



The development of a floating bridge – Bjørnafjorden

Bernardo Costa

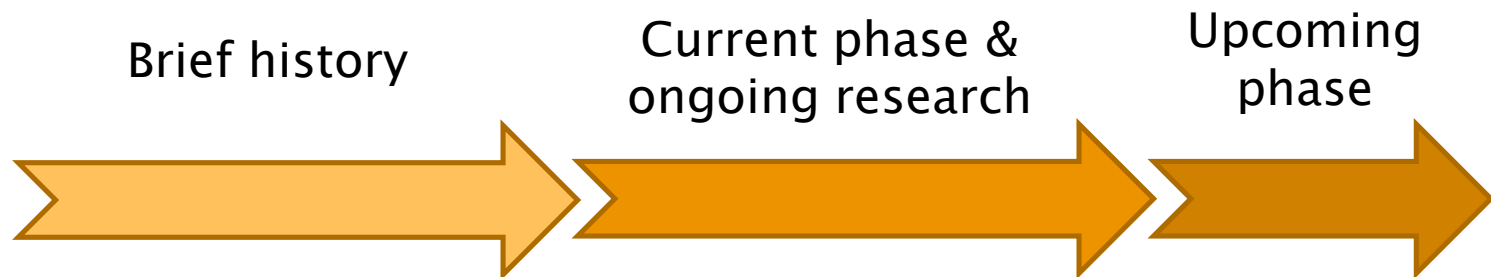
Teknologidagene 2018

1st November, Trondheim



Presentation contents

Bjørnafjorden project's:





E39 Coastal Highway Route Bjørnafjorden



2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

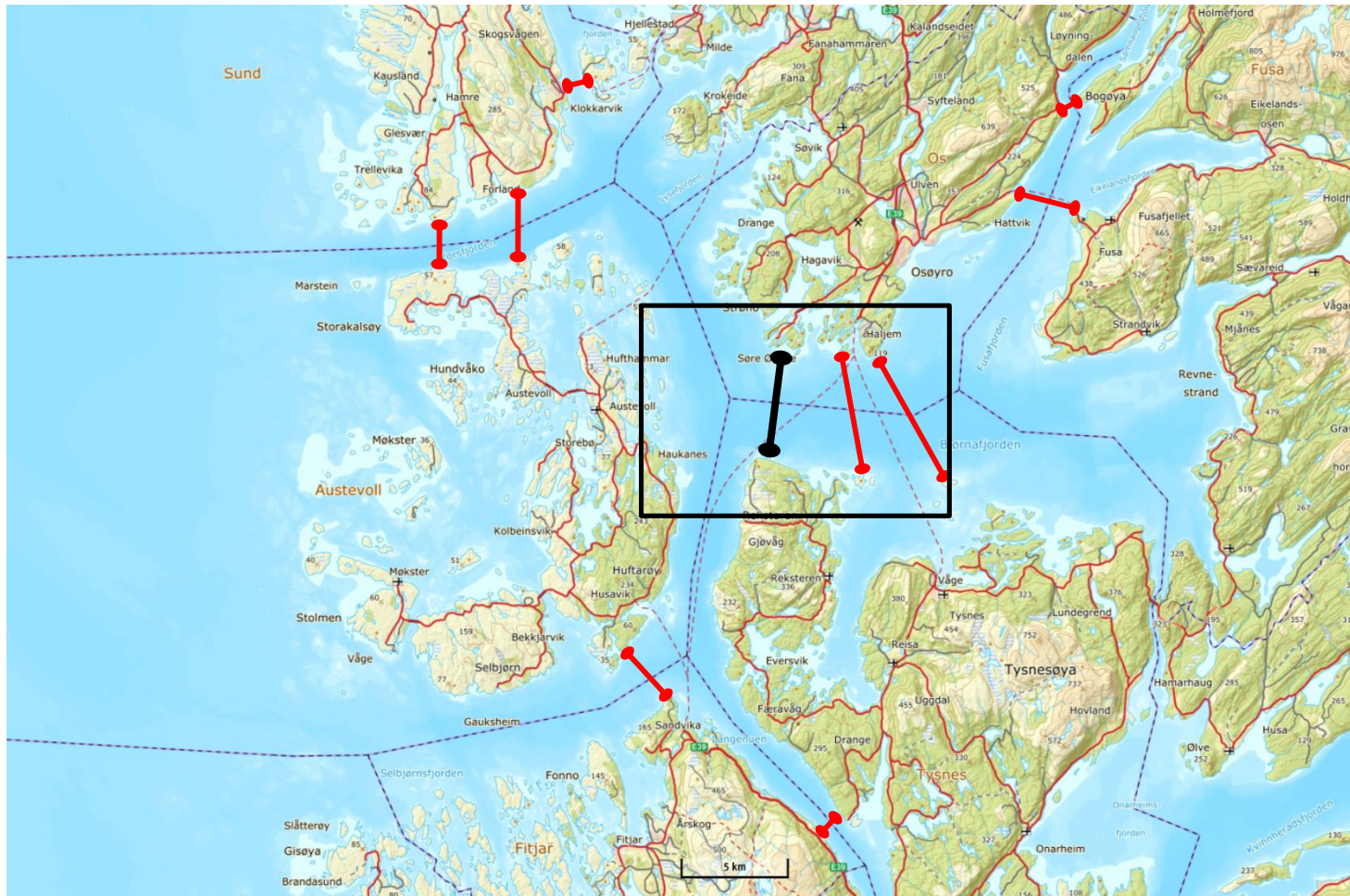
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...



Statens vegvesen

Alternative pathways



... | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...



Statens vegvesen

Concept study



... | 2008 | **2009** | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

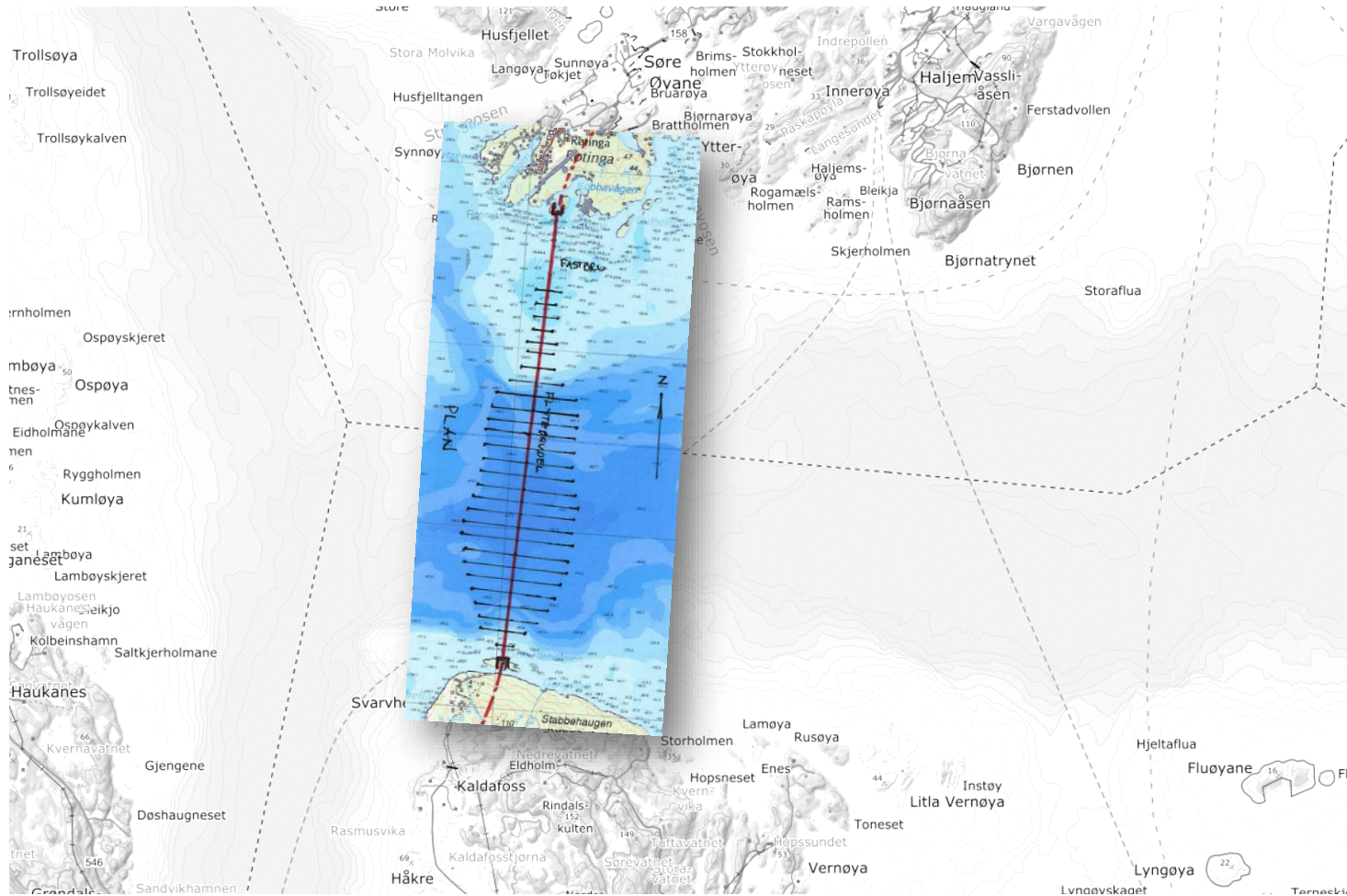
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...



Statens vegvesen

Concept study – floating bridge



... | 2008 | **2009** | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

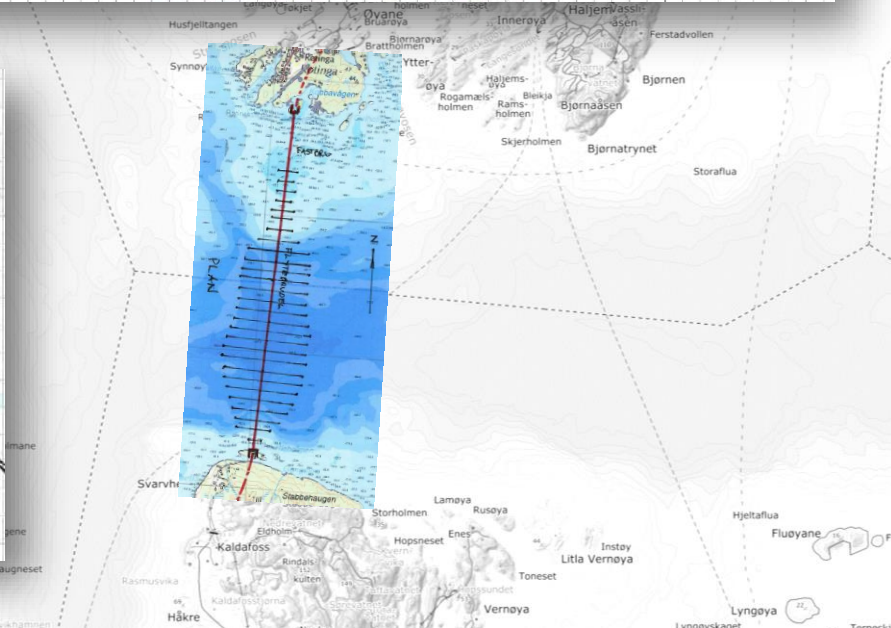
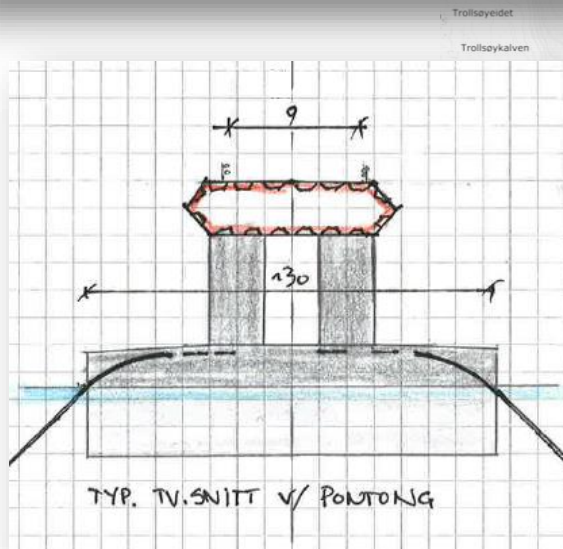
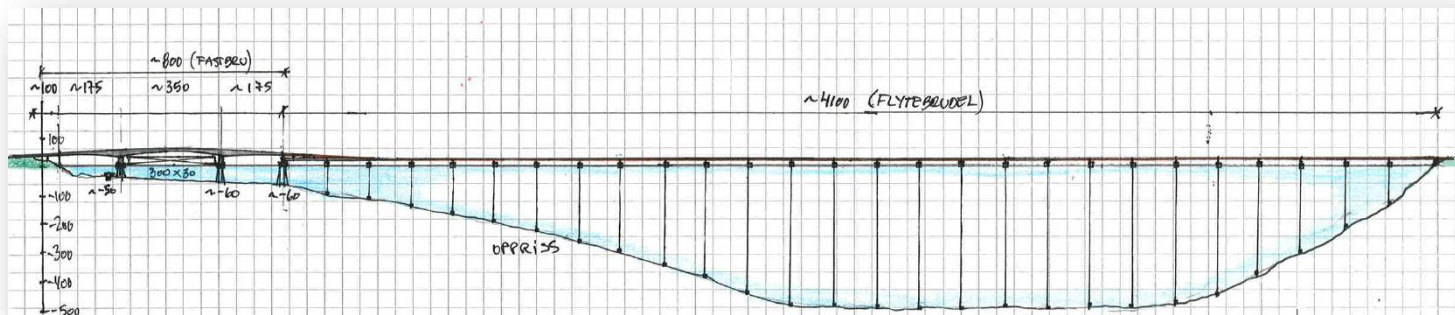
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...

Concept study - floating bridge



Statens vegvesen



... | 2008 | **2009** | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

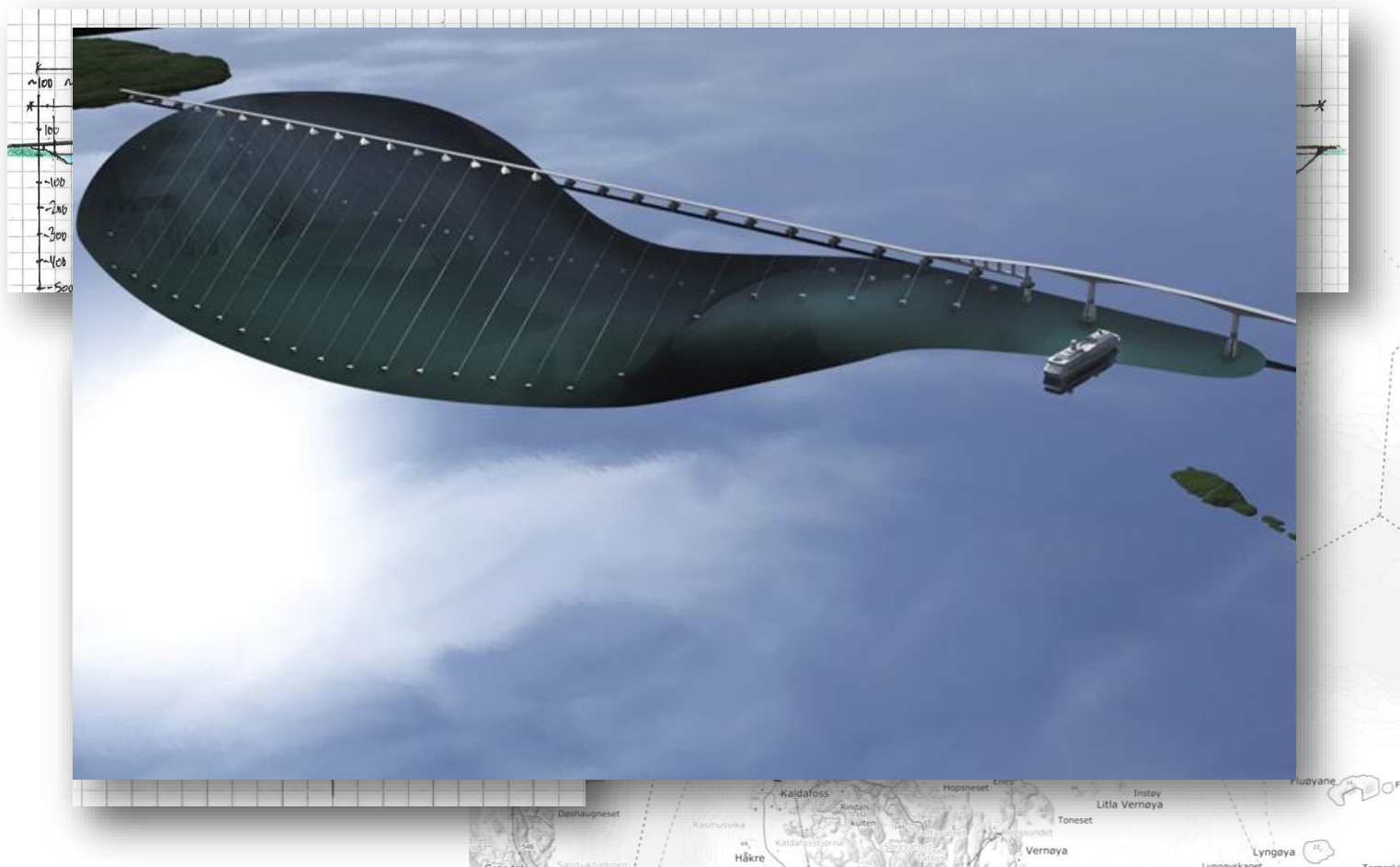
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...

