ConPaveStruc 2023

TARGET RELIABILITY FOR SERVICEABILITY OF ROADS-RELATED STRUCTURES

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Outline of Presentation

- Background & design standards
- Probabilistic analysis & calibration
- SLS Target Reliability
- Case Study 1: Reliability of crack models
- Case Study 2: SLS target reliability
- Conclusions

Reliability Analysis &- Limit State Design

Structural Engineering is the art of modelling materials we do not wholly understand, into shapes we cannot precisely analyse so as to withstand forces we cannot properly assess, in such a way that the public has no reason to suspect the extent of our ignorance’

Reliability Assessment in Structural Design

Structural reliability reference standards

- JCSS
- SANS 2394: 2004 (update ISO 2394: 2015)
- EN1990
- SANS 10160 -1 (2011)
- *fib* MC 2010 & MC 2020 (draft)

Reliability Analysis &- Limit State Design

Levels of Analysis:

- Level 1: Semi-probabilistic – most design standards (LSD)
- Level 2: Probabilistic analysis to given reliability
- Level 3: Full probabilistic analysis

Probabilistic Analysis Principles

- Safety level as measured by reliability index, β_t

$$p_f\,(d) = P[g = R - E < 0] = \Phi\,(-\,\beta_t)$$

- Reliability index linked to particular time period $\Phi\,(\beta_{t,n}) = [\Phi(\beta_{t,1})]^n$

- Consequence class

- Design life of structure

Nominal Design Working Life

Design Working Life Category	Notional Design Working Life (years)	Examples
1	10	Temporary structures (e.g. scaffolding)
2	10-25	Replaceable structural parts, e.g. gantry girders, bearings (see appropriate standards)
3	15-30	Agricultural and similar structures (e.g. buildings for animals where people do not normally enter)
4	50	Building structures and other common structures (e.g. hospitals, schools etc)
5	100	Monumental building structures, bridges and other civil engineering structures (e.g. churches)

Consequence Class - ULS

- Consider loss of human life; economic, social or environmental consequences

- **RC3** High consequence - Bridges
- **RC2** *Reference class* of medium consequences for most conventional structures.

- **RC1** Low consequences

Limit state Function for ULS Reliability Model

ULS: SANS 10160-1: $E_d \leq R_d$

LSF: g(X) = R(X) – E(X)

(R = Resistance & E = action effects)

p_f (d) = P[g (X) < 0]

Limit state Function for SLS Reliability Model

SLS: SANS 10160-1: $E_d \leq C_d$

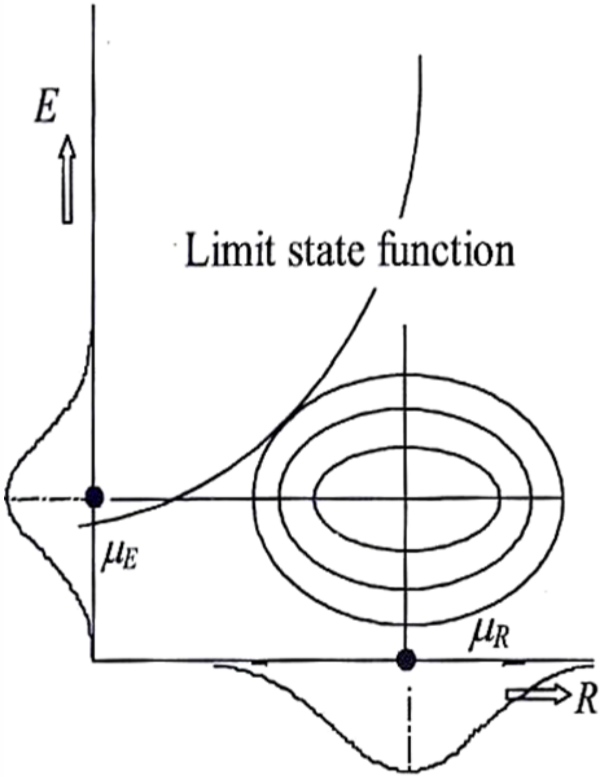
LSF: $g(X) = C(X) – E(X)$

(C = limiting design criterion (fixed value),

e.g. crack width limit)

p_f (d) = P[g (X) < 0]

