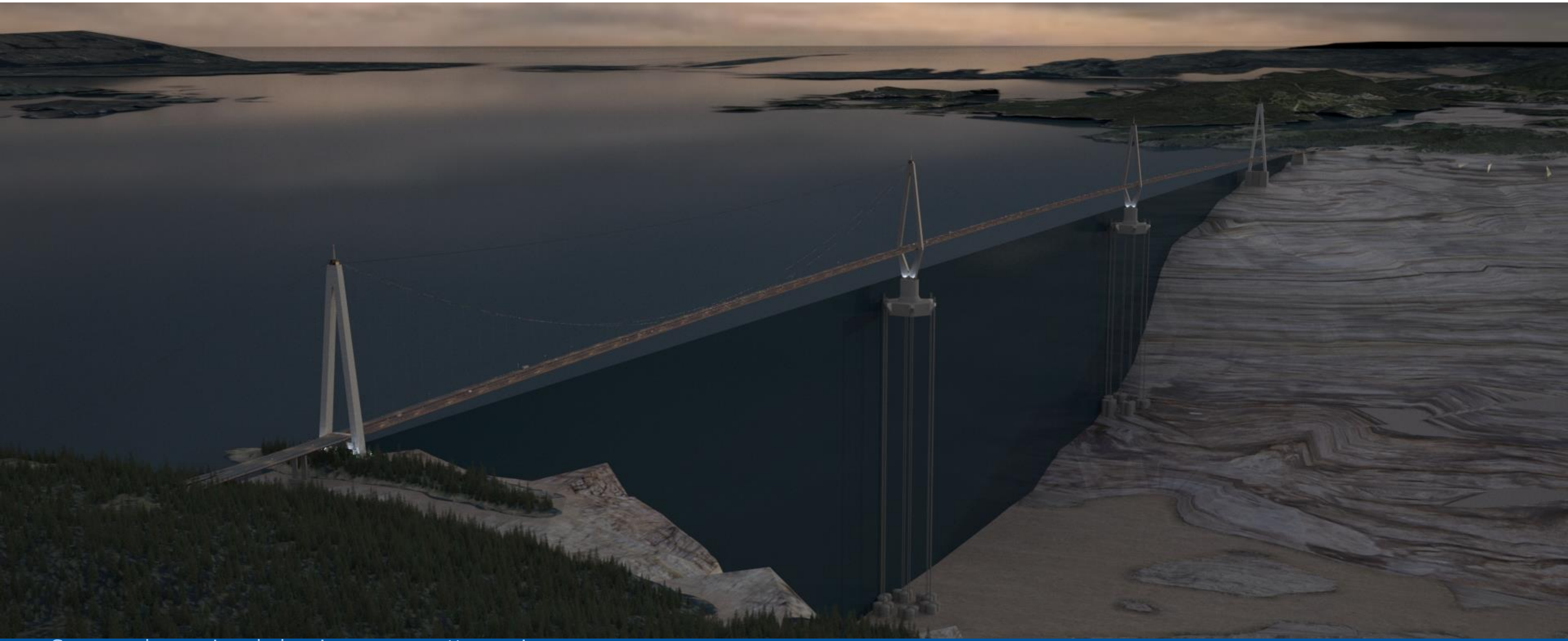
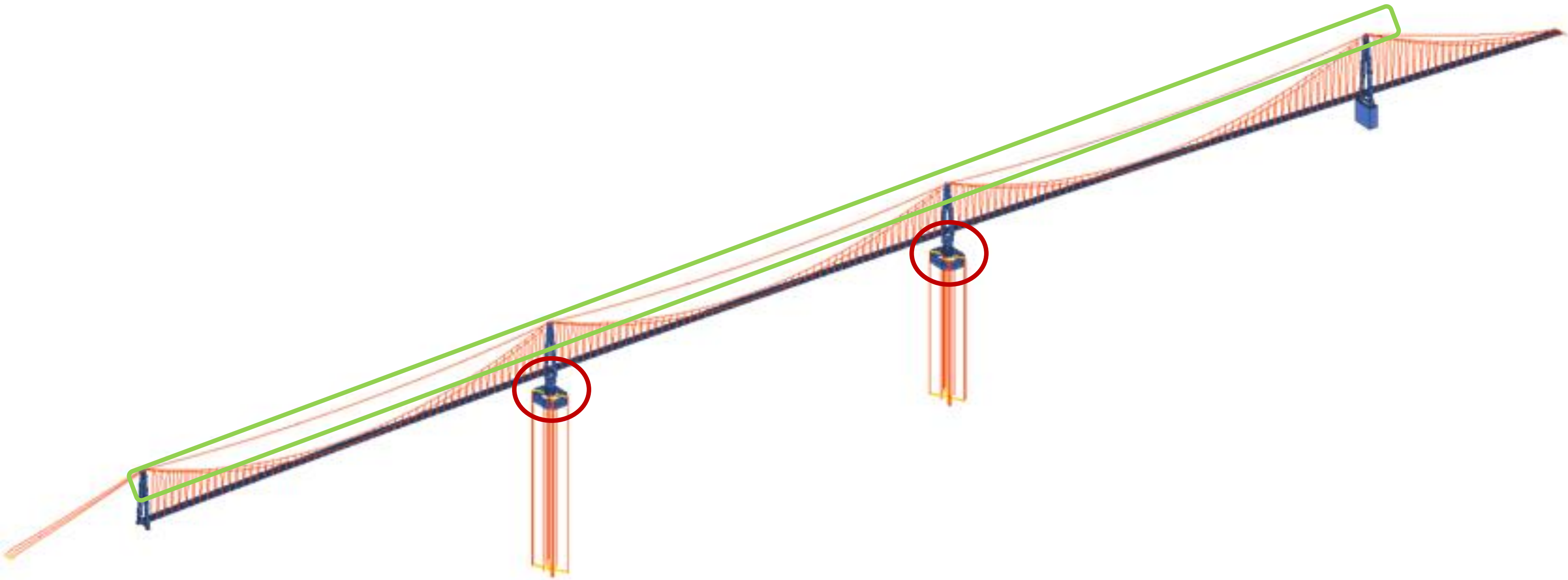
The TLP concept

Concept – main features

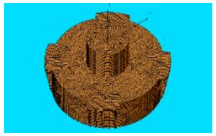
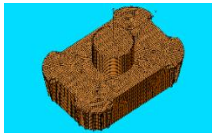
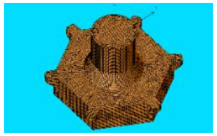
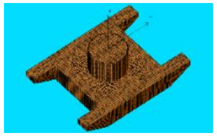
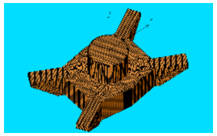
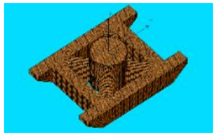
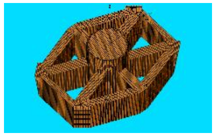