Concept study - floating bridge



Statens vegvesen



... | 2008 | **2009** | **2010** | **2011** | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

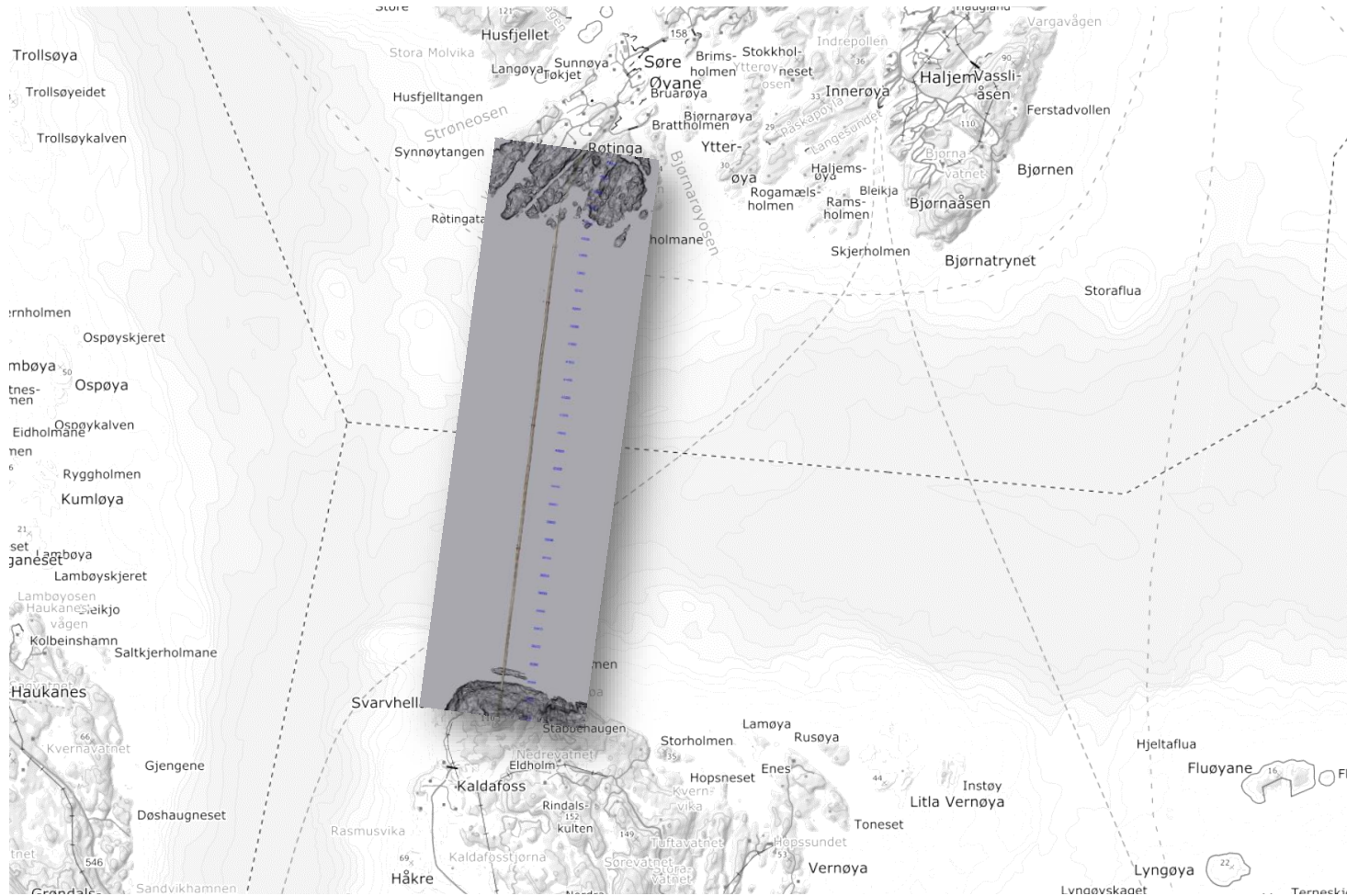
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...



Statens vegvesen

Concept study - floating suspension bridge



... | 2008 | **2009** | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

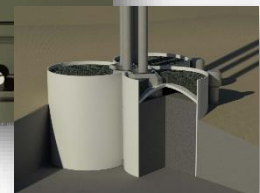
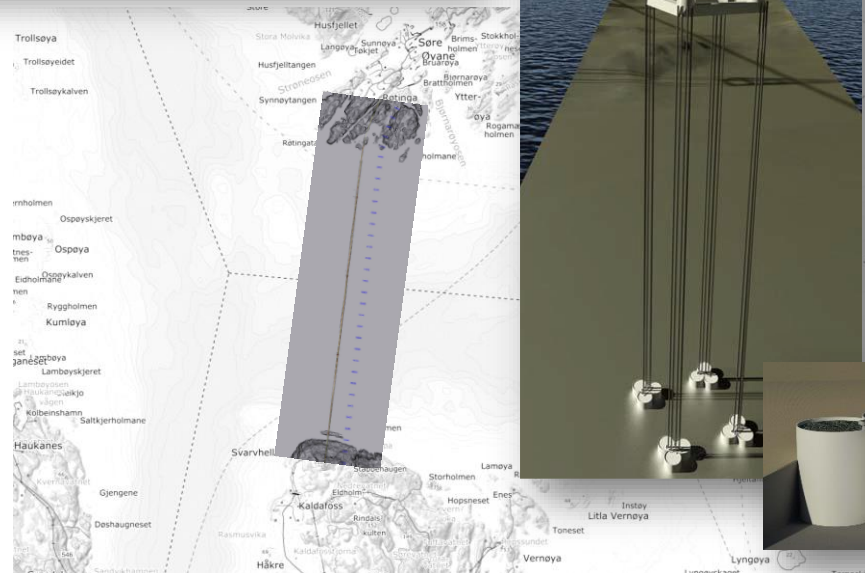
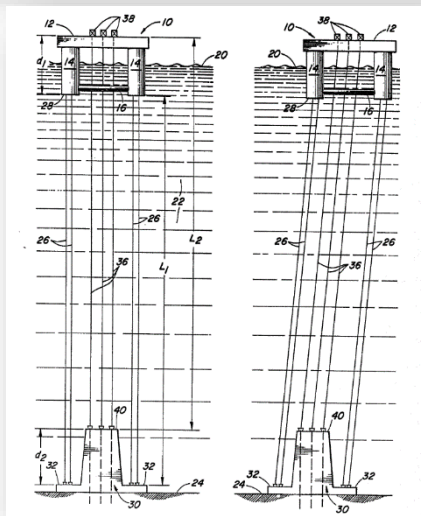
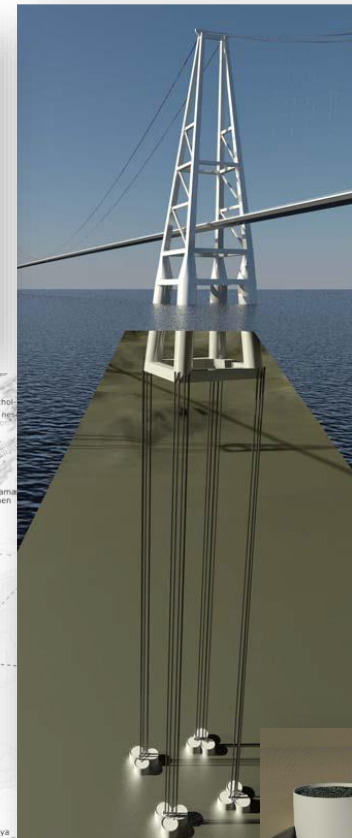
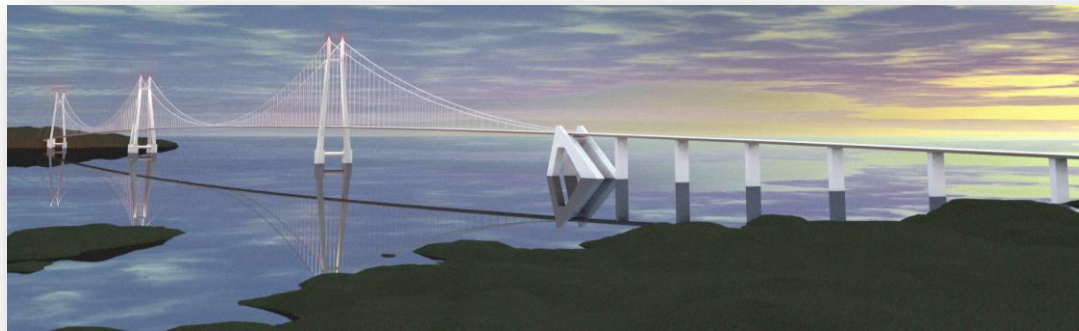
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...

Concept study - floating suspension bridge



Statens vegvesen



... | 2008 | **2009** | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

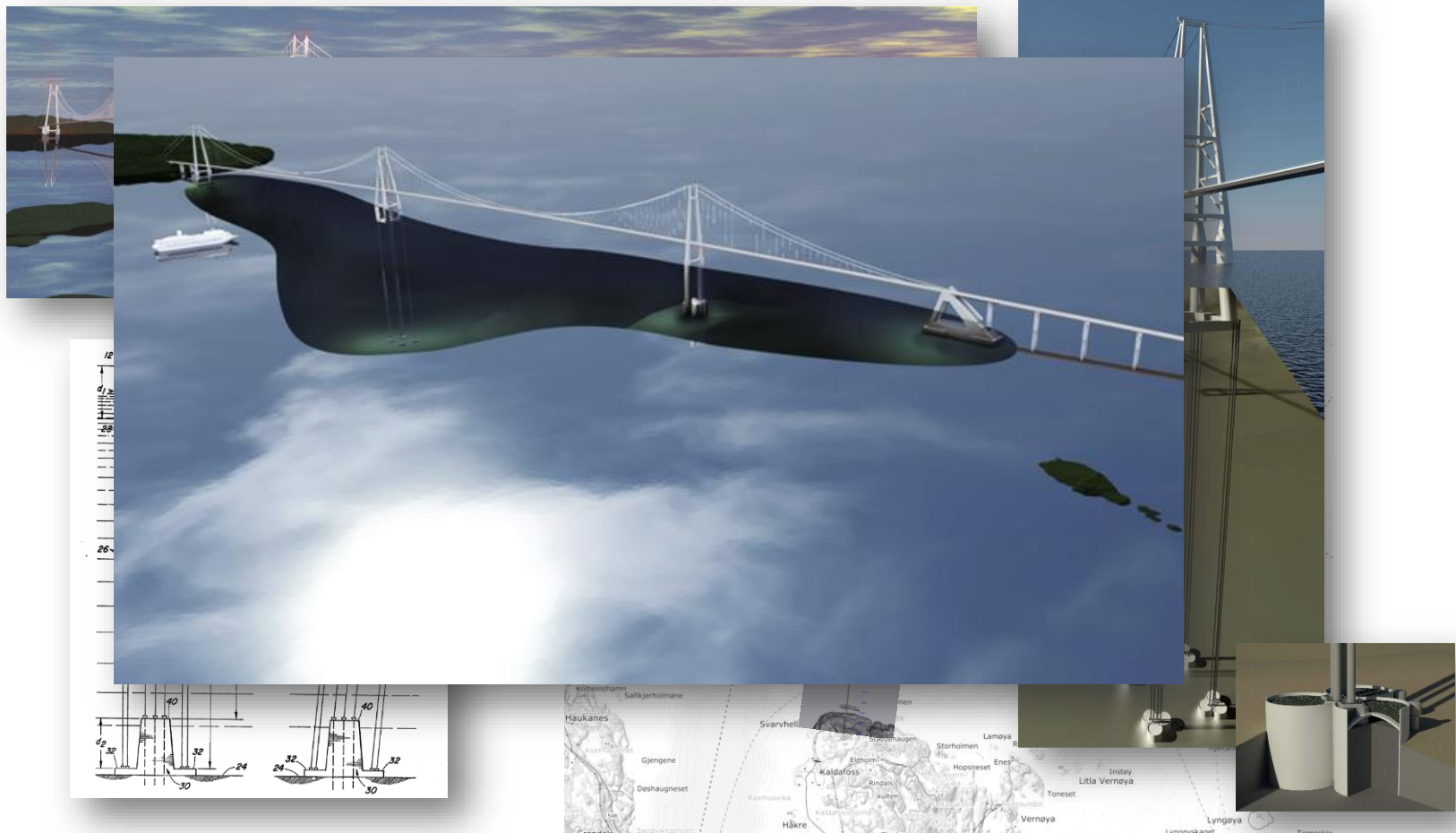
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...

Concept study - floating suspension bridge

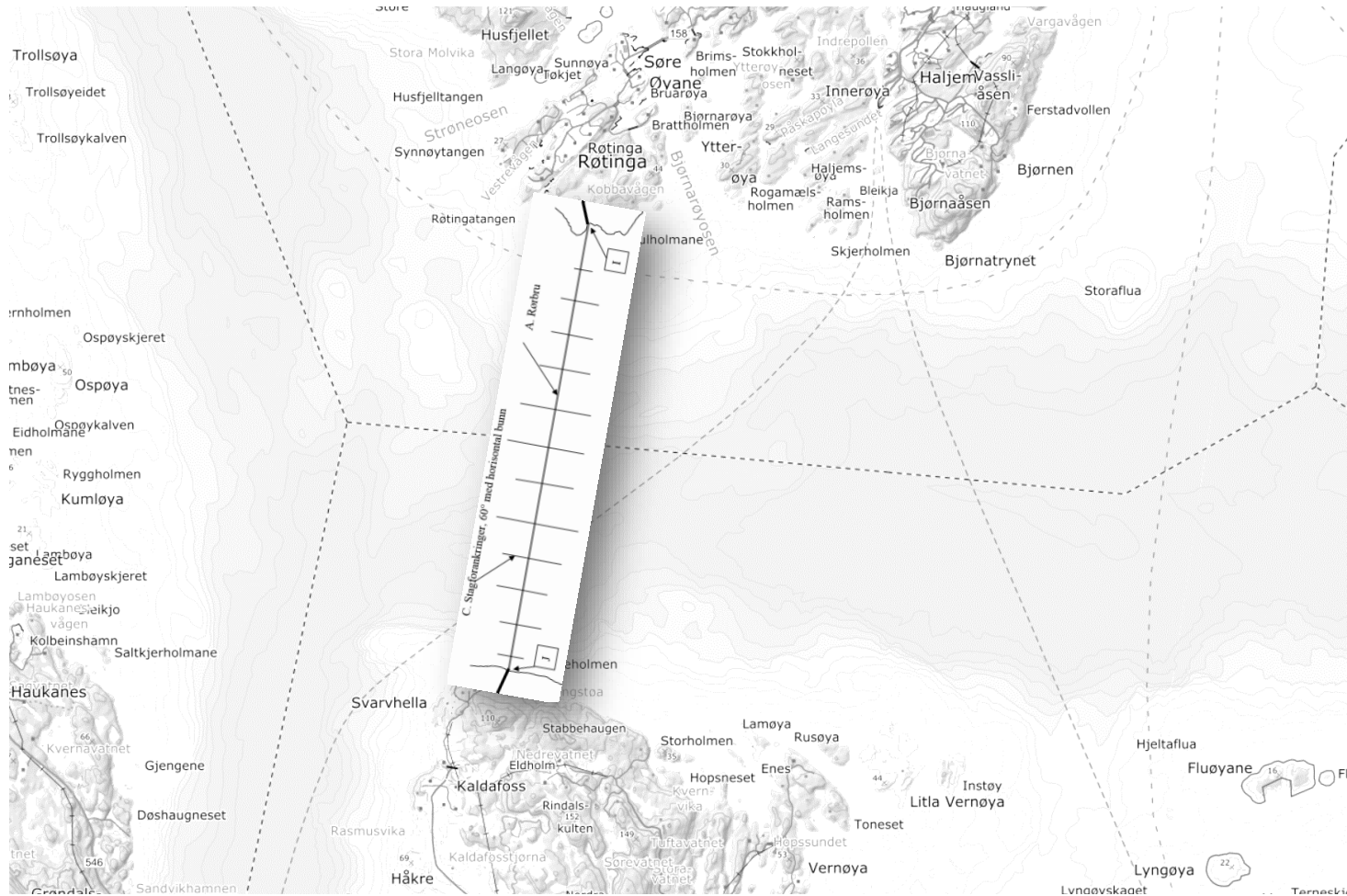


Statens vegvesen



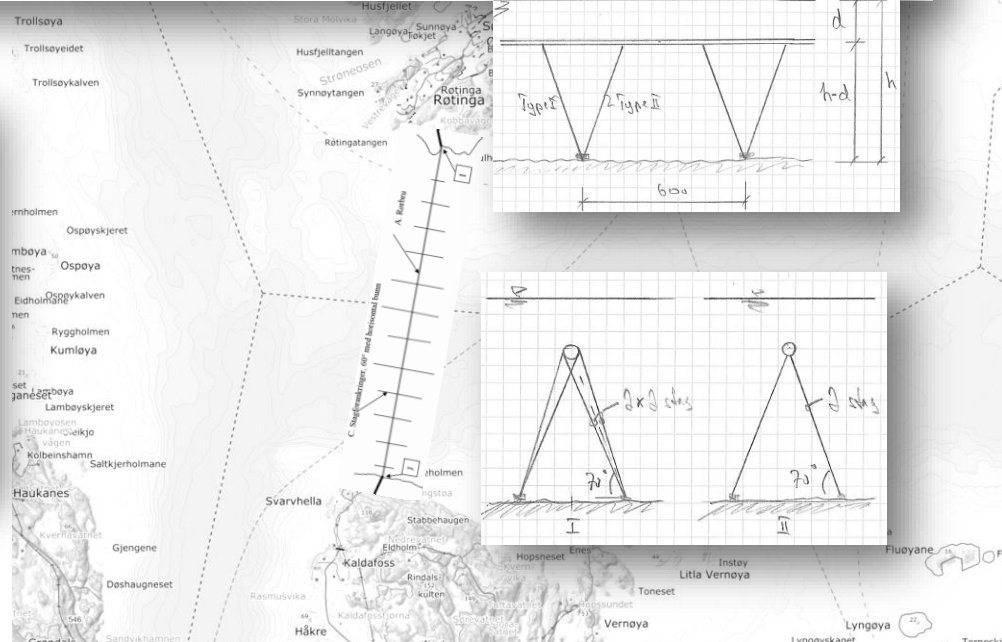
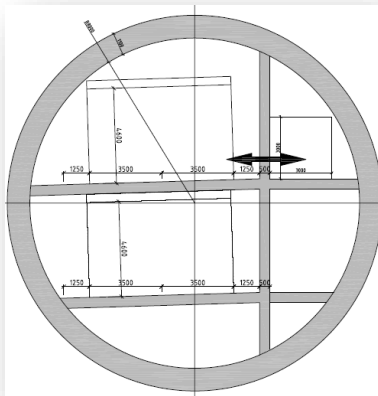
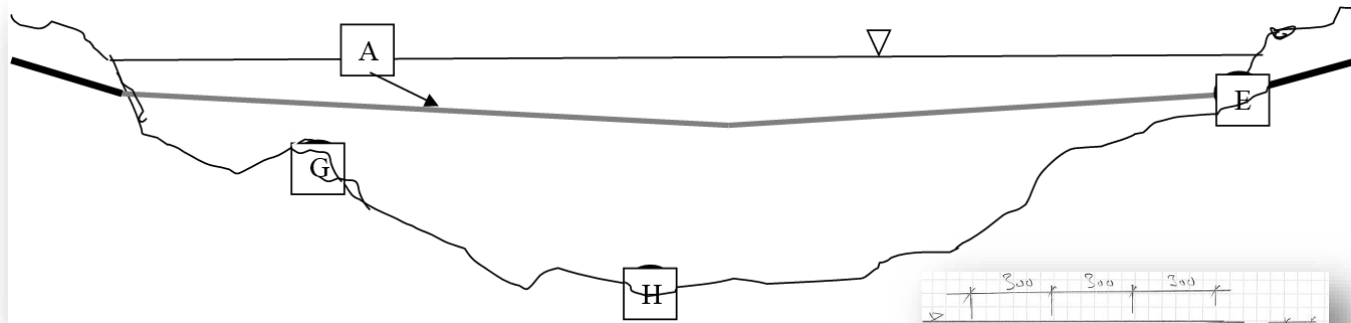
... | 2008 | **2009** | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