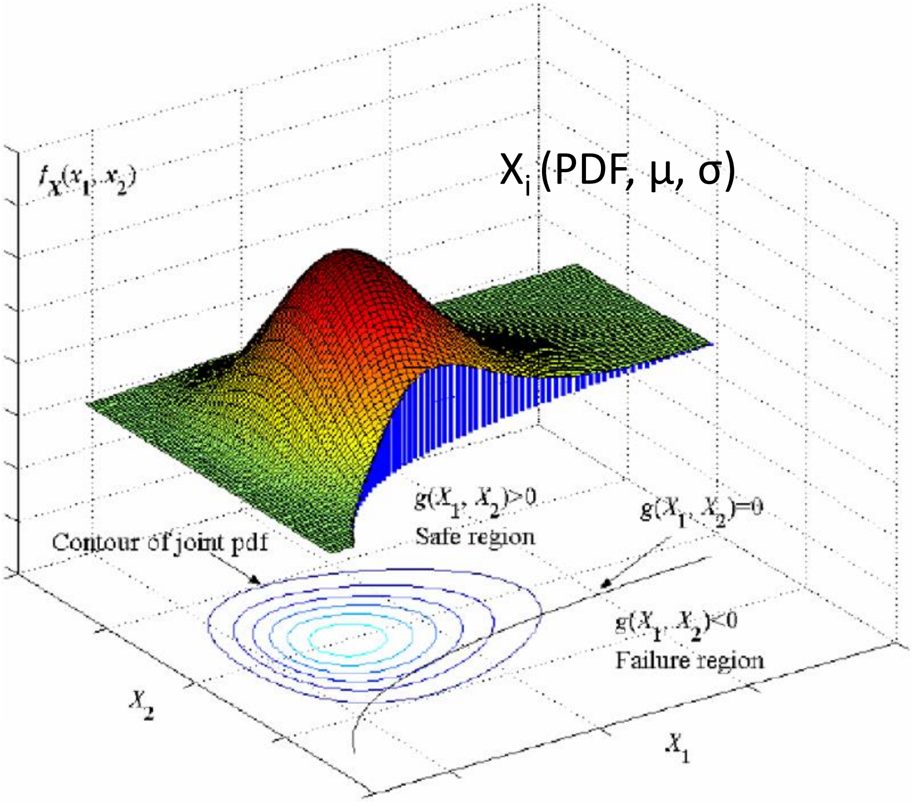
Probabilistic Analysis Methods



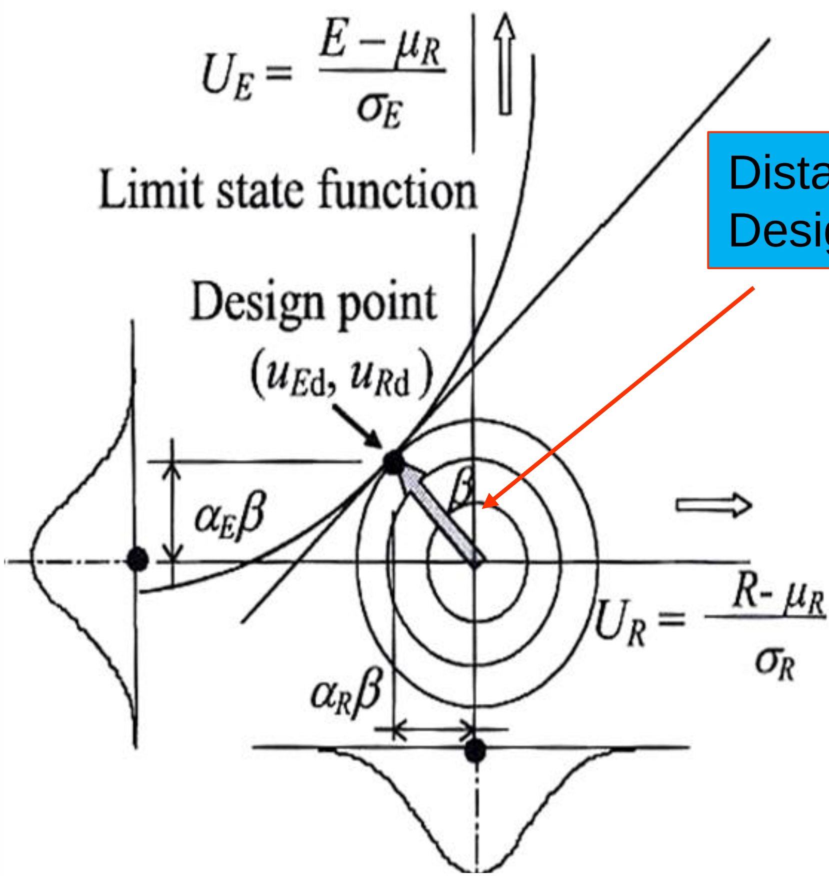
(a) Original basic variables R and E.

