JCSS Workshop on Risk Acceptance, Trondheim June 19-20.2023

Risk Analysis and Acceptance for Floating Bridges, with emphasis on (road traffic disruption due to) Ship Collisions

Torgeir Moan, prof. em., NTNU

Aim :

- establish a simplified ship impact risk-based design procedure for floating bridges with respect to traffic disruption (economic loss), fatalities.

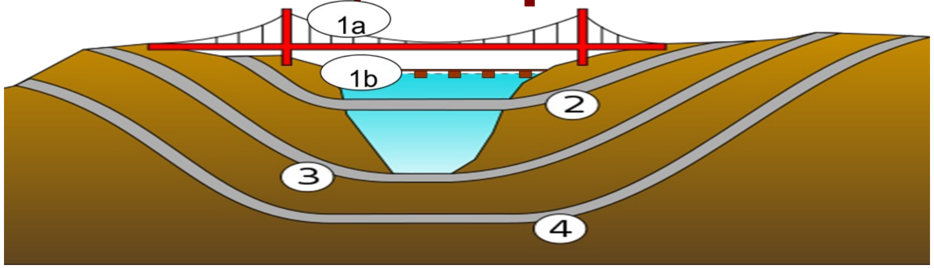
Reference:

- risk assessment of ship collisions

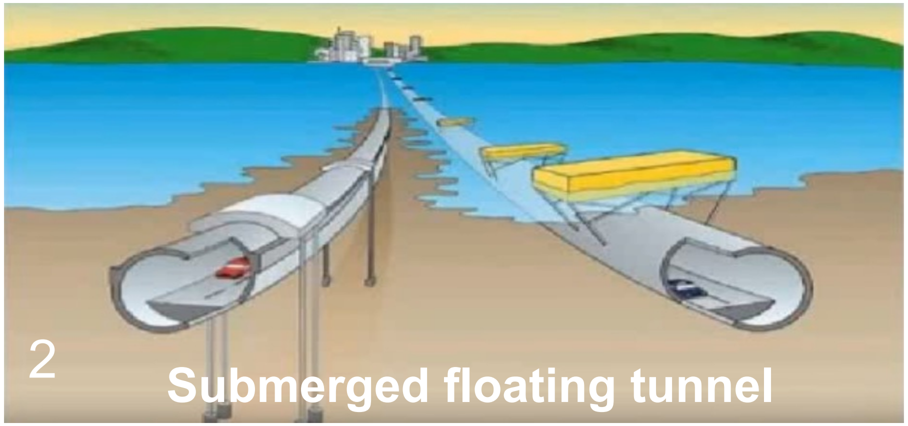
Outline

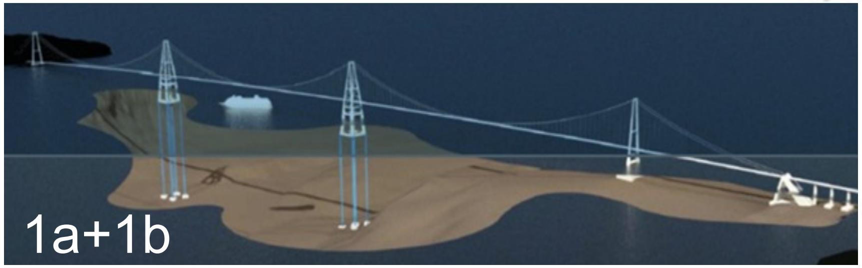
- **Introduction**
  - safety of novel fixed transport systems across wide, deep straits
  - **total risk analysis**
  - relevant regulations/standards for structural engineering
  - structural design vs. risk manangement
- **Ship impact risk analysis (with focus on road traffic disruption)**
  - **Frequency analysis**
  - **Consequence analysis**
  - analysis of ***immediate consequences,*** to determine**:**
    structural damage , hull penetration-flooding, motions ..
  - ***ultimate consequences***: (fatalities) and traffic disruption
    - Effect of ship impact on bridge motions and drivers faults….(fatalities)
    - Effect of damage and repair conditions on fulfillment of SLS,ULS req.
- **Risk estimation and acceptance**: E(C), F-N, P(total loss) and **risk of disruption vs. the impact scenario**
  - prob. of impact scenario (energy range, direction, force-identation curve… (i) and a given location (j) (girder, pontoon j1.)
  - cond. prob. of time with damage, repair (dep. on damage, repair method)
  - cond. prob. of fulfillment of SLS,ULS req. in damage and repair conditions
- **Concluding remarks - recommendations**

Safety of novel (fixed) transport systems, across wide, deep straits

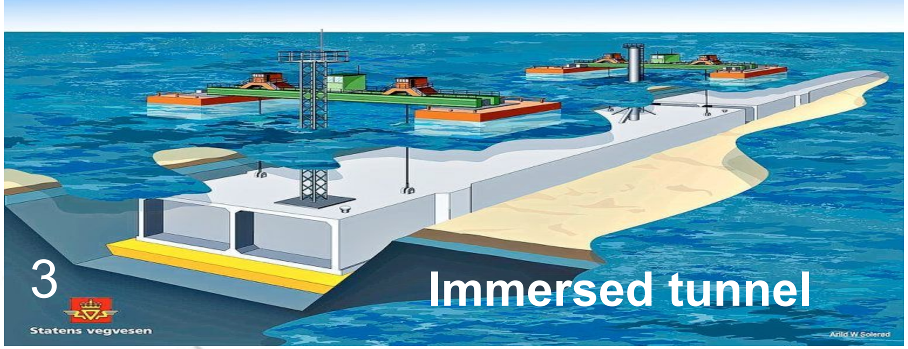


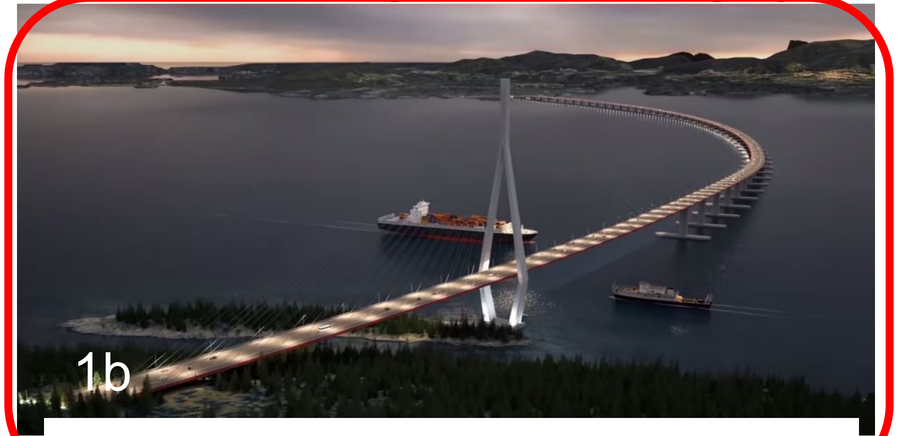

1a The 1915 Çanakkale Bridge, central span 2,023 m)