Concept study – submerged floating tube bridge



... | 2008 | **2009** | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

Concept study – submerged floating tube bridge



... | 2008 | **2009** | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

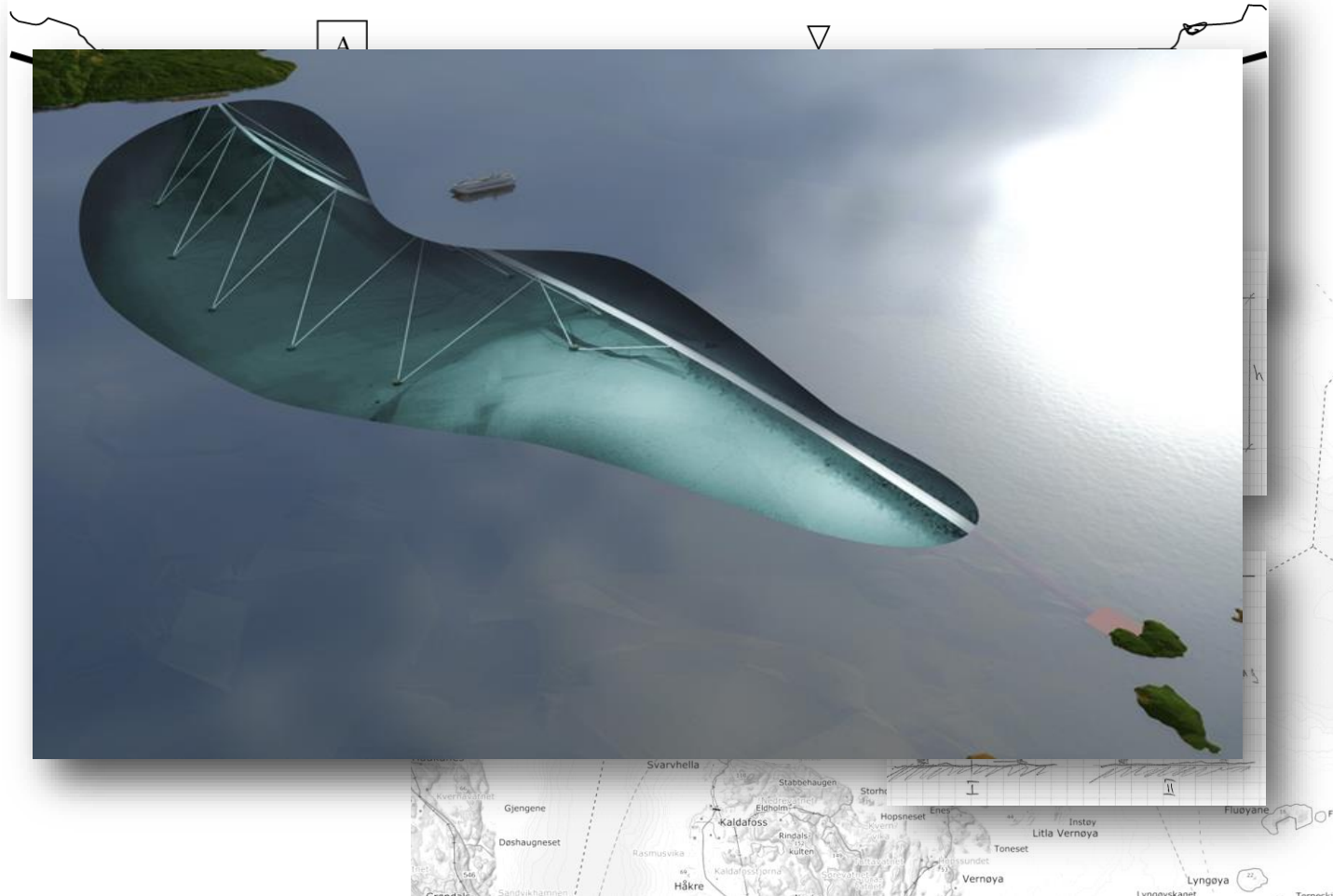
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...



Statens vegvesen

Concept study - submerged floating tube bridge



... | 2008 | **2009** | **2010** | **2011** | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

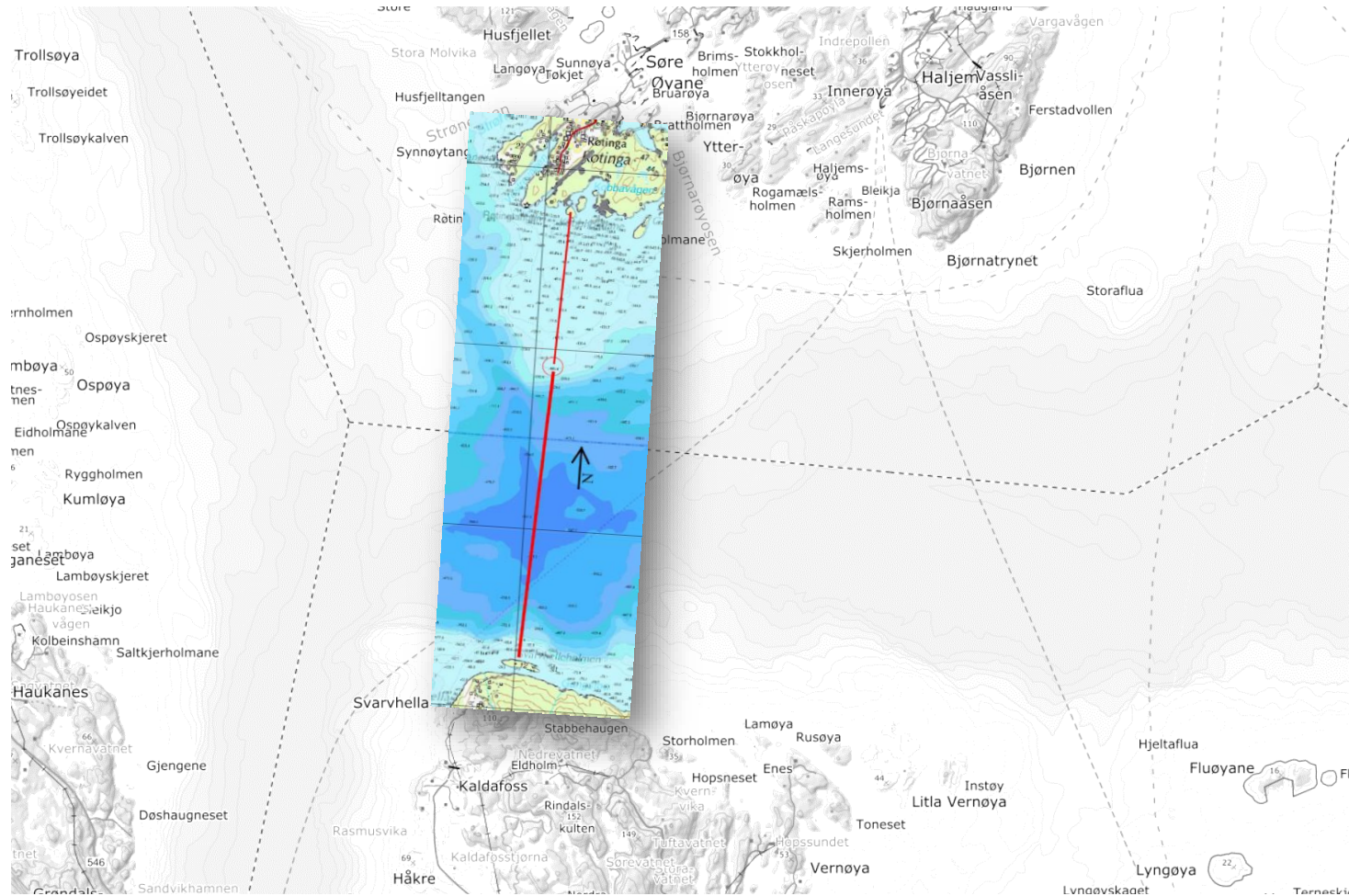
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...



Statens vegvesen

Concept study – suspension bridge



... | 2008 | **2009** | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

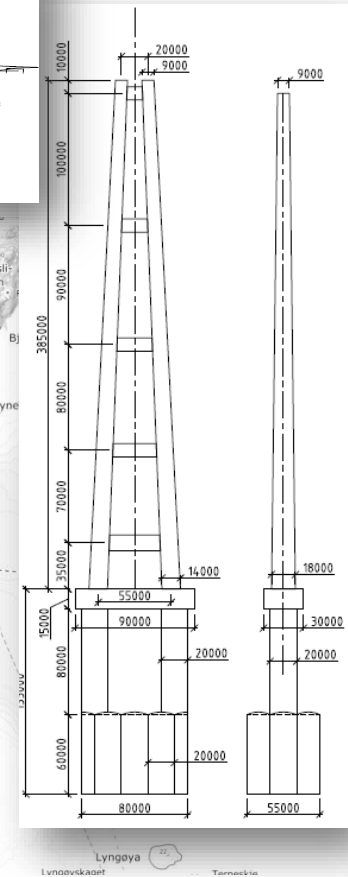
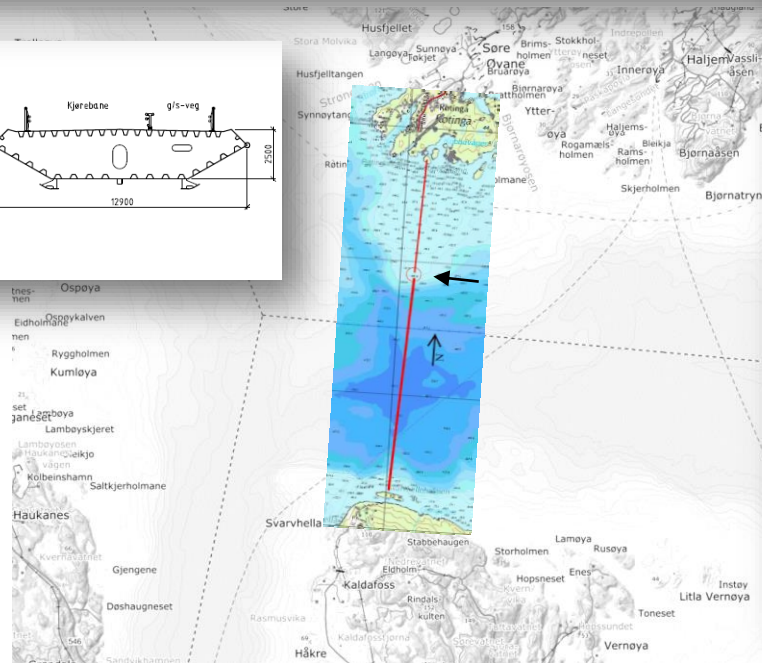
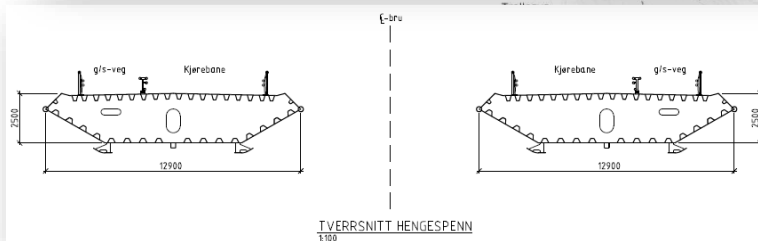
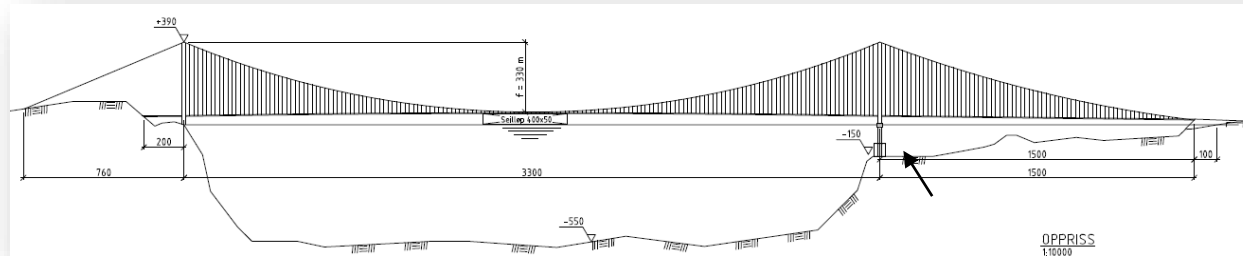
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...

Concept study - suspension bridge



Statens vegvesen



... | 2008 | **2009** | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

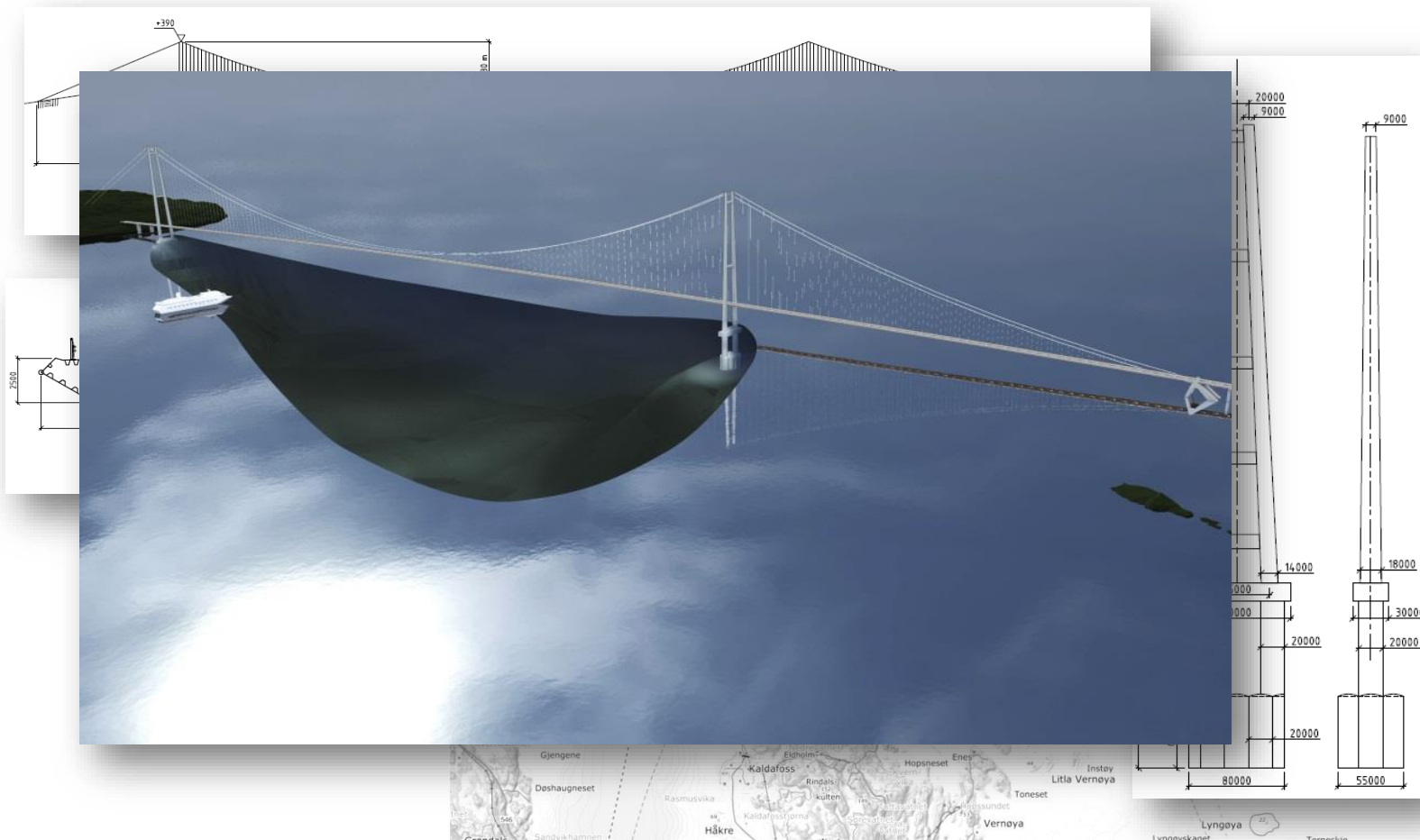
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...



