Évaluation de la fiabilité des Conduites Forcées au moyen du modèle Persalys-Penstock

Penstock Reliability Estimation with Persalys-Penstock Model

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Journée Utilisateurs PERSALYS

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Penstock diagnoses at EDF

- EDF operates more than 450 hydropower plants
- Penstock convey water from the reservoir to the turbines
- Cumulated length > 250 km
- Average age ~ 70 years
- Complete diagnoses with penstock assessment are performed periodically
  - Visual inspections (internal & external) with thickness measurements
  - Evaluation of the residual Margin Factor (MF)

$$MF = \frac{f}{\sigma_C^*}$$

f ← Allowable stress

σ_C^* ← Maximal in-service stress

Probabilistic mechanical model

Initial questions

- How does the failure probability depend on the Margin Factor ?
- What are the most important parameters influencing the failure probability ?
- What is the influence of hydraulic pressure testing on the failure probability ?

General principle

- Development of a **mechanical probabilistic model** :
  R&D project in collaboration with PHIMECA (2017-2024)
- Calculation of large Design of Experiments (DoE) and sensitivity analyses

EDF publications of the methodology and results

- European ESREL Conference (2020)
- ICOSSAR Conference - International Conference on Structural Safety And Reliability (2022)
- $\lambda\mu$ French Reliability Conference (2022)

Penstock diagnosis & assessment

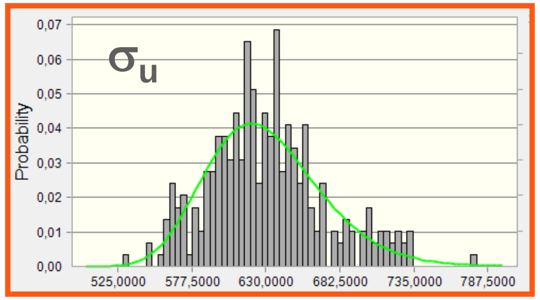
- Fitness for service of a penstock ⇔ **Margin Factor ≥ 1**

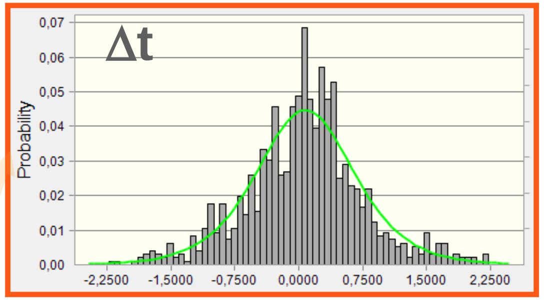
$$MF = \frac{f}{\sigma_C^*}$$

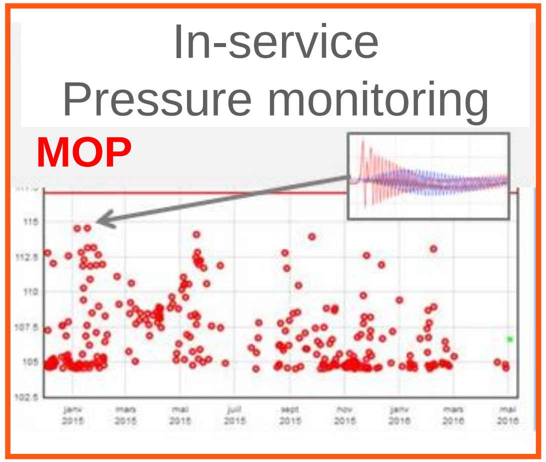
Allowable stress

Maximal in-service stress

- The Margin Factor depends on :
  - Steel mechanical characteristics
    Yield Stress σ_y & Ultimate Tensile Strength : σ_u
  - Residual Thickness $t = t_{design} + \Delta t$
  - Maximal Operating Pressure **MOP** (monitored)



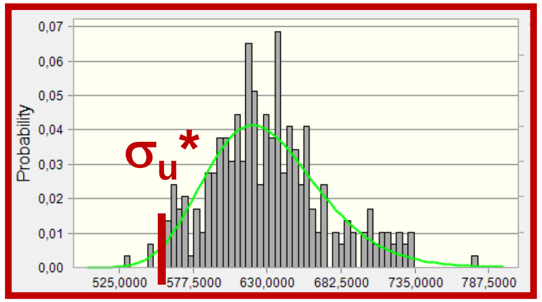


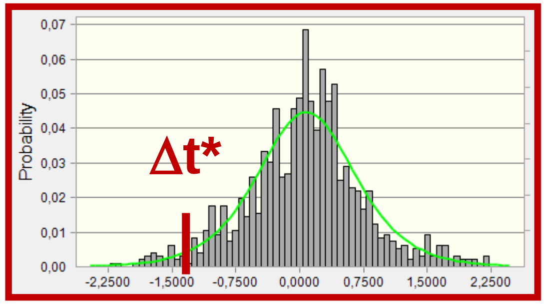


Penstock diagnosis & assessment

- Diagnoses data show that $\boldsymbol{\sigma_u}$ and $\boldsymbol{\Delta t}$ scatter can be modelled by Normal or Log-Normal distributions
- The Margin Factor is calculated by taking **calculation values** for Ultimate Tensile Strength $\boldsymbol{\sigma_u}^*$ and loss of thickness $\boldsymbol{\Delta t}^*$ at γ**=2 standard deviations** of their average values

$$MF = \frac{f}{\sigma_C^*} \qquad f = min\left(\frac{\boldsymbol{\sigma_y^*}}{1.5};\frac{\boldsymbol{\sigma_u^*}}{2.4}\right) \qquad \sigma_C = \frac{MOP \cdot R}{t_{design} + \Delta \boldsymbol{t}^*}$$





calculation values

- P_{target} ~ 10^{-7} to 10^{-6} $pipe^{-1}.year^{-1}$ (BS-7910, ISO-2394)