Analysis model



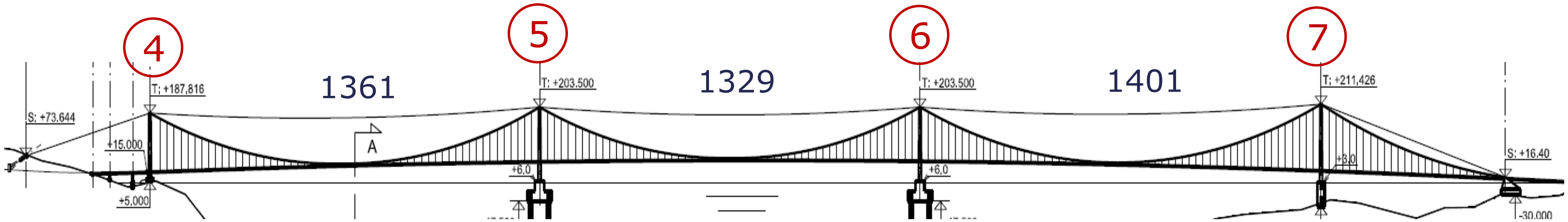
TLP Floater optimization – screening analysis

Phase 2 Design values:		13.6		1797		2705		12.0			
Hull	**Tethers used in analyses**	**Dynamic tether tension [MN]**	**Increase from Phase 2**	**Pylon weak axis [MNm]**	**Increase from Phase 2**	**Pylon strong axis [MNm]**	**Increase from Phase 2**	**Top cable tension [MN]**	**Increase from Phase 2**	**Girder vertical acceleration RMS [m/s^2]**	**Girder horisontal acceleration RMS [m/s^2]**
Monoleg concrete rev0	4x4, X=64, Y=64, Z=-20	18.9	39 %	1929	7 %	3175	17 %	10.1	-16 %	0.24	0.15
Monoleg concrete rev1	4x4, X=60, Y=90, Z=-20	15.5	14 %	1857	3 %	3245	20 %	10.6	-12 %	0.25	0.15
Monoleg_steel_Rev0_tpos1	3x4, X=50, Y=80, Z=-33	16.3	19 %	1217	-32 %	3090	14 %	11.0	-9 %	0.29	0.15
SWATER_Type2_Rev1_tpos4	3x4, X=60, Y=90, Z=-15	15.1	11 %	1946	8 %	3103	15 %	13.9	15 %	0.29	0.22
SWATER_Type4_Rev0_tpos1	3x4, X=60, Y=90, Z=-15	15.1	11 %	1999	11 %	3206	19 %	10.1	-16 %	0.25	0.20
Hfloater_Rev2_tpos3	3x4, X=60, Y=90, Z=-20	16.9	24 %	1985	10 %	3001	11 %	15.8	32 %	0.34	0.21
Xbox_Rev0_tpos1	3x4, X=60, Y=90, Z=-20	17.8	30 %	2321	29 %	2932	8 %	15.1	26 %	0.33	0.19
SWATER_Type2_Rev1_tpos1	3x4, X=60, Y=100, Z=-15	14.6	7 %	1946	8 %	3071	14 %	13.9	15 %	0.29	0.22
SWATER_Type4_Rev0_tpos0	3x4, X=60, Y=100, Z=-15	14.8	9 %	1999	11 %	3184	18 %	10.1	-16 %	0.25	0.20
Hfloater_Rev2_tpos0	3x4, X=60, Y=100, Z=-20	16.4	20 %	1985	11 %	2984	10 %	15.8	32 %	0.34	0.22
Xbox_Rev0_tpos0	3x4, X=60, Y=100, Z=-20	17.5	28 %	2321	29 %	2913	8 %	15.1	26 %	0.33	0.19
SWATER_Type4_Rev0_tpos2	3x4, X=50, Y=90, Z=-15	14.5	7 %	1474	-18 %	3213	19 %	10.0	-17 %	0.25	0.20
SWATER_Type5_Rev0	3x4, X=50, Y=90, Z=-15	13.0	-4 %	1360	-24 %	3068	13 %	10.7	-11 %	0.25	0.16
SWATER_Type4_Rev3	3x4, X=50, Y=90, Z=-15	13.8	2 %	1458	-19 %	3097	14 %	10.6	-12 %	0.26	0.17

NOTE:
Monoleg concrete tether tension is scaled with a factor 4/3 for comparison

Top cable system

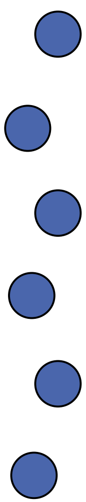


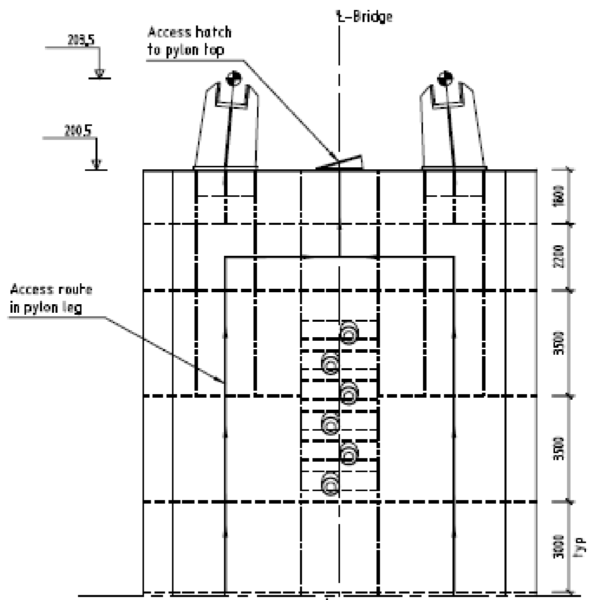
Top cables

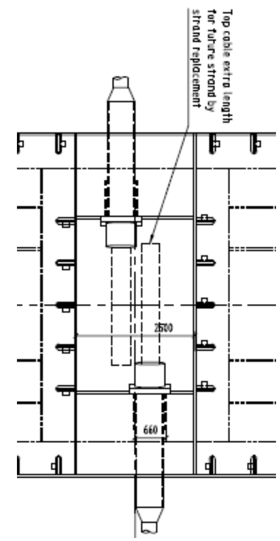
6 (2x3) (127 strands)