Statens vegvesen

Concept study - suspension bridge



... | 2008 | **2009** | **2010** | **2011** | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...

Concept study - a few others...



Statens vegvesen



... | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

Concept choice

Phase: 1 2 3 4 5

Floating bridge 

Floating suspension bridge 

Submerged floating tube bridge 

Suspension bridge  

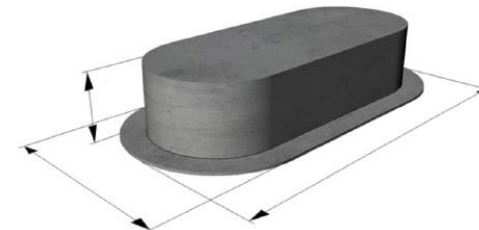
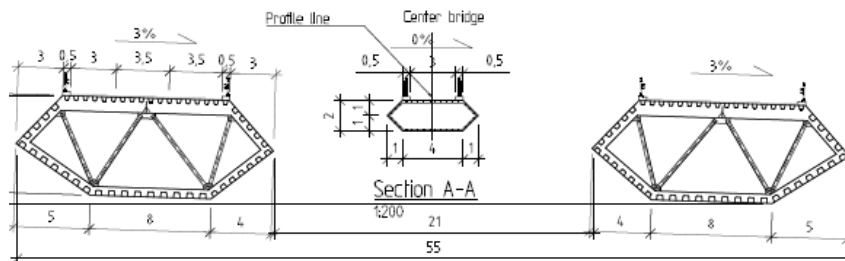
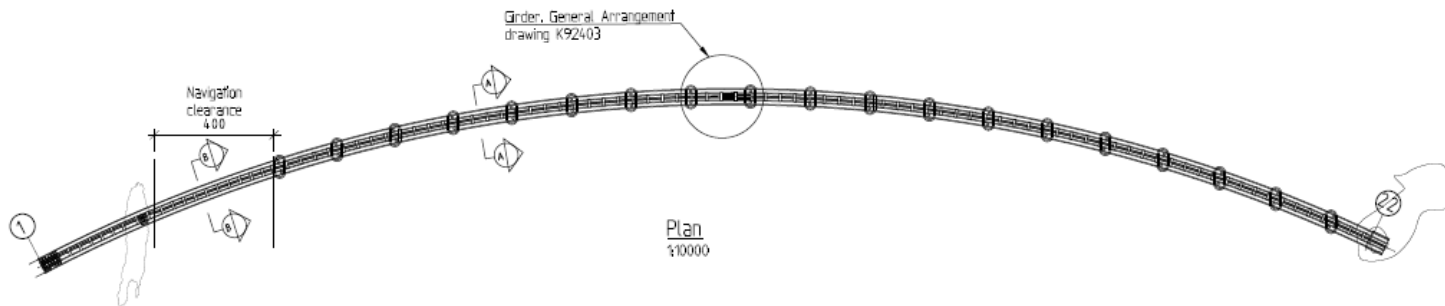
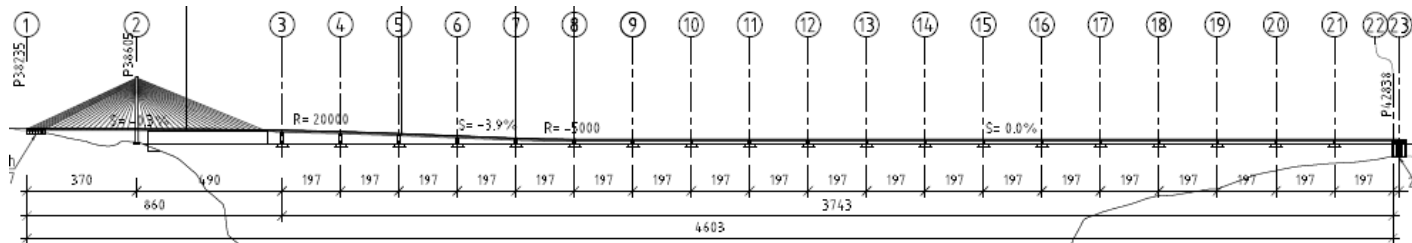
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...



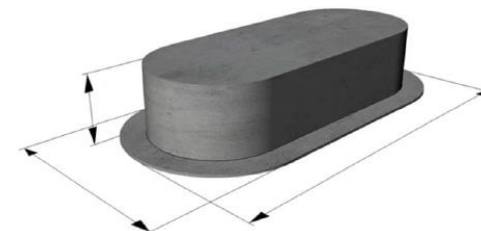
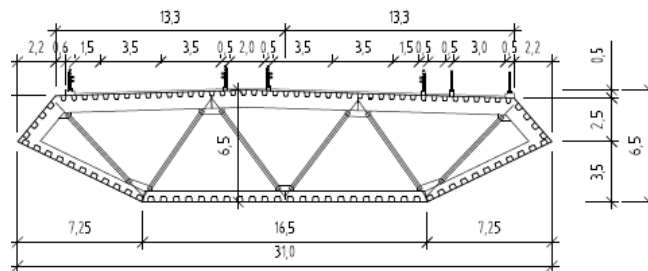
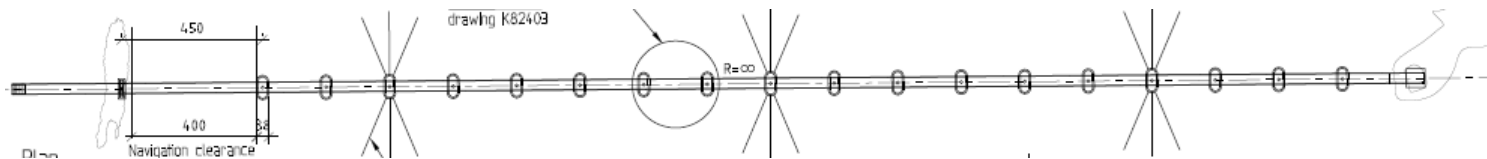
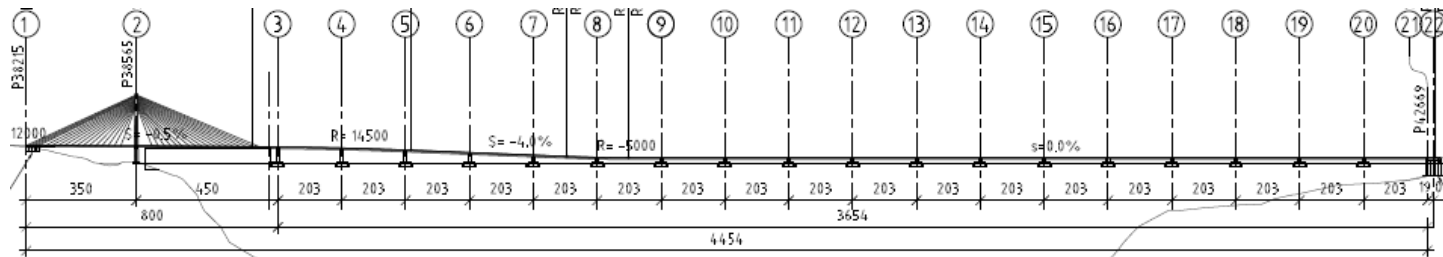
Statens vegvesen

Floating bridge – curved



... | 2008 | 2009 | 2010 | 2011 | 2012 | **2013 | 2014 | 2015** | 2016 | 2017 | 2018 | 2019 ...

Floating bridge – straight



... | 2008 | 2009 | 2010 | 2011 | 2012 | **2013 | 2014 | 2015** | 2016 | 2017 | 2018 | 2019 ...

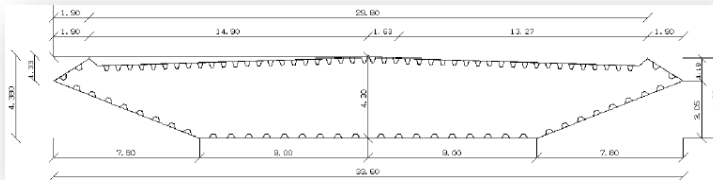
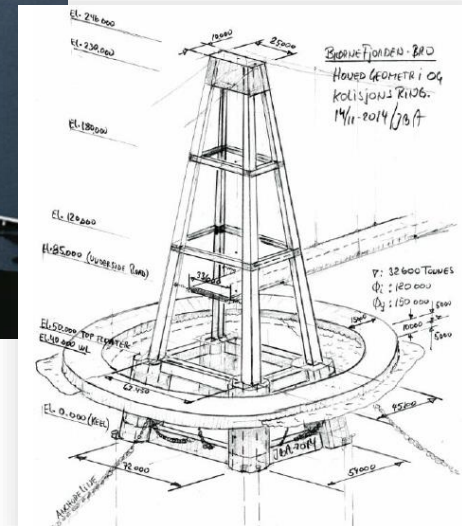
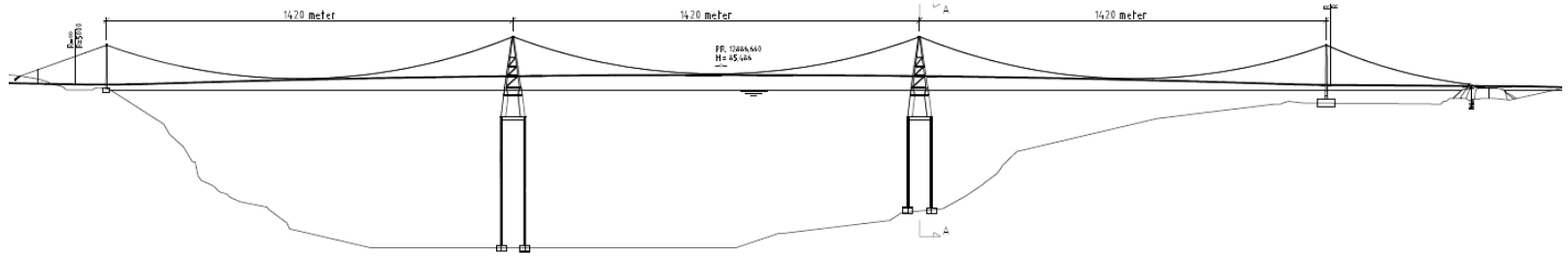
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...

Floating suspension bridge



Statens vegvesen



... | 2008 | 2009 | 2010 | 2011 | 2012 | **2013 | 2014 | 2015** | 2016 | 2017 | 2018 | 2019 ...

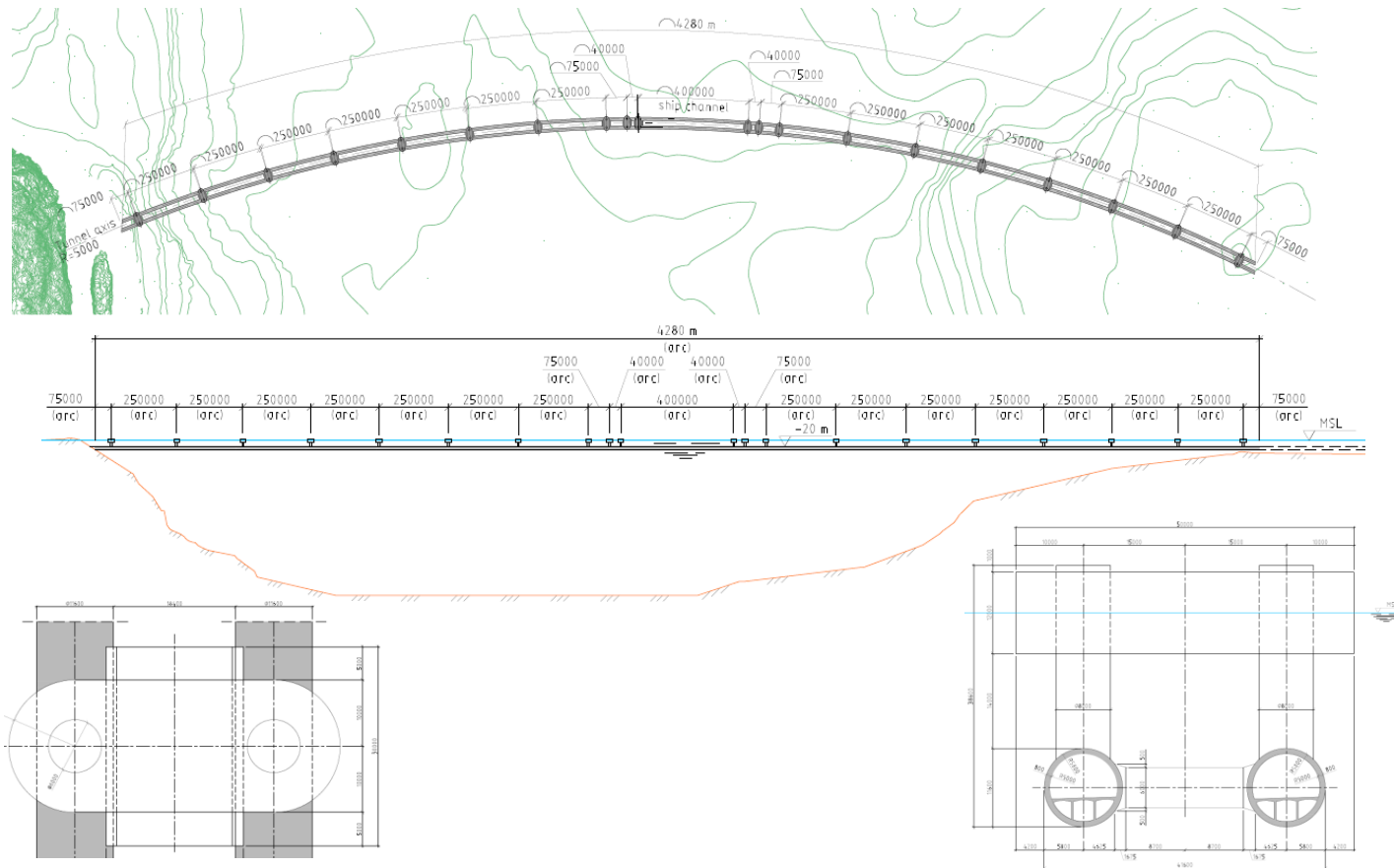
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...



Statens vegvesen

Submerged floating tube bridge



... | 2008 | 2009 | 2010 | 2011 | 2012 | **2013 | 2014 | 2015** | 2016 | 2017 | 2018 | 2019 ...

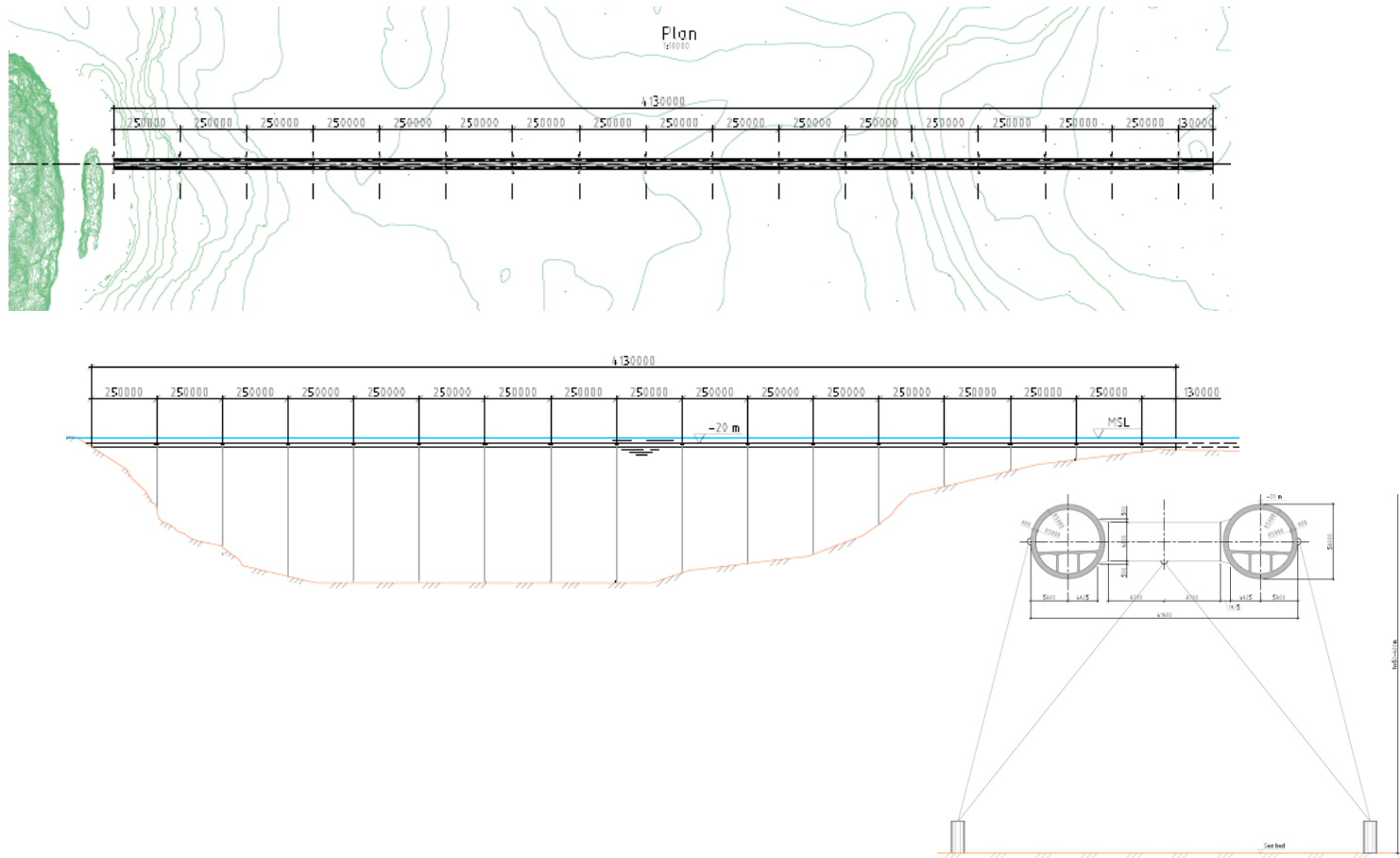
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...