2 **Submerged floating tunnel**


1a+1b

Suspension bridge with floating pylons


3 **Immersed tunnel**


1b

Bjørnafjorden bridge (≈ 5 km)

Total risk analysis (TRA) for safety manangement

- **Risk analysis** should cover all hazards & lifecycle efforts:
  - Environmental hazards, payloads etc.
  - Accidental hazards (ship impacts, rock/landslide over/under water, fires/explosions, accidental flooding of buoyancy chambers…)
  - Often 1-2 accidental hazards dominate; such as ship impacts for floating bridges But, risk mitigation measures need to be holistically assessed.
- **Target measure for risk**: Various individual/societal measures of fatalities/injury, environmental damage, costs (incl. in-serviceability)

☐ **TRA should** (ideally speaking) **serve as basis for simplified approaches** suitable for life-cycle decision-making (design….):

- SRA based on Pf given consequences of failure
- approaches to handle accidental events.

Known phenomena,
but predicted with
deceasing accuracy

With the current limitations of the TRA, it should be used with caution while it is further developed.

Relevant regulations/guidelines (relating to ship collision risk)

- Eurocodes EN 1990

  - target reliability values for «SRA component check, or ….» (CC3: $P_{ft} = 10^{-7}$)
- Eurocode1991-1-7 (accidental loads) recommends

  QRA, and use of individual and societal fatality risk. ALARP (inform.annex).

  - NOTE: DS EN 1991-1-7 (Rambøll/COWI, 2016) for road (and railway) bridges

    Method I : New bridges $P_{ft} = 10^{-7}$; Existing bridges: $P_{ft} = 10^{-6}$

    Method II: Min. $P_{ft} = 10^{-5}$ (with high risk of fatalities) + use of ALARP

    - Cost-benefit analysis of **traffic disruption**
- USA

  - ASHTO risk analysis of bridges relating to **collapse probability** of fixed bridges; simplified assessment of consequences. $P_{ft} = 10^{-4}$
- Norway

  - Handbook for bridge design, N400 (**only reg./standard** incl. Floating bridges and submerged tunnels): ALS criterion: fulfill ULS req. (LRFD = 1.0) in damaged conditions due to 10^{-4} events (adapted from offshore oil and gas regulations)

Main concern: fatality risk

Structural design vs. Risk management

- ☐ **Structural design requirements do not reflect the risk of** ultimate consequences (fatalities, envir. damage, road traffic disruption, economic losses) **very well.**
  - Typically, structural design codes, with some exceptions, refer to **component failure modes** and not **system** reliability/risk (targets)
  - The target failure prob./risk criteria relating to accidental events, is unclear
  - ALS design criteria account for accidental events, but with the purpose to avoid catastrophic events («total loss»), and not inserviceability.
- ☐ **Risk analyses, in principle, could serve this purpose, but are themselves based on many simplifications** and the question is how well they can form a rational basis for risk compliance with target values and mitigation ?
  - consider e.g. ship collision risk of bridges (especially relating to traffic disruption):
    - focus on structural collapse, with limited link to the ultimate consequences
    - «oversimplified» considerations of structural failure/damage (and repair)
    - How is the risk $R=\Sigma\, p_i \cdot C_i$ estimated? Some risk analysts make judgement considering that ALS requirements for extreme events ($\geq 10^{-4}$), are fulfilled, but neglect that fact that ALS don't consider repair conditions and the contribution from events with a high p_i and moderate C_i.

Ship impact risk and its mitigation

Estimation of the risk, in terms of the ultimate consequences:

Measures of risk:

Expected $C=\Sigma p_i \cdot C_i$

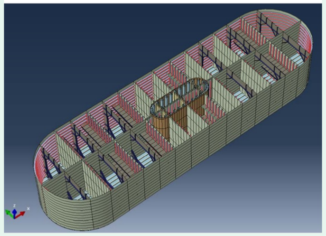
- for scenario (i) : impact energy level, -direction, location of impact

FN-diagram

P(total loss)

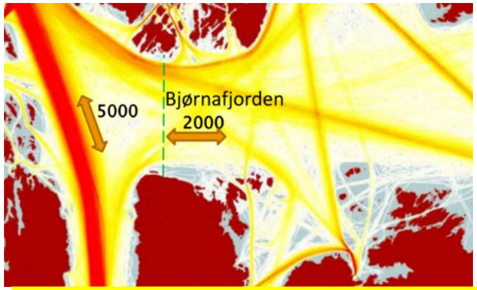
Note: the individual p_i and C_i provide a useful resoultion of the risk

- ☐ **Fatalities** and injuries to users of the bridge caused by structural damage, accelerations and visual disturbance of drivers.
- ☐ **Disruption of road traffic** due to damage (reduced capacity or buoyancy loss) or failure of the bridge
- ☐ **Costs** (according to the ALARP principle)
- ☐ As a possible consequence of risk aversion, it might be required that **"the probability of total loss"** should be low.