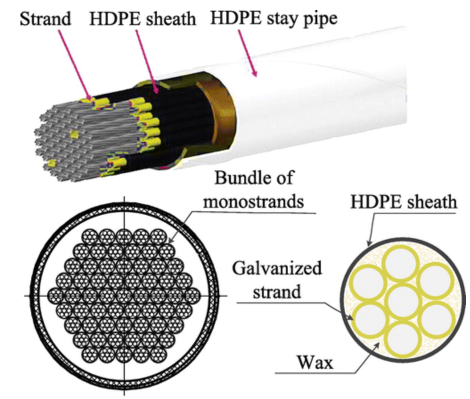
A = 0.114 m^2

Spacing: 1.0m





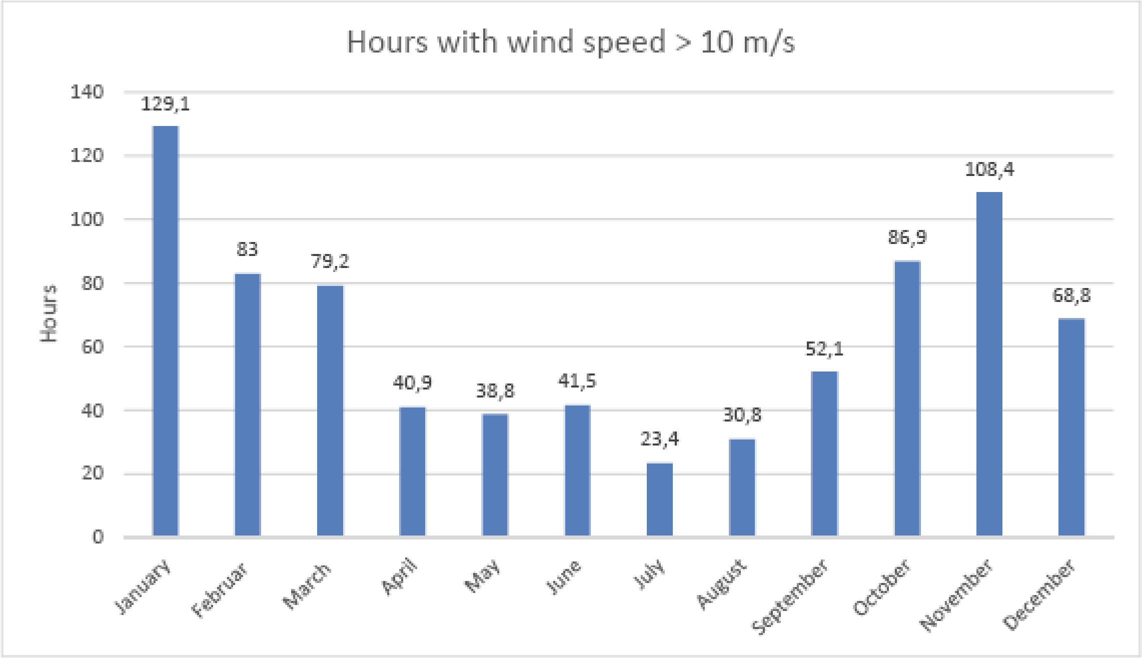




Movement during construction – w/wo Top Cable

RMS displacement in pylon top (10 m/s) – Completed pylon (wo/Storm system):

Surge:	1.6 m (wo/top cable)	/	0.0 m (w/top cable)
Sway:	0.8 m (wo/top cable)	/	0.8 m (w/top cable)
Heave:	0.0 m (wo/top cable)	/	0.0 m (w/top cable)



Accelration during construction – w/wo Top Cable

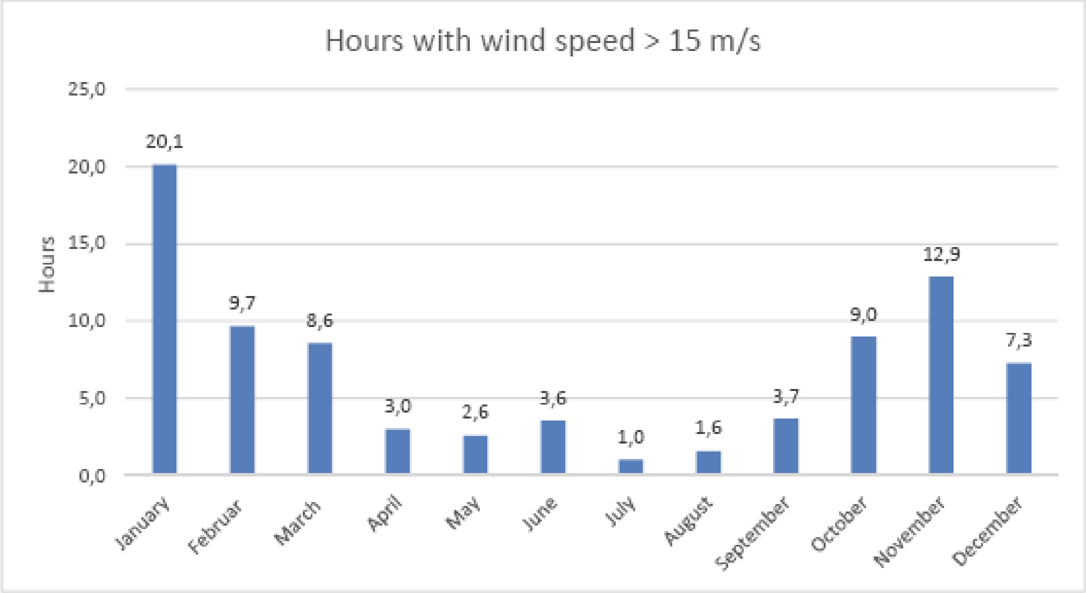
Horizontal acceleration in pylon top:

Free standing completed pylon (Design basis criteria):

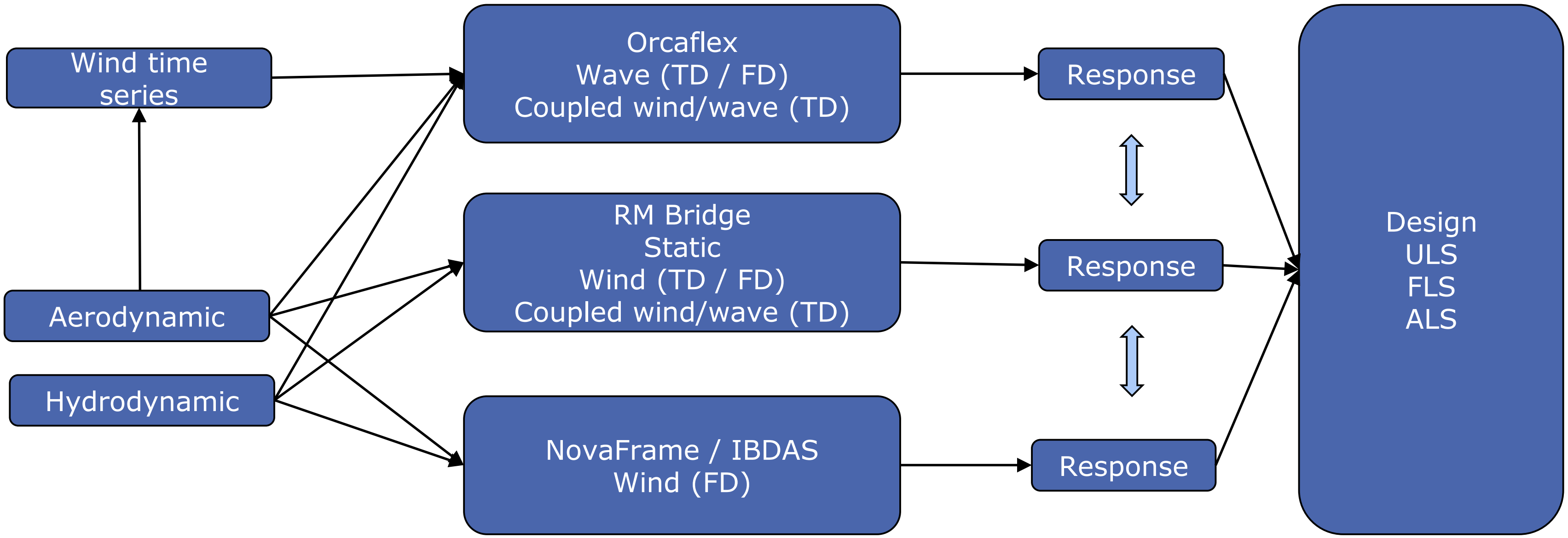
U(z=10m) = 15 m/s: a_{rms} = 0.16 m/s^2 (Criteria$_{rms}$: 0.3 m/s^2)