Statens vegvesen

Submerged floating tube bridge



... | 2008 | 2009 | 2010 | 2011 | 2012 | **2013 | 2014 | 2015** | 2016 | 2017 | 2018 | 2019 ...

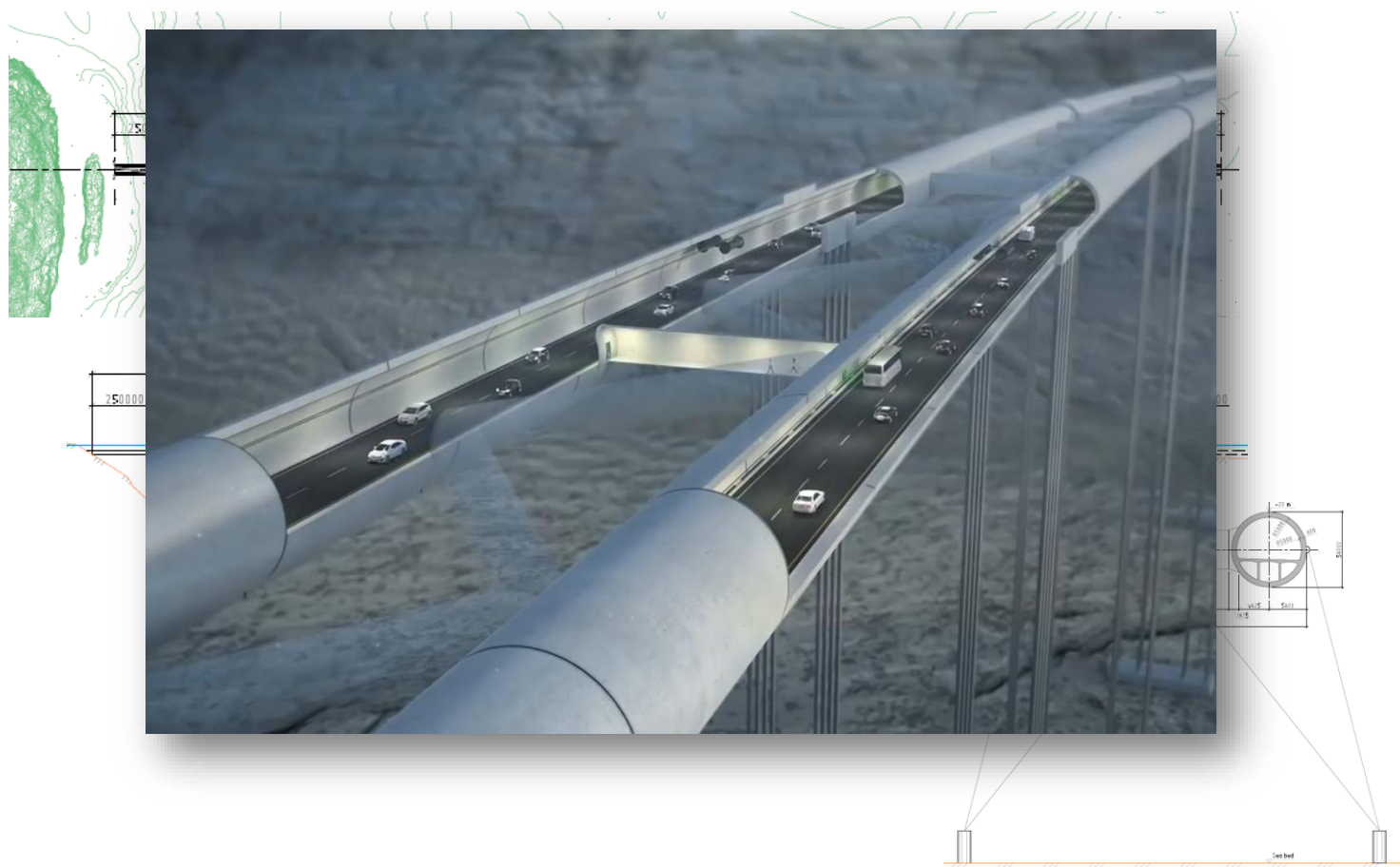
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...



Statens vegvesen

Submerged floating tube bridge





... | 2008 | 2009 | 2010 | 2011 | 2012 | **2013 | 2014 | 2015** | 2016 | 2017 | 2018 | 2019 ...

Concept choice

Phase: 1 2 3 4 5

Floating bridge 

Floating suspension bridge 

Submerged floating tube bridge  

Suspension bridge  

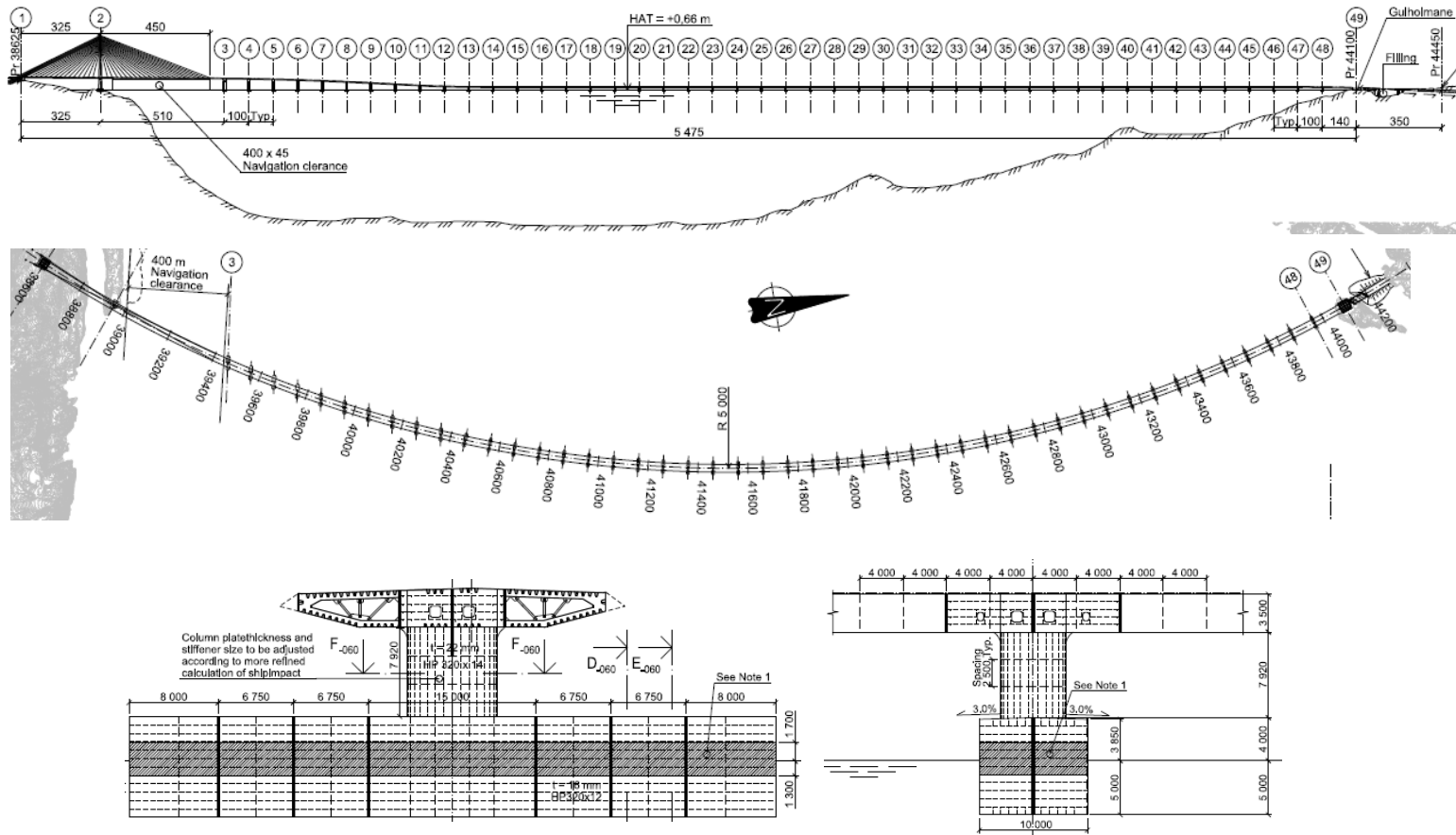
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...

Floating bridge – curved



Statens vegvesen



... | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

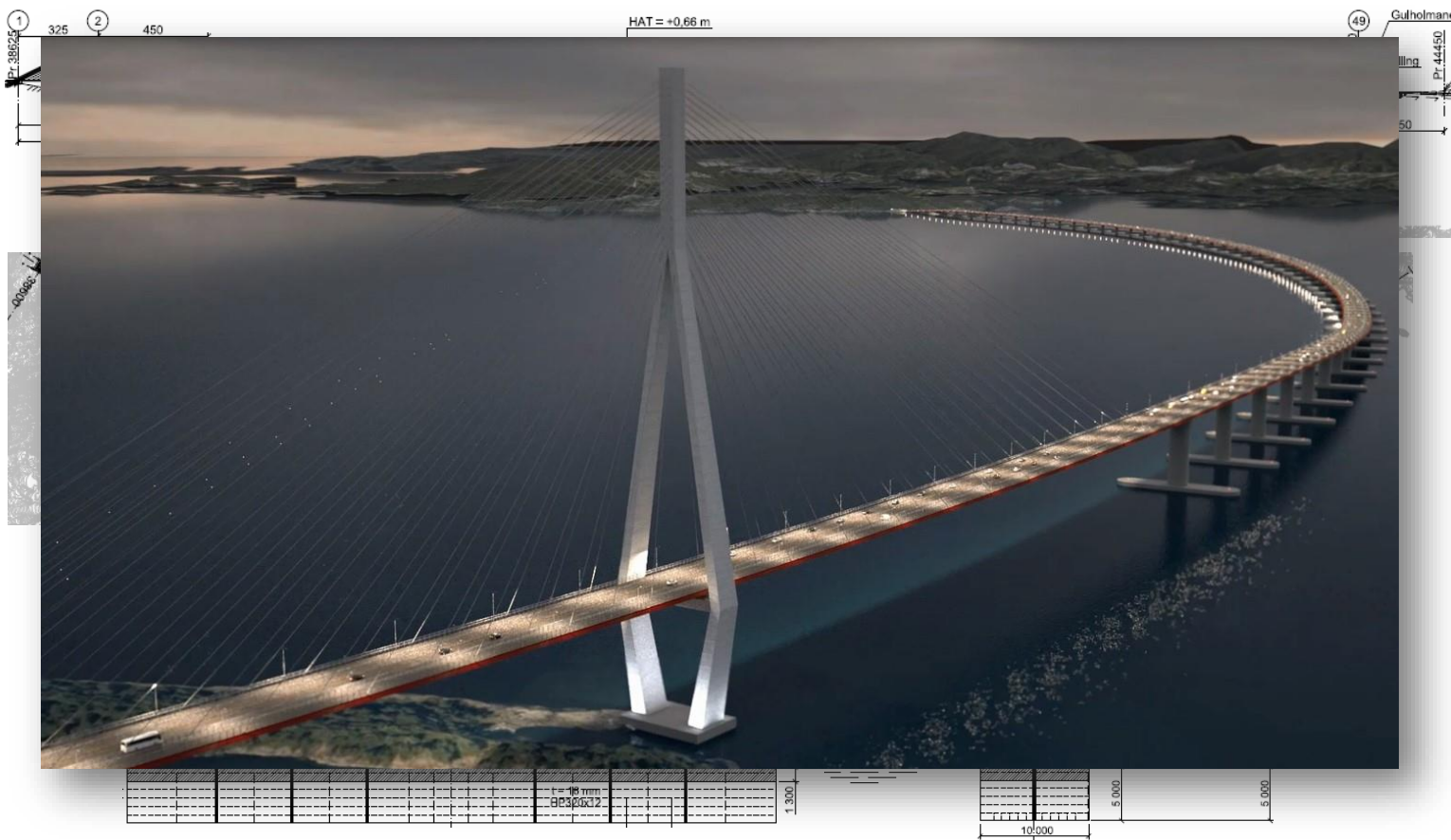
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...

Floating bridge – curved

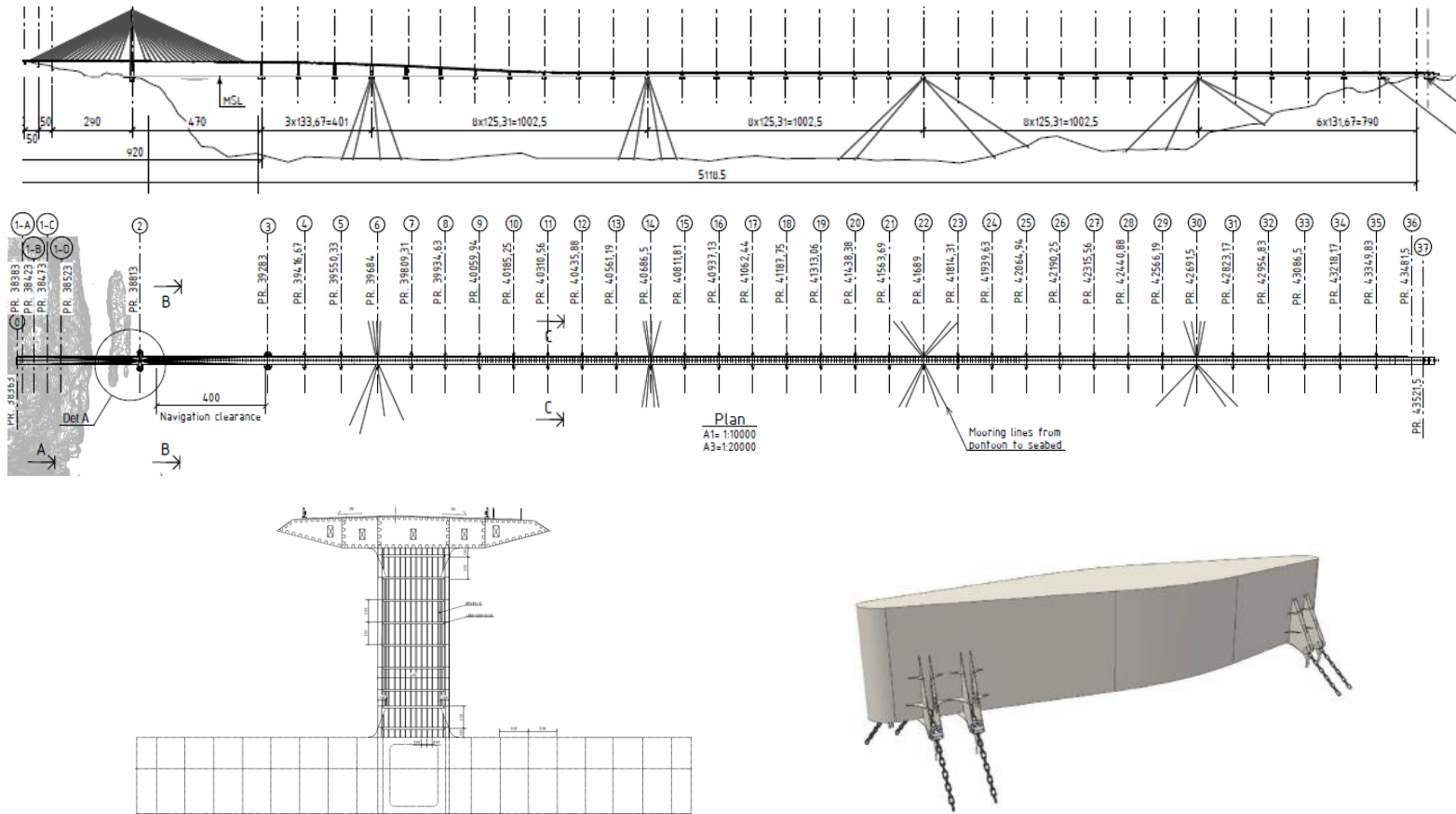


Statens vegvesen



... | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

Floating bridge – straight



... | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

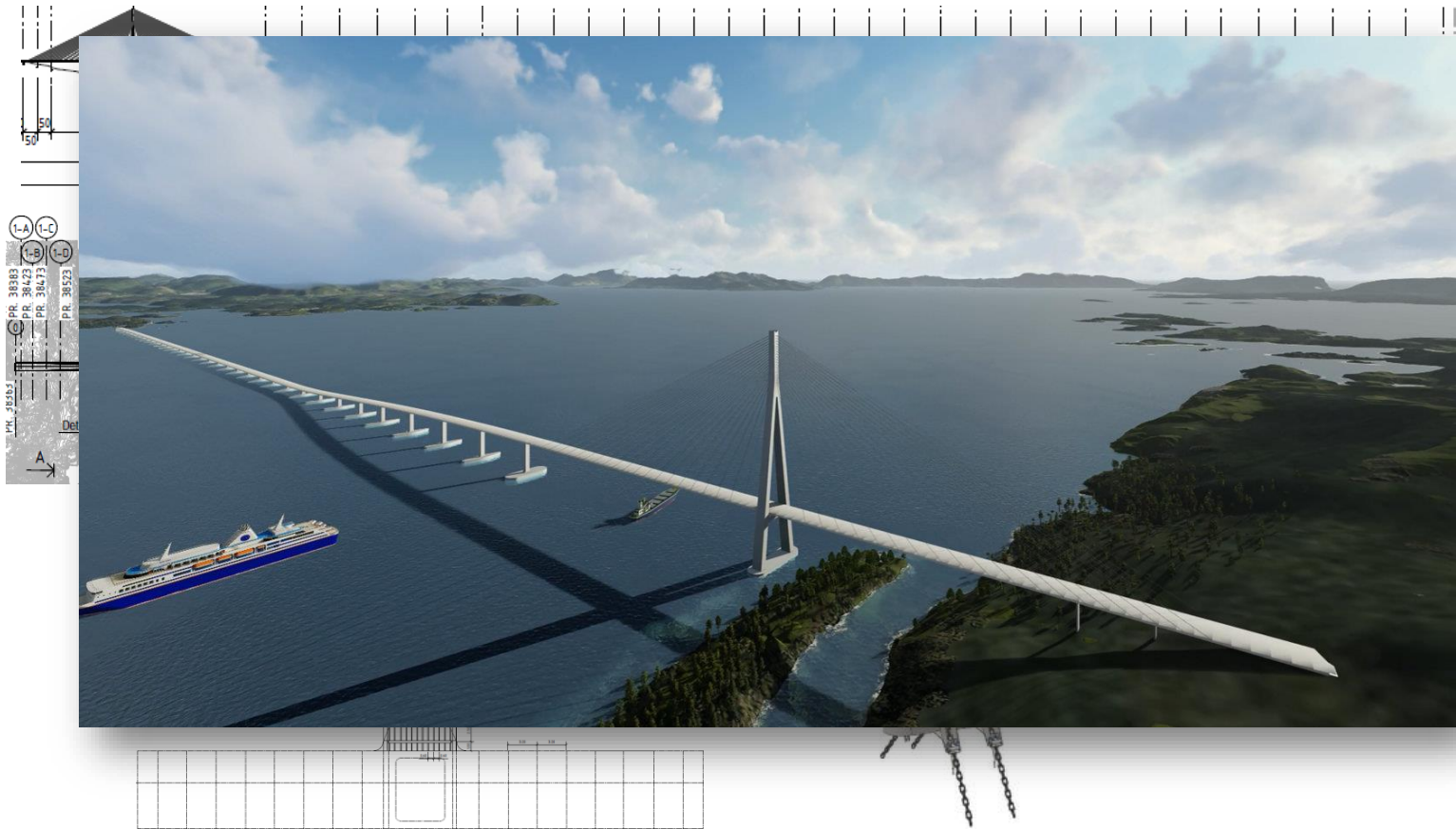
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...