Mitigation of risk; e.g. due to ship collisions	
Reduction of frequency	• Traffic control (TSS,VTS, piloting) • Design of bridge: structural configuration - navigation channel etc. • Contingency planning w.r.t. fatalities/injuries
Reduction of consequences 	▪ Provide fendering ? ▪ Strength design of columns, girder and ductility (and strength) design of pontoons ▪ Subdivision of pontoons in compartments ▪ Feasibility/choice of repair method ▪ Improving analysis method 

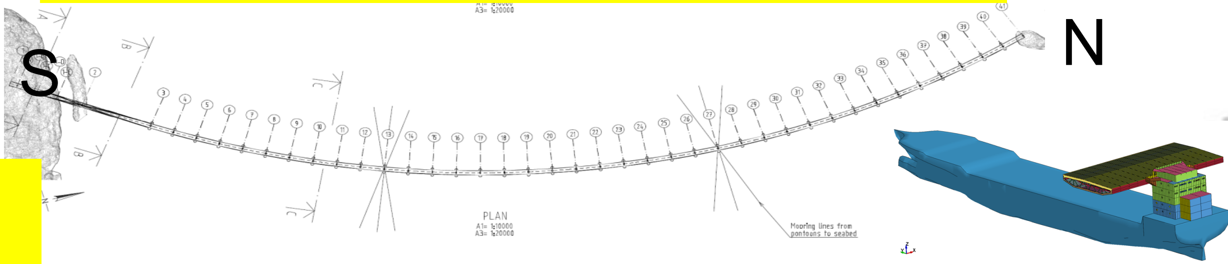
Ship collision risk analysis

☐ **frequency analysis** (traffic pattern, root causes of operational faults, bridge layout, methodology)

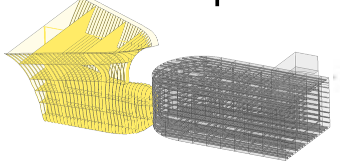


ship traffic based
on the years 2015-2016

The example analysis is carried out for a Phase 5 in pre-engineering (not the final design)



Girder impact



Pontoon impact

Major impact scenarios

- Focus on conventional surface ships and no account of autonomous ships and submarines

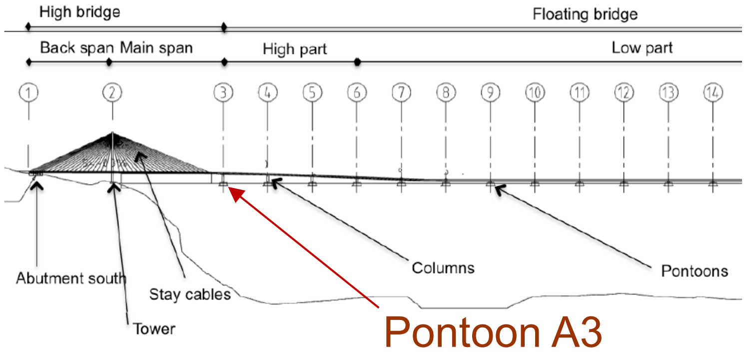
☐ **consequence analysis**

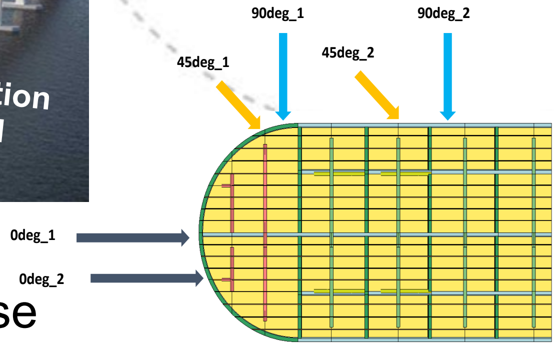
➢ **Immediate consequences**
  - structural damage and possible buoyancy loss
  - bridge girder motions

visual "disturbance") affecting driver performance (faults)

➢ **Ultimate consequences**
  - fatalities/injuries
  - traffic disruption
  - costs of repairs and traffic disruption

Frequency analysis – frequencies vs. impact energy (Rambøll study, 2020)



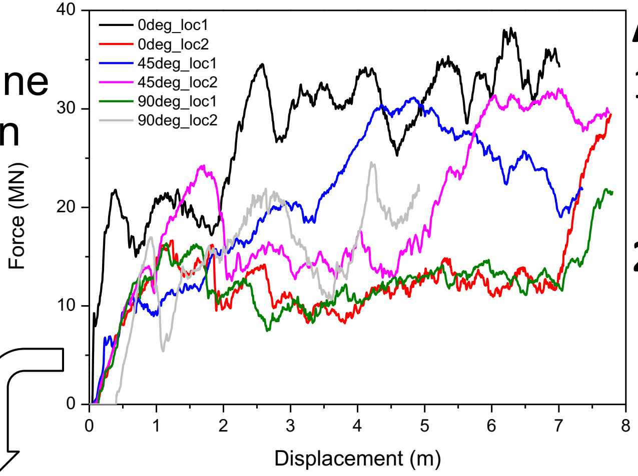


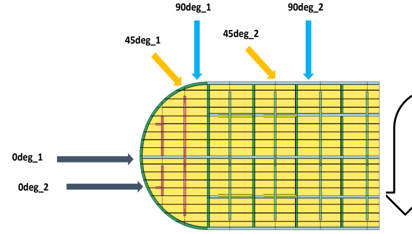
Impact frequency versus energy for 0 and 90 degrees impacts, assuming TSS and VTS for the Bjørnafjorden case