Completed pylon with top cable:

U(z=10m) = 15 m/s: a_{rms} = 0.07 m/s^2 (Criteria$_{rms}$: 0.3 m/s^2)



TLP Analysis process



- Screening analyses along 100 year contour line performed in time domain and frequency domain
- Coupled analysis in RM, up to 30 realizations pr storm event
- Gumbel used for extreme value estimation of critical components
- Conservative extreme value estimation for all components performed in RM
- Establish combination rule force/moments
- FLS: Rainflow count
- Identify and understand coupling effects

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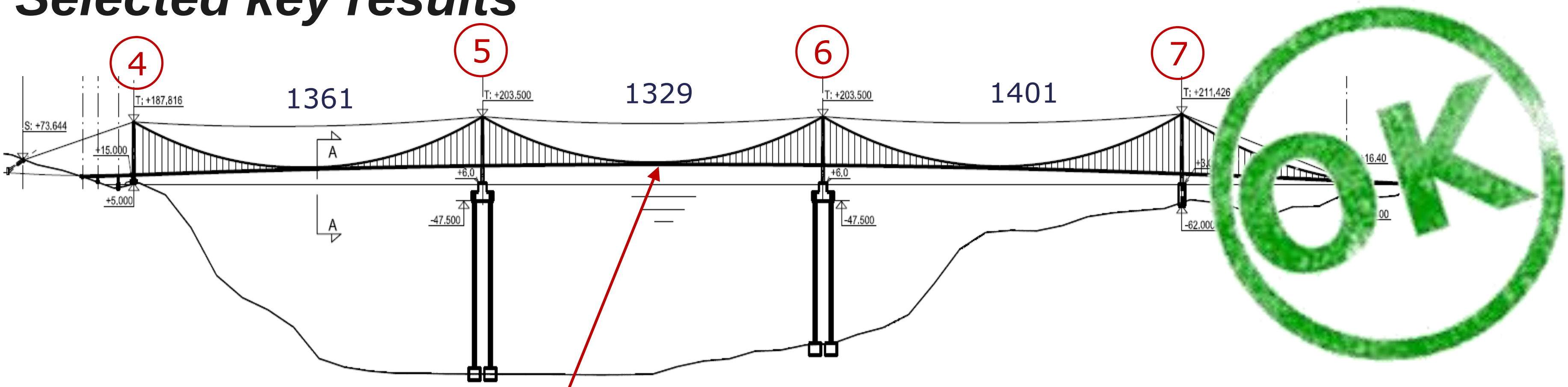
Selected key results



	Permanent loads	Temp. loads	Traffic loads	1 year environmental loads	100 year environmental loads
Bridge girder end (North) longitudinal [m]	0	-0.76/0.95	-1.37/1.36	-0.79/0.72	-1.42/1.53
Bridge girder midspan lateral [m]	0	-0.04/0.02	-0.47/0.43	-6.54/11.84	-11.42/21.98
Bridge girder midspan vertical [m]	0	-0.95/0.8	-6.84/4.76	-2.04/1.88	-3.67/3.92
Pylon top axis 5 longitudinal [m]	0	-0.16/0.13	-2.68/2.61	-0.85/0.96	-1.66/1.37
Pylon top axis 5 lateral [m]	0	-0.08/0.04	-0.08/0.09	-5.29/10.85	-9.65/19.85
Pylon foot axis 5 longitudinal [m]	0	-0.53/0.40	-1.47/1.38	-0.90/0.87	-1.64/1.80
Pylon foot axis 5 lateral [m]	0	0/0.01	-0.16/0.14	-5.44/10.87	-9.70/10.87

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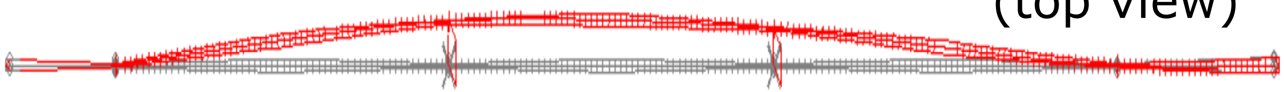
Dynamic bridge behaviour

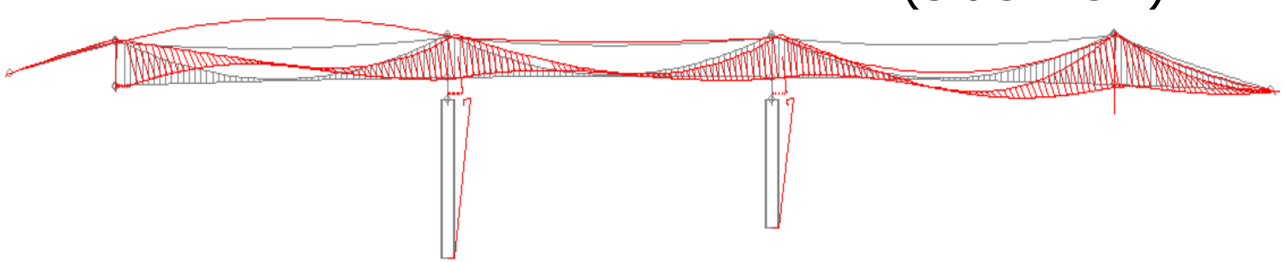
Mode type	Girder motion	Floater motion	Highest eigenperiod
Lateral	Lateral	Sway/roll/yaw	~100s
Vertical	Vertical/longitudinal	Surge/heave/pitch	~30s

- Global modes separated into lateral and vertical direction

1st lateral mode (top view)



1st vertical mode (side view)



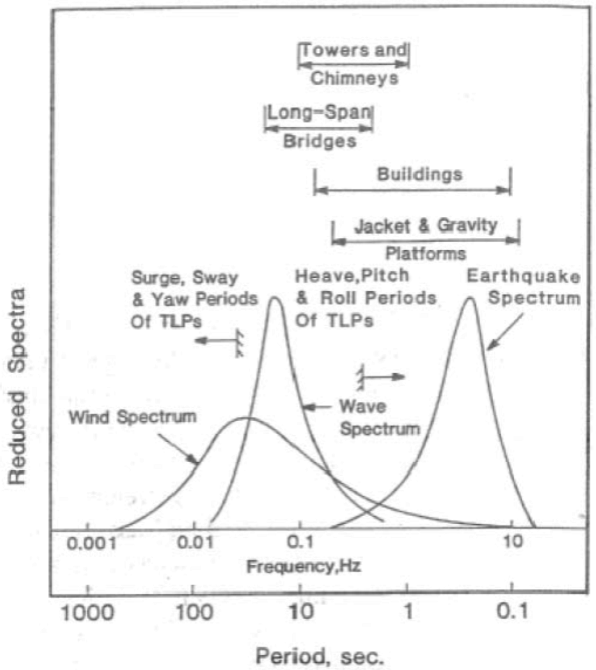
Dynamic bridge behaviour

- Weakly non-linear system
- Table shows eigenperiod with displacement due to mean wind

