Bjørnafjorden floating bridge, Norge

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COWI

Bjørnafjorden, Norway

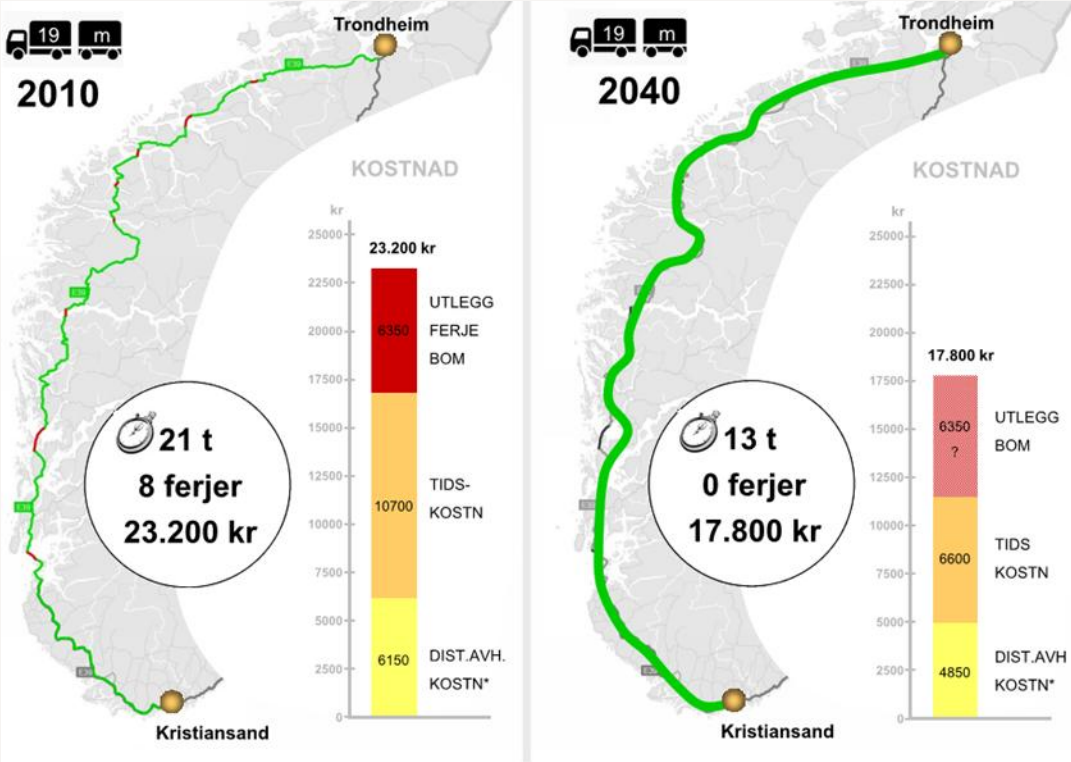
Agenda

- Ferry free E39
- Existing Norwegian Floating Bridges
- Existing North American Floating Bridges
- Sognefjorden TLP Suspension Bridge
- Bjørnafjorden crossing concepts
- Bjørnafjorden Floating Bridge

Bjørnafjorden, Norway

Route E39 Kristiansand-Trondheim

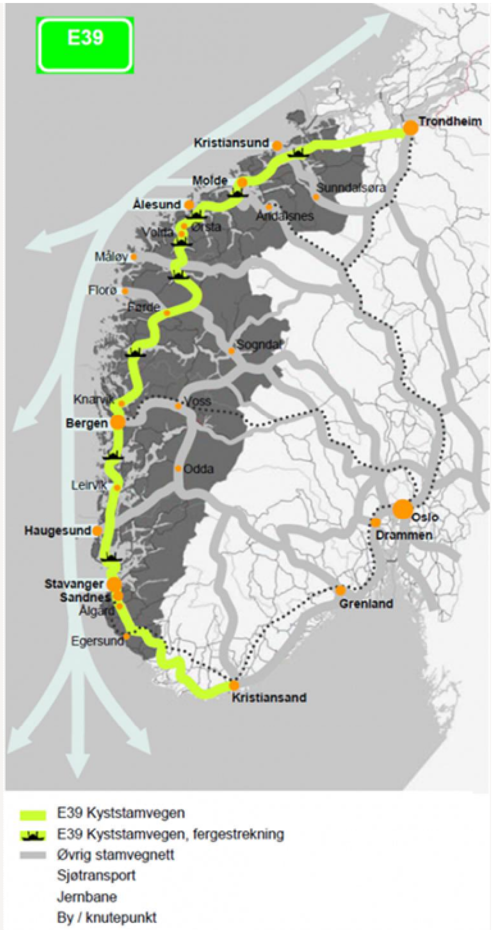
- The floating bridge at Bjørnafjorden is part of the route E39 Kristiansand-Trondheim
- The E39 route is 1100 km long and have today 8 ferry links (marked in red)
- The total budget E39 as a ferry free connection is estimated to US$ 25 billion over 20 years (2014-33)
- 50% of Norwegian traditional export value comes from this area



Bjørnafjorden, Norway

Key figures for the 8 fjord crossings at E39

- Halsafjorden, 2 km width, 5-600 m water depth
- Moldefjorden, 13 km subsea tunnel with 330 m water depth + 1.6 km bridge with 5-600 m water depth
- Storfjorden/Sulafjorden, 3.4 km width, 500 m water depth
- Voldafjorden, 2.5 km width, 600 m water depth
- Nordfjorden, 1.7 km width, 3-500 m water depth
- Sognefjorden, 3.7 km width, 1250 m water depth
- Bjørnafjorden, 4-5 km width, 5-600 m water depth
- Boknafjorden, Rogfast Subsea tunnels, 26.7 km with 390 m water depth (alt. floating bridge 7.5 km at 550 m depth)



Bergsøysund Bridge, Norway

- 1st floating bridge in Norway opened in 1992
  - 931 m bridge with 8 spans
  - Steel truss girder and concrete pontoons
  - Typical span of 106m with 6m clearance
  - On the route E39, south of Kristiansund
  - Installed in one piece/operation
  - Designed using "recent" technology from American floating bridges and Norwegian offshore platforms

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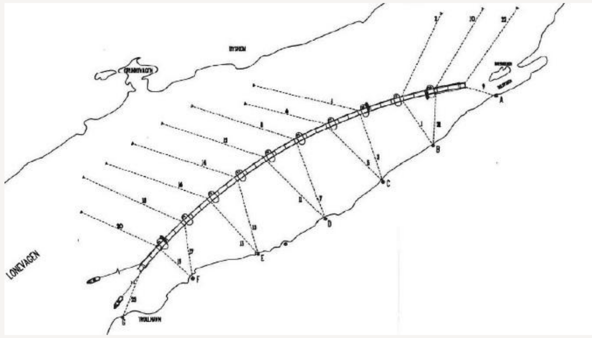
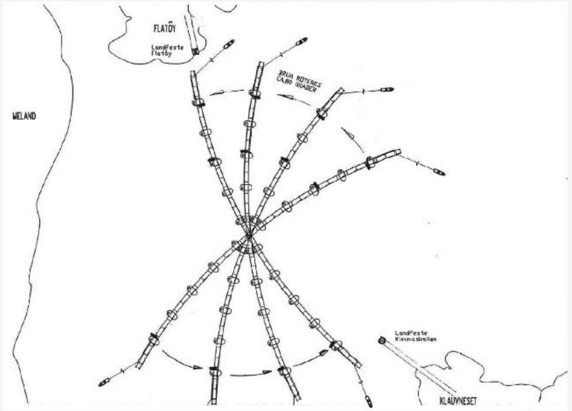
Nordhordland bridge, Norway

- Longest self-anchored floating bridge, 1994
  - 1243 m floating low level and approach bridges
  - Cable stayed concrete main bridge on land
  - 10 light weight concrete pontoons (22 kN/m³)
  - Orthotropic steel girder for floating bridge part
  - Navigational span of 172m x 32m
  - On the route E39, north of Bergen
  - Floating bridge installed in one piece/operation





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Floating Bridges with COWI involvement

- William R. Bennett Bridge, Kelowna, BC, Canada, opened 2008
  - Detailed design, construction services
- SR 520 Floating Bridge, Seattle to Medina, WA, USA, 2011
  - Bid Design
- Sognefjorden, Norway, 2013
  - Conceptual design
- Bjørnafjorden, Norway, ongoing
  - Conceptual & preliminary design