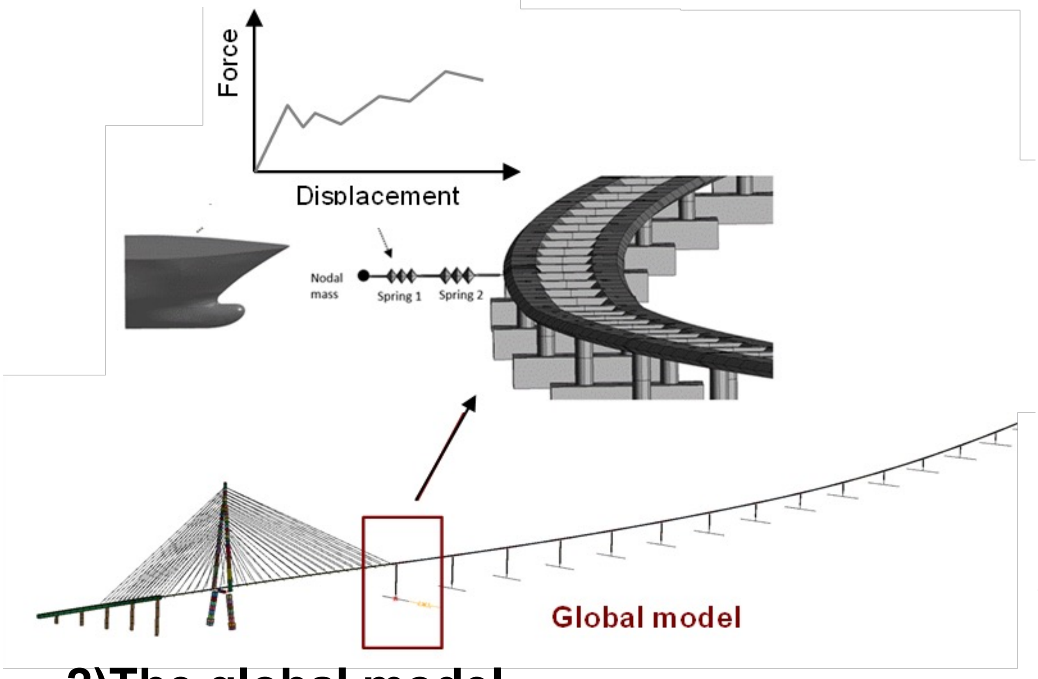
Energy (MJ)	Annual frequency					
	Pontoons 3-5		Pontoons 6-40		Girder (North and South)	
	0 degree	90 deg	0 degree	90 deg	0 degree	90 deg
0-25	1.85E-03	3.31E-06	4.54E-02	2.72E-05	7.86E-05	2.50E-05
25-50	3.58E-04	8.33E-04	1.07E-02	1.73E-02	1.03E-04	3.97E-06
50-100	4.80E-05	1.69E-04	4.51E-04	3.19E-03	1.28E-04	1.46E-05
100-150	1.24E-05	4.88E-05	7.04E-05	6.55E-05	4.50E-05	2.37E-05
150-200	1.59E-06	1.06E-05	1.40E-05	1.98E-05	1.08E-05	1.07E-05
200-400	2.2 E-06	3.9 E-06	1.7 E-05	3.9 E-06	1.6 E-05	2.5 E-06
400-600	7.0 E-07	2.7 E-06	7.1 E-06	2.3 E-06	7.3 E-06	1.4 E-06
> 600	4.1 E-07	1.2 E-06	2.8 E-06	8.0 E-07	1.8 E-06	3.4 E-07

Impact response analysis procedure

1) Local nonlinear analysis to determine the force-indentation curve (influenced by many factors)







2)The global model

A three – step analysis procedure:

1) local nonlinear FE analysis, to evaluate the force- displacement relationship in the impact region.

2) global analysis, to

(a) identify the energy distribution between the local structural damage and the global motion.

Local deformation energy could be of the order of 10-75 % of the total (kinetic) energy.

(b) obtain the overall bridge response

Notes:

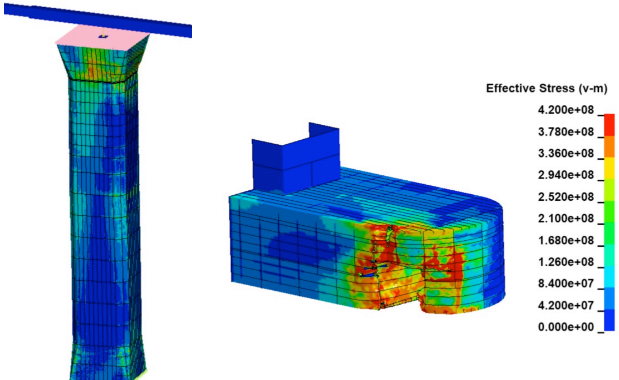
- The default global model of columns/girder is based on linear beam model
- alternative : column of impacted pontoon: nonlinear FE shell model (LSDYNA)

3) Based on the results of the

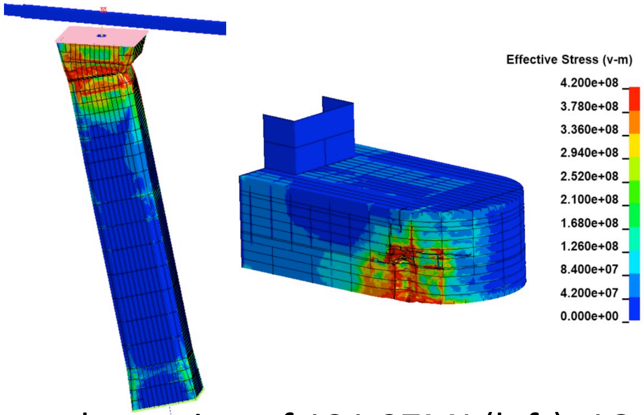
- the global response analysis, and
- the step 1)

the damage/flooding are determined

Structural damage (examples)



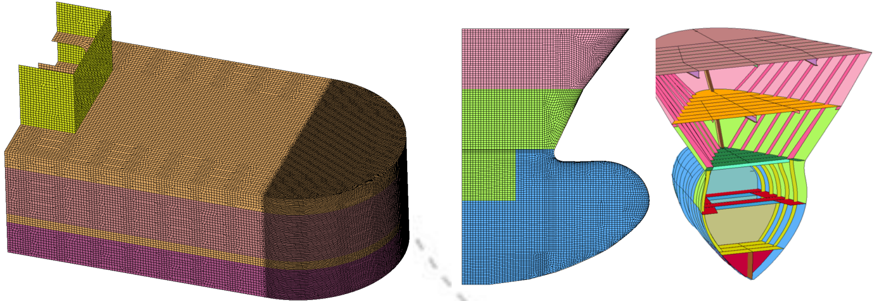
Energy absorption of 36.65MJ (left), 62.4 MJ (right) at 125 MJ. **Curve B.**



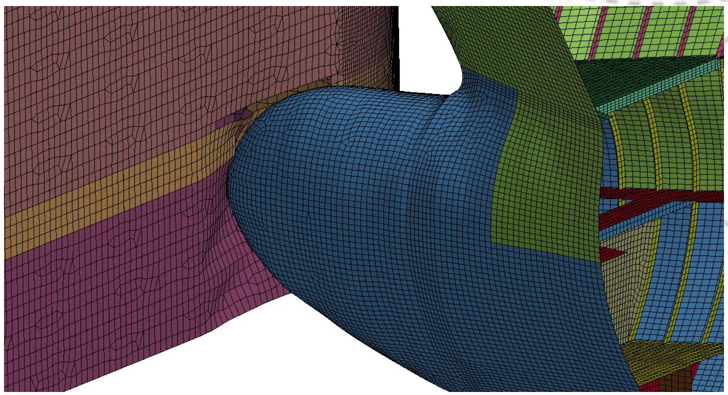
Energy absorption of 121.97MJ (left), 16.1MJ (right) at 125 MJ, **Curve A**

Impact on pontoon A3 at a 90-degree dir.