(Source: Holický (2009))

$$p_f = \int f_{X_i}(X_i)\, dx_i$$



FORM algorithm: Transformed Variables



Distance from Origin to Design Point = β

Reliability Index $\beta = \frac{\sum x_i'^{*}\left(\frac{\delta g}{\delta X_i'}\right)_*}{\sqrt{\sum\left(\frac{\delta g}{\delta X_i'}\right)_*^2}}$

Transformed RV $X_i^N(\mu_N, \sigma_N)$.

Directional cosines

$\alpha_i^* = (\delta g/\delta X_i')_* / \sqrt{(\Sigma(\delta g/\delta X_i')_*^2)}$

Source: Holický (2009)

Calibration of Reliability Model

- Design value of variable from FORM

$$x^* = \mu_x - \alpha_x \beta \sigma_x$$

- Theoretical psf's

$$\gamma_X = \frac{x^*}{\mu_x}$$

- Calibration & optimisation for target reliability, β_t

→ final design psf's

Target Reliability, β_t

- Cost optimisation to obtain β_t

$$C_{total} = C_o + C_1 d + \Sigma\, C_f\, p_f\,(d)$$

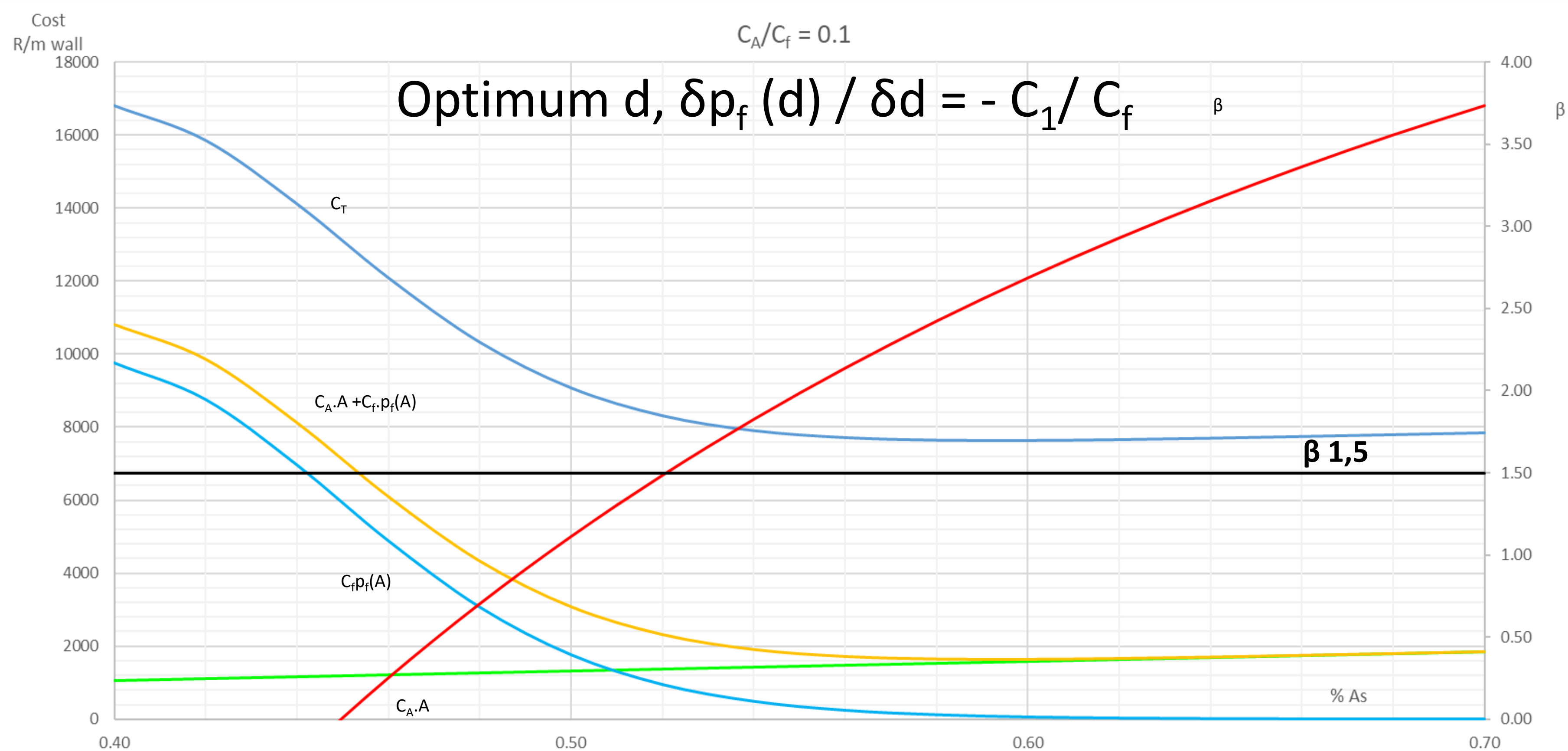
- Decision parameter, d
- Societal costs
- Sustainability