Main steps of the study

- 1st structural reliability model : with **plastic collapse** failure criterion for <u>corroded pipe wall outside welded joints</u>
- 2nd structural reliability model : with generalized **fracture mechanics** failure criterion <u>for welded joints</u> with residual manufacturing flaws
- Extension of both models to pipes with a hydrostatic pressure test before commissioning : evaluation of **conditional failure probabilities**
- Evaluation of failure probabilities distributions :
  - Large calculation grids (Design of Experiments)
  - In-depth analysis for understanding the most influential factors

Probabilistic mechanical model

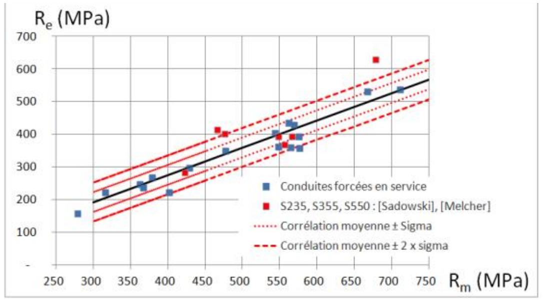
Principles of the model :

- Uncertainties and scattering on different data are modeled by **random variables**
- **Failure criterion** = overcrossing of a limit state involving : yield strength, ultimate stress and toughness of steel based on the BS7910:2019 standard
- Progressive decrease of the Margin Factor due to **loss of thickness** (corrosion) is modeled for the estimation of the annual failure probability

Probabilistic mechanical model

Random variables associated to risk of plastic collapse (base material out of welds)

Variable	Description	Distribution
σ_u	Ultimate tensile strength (MPa)	Lognormal
ε	Deviation to the general correlation σ_y - σ_u	Normal
Δt_{extra}	Manufacturing extra thickness (mm)	Normal
Δt_{corr}	Thinning due to corrosion (mm)	Normal



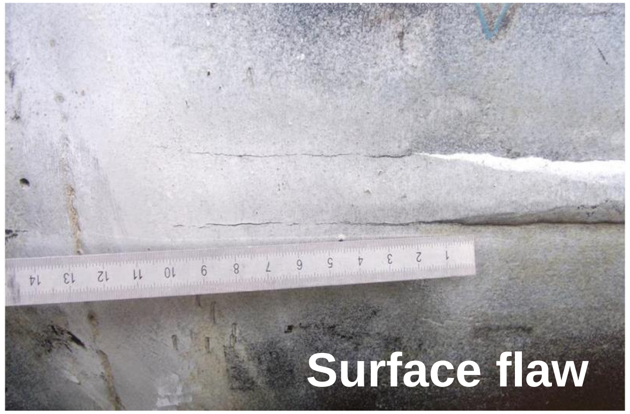
$$\boldsymbol{\sigma_y} = A \cdot \boldsymbol{\sigma_u} - B + \boldsymbol{\varepsilon}$$

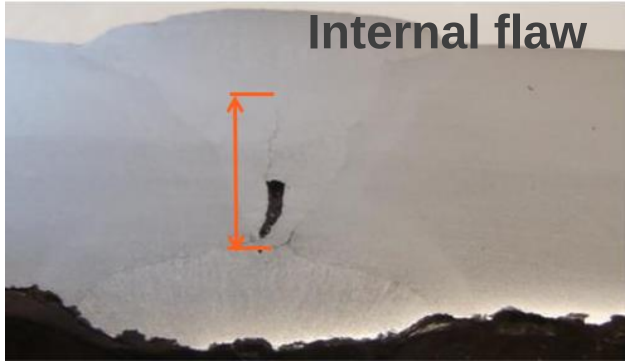
- Upper bound for annual corrosion rate : $\Delta t_{annual} = 100\ \mu m.year^{-1}$
- Residual thickness – Year N : $t_N = t_{design} + \Delta t_{extra} - \Delta t_{corr}$
- Residual thickness – Year N+1 : $t_{N+1} = t_N - \Delta t_{annual}$

Probabilistic mechanical model

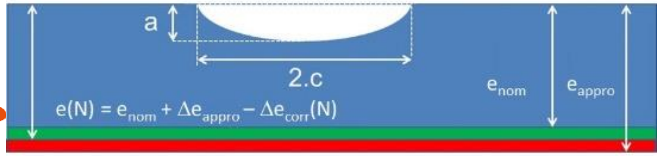
Random variables associated to both plastic and brittle failure modes (with potential residual defects in welds)