The force-indentation curve A is more stiff than curve B, and implies less pontoon damage but more column/girder response (damage)



The pontoon model The 2200-ton vessel FE model



Initial fracture at a displacement of 0.6 m corresponding to an internal energy dissipation of 4.5 MJ (corresponding to an impact energy of 8-10 MJ), shows

This example illustrates the importance of low energy, “high frequency” impacts.

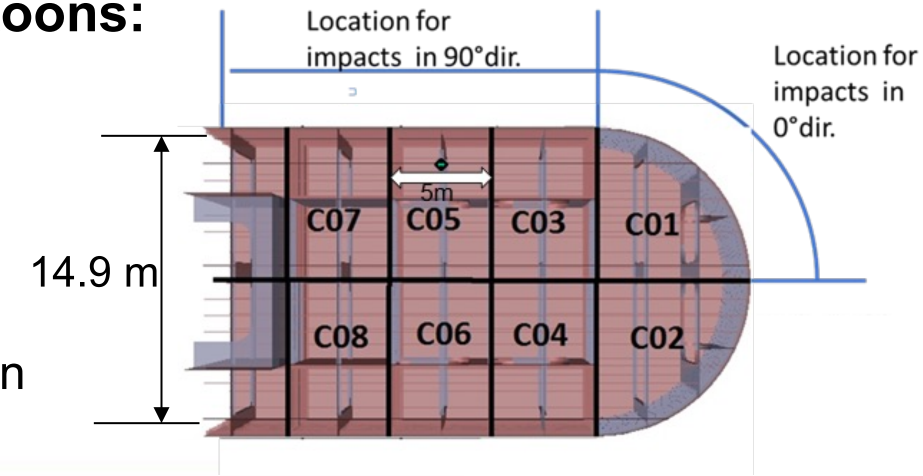
Example: Column, girder, pontoon response due to a 90-degree impact on pontoon A3.

Case	Column bending & torsion (MNm)			Girder bending & torsion (MNm)			Energy dissipation (MJ)		Indentation (m)	Force vs. disp curve
	Roll	Pitch	Torsion	Strong axis	Weak axis	Torsion	Column	bow-pontoon		
15MJ_beam	10.99	-84.21	-388.10	-208.97	-197.46	0.11	Elastic	11.39	1.12	Curve D
	-3.60	-280.24	-37.40	-30.81	-323.01	1.55				
27MJ_beam	11.36	-87.62	-386.16	-207.97	-199.73	-0.23	Elastic	19.6	3.12	Curve D
	1.05	-423.45	-85.49	-35.71	-398.46	-0.32				
125MJ_shell	21.35	-284.00	-642.89	-343.89	-271.43	0.40	36.7	62.4	6.17	Curve B
	-10.18	-1042.18	-111.18	-53.75	-690.27	9.93				
150MJ_shell	19.90	-248.43	-641.90	-338.91	-276.83	-0.12	74	70.2	6.63	Curve B
	-1.66	-1028.79	-275.18	-144.49	-681.48	9.19				
200MJ_shell	22.68	-308.87	-641.48	-342.77	-273.35	1.61	134.14	84.57	7.4	Curve B
	1.17	-1021.16	-328.15	-62.48	-670.36	7.22				

Interpretation of damage in the pontoons:

Based on
- impact locations/directions,
- force-indentation curve
- indentation in the pontoon and
- pontoon geometry,

an assessment of flooding of pontoon compartments, is made.



Bridge in damaged and repair conditions

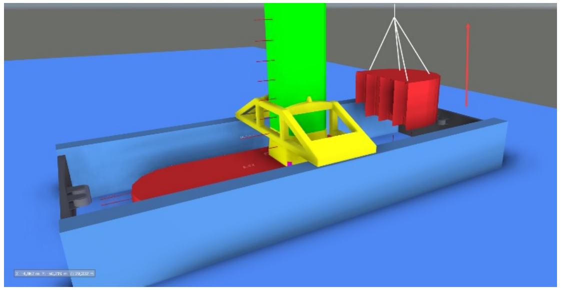
Equiment to provide dry atmosphere during repair of pontoons /(column):

- Use of cofferdam or another simple method

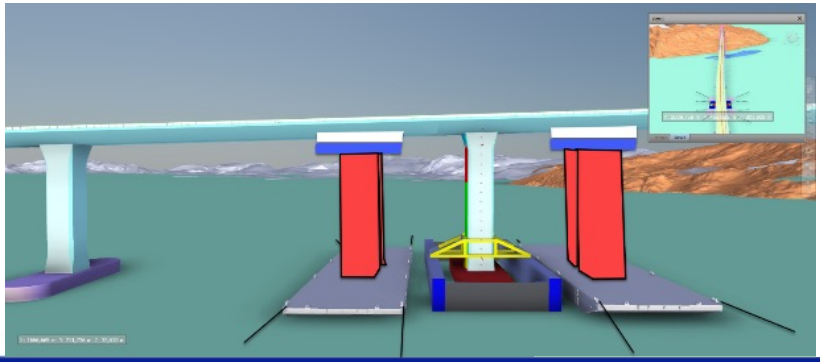
Estimated needed repair time: 2-20 months

- Use of drydock

  (the displacement of the drydock is 4 times or more larger that that of the pontoon



- Use of barges/temporary columns to provide girder support during repair of column/pontoon

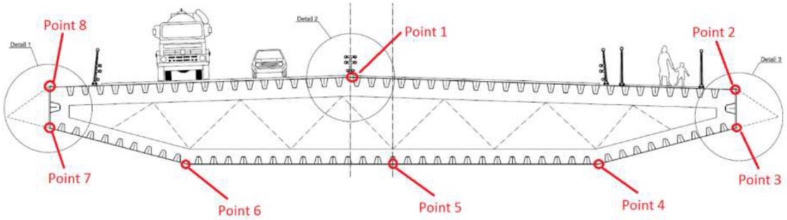


Response analysis of the bridge girder in the damaged and repair conditions

ALS: fulfillment of ULS req. (100 yr.-E-loads; γ=1.0) for 10-4 damage

Permit road traffic: Fulfillment of normal SLS, ULS criteria in damaged and repair conditions; e.g.