Floating bridge – straight



Statens vegvesen



... | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

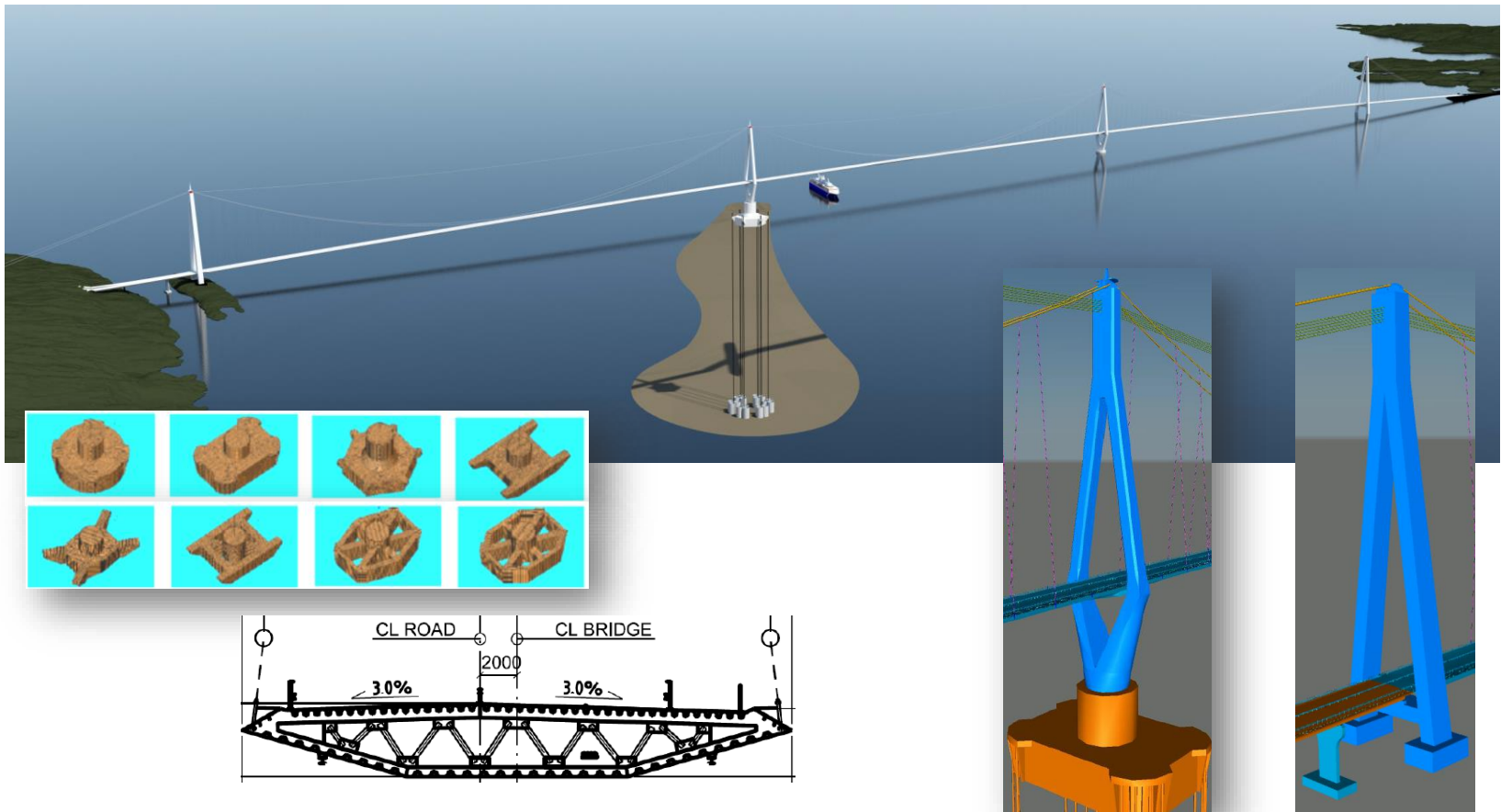
Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...

Floating suspension bridge



Statens vegvesen




... | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

Concept choice

Phase: 1 2 3 4 5

Floating bridge 

Floating suspension bridge 

Submerged floating tube bridge 

Suspension bridge 

Bjørnafjorden

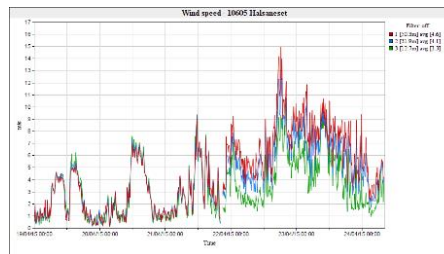
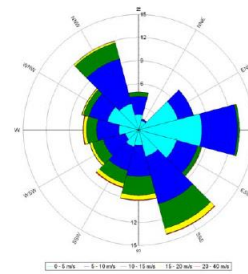
Phase: 1 - 2 - 3 - 4 - 5 - ...



Statens vegvesen

Further developing the design basis.
A few examples:

- Wind, waves, currents and temperature measurements.



... | 2008 | 2009 | 2010 | 2011 | 2012 | **2013 | 2014 | 2015 | 2016 | 2017 | 2018** | 2019 ...

Bjørnafjorden

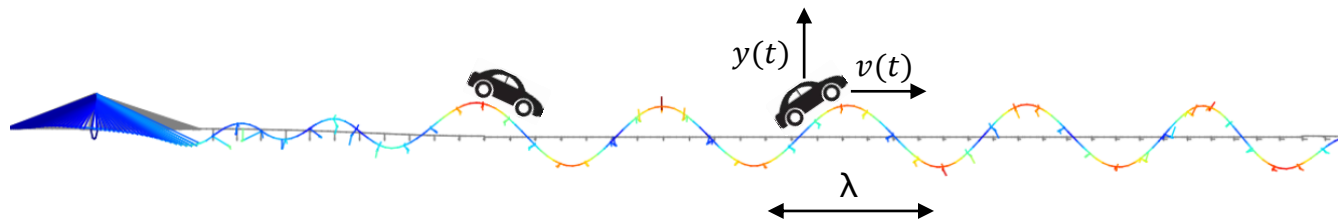
Phase: 1 - 2 - 3 - 4 - 5 - ...

Further developing the design basis.

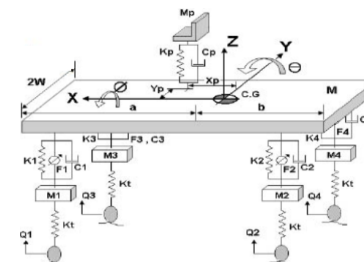
A few examples:

- Vehicle-bridge motions: comfort and safety.

$$y(t) = \sin\left(\frac{v(t)t}{\lambda} 2\pi\right) \cdot \sum_n \sin(\omega_n t + \psi_n)$$



=



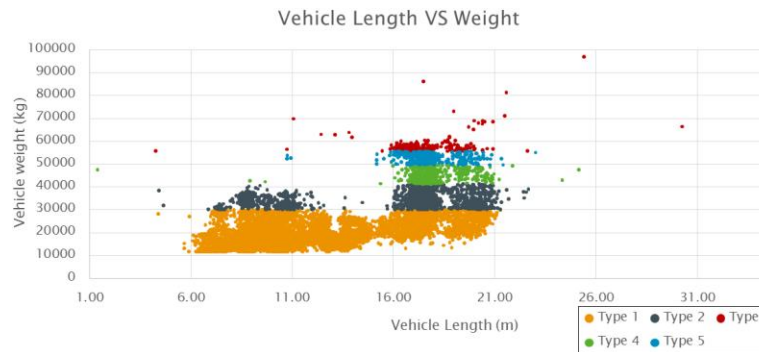
Further developing the design basis.
A few examples:

- Fatigue load model: traffic measurements.

Real traffic ?








Measurements



Load models

Table 4.7 - Set of equivalent lorries

VEHICLE TYPE	TRAFFIC TYPE					Wheel type	
	1	2	3	4	5		
	4,5	70	130	20,0	40,0	80,0	A B
	4,20	1,30	70	120	120		A B
	3,20	5,20	1,30	1,30	90	90	A B C C
	3,40	6,00	1,80	1,80	90	90	A B B
	4,80	3,60	4,40	1,30	70	130	A B C C

Bjørnafjorden

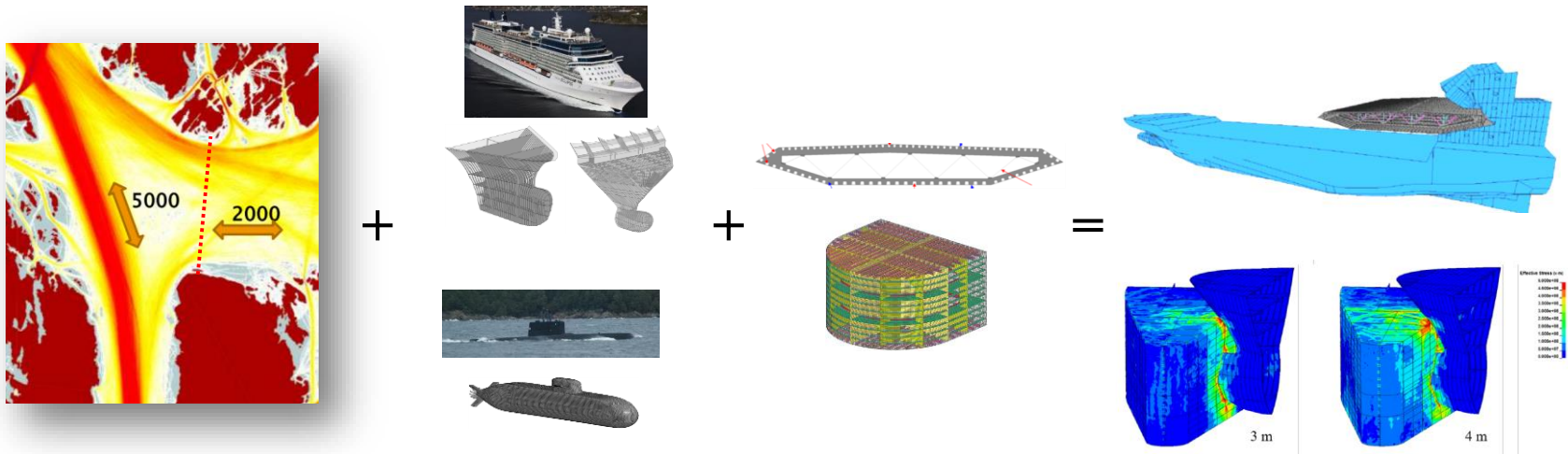
Phase: 1 - 2 - 3 - 4 - 5 - ...



Statens vegvesen

Further developing the design basis.
A few examples:

- Ship impact: risk and consequence.



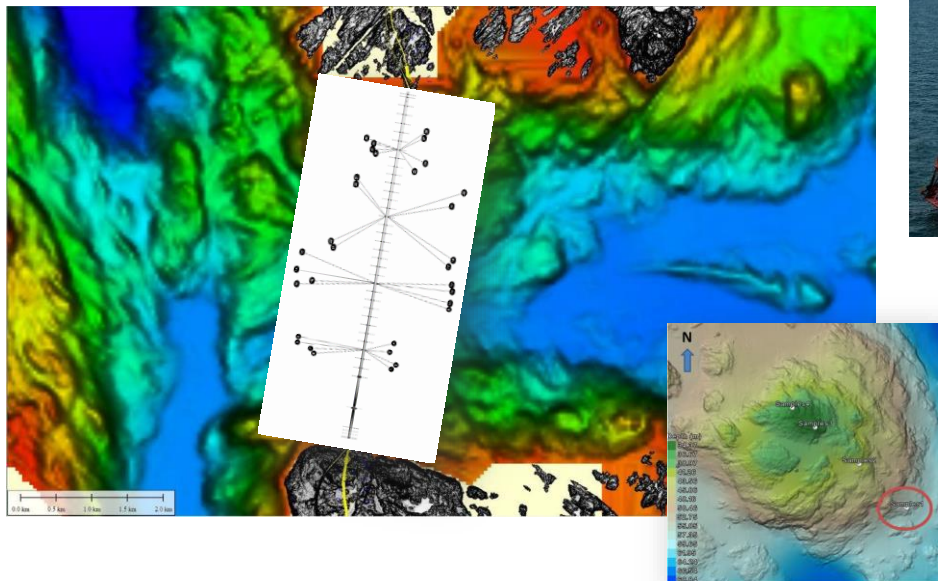
... | 2008 | 2009 | 2010 | 2011 | 2012 | **2013 | 2014 | 2015 | 2016 | 2017 | 2018** | 2019 ...

Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...

Further developing the design basis.
A few examples:

- Bedrock and bathymetry investigations.

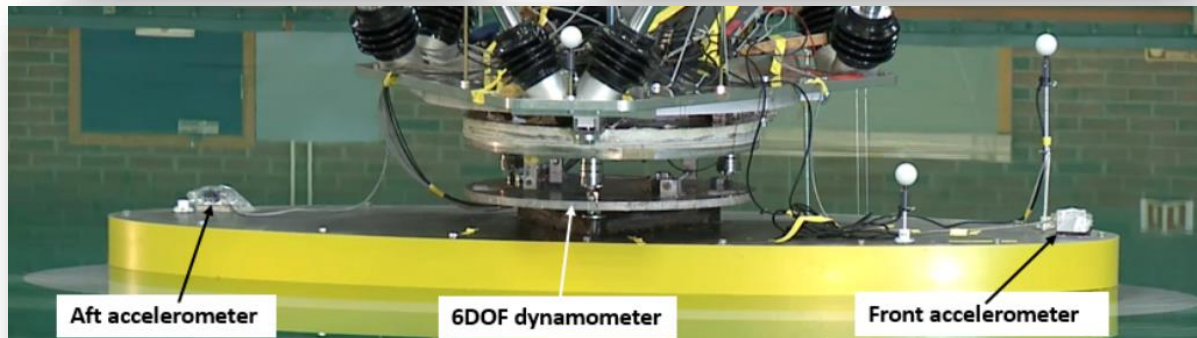
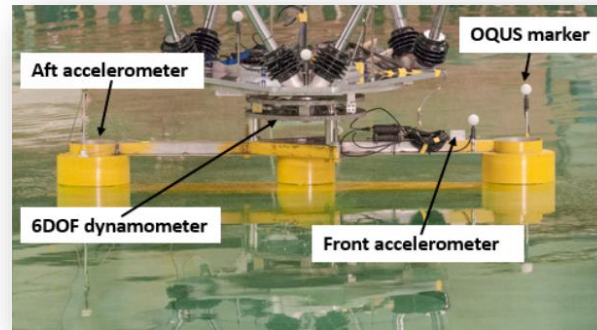
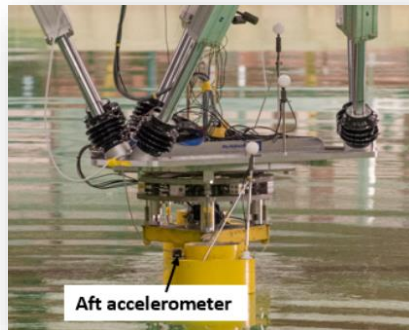


... | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | **2014 | 2015 | 2016 | 2017 | 2018** | 2019 ...

Phase: 1 - 2 - 3 - 4 - 5 - ...