	Vmean=0m/s	Vmean=30m/s, lateral	Vmean=30m/s, longitudinal
1st lateral	87.06s	86.63s	87.05s
1st vertical	27.95s	27.94s	27.92s

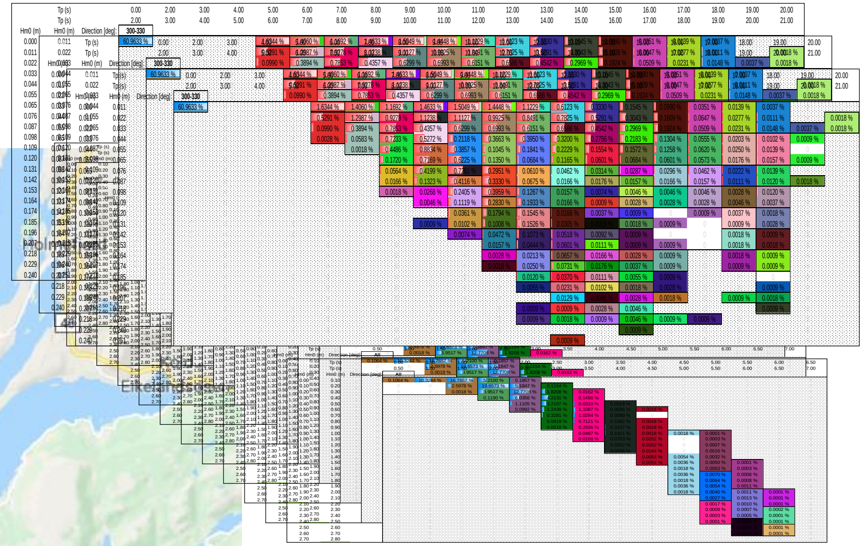
Dynamic bridge behaviour

Frequency-domain	Range	Limit state	Primary excitation
Low-frequent	<0.05Hz (>20s)	ULS / FLS	Wind
Wave-frequent	0.05-025Hz (4-20s)	ULS / FLS / SLS (accelerations)	Wind / 1st order wave
High-frequent	>0.25Hz (<4s)	SLS (accelerations)	Wind



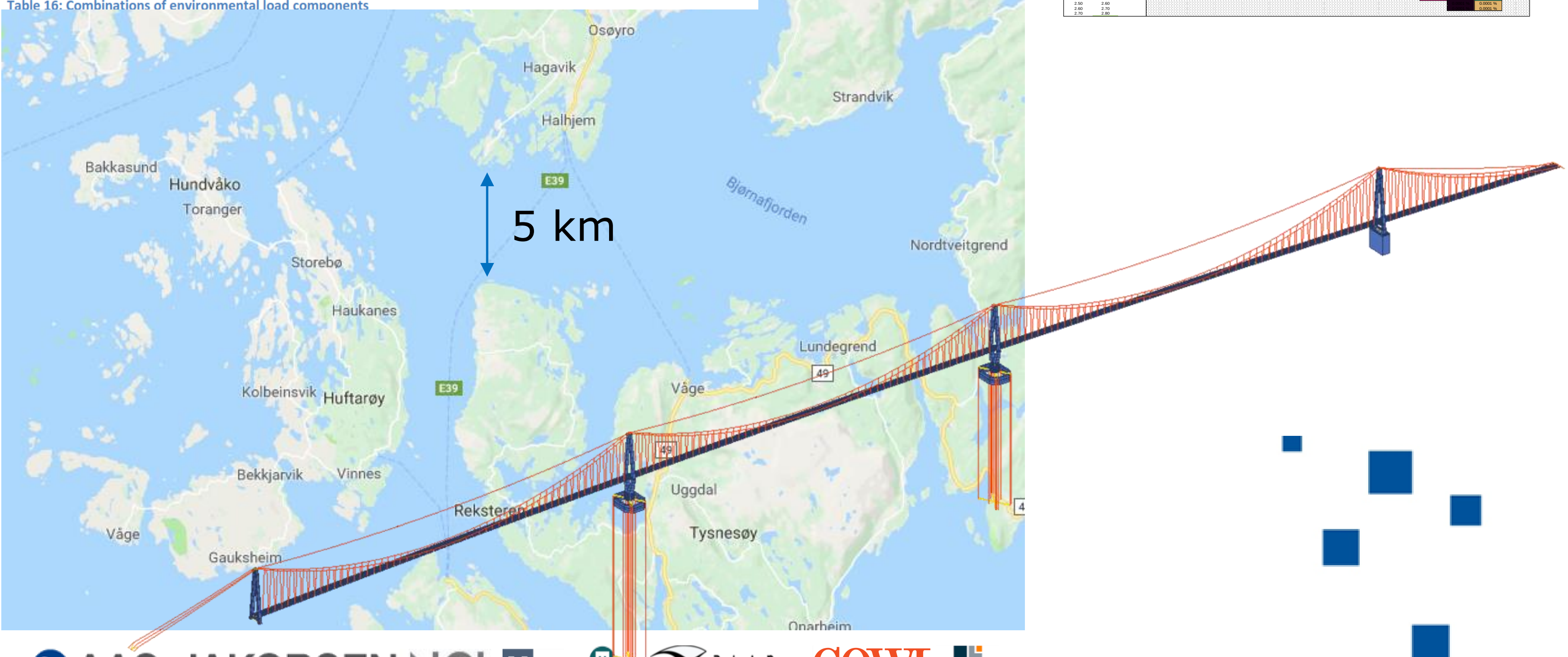
- Environmental load response (mainly) governed by wind
- Resonant response from 1st order wave excitation contributes to ULS, FLS and SLS

Keeping track of the results



Return period (Years)	Wind	Waves		Current	Sea level	
		Wind generated	Swell		Astronomical	Surge
1	1	1	1	1	HAT	1
10	10	10	1	10	HAT	10
	1	1	10	1	HAT	1
100	100	100	10	100	HAT	100
	10	10	100	10	HAT	10
10000	10000	10000	100	10000	Mean	10000
	100	100	10000	100	Mean	100

Table 16: Combinations of environmental load components



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Systematization

Naming system

A	Wave loads	F_{Wave}	A231501
B	Swell loads	F_{Swell}	B209001
C	Wind loads	F_{Buff}	C418001
D	Current loads	F_{Curr}	D000000
E	Coupled event		E001