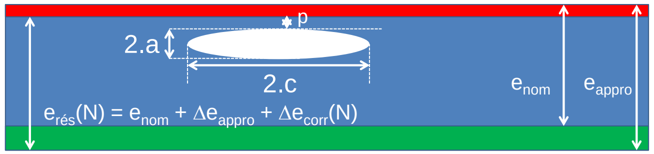
Variable	Description	Distribution
σ_u	Ultimate tensile strength (MPa)	Lognormal
ε	Deviation to the general correlation σ_y - σ_u	Normal
Δt_{appro}	Manufacturing extra thickness (mm)	Normal
Δt_{corr}	Thinning due to corrosion (mm)	Normal
a	Flaw maximum height (mm)	Uniform [0; a_{max}]
$\sigma_{rés}$	Welding residual stress (MPa)	Uniform or normal
K_{IC}	Steel toughness (MPa.m$^{1/2}$)	Weibull





Potential residual flaws in welds





Probabilistic mechanical model

Parameters depending on the manufacturing & NDT processes

- **Residual stress σ_{res}** depends on the relief process
  - No stress relief ("as welded") $0.6\ \sigma_y \leq \sigma_{res} \leq \sigma_y$
  - Partial mechanical relief $0.4\ \sigma_y \leq \sigma_{res} \leq 0.6\ \sigma_y$
  - Post welding Heat Treatment $\sigma_{res} \sim 0.2 \times \sigma_y$
  - Hooped penstock (self banded) $\sigma_{res} \sim 0$
- **Height a_{max} of residual manufacturing flaws** depends on the detectability performance of Non-Destructive Testing (NDT)
  - High performance NDT (surface flaws : a_{max} = 1 mm to 1,5 mm)
  - Standard performance NDT (surface flaws : a_{max} = 1,5 mm to 2 mm)
  - Low performance NDT (surface flaws : a_{max} = 2 mm to 4 mm)

Failure criterion

- Outside welds (base metal)

$$G = L_R^{max} - L_R < 0$$

- In welds

$$G = f(L_R) - K_R < 0$$

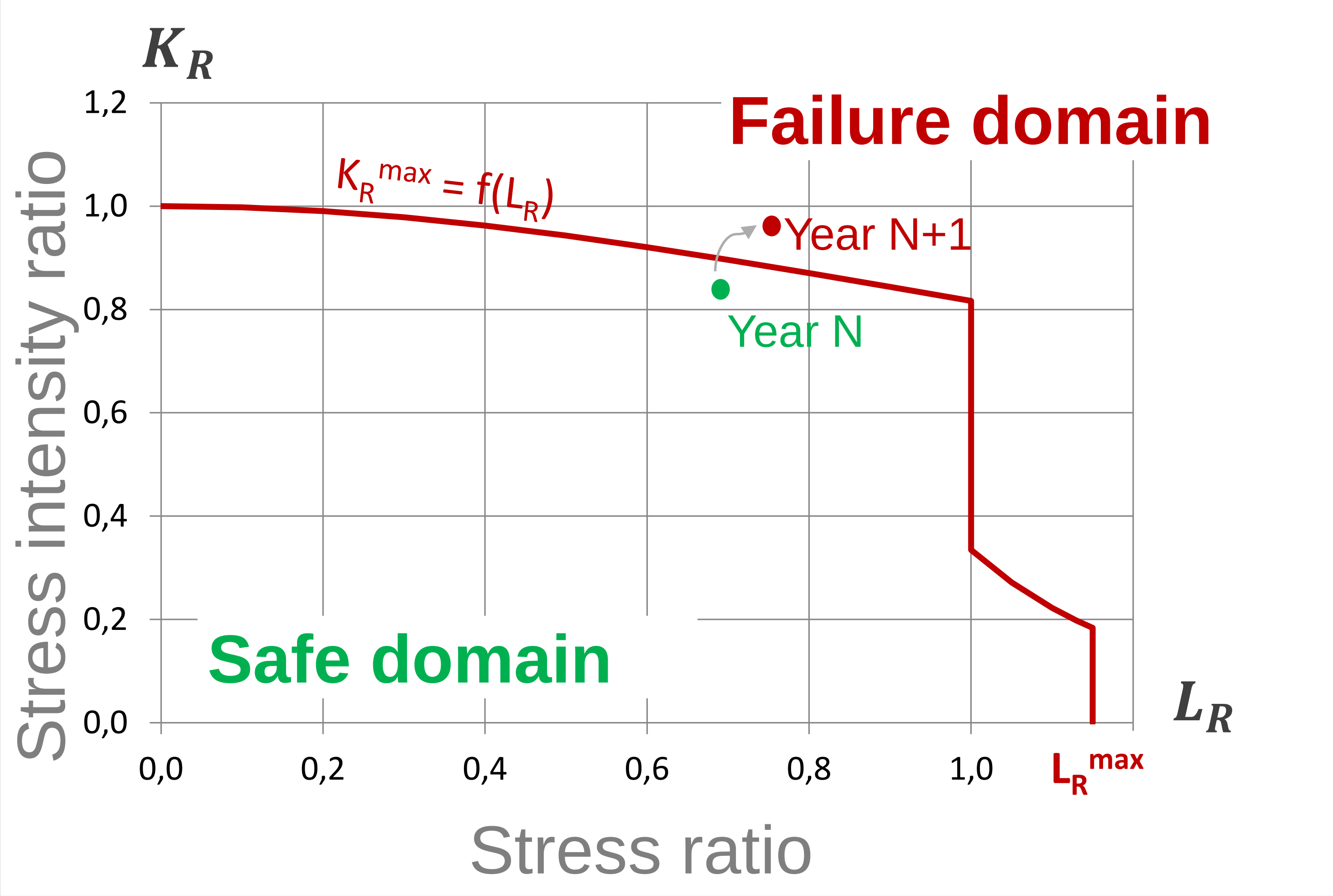
With :

$$L_R = \frac{\sigma_C}{\sigma_y} \qquad K_R = \frac{M \cdot (\sigma_C + \sigma_{res}) \cdot \sqrt{\pi \cdot a}}{K_{IC}}$$