ULSb: no traffic , selfweight (γ =1.2),
100 yr E-loads (γ =1.6)



The displacement of the drydock is 4 times that of a pontoon

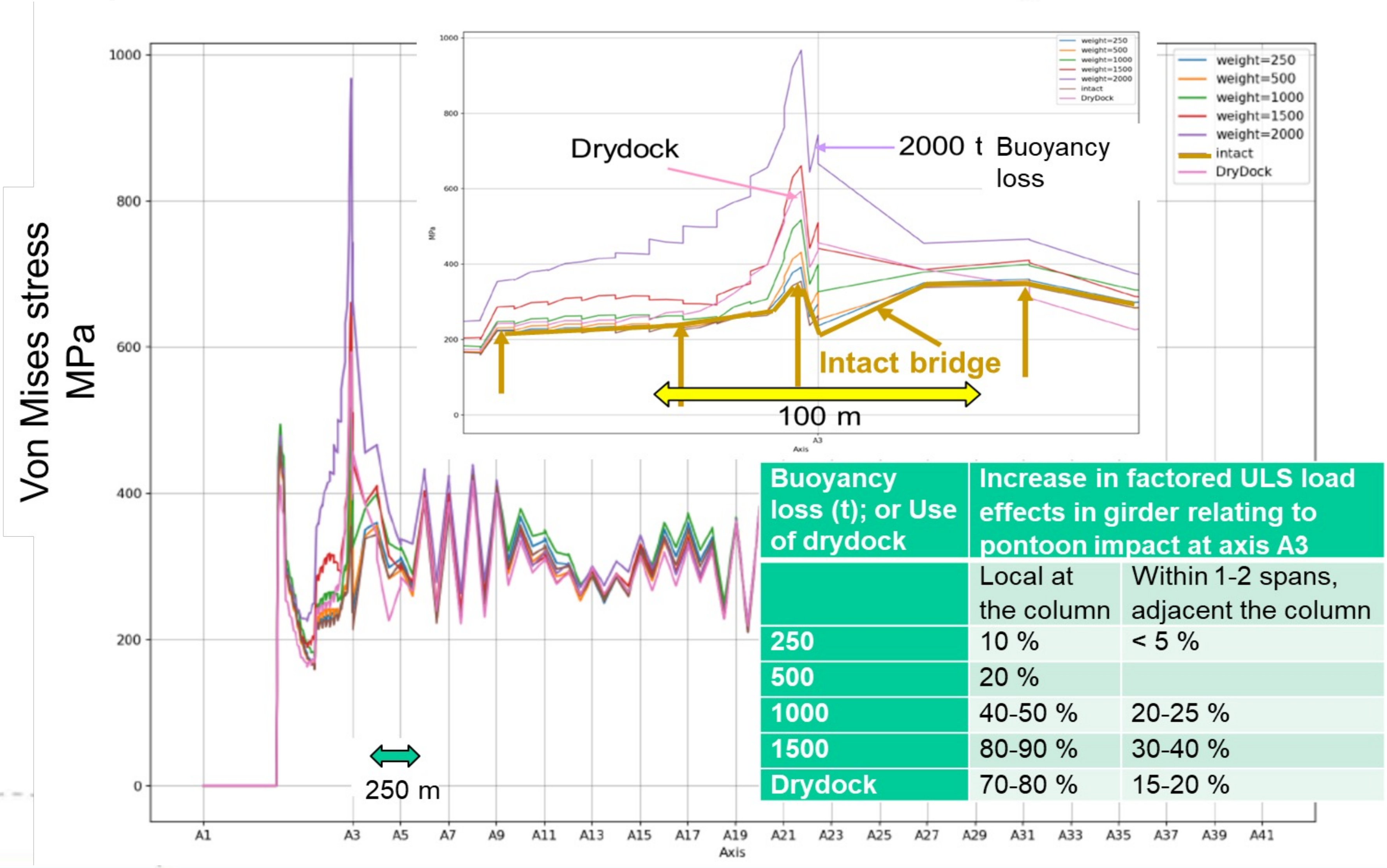
Repair scenario - pontoon carried by a drydock

Assumptions:

- The column and girder are assumed to be undamaged
- Permanent loads, effect of damage and environmental loads are considered – with a wide variation of wave, wind conditions.

Factored load effects in the girder in damaged/ repair conditions after pontoon impact at A3

(envelope curves of max. load effect in the cross section over all load conditions)



Buoyancy loss (t); or Use of drydock	Increase in factored ULS load effects in girder relating to pontoon impact at axis A3	
	Local at the column	Within 1-2 spans, adjacent the column
250	10 %	< 5 %
500	20 %	
1000	40-50 %	20-25 %
1500	80-90 %	30-40 %
Drydock	70-80 %	15-20 %

Estimation of road traffic disruption risk

☐ The traffic disruption is estimated for the girder, pontoons A3-A5 and A6-A40 separately, considering directions (0°, 90°), and various impact energy intervals.

☐ The frequency of traffic disruption in days/year is estimated by:

$$T_{tr} = \Sigma_i \; p_i \cdot 30 \cdot t_{tri}$$

- p_i is the annual frequency of impact scenario, i (impact location, direction, -energy)
- t_{tri} is the traffic disruption time (in months) for scenario, i, based on the following information:
  - the estimated damage
  - **the time in damaged/repair conditions**, in months (2.6 – 30 months), based on the **information about damage and** consideration of alternative repair methods.
  - the **response in the damaged and repair condition: check whether SLS, ULS criteria are fulfilled (if NOT, traffic disruption is implied)**

Note:

The uncertainty in impact analysis (especially force-displacement curve),

Interpretation of damage w. r. t. potential flooding, etc., is considered.