Normalised:

$$C_{total} / C_o = 1 + C_1 d / C_o + (\Sigma\, C_f\, p_f\,(d)) / C_o$$

Cost Optimisation & β_t

For target reliability and design partial safety factors scheme



SA Target Reliability Index Values

Ultimate Limit State

- β_t = 3,0 general level for buildings

  Reference period 50 years

  Consequence class RC2

- 1 year - β_t = 3,9

SA Target Reliability Index Values

Serviceability Limit State

- Reversible states $\beta_t = 0$ e.g. small deflections
- Irreversible states $\beta_t = 1{,}5$ e.g. cracking for 50 years

1 year: $\beta_t = 3{,}0$

100 year: $\beta_t = 1{,}0$

SA Reliability Index Values: Design Standard for Bridges & Culverts

ULS

- TMH7 β ???

- Design Life 100 years

SLS

- TMH7 – no guidance

Assessment of SLS in Design Standards

- No probabilistic analysis done!
- Research questions:
  - Are the existing standards sufficient?
  - If not, when/why?

ULS Target Reliability - Bridges

- Van der Spuy & Lenner (2021)
- Bridge traffic loading – TMH7 NA loads
- Design life 100 years
- RC3 and β_t of 3,5 (50 years)

ULS Target Reliability - Bridges

- Way & Viljoen (2022)
- New concrete bridges
- Cost optimisation
- LQI to ISO 2394: 2015
- Structural redundancy factor
- Recommended ULS β_t of 4,2 (50 year)

Case Study 1:
Reliability of SLS Concrete Crack Models

Reliability Model for Load-induced Cracking

- Assessment of performance of crack models to determine ‘best-fit’ model
- Limit State Function

$$g = w_{limit} - \theta .\ W_{predict}$$

- Target Reliability, β_t and design formulations
- Flexure and direct tension crack models
- Short- and Long-term loading

SLS Model Uncertainties

- Sources of Uncertainty in model
- Variables with known uncertainty (CoV)
- Level of model uncertainty
- Significant uncertainty – include in LSF as RV (θ)