σ_C : In-service stress
σ_y : Yield stress

σ_{res} : Residual stress
K_{IC} : Steel toughness

BS-7910



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Failure criterion

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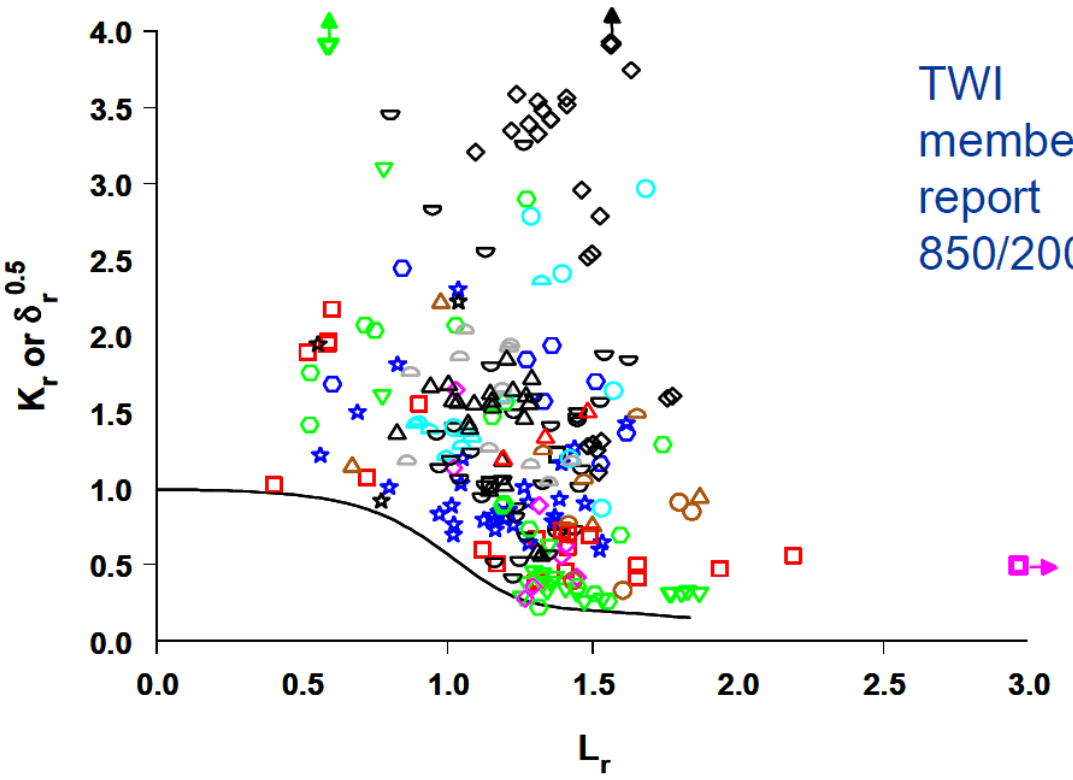
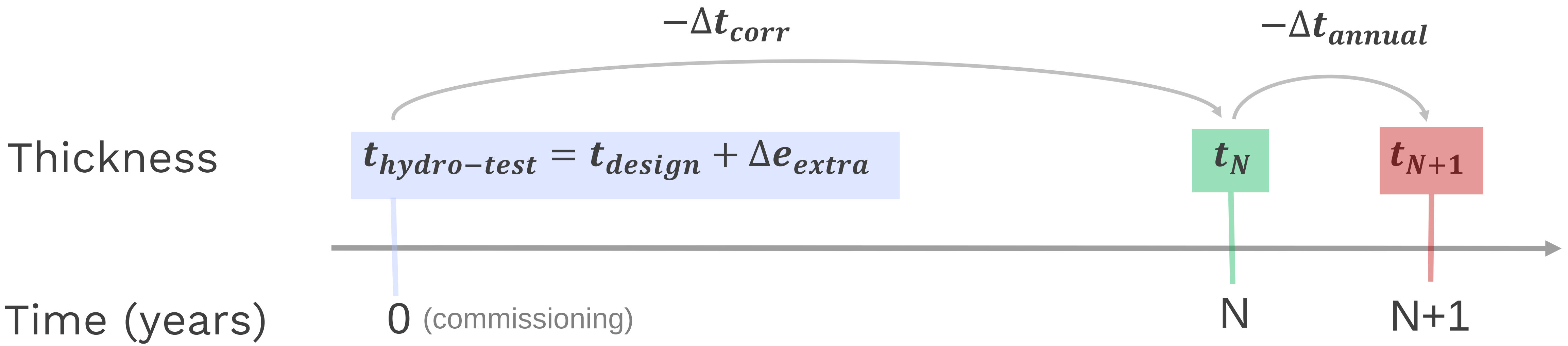