Example: Expected traffic disruption for impact on Pontoons 6-40, assuming TSS and VTS (traffic control) for the Bjørnafjorden concept Phase 5.

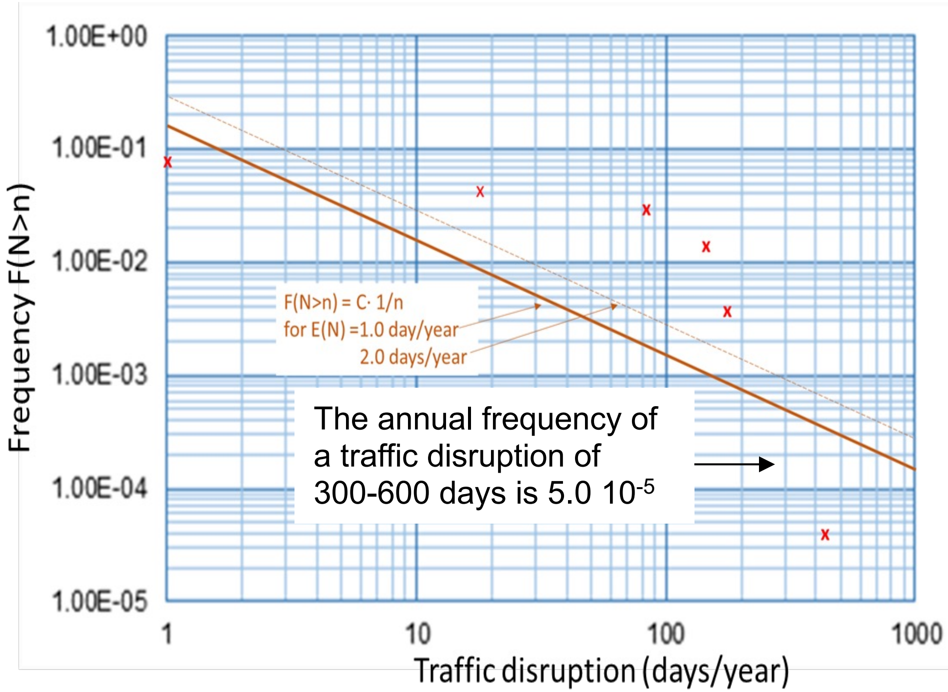
Notation: BL-buoyancy loss, C-Column, G-girder

Dir.	Energy (MJ)	Annual frequency of impact, p_i	Response during the impact	Response in damaged condition	Response in repair condition	Repair time$^{1)}$ (months)	Expected cond. traffic disruption (months)$^{2)}$	Expected traffic disruption, t_{tri} (days/year)$^{2), 3)}$,
0°	0-25	4.54E-02	BL=581 C,G=nd	G:exceeds by 15-20%, C: by 5%, but it is anyway small	Use of DD : G exceeds by 15 % (<5%); C by 25-90%$^{3)}$	3.4	2.2	3.00/ 3.18
	25-50	1.07E-02	″	″	″	6.8	4.4	1.40/ 1.49
	50-100	4.51E-04	″	″	″	7.8	5.5	0.07/ 0.08
	>100							negligible
90°	0-25	2.72E-05	BL=482 t C,G=nd	G:exceeds by 20%, C: by 5%, but is small	″	2.6	0.8	0.00
	25-50	1.73E-02	″	″	″	5.8	2.8	1.45/ 1.54
	50-100	3.19E-03	BL=482 t C-local d., G-nd	″	″	8	5.5	0.53/ 0.56
	100-150	6.55E-05	BL=494 t C-local d. G-d	″ Possibly educed strength of G$^{4)}$	″	11.5-19	7.8-15.3	0.02
	>150							negligible

Summary of the traffic disruption risk estimate

- **Girder impacts do virtually not contribute to the traffic disruption.**

- The **expected annual traffic disruption** relating to impact on **pontoons** in
  - -the tall bridge (A3-A5) : **0.3 days**;
  - -the low bridge (A6-A40): **6.9 days,** of which **6.3 days** refer to impacts with an energy in the range 0-50 MJ.
  - - The repair of the pontoons with the use of a drydock have a key influence **since the ULS design criteria are not satisfied.**



The annual frequency of a traffic disruption of 300-600 days is 5.0 10^{-5} →

FN diagram

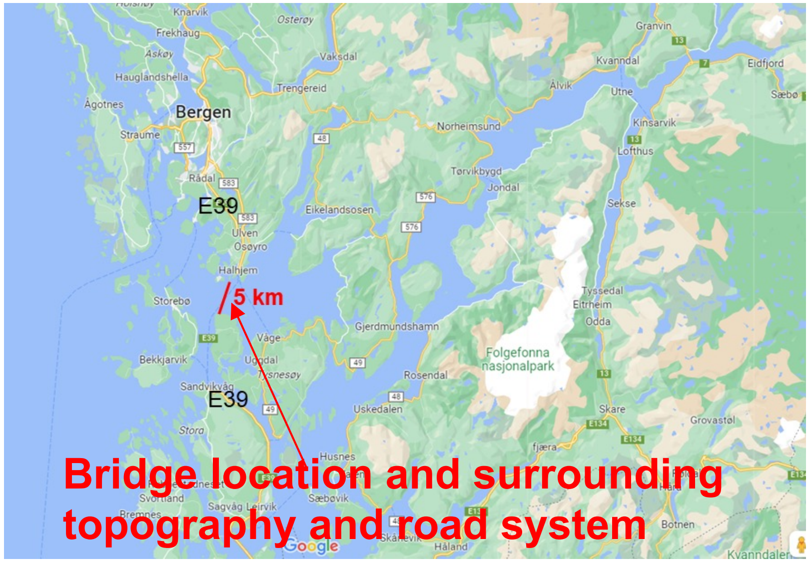
☐ An obvious lesson:

- reduce the risk associated with events with energy in the range of 0-50 MJ, by introducing an additional criterion with energy in this range and require that SLS,ULS criteria are fulfilled in the damaged and repair conditions.

Target level for road traffic disruption,

(the main potential economic loss).