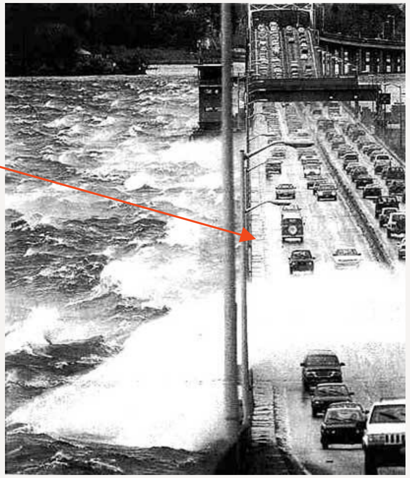
William R. Bennett Bridge, Canada

- 690 m of floating concrete pontoons with an elevated deck
  - Preliminary and detailed Design
  - Design Criteria and construction services
- Bridge details
  - 75 years service life
  - 52m navigation span with 18m clearance
  - 5 traffic lanes

SR 520 Floating Bridge, Seattle, WA, USA

- 2.35km floating bridge: The world's longest
  - Design & Build: Bid design for JV of contractors
  - Pontoons (concrete) and elevated superstructure (6 lanes)
  - Transition spans and approach spans
  - Alternative pontoon design allowed a significant saving
- Bid design involves disciplines within
  - Sophisticated combined wind and wave loading
  - Live loads
  - Buoyancy and floating stability
  - Damage and flood scenarios

Existing bridge



New bridge to open in spring '16

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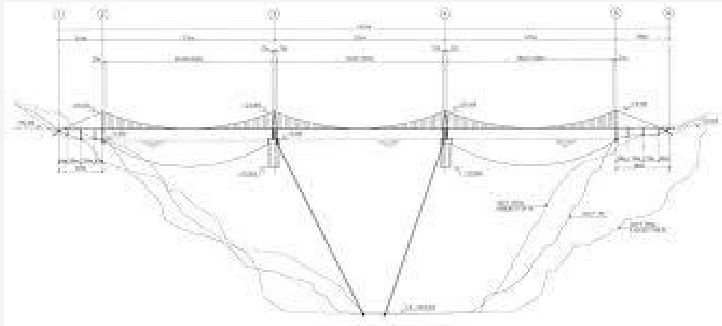
Sognefjorden, tension leg suspension bridge, Norway



- Multiple span suspension bridge
- 3 main spans of 1234m
- 3700m wide and 1300m deep fjord
- Total bridge length of 4.4km
- 2 x 2 traffic lanes
- Pedestrain/cycle path

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Sognefjorden, tension leg suspension bridge, Norway

- Bridge design details
  - 250m steel towers
  - Orthotropic steel box girder
  - 180m 9-cell Condeep type floating pontoons
- The conceptual design involves disciplines within:
  - Structural analyses
  - Wind and wave dynamics
  - Cable and ship impact dynamics
  - Marine geotech and operations

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Bjørnafjorden, Norway

3 different concepts are being considered for the crossing

› Floating bridge with cable stayed main bridge

› 3-span suspension bridge with central TLP's

› Tubular Bridge (submerged tunnel)

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Bjørnafjorden, Norway

2 different layouts are being considered for the floating bridge

› Curved bridge alignment

  › Twin box girder with cross beams (vierendeel)

  › Anchored in each abutment c/c 4.6km

  › Lateral forces obtained by horizontal arch

› Straight bridge alignment

  › Mono box girder

  › Laterally anchored by mooring lines

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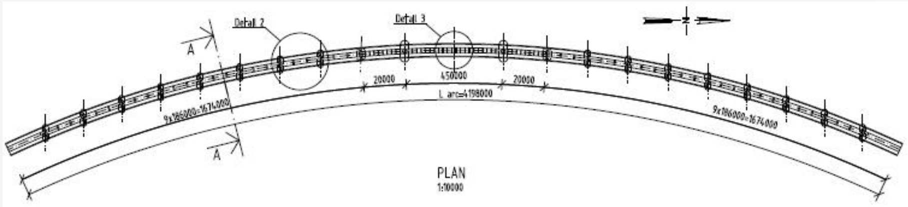
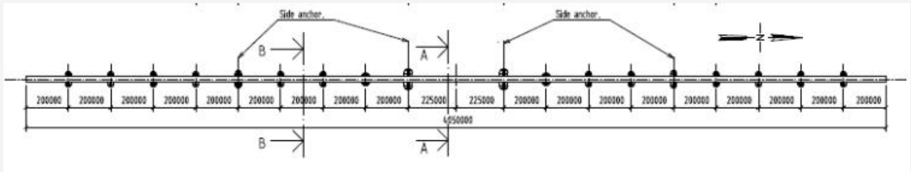
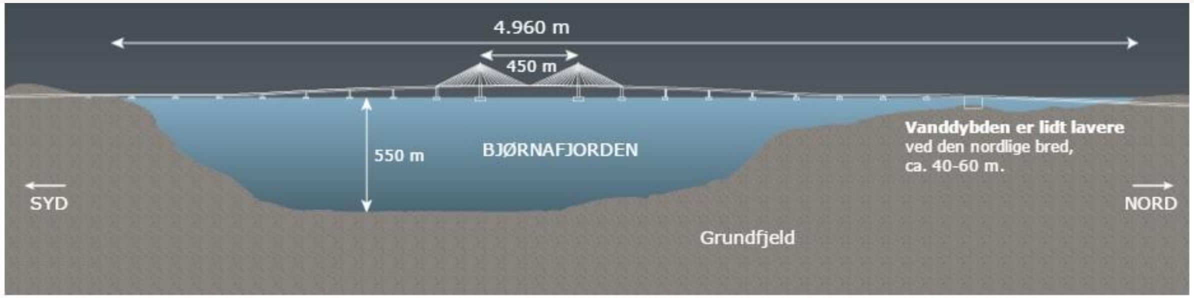
Bjørnafjorden, Norway

General bridge details

- Central 450m cable stayed main span
  - 400m x 45m navigation clearance
  - Aerodynamic bridge girder
- 200m typical spans
- Light weight concrete pontoons
- Steel superstructure
  - 160m towers
  - Orthotropic deck
- 2 x 2-lane highway
  - 110 km/t







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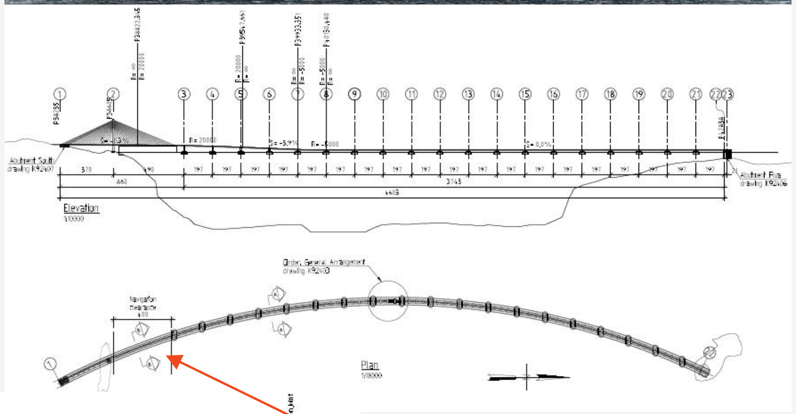
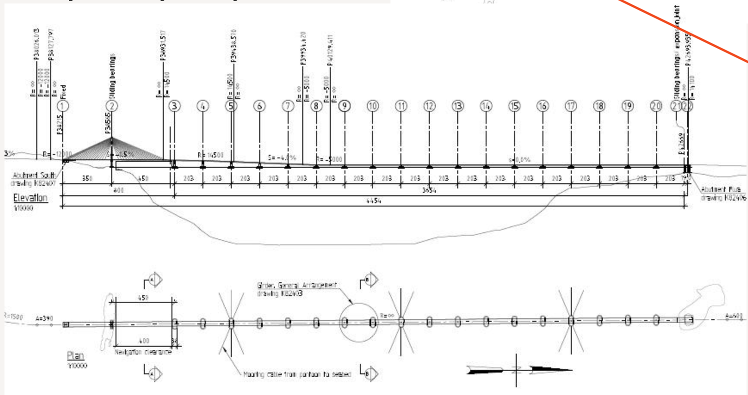
Alternative/preferred alignment