TWI members' report 850/2006

The BS-7910 limit-state function
is a conservative low boundary for resistance
(based on more than 300 failure cases)

Failure probabilities



- **Annual failure probability** :

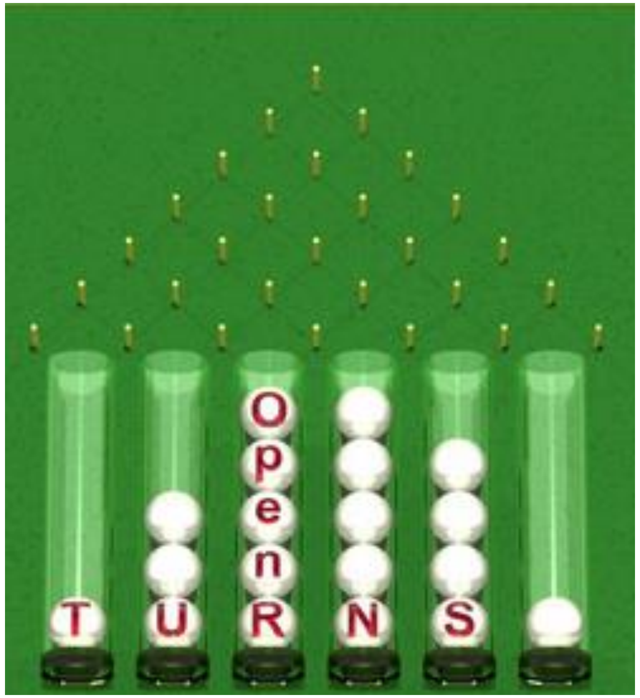
$$P_{annual}(N) = P(\, G_{N+1} < 0 \mid G_N \geq 0 \,)$$

- **<u>Conditional</u> annual failure probability** with initial hydraulic test :

$$P_{cond}(N) = P\left(G_{N+1} < 0 \mid G_N \geq 0 \cap G_{hydro-test} \geq 0\right) = \frac{P\left(G_{N+1} < 0 \cap G_N \geq 0 \cap G_{hydro-test} \geq 0\right)}{P\left(G_{hydro-test} \geq 0 \cap G_N \geq 0\right)}$$

Model implementation : Persalys-Penstock

- **Using the OpenTURNS® library**
  https://openturns.github.io/www/index.html



- **Implementation in the Persalys probabilistic tool**
  https://persalys.fr/

- **Calculation of low probabilities with simulation methods**
  - First/Second Order Reliability Method (FORM/SORM) + Importance Sampling
  - Multi-start option is often necessary to solve convergence issues (due to multiple failure modes : brittle rupture / plastic collapse)
  - Additional methods : SUBSET simulation and Line Sampling

Probabilistic mechanical model

Implementation in the software : Persalys-Penstock

Persalys
Version 15.1-pen1.8.

Failure criteria and safety coefficients

Probabilities and margins | FM and Loading | Geometry | Material (Re, Rm) | Fracture mechanics | Pressure shaft | Calculation method

Studied probability

Probability — Annual given initial hydrostatic pressure test

Definition

Failure criterion

- ○ Plastic instability (without plan defect)
- ◉ Fracture mechanics (with plan defect)

With or without planar flaws

Type of penstock

- ◉ Exposed penstock
- ○ Pressure shaft

Admissible constraint

- ◉ $f_n = \min(Y^{calcul} / sc_Y \; ; \; UTS^{calcul} / sc_{UTS})$
- ○ $f_x = 0.95 \times Y^{calcul}$

Allowable stress

sc_{UTS} 2.4

sc_Y 1.5

Usual cases : [2.4, 1.5] , [2.7, 1.6]

Calculation values

☑ Use γ coefficients on standard deviations

Calculation values

Coefficient on the UTS standard deviation — 2

Coefficient on the loss of thickness standard deviation Δe — 2

Material characteristics

Probabilities and margins | FM and Loading | Geometry | Material (Re, Rm)

Ultimate Tensile Stress (UTS)

σ_u

R_m^{calcul} = 477 (MPa)

Distribution — Normal — μ (MPa) 530

cv 0.05

Yield Stress (Y)

σ_y

☑ Correlated with UTS

R_e^{calcul} = 309 (MPa)

$Y = [A \times UTS - B + Ec(B)] + \varepsilon$ with $\varepsilon \sim \mathcal{N}(0, \omega \times \mu_Y)$

A — 0.78

B (MPa) — 49

Ec(B) (MPa) — 0

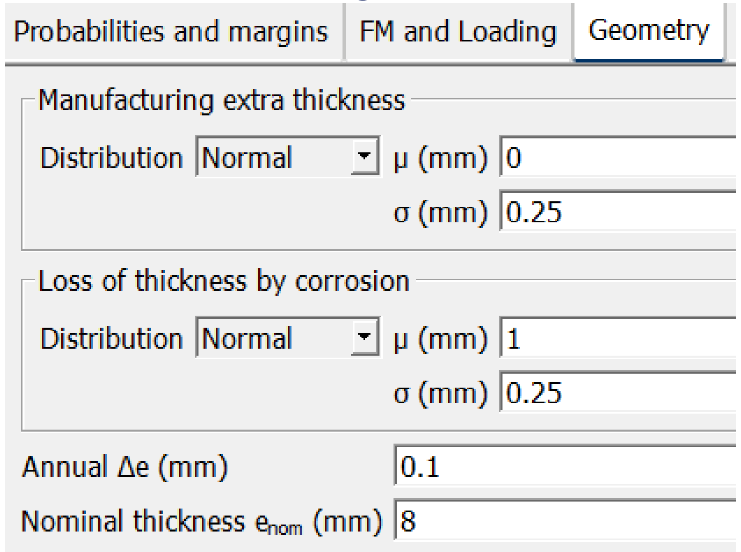
ω — 0.05

Probabilistic mechanical model

Implementation in the software : Persalys-Penstock

Persalys
Version 15.1-pen1.8.