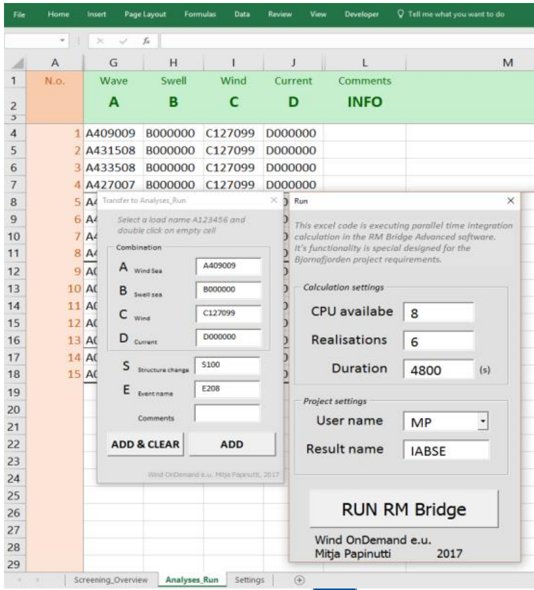
- E001: A231501 B209001 C418001 D000000

C = Wind

Return period 100y

180° Angle of attack

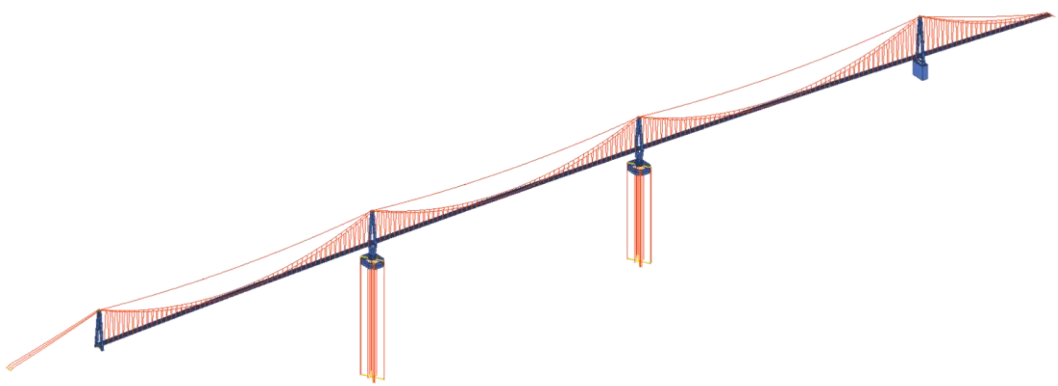
Predefined wind profile



ANALYZING

$$\left(\mathrm{M}+\mathrm{M}_{hy}(\omega)\right)\cdot\ddot{u}+\left(\mathrm{C}_{str}+\mathrm{C}_{hy}(\omega)+\mathrm{C}_{ae}\right)\cdot\dot{u}+(\mathrm{K}+\mathrm{K}_{ae})=\mathrm{F}_{Wave}+\mathrm{F}_{Swell}+\mathrm{F}_{Buff}$$

Event	Wind Sea Waves	Swell Waves	Wind	
E001	A433508	B000000	C127099	F_{wave}
E002	A000000	B431513	C127099	F_{Swell}
E003	A000000	B000000	C427021	F_{Buff}
E005	A433508	B431513	C427021	$\mathrm{F}_{wave}+\mathrm{F}_{Swell}+\mathrm{F}_{Buff}$

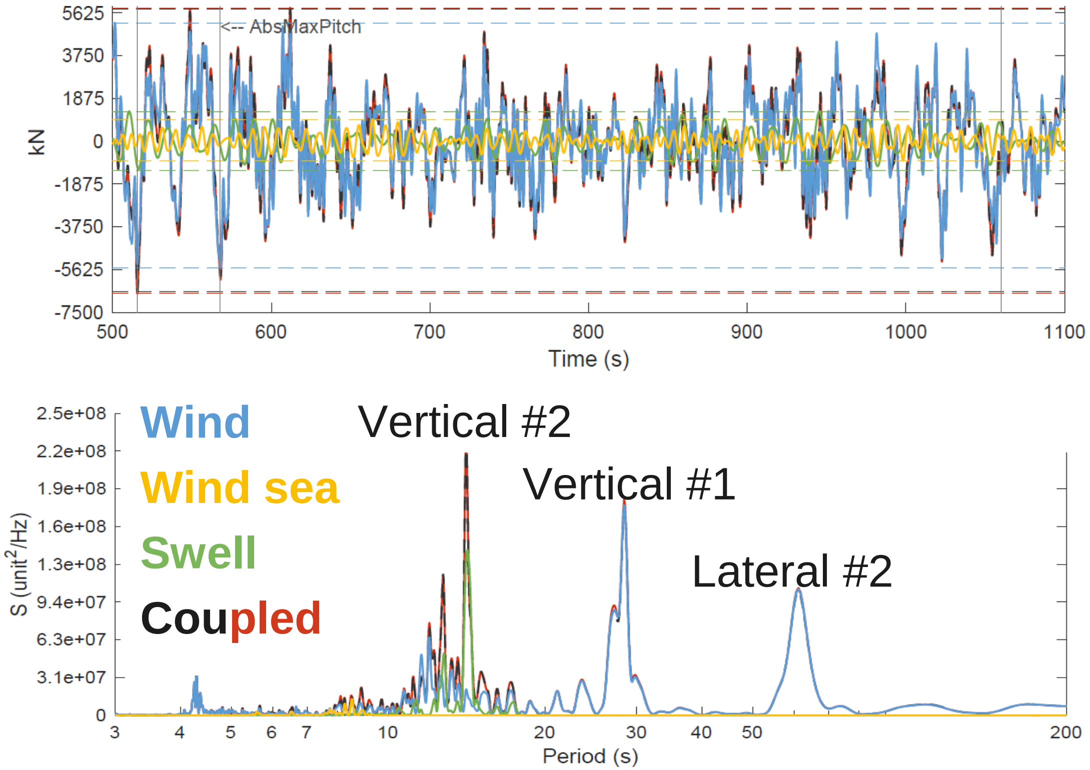


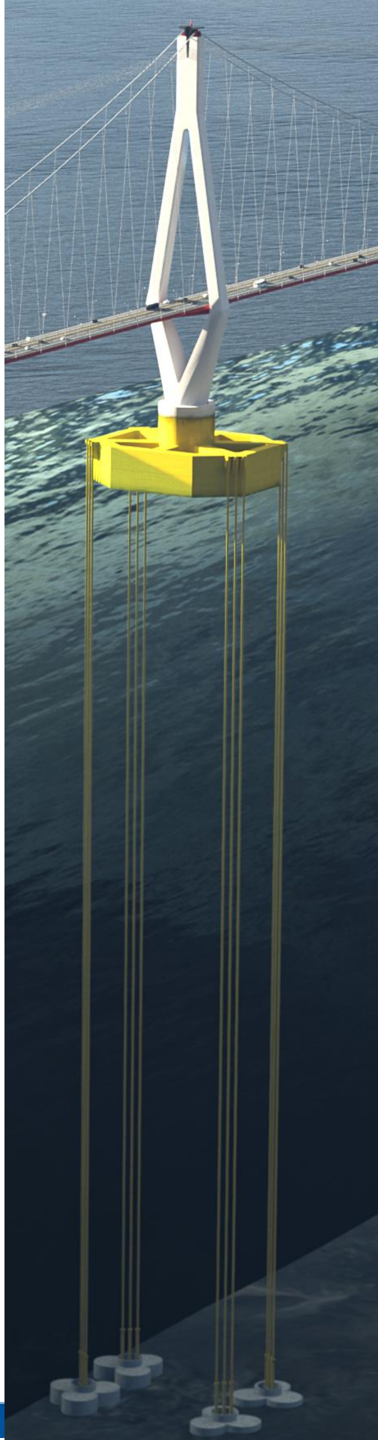
Coupled Dynamic bridge behaviour

Case study: critical 100y storm:

- **Wind from west (Vref=37m/s at girder height)**
- **Windsea from northwest (Hs=2.4m, Tp=5.9s)**
- **Swell from northwest (Hs=0.34m, Tp=14s)**

Dynamic tether response





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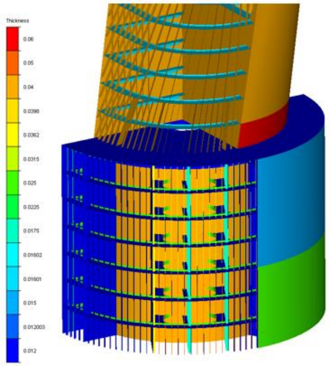
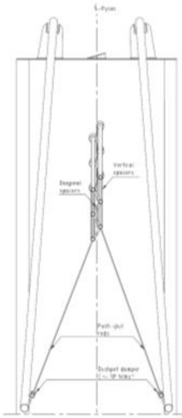
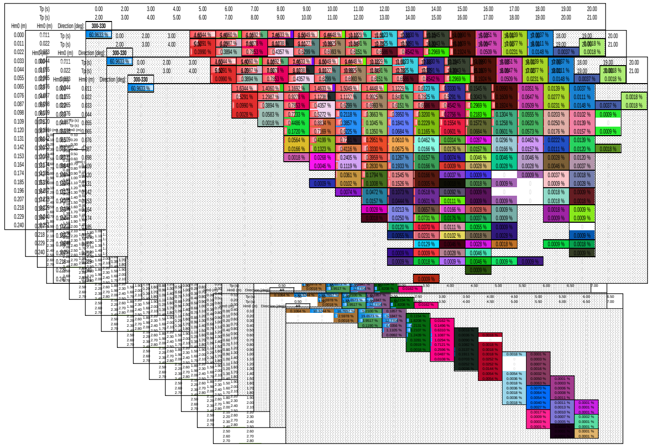
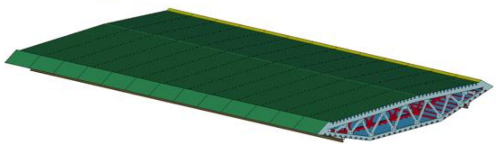
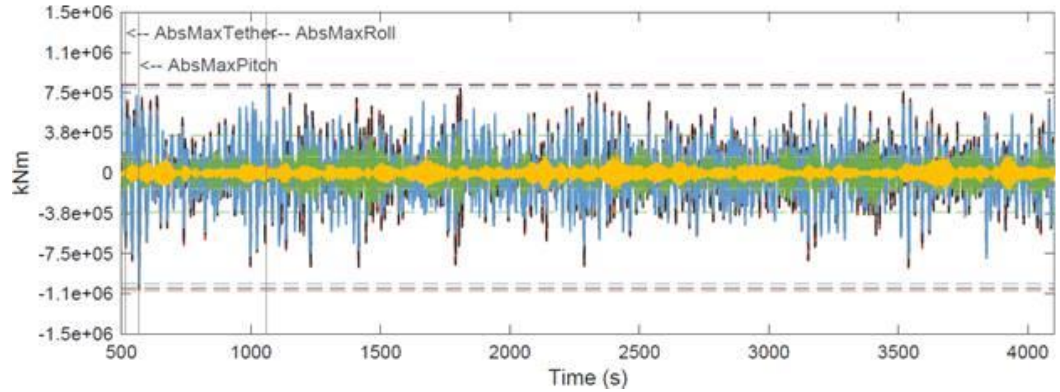
Analyse snapshots











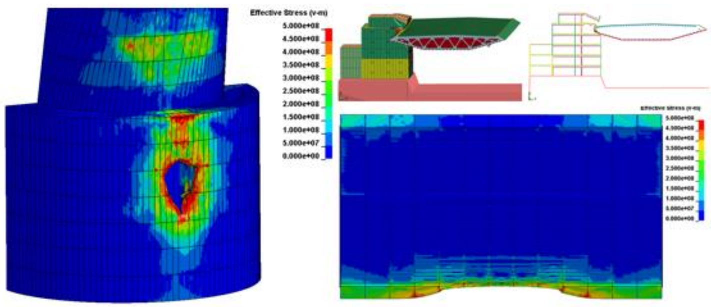
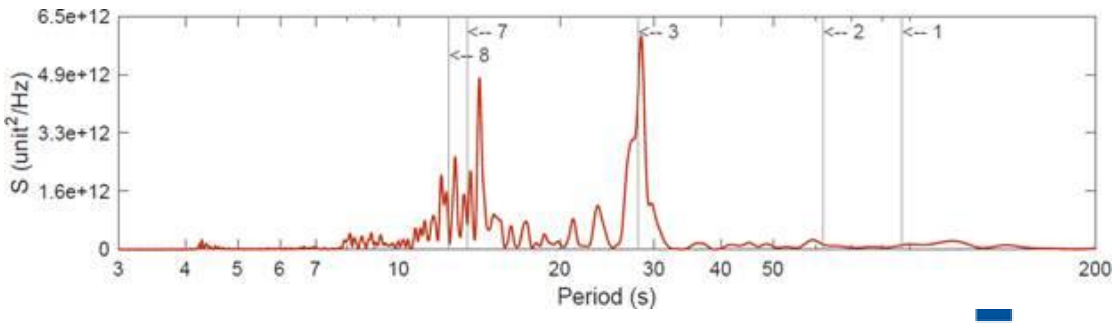


Figure 59 Damage to the floater hull (left) and the bridge girder (right) after a 10^{-4} damage event.