- South navigation span
  - Terrain suitable for elevated abutment (+55m)
- Concrete tower & main bridge on land
- 450/490m cable stayed main span
- 197m/203m typical spans
  - Steep alignment after anchor pier (4%)
  - Main part is low level
  - 11.5m clearance (typical)
- Cost optimal





World record single-tower cable stayed span (450m/490m)

Bjørnafjorden, Norway

Design basis

- NPRA Handbooks
  - N100 & N400
- Eurocode NS-EN199X
  - EN 1990-1993
- DNV rules and regulations
  - Floating bridges are not covered by the Eurocode system
- Ultimate limit state typically governs design (Q-ENV)
  - Ship impact: Locally piers, girder and pontoon walls
  - Construction: Free standing tower (straight bridge, 100 year storm)
  - Fatigue not yet analysed

Bjørnafjorden, Norway

Design basis

› Wave conditions

› N-Parallel

› W-Perpendicular

		Wind driven sea				Ocean swell					
Hs[m]	Tp [s]:	3.0	4.0	5.0	6.0	12.0	14.0	16.0	17.0	18.5	20.0
Wave dir:	Wave dir [deg]:										
N	180	0.9	1.6	na	na	na	na	na	na	na	na
N-NW	202.5	0.9	1.6	2.5	na	na	na	na	na	na	na
NW	225	0.9	1.6	2.5	3	0.4	0.4	0.4	0.2	0.2	0.2
W-NW	247.5	0.9	1.6	2.5	3	0.4	0.4	0.4	0.2	0.2	0.2
W	270	0.9	1.6	2.5	3	0.4	0.4	0.4	0.2	0.2	0.2

› Wind conditions

Return period	Velocity at 10 m [m/s]	Velocity at 52 m [m/s]
1	22.9	28.4
100	31.7	39.3

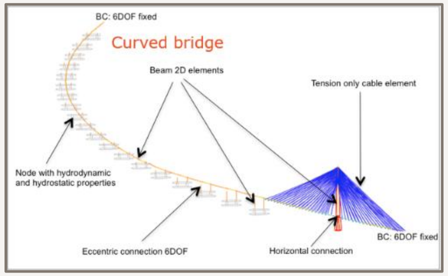
› Comfort criteria

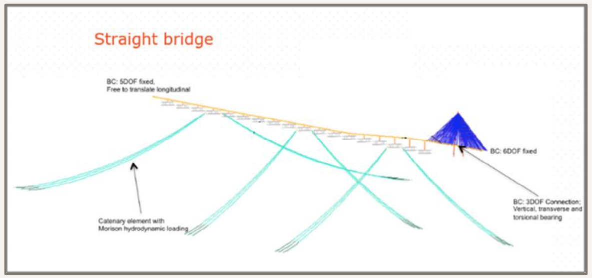
Motion	Load	Criterion
Vertical deflection due to traffic	0.7 x traffic	Approx. 1 m
Rotation about bridge axis (roll) due to traffic	0.7 x traffic	1 deg
Rotation about bridge girder axis (roll) due to env. loads	1 year storm	1.5 deg
Vertical acceleration	1 year storm	0.5m/s2
Horizontal acceleration	1 year storm	0.3m/s2

Bjørnafjorden, Norway

Analysis methods

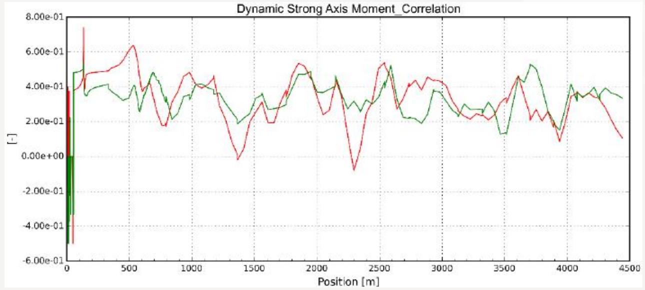
- Waves
  - Fetch and diffraction analysis for wind driven and swell wave conditions
  - Orcaflex, Time domain, Geometric and hydrodynamic non-linear effects
- Wind
  - Frequency domain, NovaFrame, Geometrical non-linear effects taken into account
  - Vortex shedding, divergence and galloping investigated (flutter pending future WTT)
- Other loads
  - Permanent, temperature, tidal and traffic loads (static)
  - RM Bridge, static



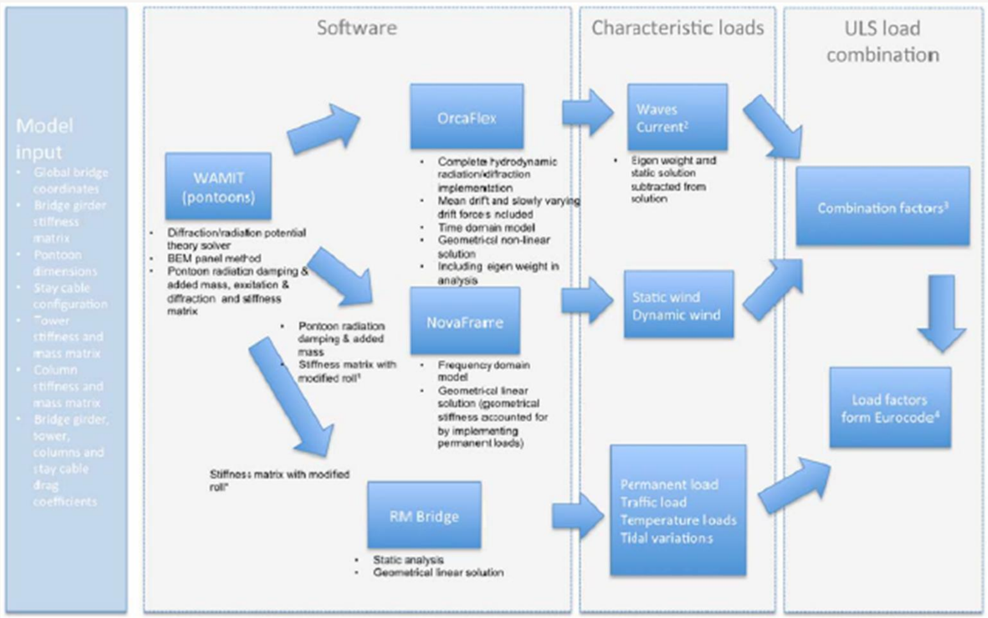


Bjørnafjorden, Norway

Analysis methods



- › 3 programmes used separately
  - › Design forces obtained by combination factors
- › Correlation between wind and waves for bridge girder
  - › Initially α = 0.8 (dynamic)
  - › Examined in OrcaFlex
  - › Reduced to α = 0.6
- › Future software
  - › To cover all load effects



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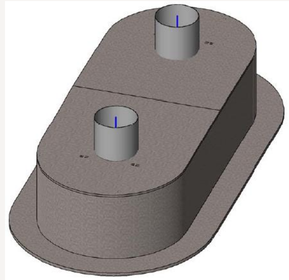
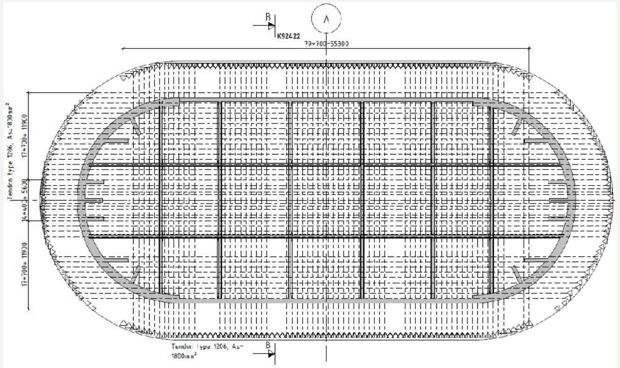
Bjørnafjorden, Norway

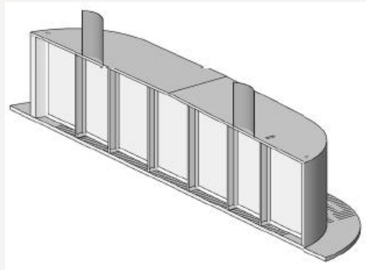
General pontoon design

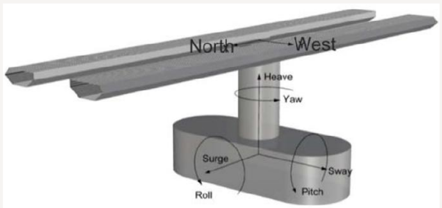
- Light-weight concrete
- Post-tensioned
  - Watertight with no cracks
- Designed and optimized for:
  - Wind and swell generated waves
  - Heave and surge modes
  - Ship impact (local strengthening)
  - Co-existent wind and waves
  - Roll from eccentric traffic
  - Flooding (2 cells)