Geometry, thickness

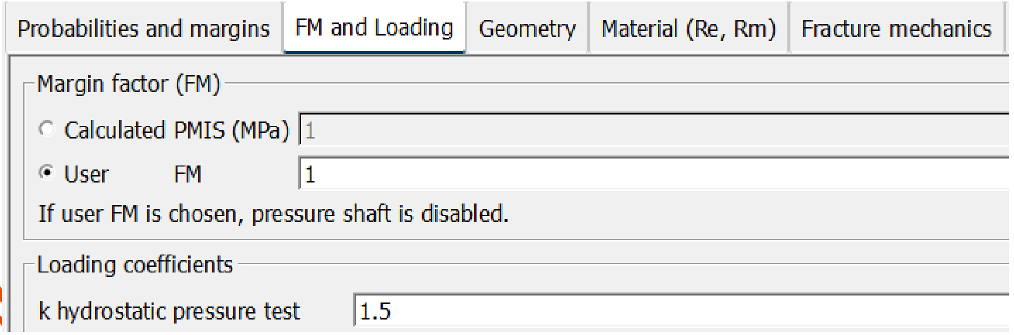


Δt_{extra}

Δt_{corr}

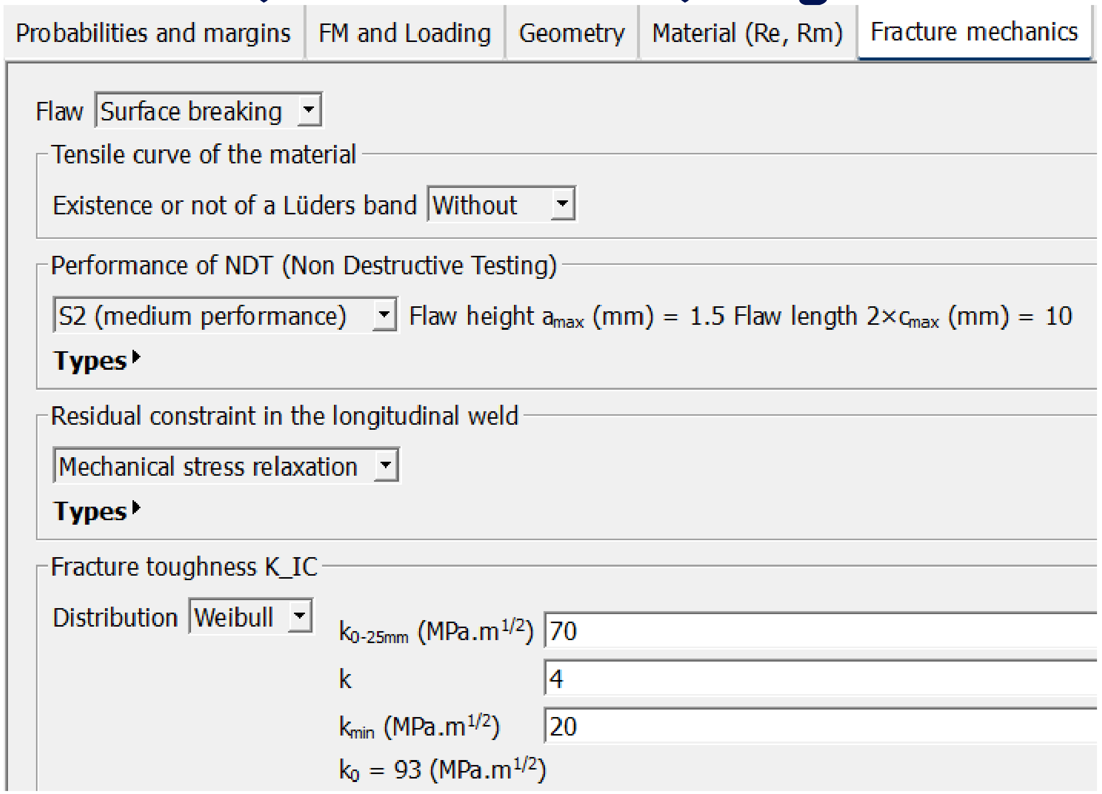
Δt_{annual}

Margin Factor & loadings



MF

Fracture mechanics: NDT, residual stress, toughness



Probabilistic mechanical model

Implementation in the software : Persalys-Penstock

Persalys
Version 15.1-pen1.8.