SLS LSF: $g(X) = C(X) - \theta . E(X)$

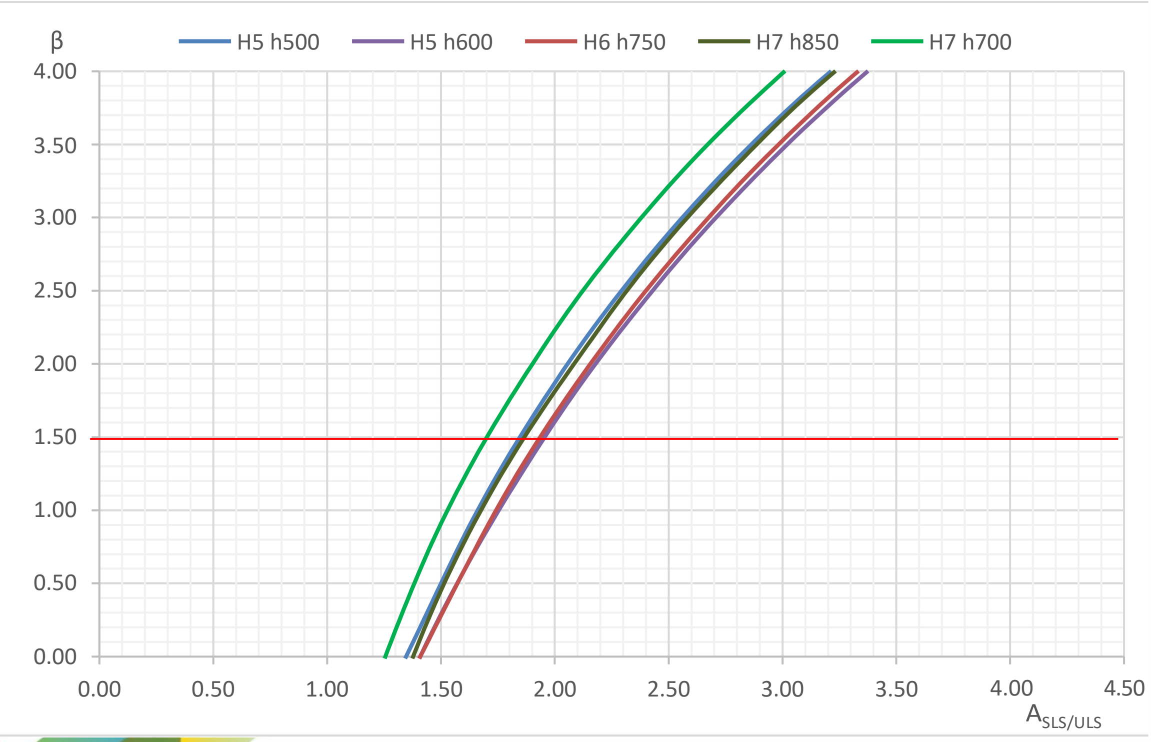
Results of Reliability Analyses

- Quantification of model uncertainty as RV, θ
- Flexural cracking

Load Case	Statistical parameter	EN 1992	MC 2010	BS 8007 w = 0.2 mm	BS 8007 w = 0.1 mm
Short term	Mean	1.107	1.052	1.185	1.112
	CoV	0.397	0.376	0.380	0.459
	PDF	LN	LN	LN	LN
	Count	164	164	164	164
Long term	Mean	1.443	1.127	1.502	1.514
	CoV	0.331	0.380	0.336	0.357
	PDF	LN	LN	LN-N	LN-N
	Count	30	30	30	30

Reliability of 'Best-fit' crack model

- MC 2010 applied to typical WRS
- β range 2,4 -3,2 (compare to β 1,5, 50 years)



Case Study 2:
SLS Target Reliability Analysis

Way, McLeod & Viljoen, 2023

- Bridges and Water Retaining Structures (WRS)
- Generic Cost Optimisation Equations

$$z = 1 + \frac{C_1}{C_0} \cdot d + \frac{\omega}{\gamma} \cdot \left(1 + \frac{C_1}{C_0} \cdot d + \frac{A}{C_0}\right) + \frac{C_F}{C_0} \cdot \frac{p_f}{\gamma}$$