Criteria	Type	Requirement	Consequence	Chosen design
Free board	Safety	4.0m	More concrete -> higher pontoon eigen weight	4.0m
Vertical deflection due to traffic	Function	<1.0m	C_{33}>~10 MN/m	17.5 MN/m
Rotation about bridge axis due to traffic	Function	<1.0deg	C_{44}>~2500 MNm/rad	2600 MNm/rad -> 4600 MNm/rad
Wall thickness	Safety	0.6m longside, 1.0m shortside	More concrete -> higher pontoon eigen weight	0.6m longside, 1.0m shortside









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Pontoon design optimisation

› To limit weak axis bending in girder

› Mainly caused by heave modes (total bridge)

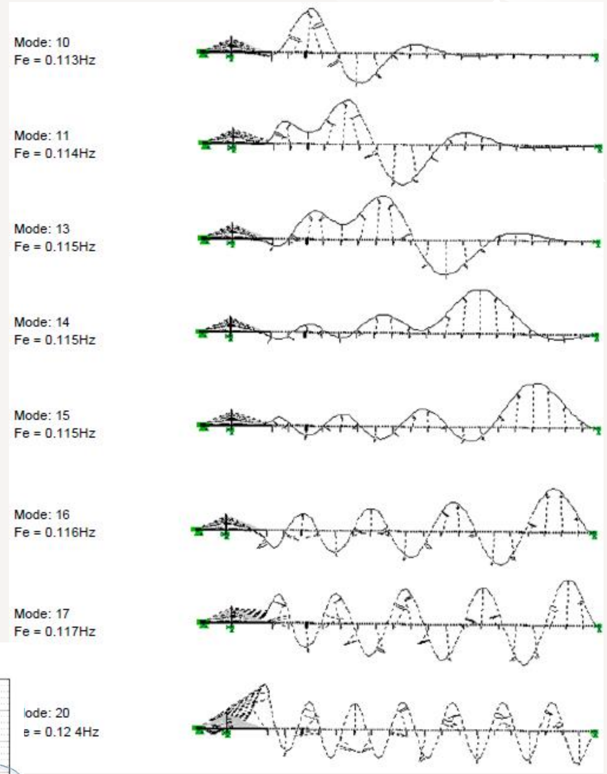
  › Surge/pendulum modes (elevated bridge part)

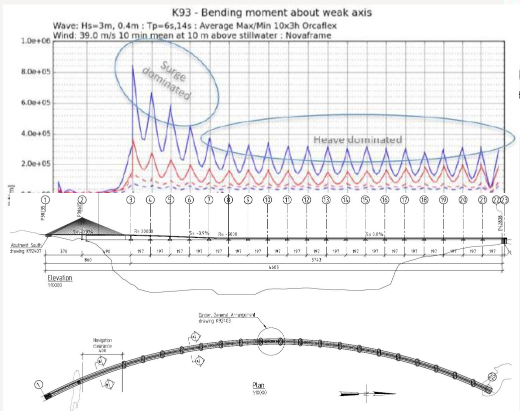
› Avoid vertical wave triggered eigen modes

  › Eigen periods above wind driven sea (primarily)

  › Parameters; mass, depth, length, width, form, span

  › Closely spaced modes ($f_{10} \approx f_{20}$)





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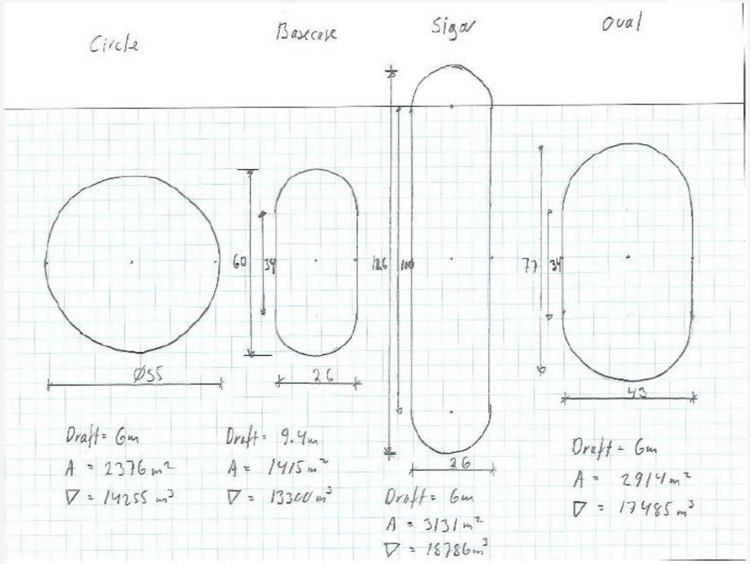
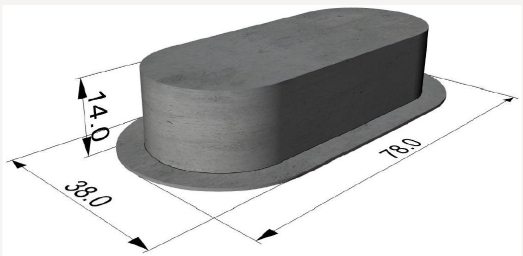
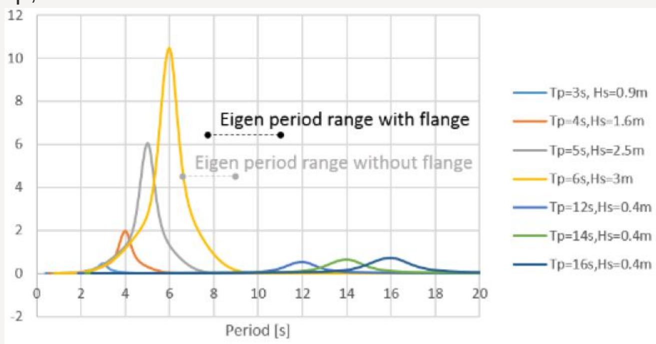
Pontoon design optimisation



- Examined parameters
  - Form: Circular, basecase, oblong, "oval"
  - Draft & displacement (minor influence)
  - Added mass (flange & keel, major influence)
  - Span length (150m & 200m)
- Wave and heave eigen periods
  - $T_{p,wind}$ = 4 - 6s < T_{heave} = 7.8s – 10.8s < $T_{p,swell}$ =12-20s

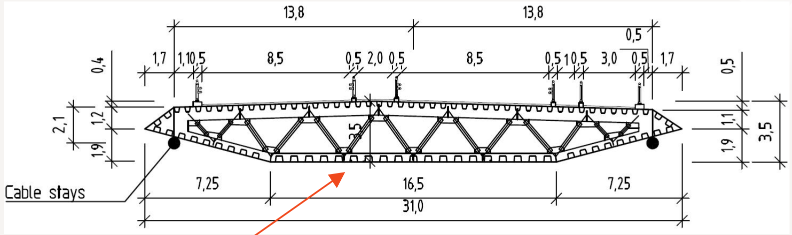


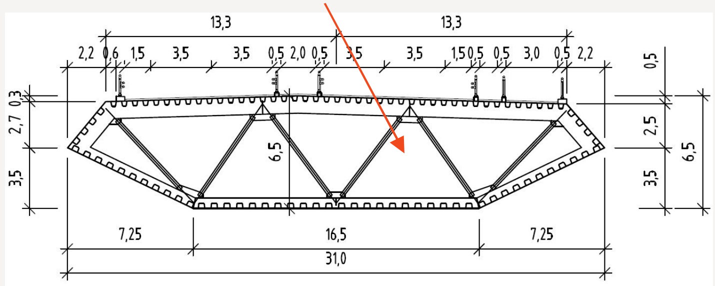


Bjørnafjorden, Norway

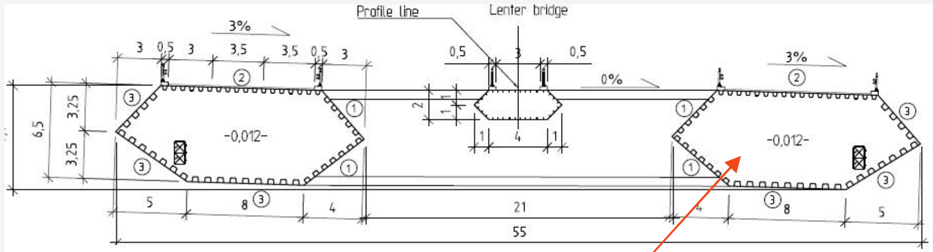
General superstructure design

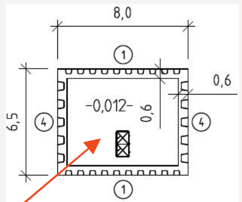
- High-strength S460 steel
- Orthotropic steel girders
- Designed and optimized for:
  - Co-existent wind and waves
  - Vierendeel
  - Ship impact
  - Aerodynamics