Méthodes de calcul applicables

Fonction de performance

Type de fonction de performance

Méthode

- (•) FORM IS
- ( ) Subset
- ( ) Line Sampling
- ( ) FORM
- ( ) Monte-Carlo
- ( ) Random Quasi-Monte Carlo
- ( ) Simulation directionnelle
- ( ) Stratification directionnelle adaptative

Options de calcul

Probabilités et marges | FM et chargement | Géométrie | Matériau (Re, Rm) | Mécanique de la rupture | Puits blindés | Méthode de calcul

Paramètres de méthode de simulation

Nombre maximal de simulations	50000
Maximum coefficient de variation	0.1
Ecart-type de la distribution instrumentale	1

☐ Utiliser une distribution instrumentale modifiée

Coefficient de l'écart-type de la distribution modifiée $k \times d\beta / \alpha_{max}$ 1

Paramètres FORM

Nombre d'itérations 500

☑ Test automatique des algorithmes FORM ☑ Préférer une recherche rapide

Algorithme d'optimisation AbdoRackwitz

Nombre de points de départ	10	Ordre du quantile pour l'échantillon multi start	0.0001
Erreur absolue	1e-05	Erreur sur les résidus	1e-05
Erreur relative	1e-05	Erreur sur la contrainte	1e-05
Epsilon d'appartenance à l'état-limite	0.001		

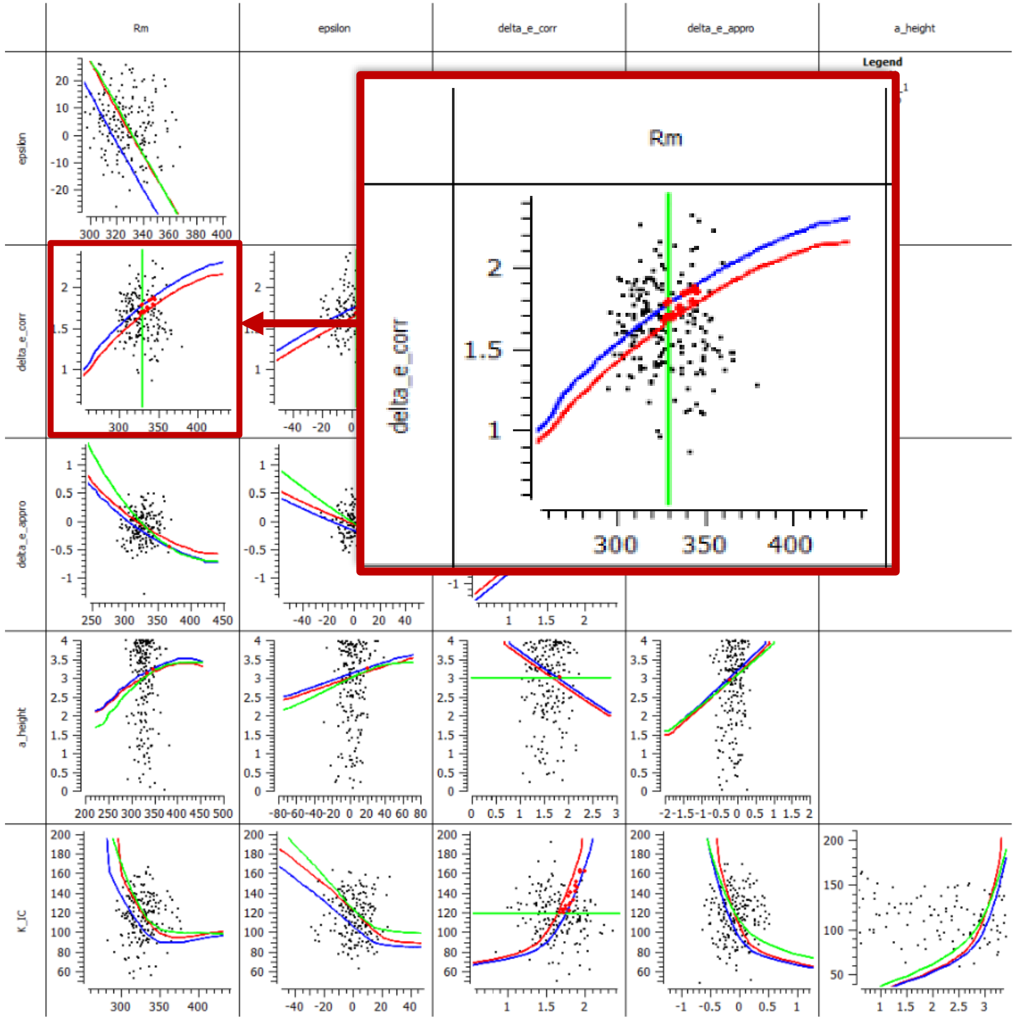
Choix des résultats renvoyés en sortie

☑ Points de défaillance les plus probables ☑ Facteurs d'importance ☑ Indices de sensibilités

Model implementation

- **Limit state analysis**

Persalys
Version 15.1-pen1.8.