$$p_f = P(R(d) < S)$$

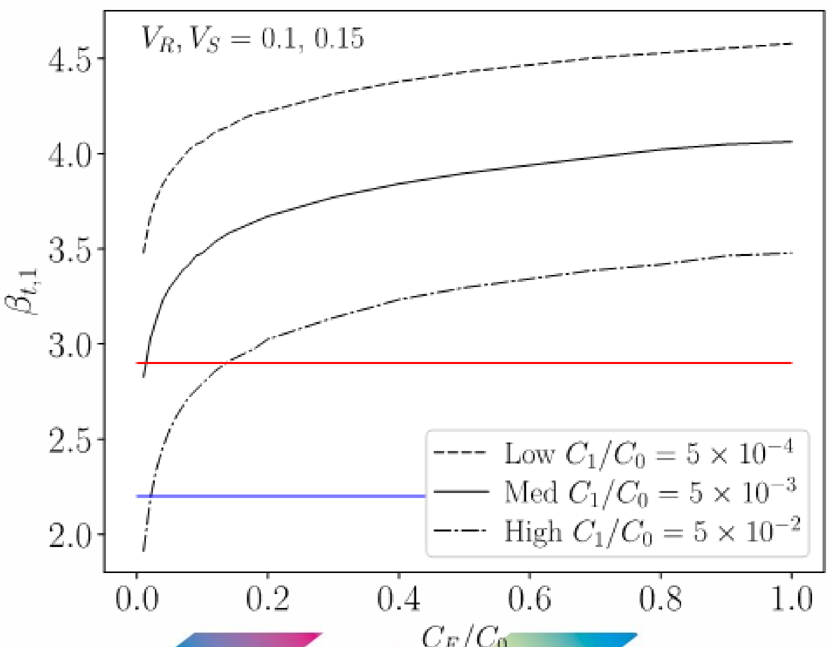
Generic Costs

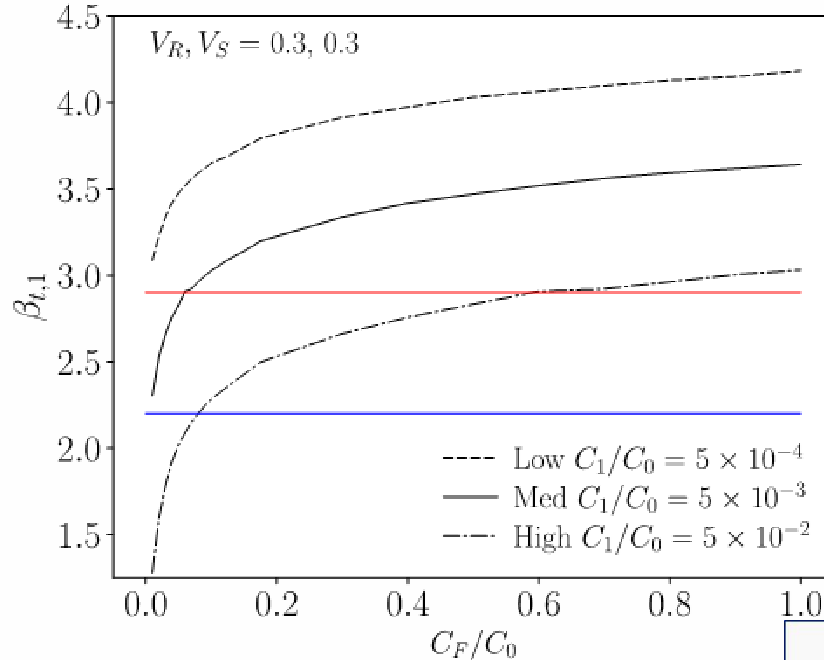
- Annual ULS Target Reliability
- Costs of failure vs costs of safety measures

Source	Rackwitz, JCSS PMC, MC2020 draft	MC2010, EN1990	ISO 2394:1998
	C_F/C_0 qualitative descriptions		
C_1/C_0	"Insignificant"	"Small"	"Small"[1]
Low	2.3	-	3.5
Medium	1.7	2.9	2.9
High	1.3	-	2.2

SLS Cost Optimisation

- Return period 1 year
- SLS failure costs range $0,01 \leq C_f / C_0 \leq 1$





Results: SLS Target Reliability

Proposed Annual SLS Target Reliability

Failure cost	Cost of safety C_1/C_0		
	Low	Med.	High
Insignificant or Reversible SLS $C_F/C_0 < 0.01$	2.2		
Minor SLS (typical) $0.01 < C_F/C_0 \leq 0.05$	3.5	2.9	2.2
Moderate SLS $0.05 < C_F/C_0 \leq 0.20$	3.9	3.3	2.6
Great SLS $0.20 < C_F/C_0 \leq 1.0$	4.2	3.6	3.0

SLS Target Reliability Initial Conclusions

- Bridges – if low failure cost category, β_t 2,2 (1 year)
- WRS – low to high failure cost categories depending on leakage, β_t up to 3,6 (1 year)
- Culverts – similar to WRS

SLS Target Reliability Conclusions

- Single SLS target reliability insufficient
- Current SLS target reliability too low in some instances.
- SLS Bridges – more work required!

Research related to Bridges and SLS

- Inclusion of sustainability in reliability of structures & Limit State Design
- SLS Target reliability
- Long term effects and SLS
- Health monitoring

THANK YOU