Straight main and floating bridge girders



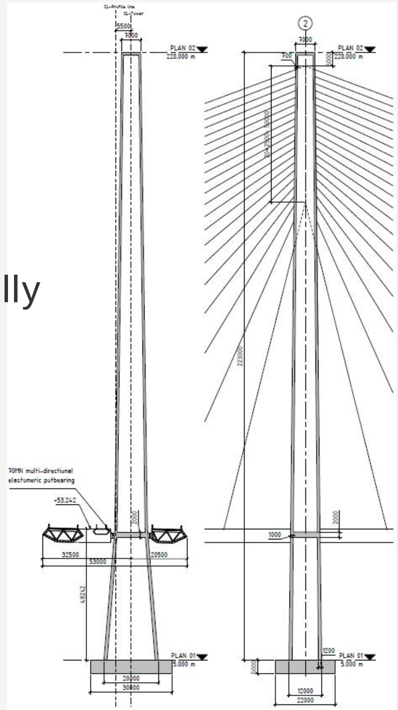


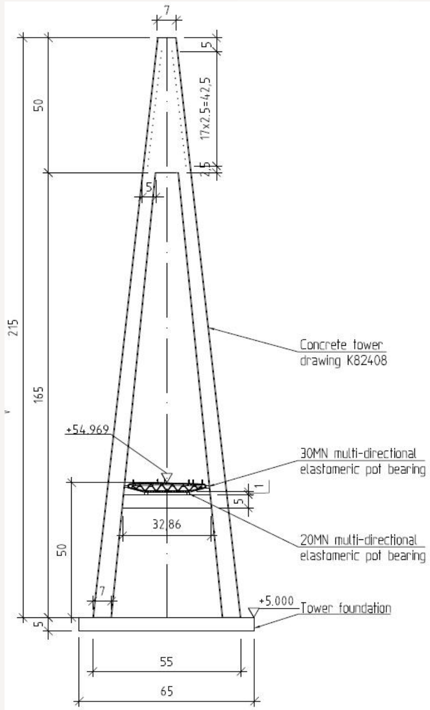
Curved twin box girder and cross beam

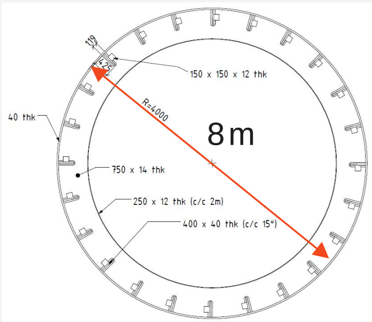
Bjørnafjorden, Norway

General superstructure design

- Reinforced concrete towers on land
  - Mono-tower / A-shaped
  - Girder free longitudinally and restrained laterally
  - 5.5m eccentricity
- Steel piers and floating towers (S460)
  - Monolithic connected to bridge girder







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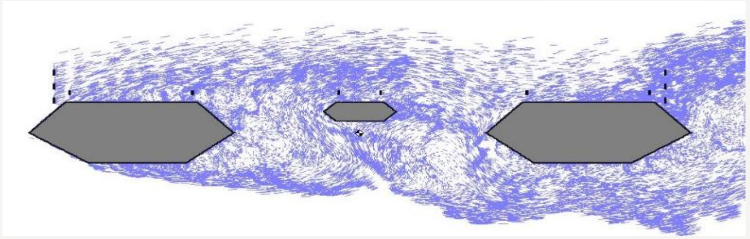
Superstructure design development



- Wave/tidal loads ⇒ Span length ⇒ Girder height
- CFD analysis ⇒ Bridge girder and tower shape
- Diaphragm & individual pedestrian girder ⇒ Quantities
- Main bridge on land in south ⇒ Cost optimal
- Cross beam size and position/spacing ⇒ Global buckling and local stress peaks
- Connection at tower; Monolithic ⇒ free
- Stay cables ⇒ compact design (drag)
- Minimum clearance increased to 11.5m ⇒ Girder head-on-bow avoided

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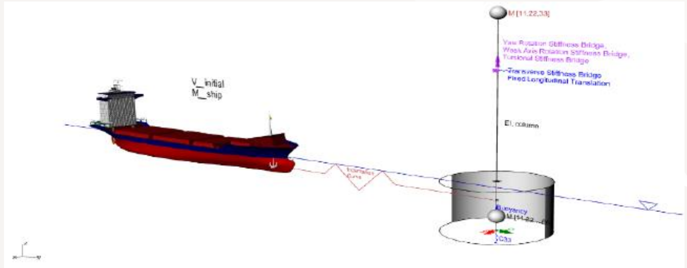
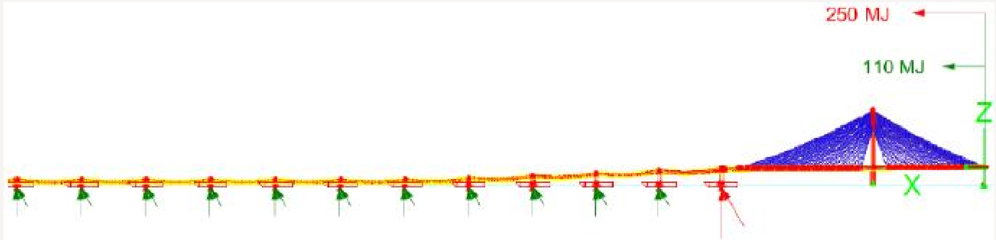
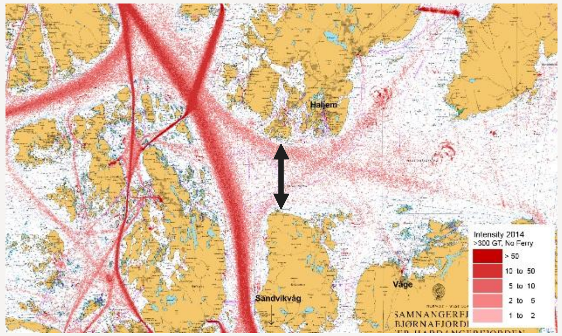
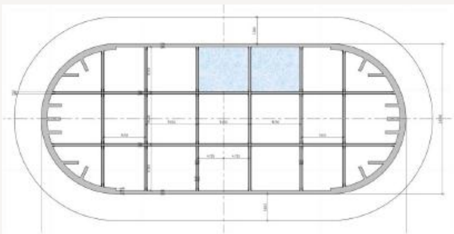
Ship impact analysis

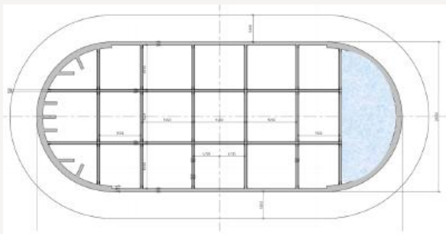




- Head-on-bow collisions with pontoon
- Deckhouse collision with girder
- Monte Carlo simulation
  - 250 MJ at anchor pier
  - 110 MJ elsewhere
- Ship impact governs
  - Girder and top column design locally (HoB)
  - Pontoon wall thickness 1.1m







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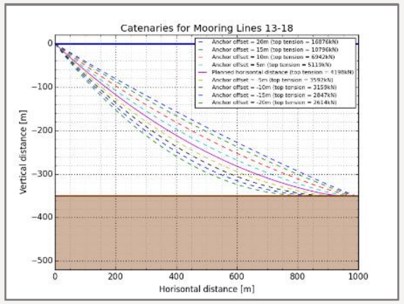
Bjørnafjorden, Norway