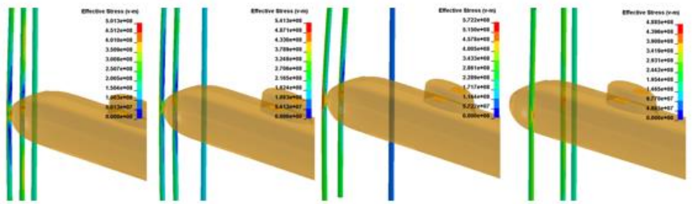
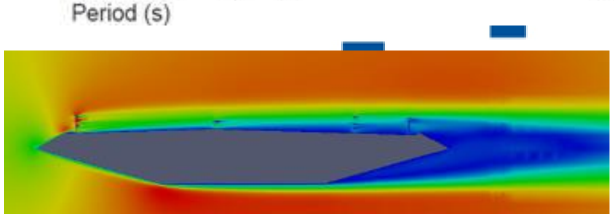
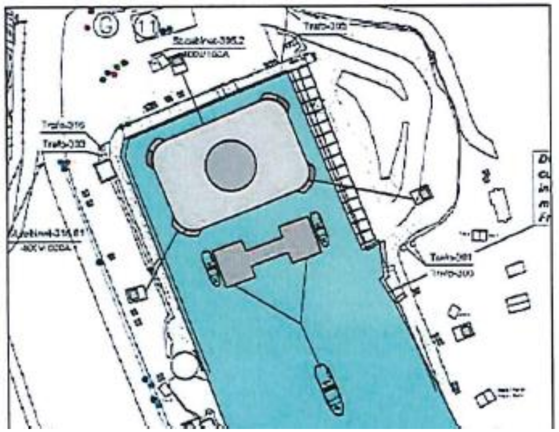
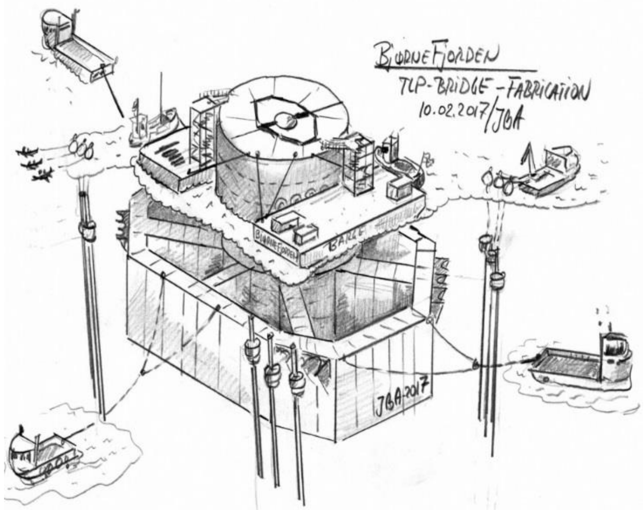


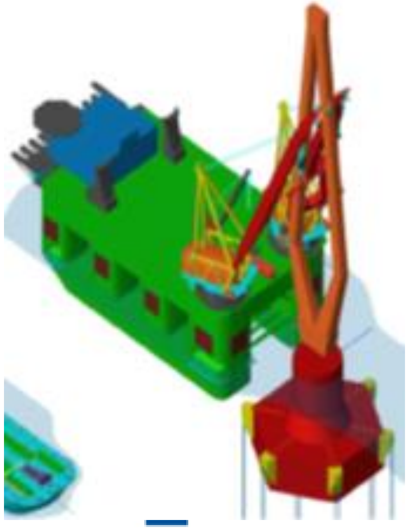
Figure 60 Deformation history for submarine impact at location 2, at 250 m water depth.



TLP construction and installation







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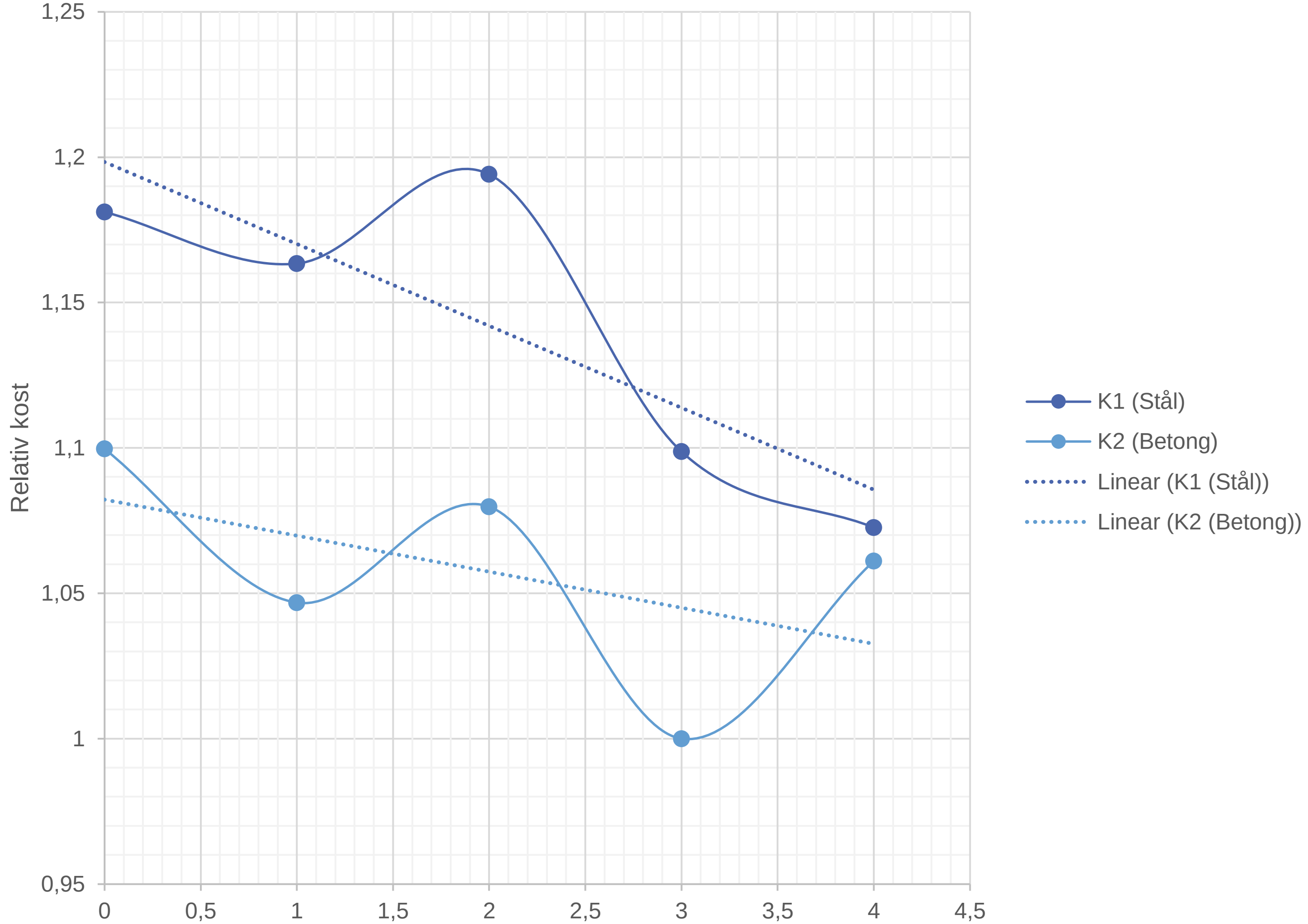
TLP Cost development during design



Summary

The E39 project – bridges

E39 – Challenges and solutions – focus on TLP suspension bridge