Further developing the design basis.
A few examples:

- Wave model tests



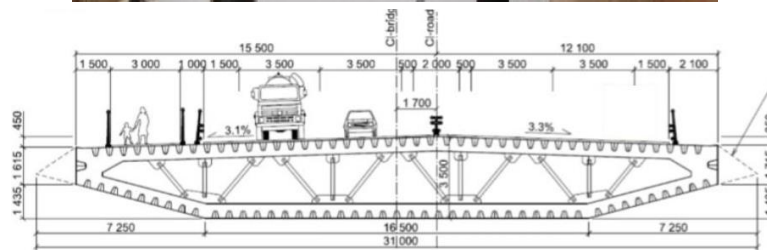
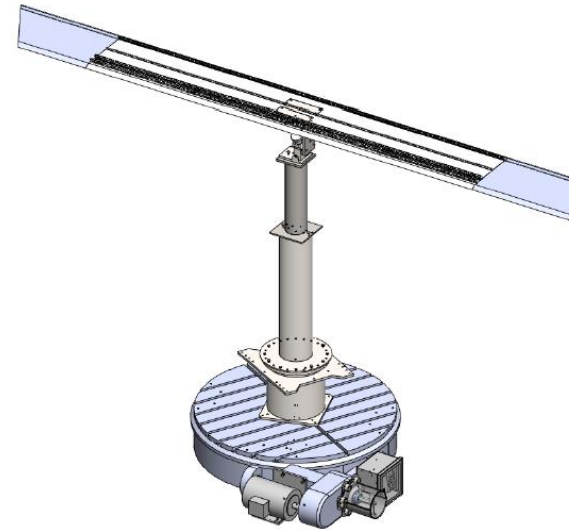
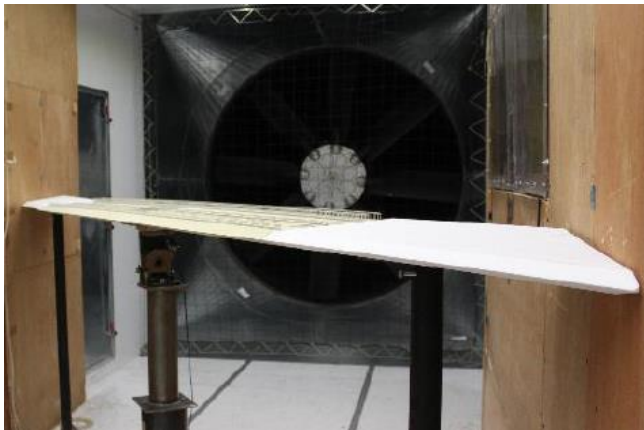
... | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...

Further developing the design basis.
A few examples:

- Wind model tests: skew winds, static coefficients.



... | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

Bjørnafjorden

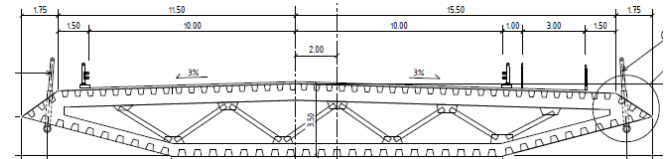
Phase: 1 - 2 - 3 - 4 - 5 - ...



Statens vegvesen

Further developing the design basis.
A few examples:

- Wind and wave-induced-turbulence



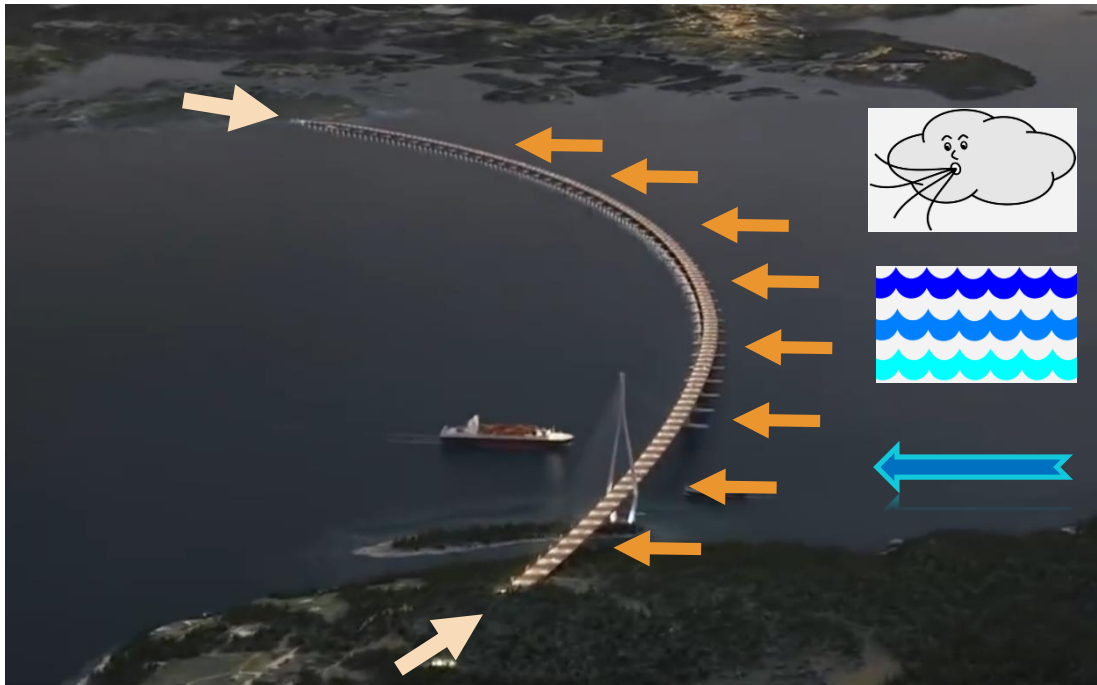
... | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

Bjørnafjorden

Phase: 1 - 2 - 3 - 4 - 5 - ...

Further developing the design basis.
A few examples:

- Dynamic buckling on a curved floating bridge



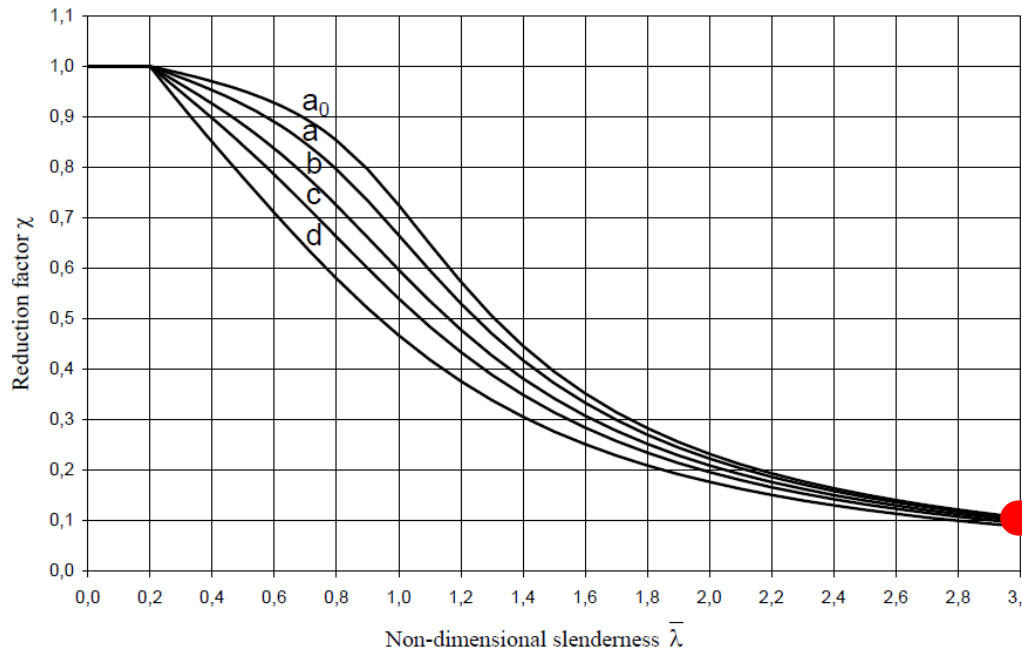
wind

waves

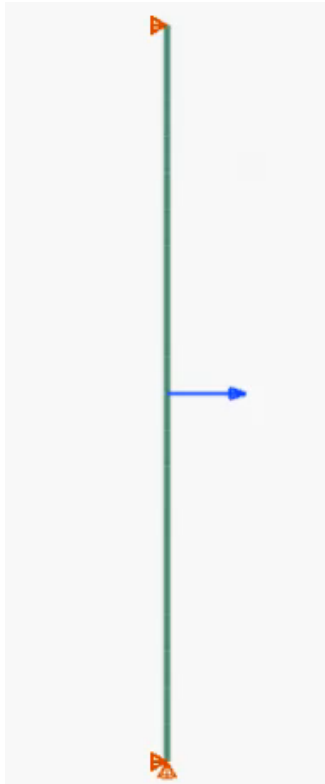
currents

... | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

Eurocode 3 - Static buckling curves

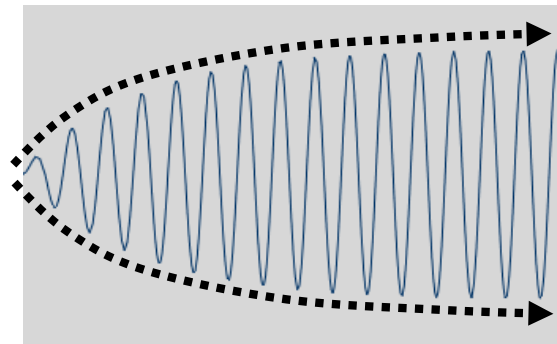


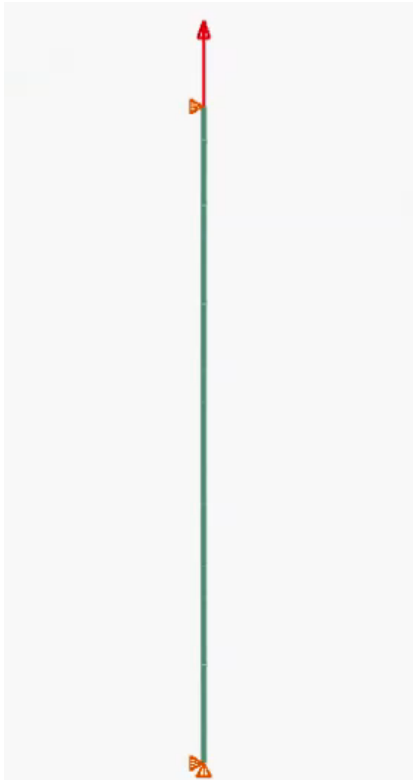
$$N_{cr} \approx 0.1 \times N_{pl,Rd}$$



$$f_{load} = f_{natural}$$

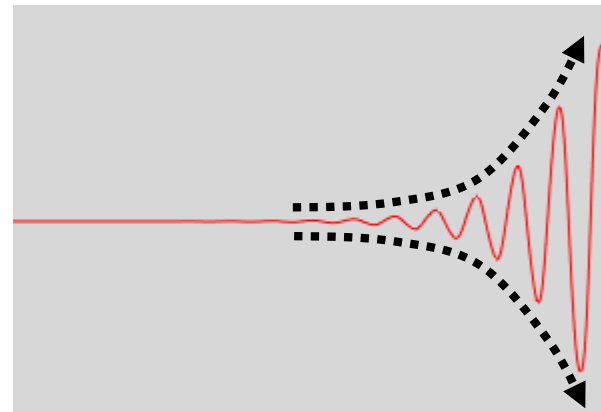
Response:





$$f_{load} = 2 \times f_{natural}$$

Response:



increasing exponentially

geometric stiffness



$$\tilde{M} \ddot{y} + \tilde{C} \dot{y} + \left(\tilde{K} - \tilde{K}_G N(t) \right) y = \tilde{F}(t)$$

Axial force:

$$N(t) = A \cos(2\omega_n t)$$

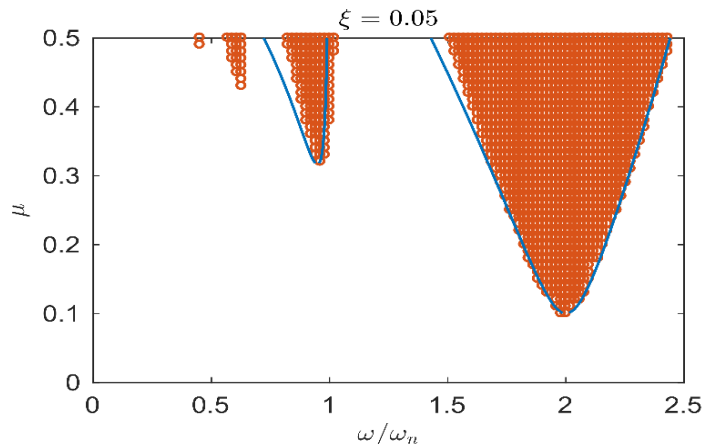
Generalized geometric stiffness:

$$\tilde{K}_G = \int_0^L (\varphi'(x))^2 N(x) dx$$

Critical axial force amplitude: [1]

$$A_{cr,harmonic} = 4\zeta \frac{\tilde{K}}{\tilde{K}_G}$$

Instability regions



Dynamic buckling, as a parametric excitation, depends on:

- Stiffness & geometric stiffness
- Axial force amplitude, frequency and duration
- Damping

[1] Dynamic stability of structures, Wei-Chau Xie (2016)

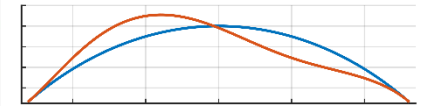
Bjørnafjorden

Dynamic buckling

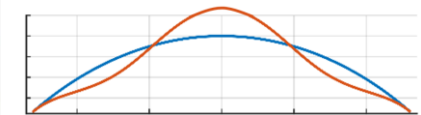
Harmonic loads & response.

1st mode

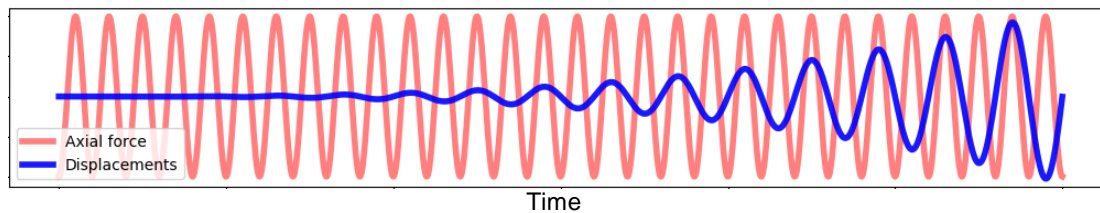
— = compression
— = tension



2nd mode



Axial force modelled as: $\Delta T(t) + \text{modal kinematic constraints}$

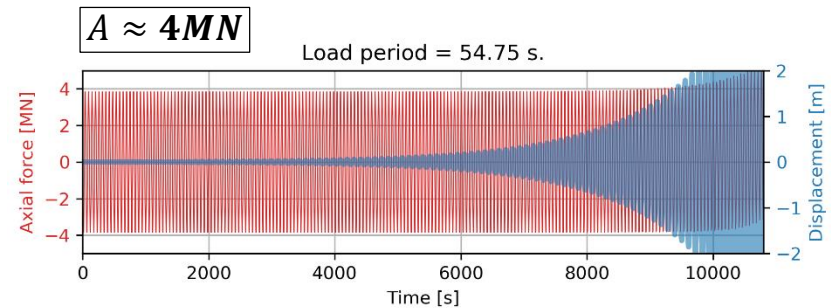
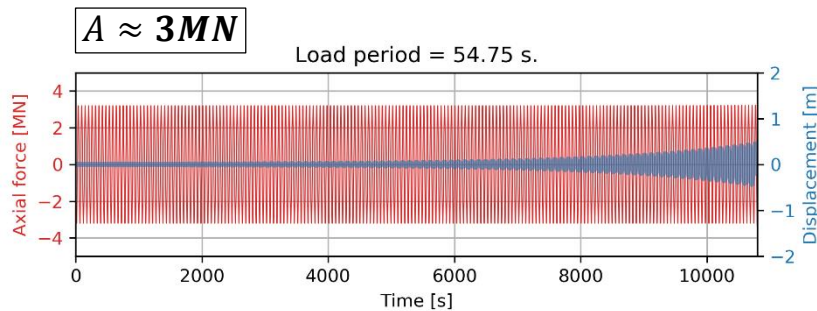
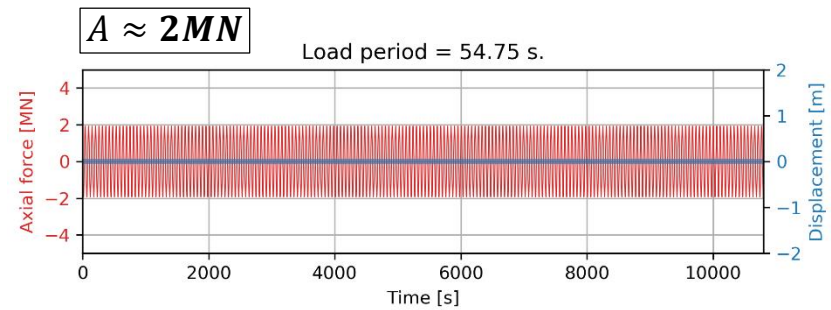
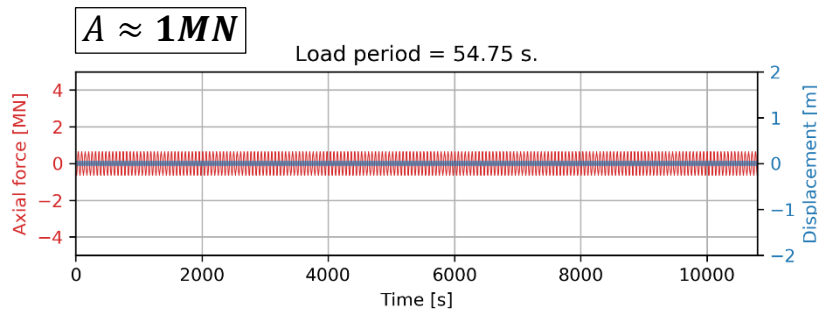


$$f_{load} = 2 f_{natural}$$

... | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

Axial force amplitude A :

$$N_{cr,static} \approx 70 \text{ MN (compression)}$$



$$A_{cr} \approx 2.4 \text{ MN}$$

MODE	f_n [Hz]	T [s]	$A_{cr,harmonic}$ [MN] (1% damping)	Damping
1	0.0091	109.9	2.4	...
2	0.0169	59.2	3.9	...
3	0.0306	32.7	6.1	...
4	0.0444	22.5	9.5	...
5	0.0644	15.5	12	...
6	0.0821	12.2	16	...
7	0.1033	9.7	60	...
8	0.1105	9.0	27	...
9	0.1399	7.1	50	...
10	0.1689	5.9	90	...
11	0.2035	4.9	160	...
12	0.2393	4.2	280	...