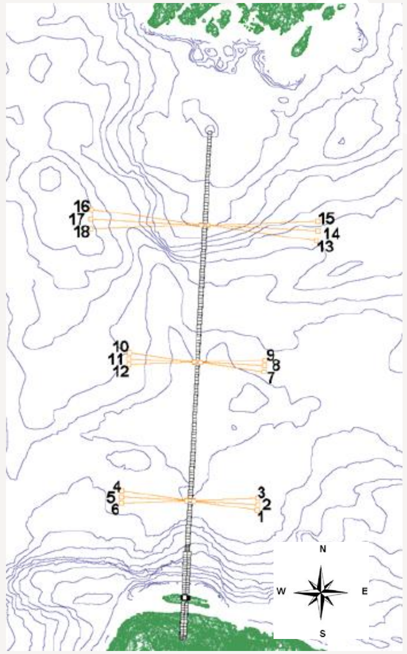
Mooring cables (straight bridge)

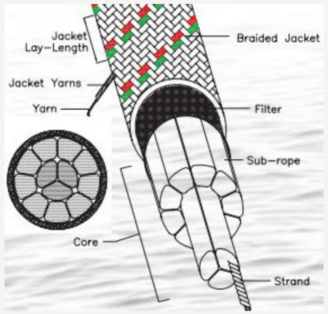
› 6 x 3 mooring lines with 25 design life

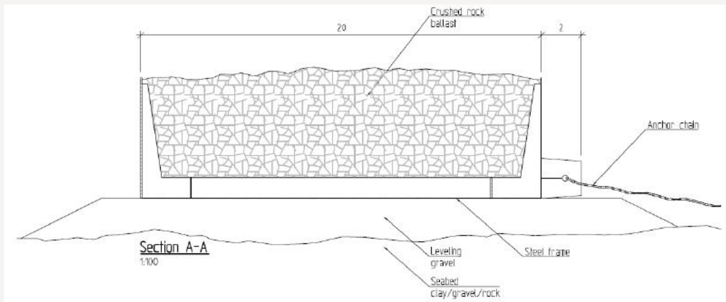
- › Governed by ULS
- › Accidental loss of cable (pending 2 cables, possible 6 x 4 lines)
- › Gravity anchors



	Bottom chain	Wire	Top chain
Type	R4 studless	Mooring rope	R5 studless
Length	100m	640m / 920m	20m
MBL	25.2 MN	24.5 MN	27.9 MN
Diameter	175mm	290mm	175mm







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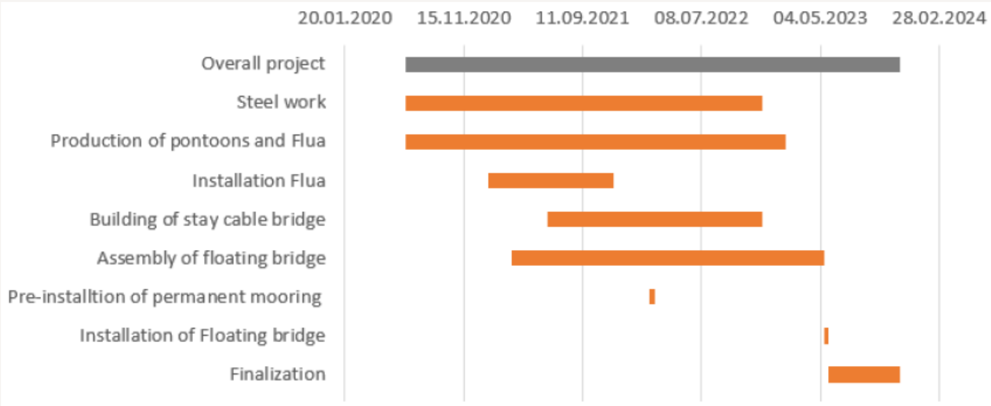
Bjørnafjorden, Norway

Key figures with south navigation span

Curved Bridge		
Steel	118700	tonnes
Concrete	145770	m^3
Stay cables	1900	tonnes
Ballast	105000	m^3

Straight Bridge		
Steel	80100	tonnes
Concrete	133240	m^3
Stay cables	1050	tonnes
Ballast	63500	m^3
Mooring cables	18	nos



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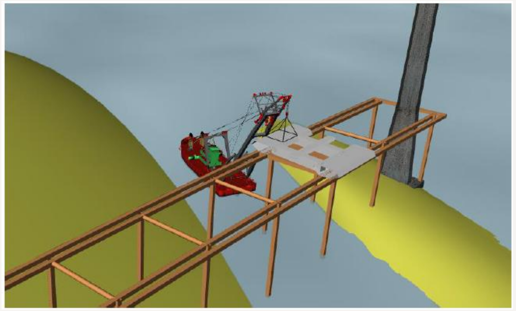
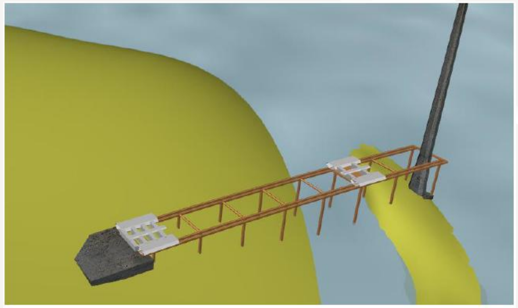
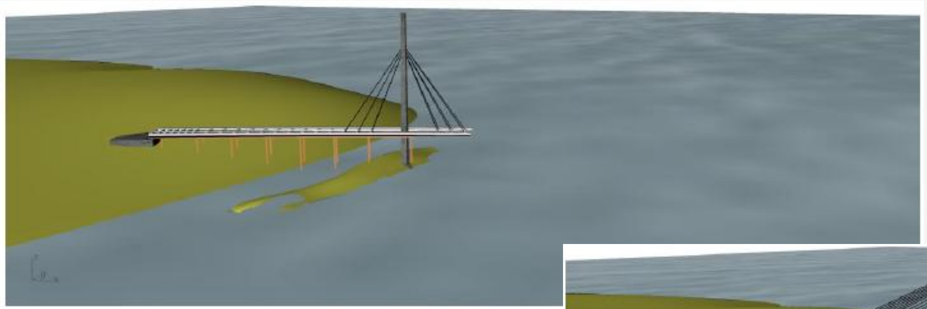
Bjørnafjorden, Norway

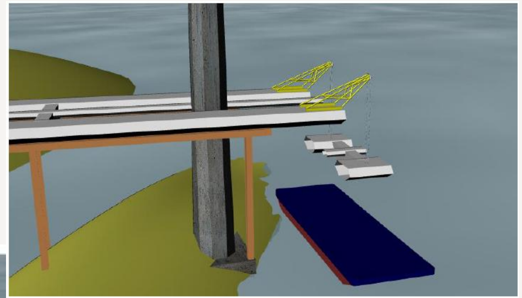
Main bridge construction

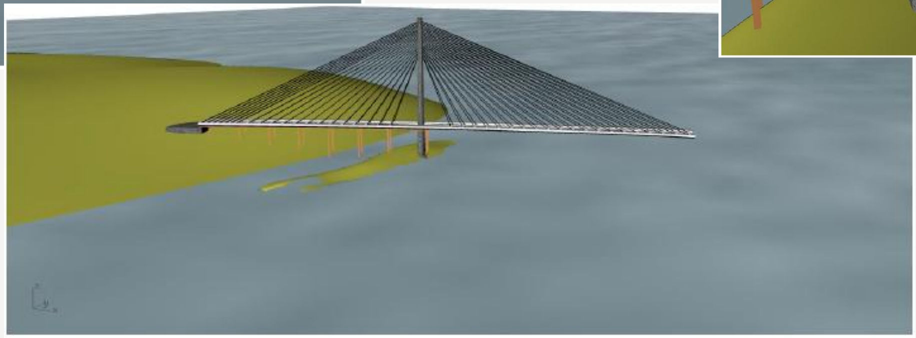
- Side span on scaffolding
- Main span by free cantilever
- Main bridge designed for 100 year storm during construction