- Target level is typically not defined in absolute terms, and should be based on cost-benefit analysis
- For this bridge the cost of traffic disruption dominate over repair costs, due to:
  - the time lost of detour (or, reinstalling the ferry system)
  - additional traffic on roads with lower standard; implying a higher risk of traffic accidents



Bridge location and surrounding topography and road system

➢ **Tentatively, the acceptable accidental traffic disruption may be assumed to be up to 1-2 days/year** (in addition to that due to traffic accidents, fires and possibly planned maintenance).

❑ Other issues

What is optimal use of resources to ensure traffic flow in a road network system?

Selected recommendations based on the risk analysis of traffic disruption

(already introduced in the FEED phase)

Traffic disruption is avoided if the bridge can be used (fully or partly) by fulfilling SLS, ULS requirements in damaged and repair conditions.

- the significant contribution from low energy, frequent impact events suggest introducing a new ULS type design criterion referring to such cases,
- consider **alternative compartment subdivision** in pontoons and possible strengthening of columns and the girder
- **reduce the vulnerability of fracture** to low energy impacts (say, below 12-15 MJ) by using more ductile, (stainless) steels in pontoons

- **improve the frequency analysis** for low energy events
- properly **reflect uncertainties** , especially the impact force-indentation curves for pontoon impact, inyerpretation of damage (flooding)..

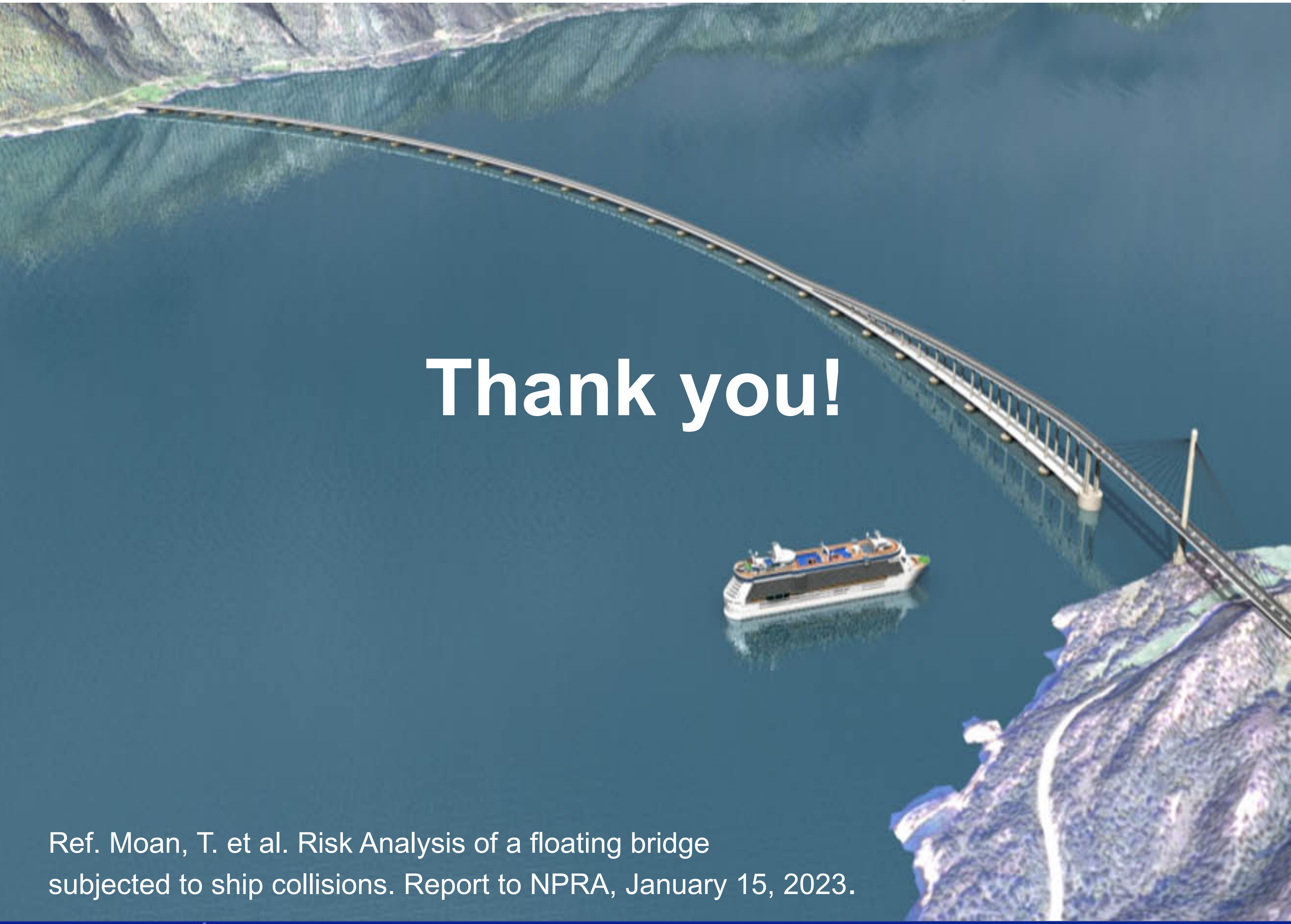
- consider **alternative repair strategies** (winter/summer repair) and methods for moderate damage (avoid use of drydock)

Acceptance of fatality risk

- NPRA: «The fatality risk should be the same or less than that on highways with the same standard»
- Ref.: empirical average fatalities per billion vehicle-km,
  i. e. prob. of death: $p_d = k{\cdot}10^{-9}$ where the basic k is of the order of
  0.2-4 and has been decreasing year by year
  (possibly with risk aversion)
  serves as basis for establishing the acceptable fataity rate for a given bridge
- Ship collisions add to the risk of fatality. On the other hand, the fatality rate also varies. The main issue is then:
  - how much deviation from average traffic accident : fatality/billion vehicle-km, is acceptable for similar highways?

Fatality risk due to ship impacts in the present project

- We estimate the fatality risk associated with collisions based on the motions (accelerations) imposed in the vicinity of the impact and simulation of driving; and the scenario after the impact.
- The fatality risk due to collisions, is estimated to be two orders of magnitude less than the expected traffic accident risk; incl. that associated with dangerous cargo.



Thank you!

Ref. Moan, T. et al. Risk Analysis of a floating bridge subjected to ship collisions. Report to NPRA, January 15, 2023.