Standard deviation of the
axial force, for mode m



$$\sigma_{N,m} < \gamma A_{cr,harmonic,m}$$

$$\gamma = 0.5 \quad [1]$$

[1] Dynamic stability of structures, Wei-Chau Xie (2016)

Dynamic buckling

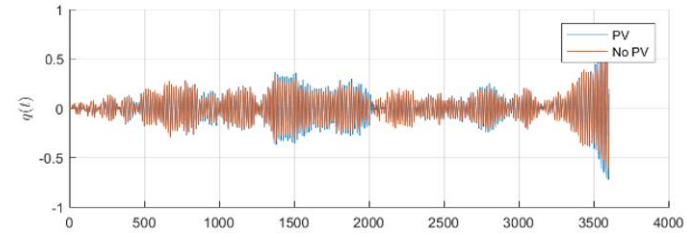
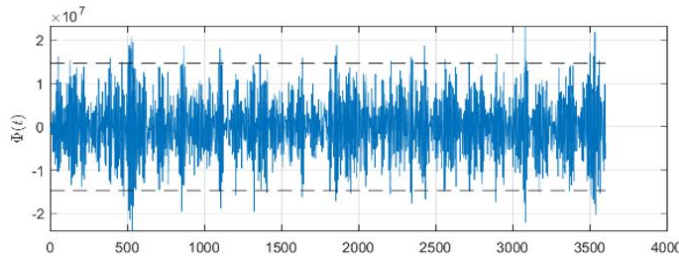
Stochastic loads & response. Worst cases of 100,000 simulations.

PV: Axial force variation
(narrow band at $2 f_n$)

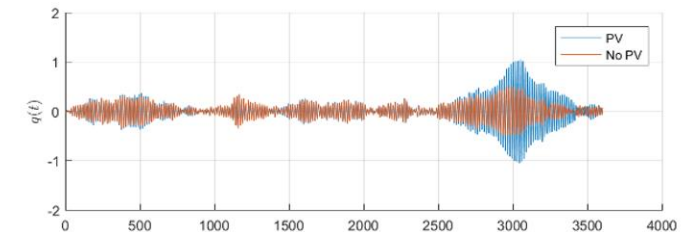
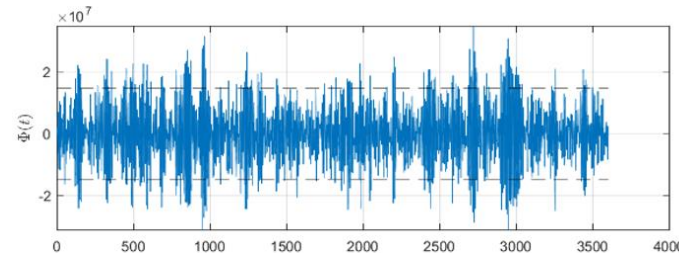
Displacements response

PV
No PV

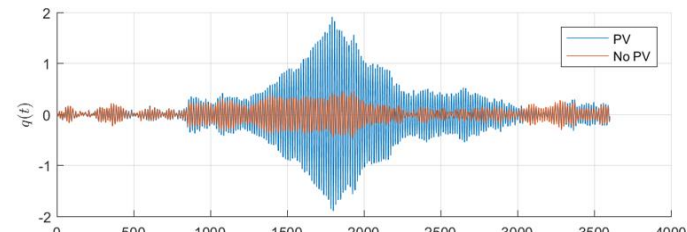
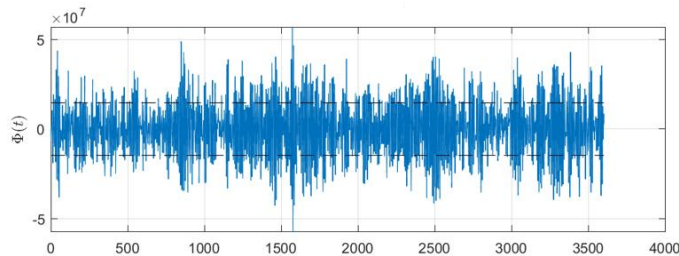
$\gamma = 0.4$



$\gamma = 0.6$

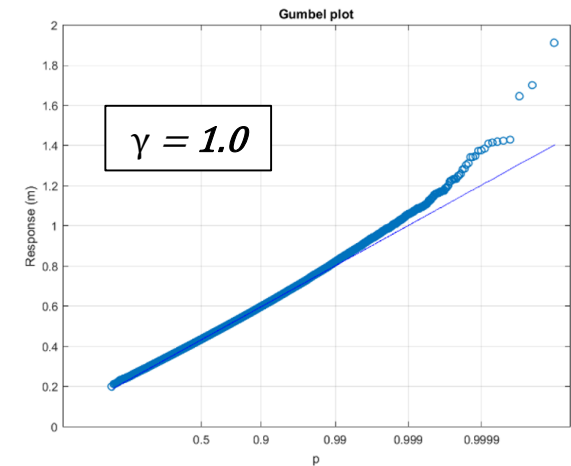
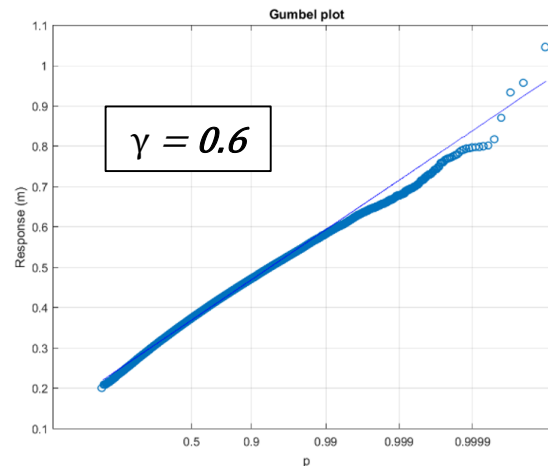
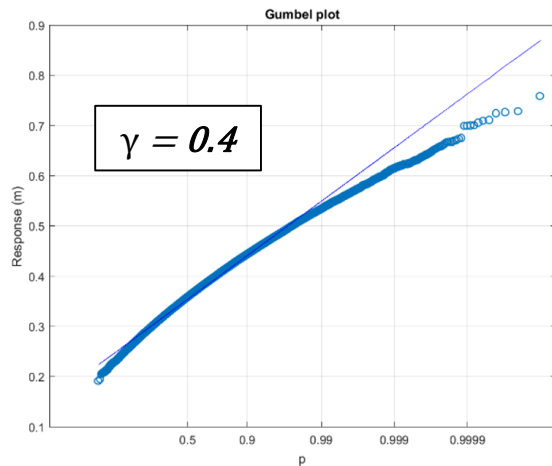


$\gamma = 1.0$



... | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...

Gumbel plots



... | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 ...



MODE	1	2	3	4	5	6	7	8	9	10	11
1											
2	1.85										
3	3.35	1.81									
4	4.86	2.62	1.45								
5	7.04	3.81	2.10	1.45							
6	8.98	4.85	2.68	1.85	1.27						
7	11.30	6.11	3.37	2.33	1.60	1.26					
8	12.09	6.53	3.61	2.49	1.72	1.35	1.07				
9	15.31	8.27	4.57	3.15	2.17	1.71	1.36	1.27			
10	18.47	9.98	5.52	3.80	2.62	2.06	1.64	1.53	1.21		
11	22.26	12.03	6.65	4.58	3.16	2.48	1.97	1.84	1.45	1.20	
12	26.18	14.15	7.82	5.39	3.72	2.92	2.32	2.17	1.71	1.42	1.18

Example:
 mode 9 ~ 7sec
 mode 5 ~ 15sec ↻ excite

█ Frequency ratios close to 2



MODE	1	2	3	4	5	6	7	8	9	10	11
1											
2	1.85										
3	3.35	1.81									
4	4.86	2.62	1.45								
5	7.04	3.81	2.10	1.45							
6	8.98	4.85	2.68	1.85	1.27						
7	11.30	6.11	3.37	2.33	1.60	1.26					
8	12.09	6.53	3.61	2.49	1.72	1.35	1.07				
9	15.31	8.27	4.57	3.15	2.17	1.71	1.36	1.27			
10	18.47	9.98	5.52	3.80	2.62	2.06	1.64	1.53	1.21		
11	22.26	12.03	6.65	4.58	3.16	2.48	1.97	1.84	1.45	1.20	
12	26.18	14.15	7.82	5.39	3.72	2.92	2.32	2.17	1.71	1.42	1.18

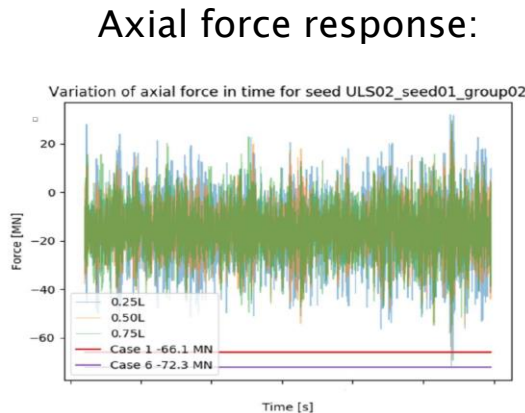


Frequency ratios close to 2

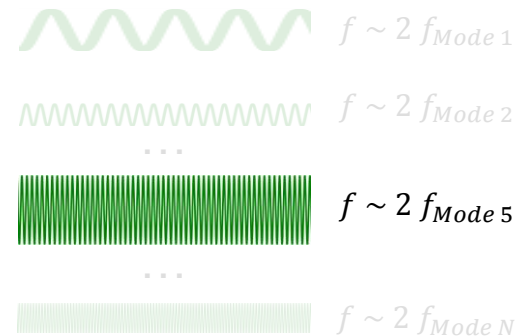


Modes with anti-symmetric axial force distributions

Most severe environmental conditions for Mode 9



Band pass filtered response:



Adjust for damping n :

$$A_{cr, n} = A_{cr, n, 1\% \text{ damping}} \times \frac{\zeta_n}{0.01}$$

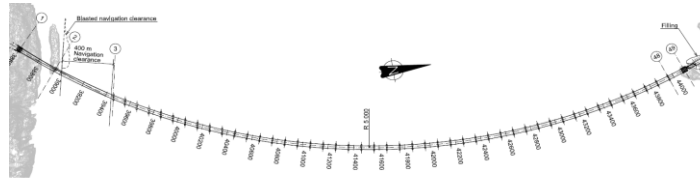
$\sigma_{N, n}$ – axial force SD. n
 ζ_n – damping ratio n

Stability criteria:

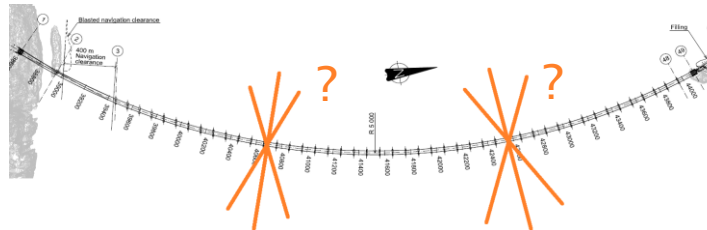
$$\sigma_{N, n} < 0.5 A_{cr, n}$$

Choosing a floating bridge concept

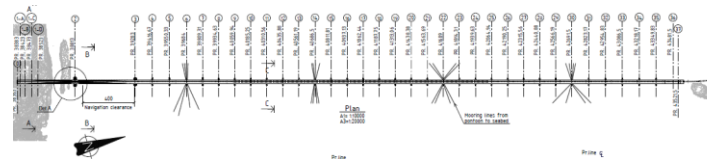
Alternative 1



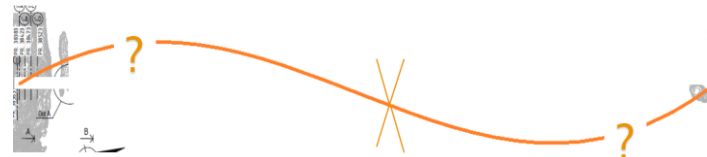
Alternative 2



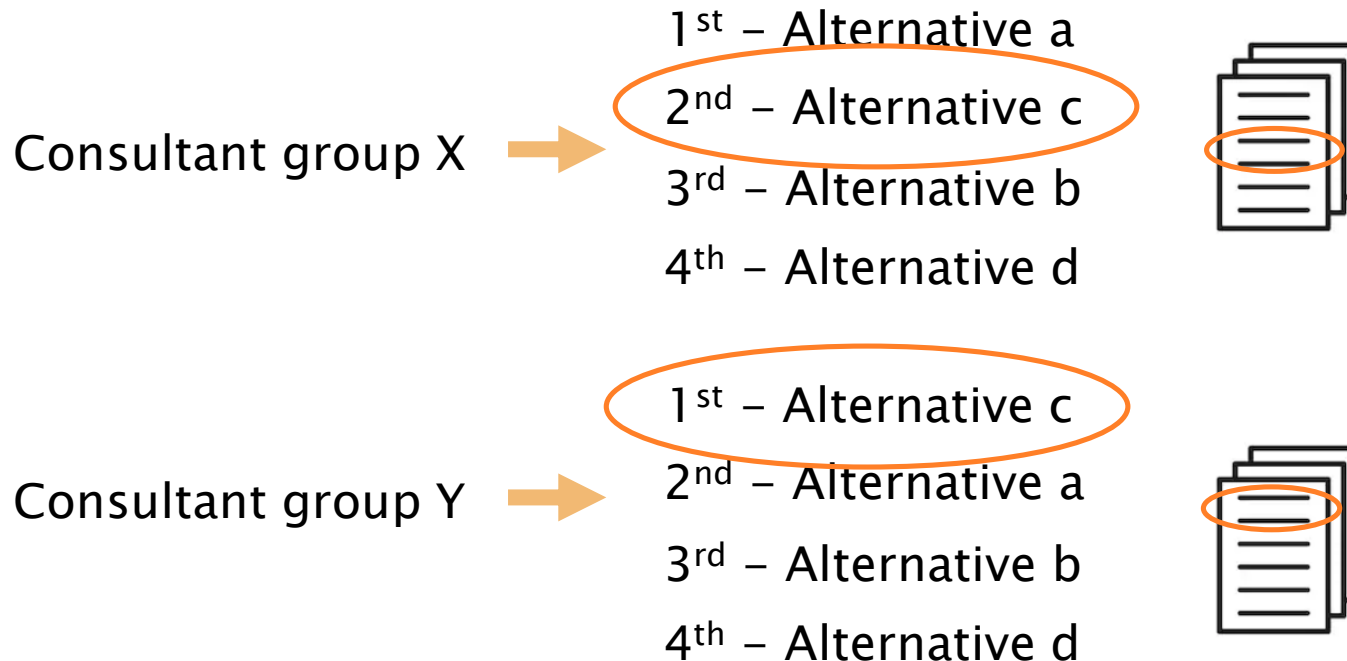
Alternative 3



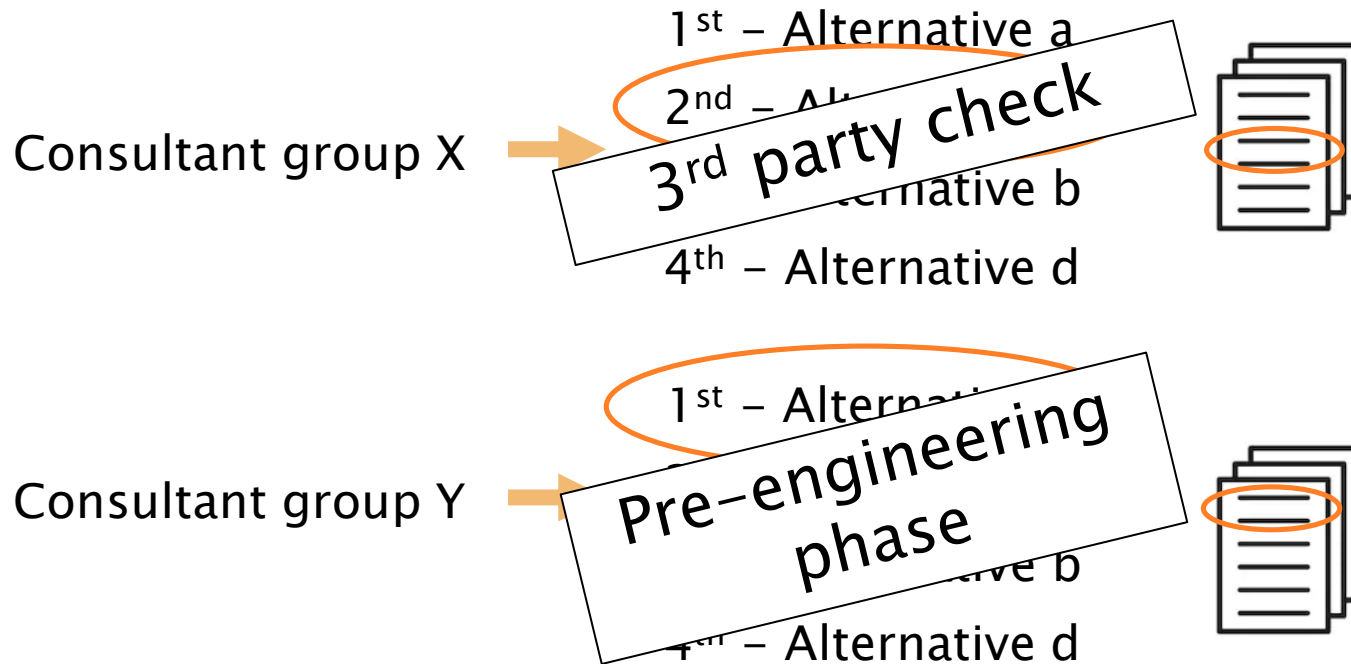
Alternative 4



Choosing a floating bridge concept



Choosing a floating bridge concept





Statens vegvesen

Good luck, dedication and
inspiration for the next
phase!



Statens vegvesen

Thank you for your attention.