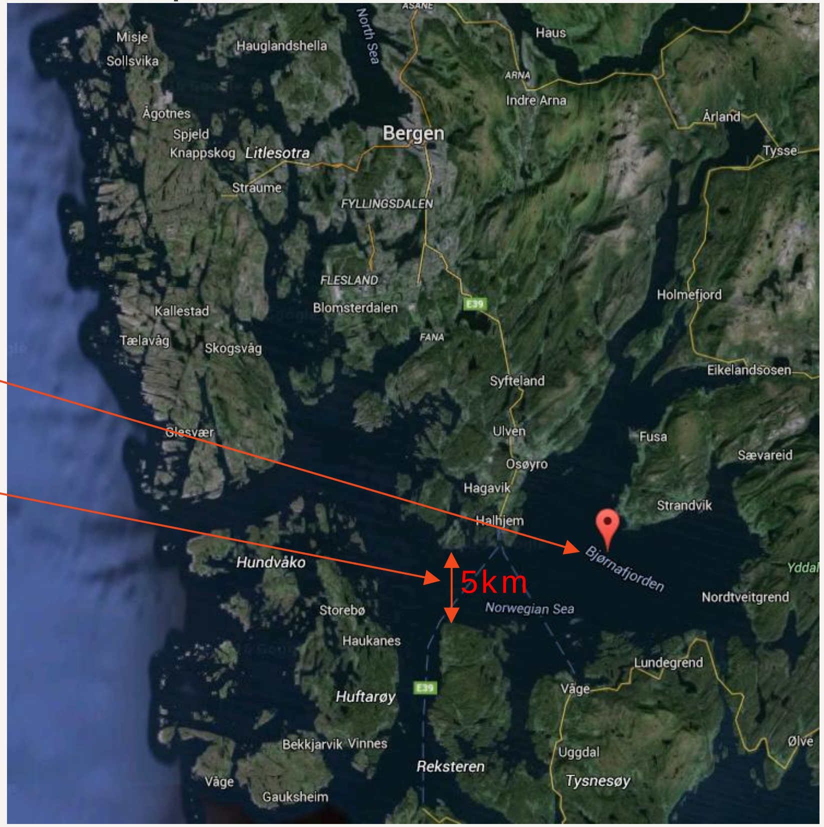


COWI

Bjørnafjorden, Norway

Construction floating bridge / Marine Operations

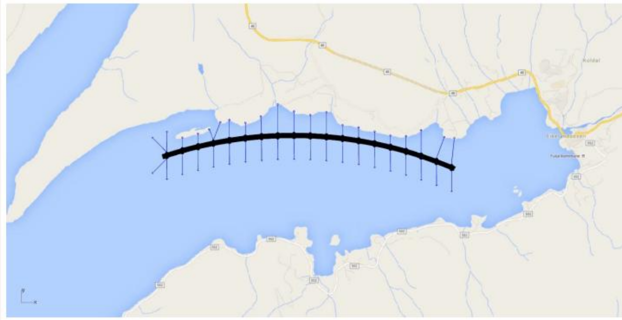
- Production of pontoons/abutments
  - Dry or floating dock
- Floating assembly location
  - Pontoons, columns and bridge girder
  - Sheltered inside Bjørnafjord
- Bridge location
  - Stay cable bridge
  - Abutment at Flua
  - Mooring cables (straight bridge)
  - Installation of floating bridge

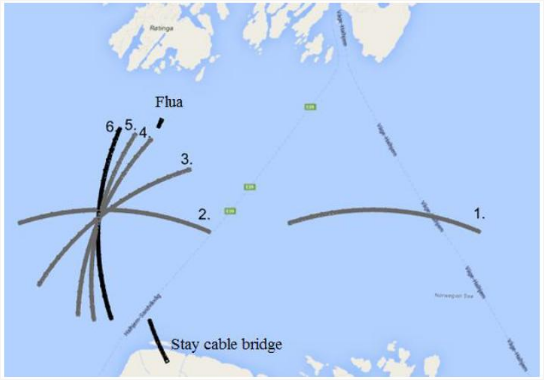


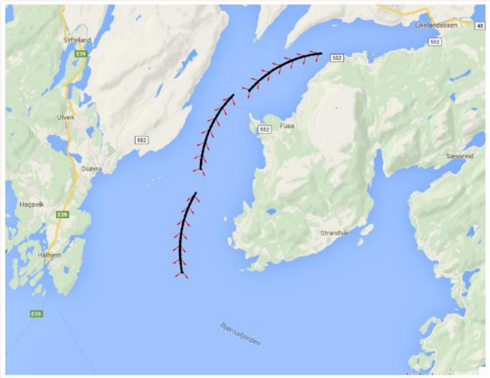
Bjørnafjorden, Norway

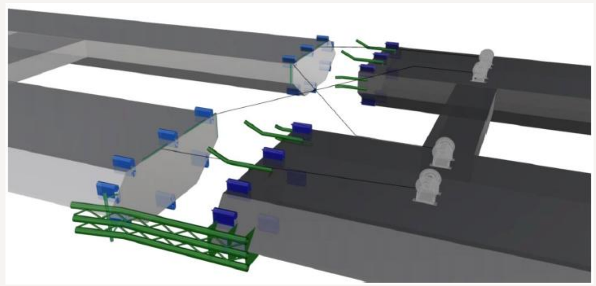
Construction floating bridge / Marine Operations

- 1 total floating bridge section of 3750m
- Assembled at shallow "still" water
- Towed to site in a single weather restricted operation
- Temporary guide/winch and joint brackets









COWI

Bjørnafjorden, Norway

Future investigations in spring '16

- Further parametric studies
- Increase navigational clearance from 45m to 55m
  - Surge/pendulum motion sensitive
- Alternative pontoon design (further optimisation)
- Sensitivity study
  - Superstructure stiffness ±10%
- Geotechnical site investigations (NGI)
  - South abutment and tower foundation on land
  - North abutment on Flua at 40m water depth
  - Mooring anchor positions at 550m water depth

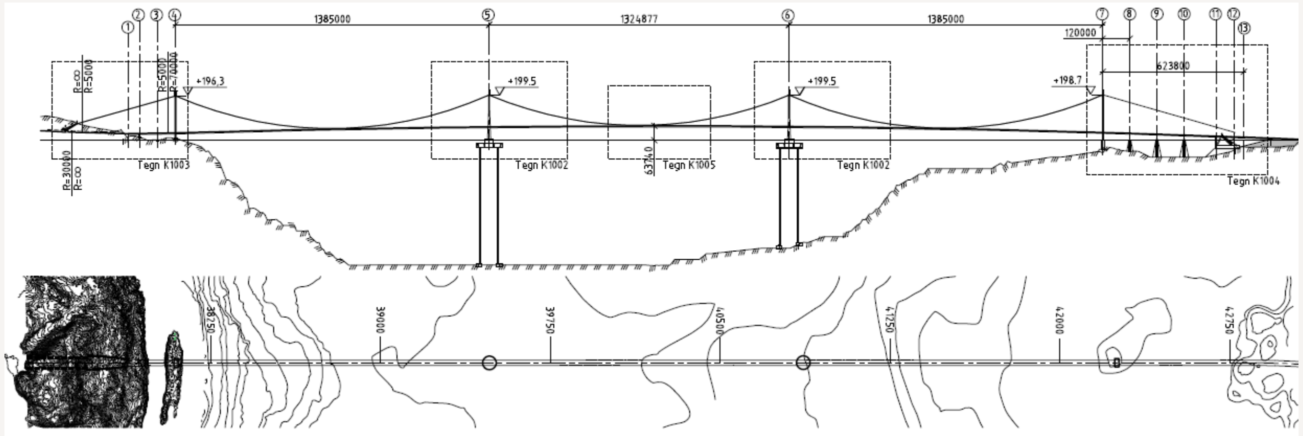
Bjørnafjorden, Norway

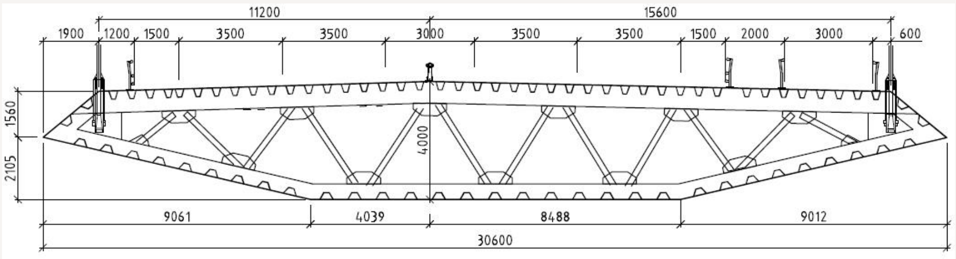
Tension Leg Platform Suspension Bridge (TLP)

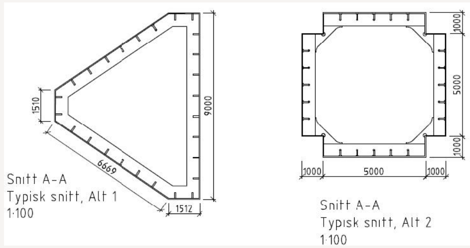
- Offshore & suspension bridge technology
- 3 suspended spans, 4095m total
- 2 floating tower foundations, TLP's
  - Steel towers
  - Steel or concrete foundation/platforms
  - Steel pipe tension legs, 6-8 pr. TLP
- Concrete towers on land & Flua (40m water depth, N)
- Orthotropic steel girder
- Steel or concrete viaduct bridge girder

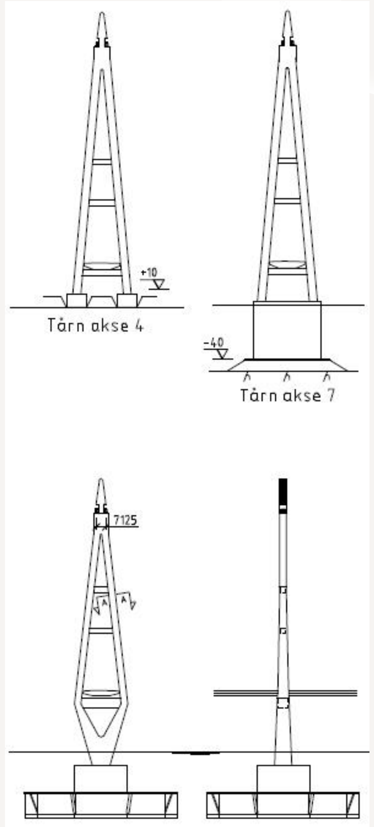
Bjørnafjorden, Norway

Tension Leg Platform Suspension Bridge (TLP)









COWI

Bjørnafjorden, Norway

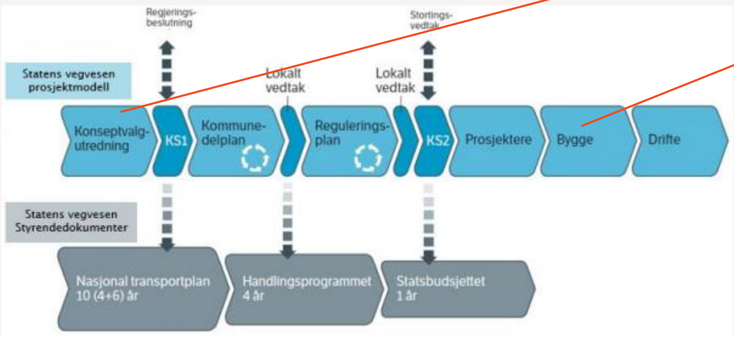
Concept and time frame

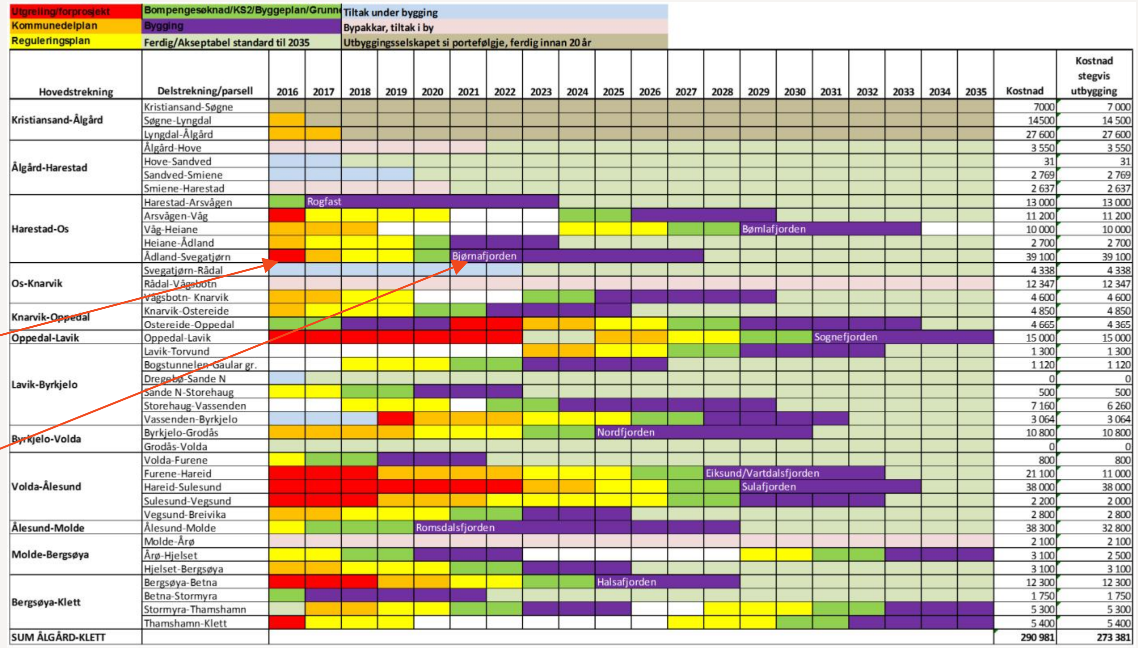
› Above or below water?

 › Expert group meeting 2/3-16

 › Investeringsanslag 10/3-16

› SVV general project model





Utgreiing/forprosjekt | Bompengesøknad/KS2/Byggeplan/Grunn | Tiltak under bygging
Kommunedelplan | Bygging | Bypakkar, tiltak i by
Reguleringsplan | Ferdig/Akseptabel standard til 2035 | Utbyggingsselskapet si portefølgje, ferdig innan 20 år

Hovedstrekning	Delstrekning/parsell	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	Kostnad	Kostnad stegvis utbygging
Kristiansand-Ålgård	Kristiansand-Søgne																					7000	7 000
	Søgne-Lyngdal																					14500	14 500
	Lyngdal-Ålgård																					27 600	27 600
Ålgård-Harestad	Ålgård-Hove																					3 550	3 550
	Hove-Sandved																					31	31
	Sandved-Smiene																					2 769	2 769
	Smiene-Harestad																					2 637	2 637
Harestad-Os	Harestad-Arsvågen		Rogfast																			13 000	13 000
	Arsvågen-Våg																					11 200	11 200
	Våg-Heiane														Bømlafjorden							10 000	10 000
	Heiane-Ådland																					2 700	2 700
	Ådland-Svegatjørn						Bjørnafjorden															39 100	39 100
Os-Knarvik	Svegatjørn-Rådal																					4 338	4 338
	Rådal-Vågsbotn																					12 347	12 347
	Vågsbotn- Knarvik																					4 600	4 600
Knarvik-Oppedal	Knarvik-Ostereide																					4 850	4 850
	Ostereide-Oppedal																					4 665	4 365
Oppedal-Lavik	Oppedal-Lavik																Sognefjorden					15 000	15 000
Lavik-Byrkjelo	Lavik-Torvund																					1 300	1 300
	Bogstunnelen-Gaular gr.																					1 120	1 120
	Dregebø-Sande N																					0	0
	Sande N-Storehaug																					500	500
	Storehaug-Vassenden																					7 160	6 260
	Vassenden-Byrkjelo																					3 064	3 064
Byrkjelo-Volda	Byrkjelo-Grodås										Nordfjorden											10 800	10 800
	Grodås-Volda																					0	0
Volda-Ålesund	Volda-Furene																					800	800
	Furene-Hareid													Eiksund/Vartdalsfjorden								21 100	11 000
	Hareid-Sulesund														Sulafjorden							38 000	38 000
	Sulesund-Vegsund																					2 200	2 000
	Vegsund-Breivika																					2 800	2 800
Ålesund-Molde	Ålesund-Molde					Romsdalsfjorden																38 300	32 800
Molde-Bergsøya	Molde-Årø																					2 100	2 100
	Årø-Hjelset																					3 100	2 500
	Hjelset-Bergsøya																					3 100	3 100
Bergsøya-Klett	Bergsøya-Betna										Halsafjorden											12 300	12 300
	Betna-Stormyra																					1 750	1 750
	Stormyra-Thamshamn																					5 300	5 300
	Thamshamn-Klett																					5 400	5 400
SUM ÅLGÅRD-KLETT																						290 981	273 381