- **Visualization of limit state functions and design point localization are possible, both :**
  - In the physical space
  - In the standard space
- **The effect of the initial Hydraulic Test can be shown**

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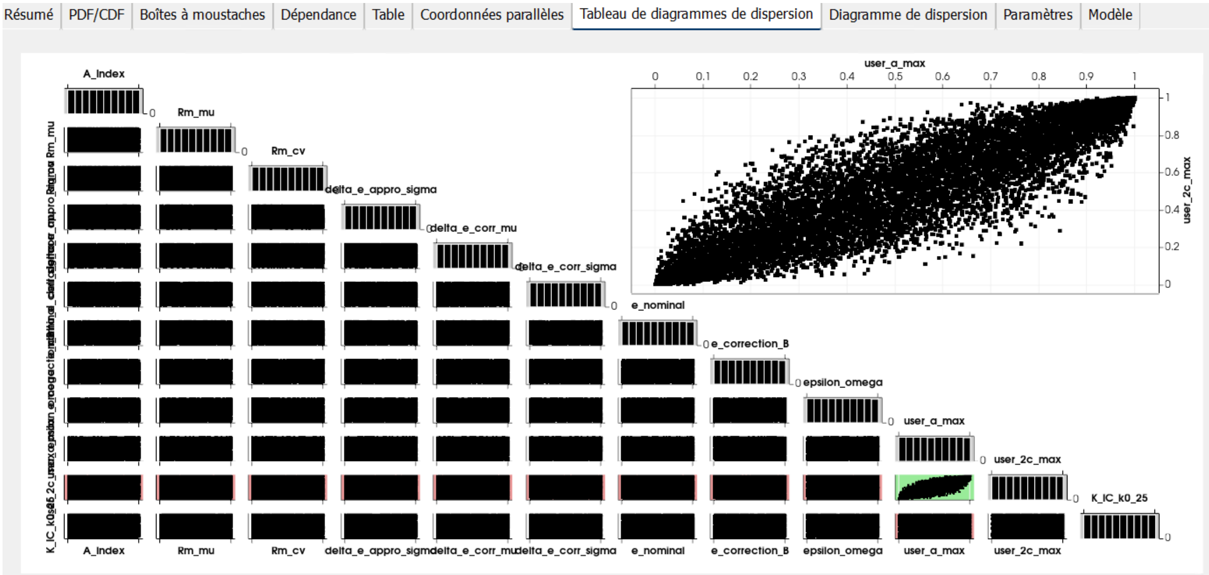
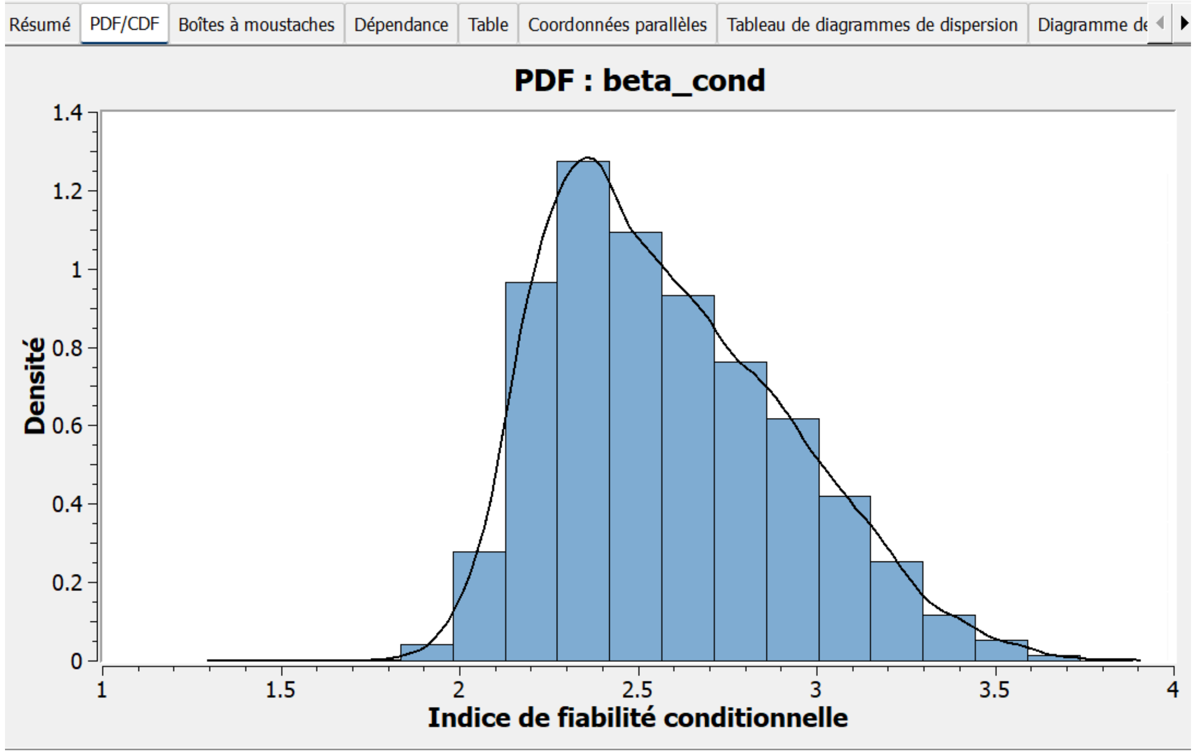
Model implementation

- **Example of a hooped penstock in an incidental situation after the rupture of a hoop**
  Scattering of conditional failure probability with MF=0,6

  - **DoE : 20 000**
    - Size : 20 000
    - Random DoE





Design of Experiments

- Major penstock configurations (thickness, material characteristics, loss of thickness scatter, welding residual stress, stress relief…) have been calculated by using **large probabilistic Design of Experiments** (DoE)

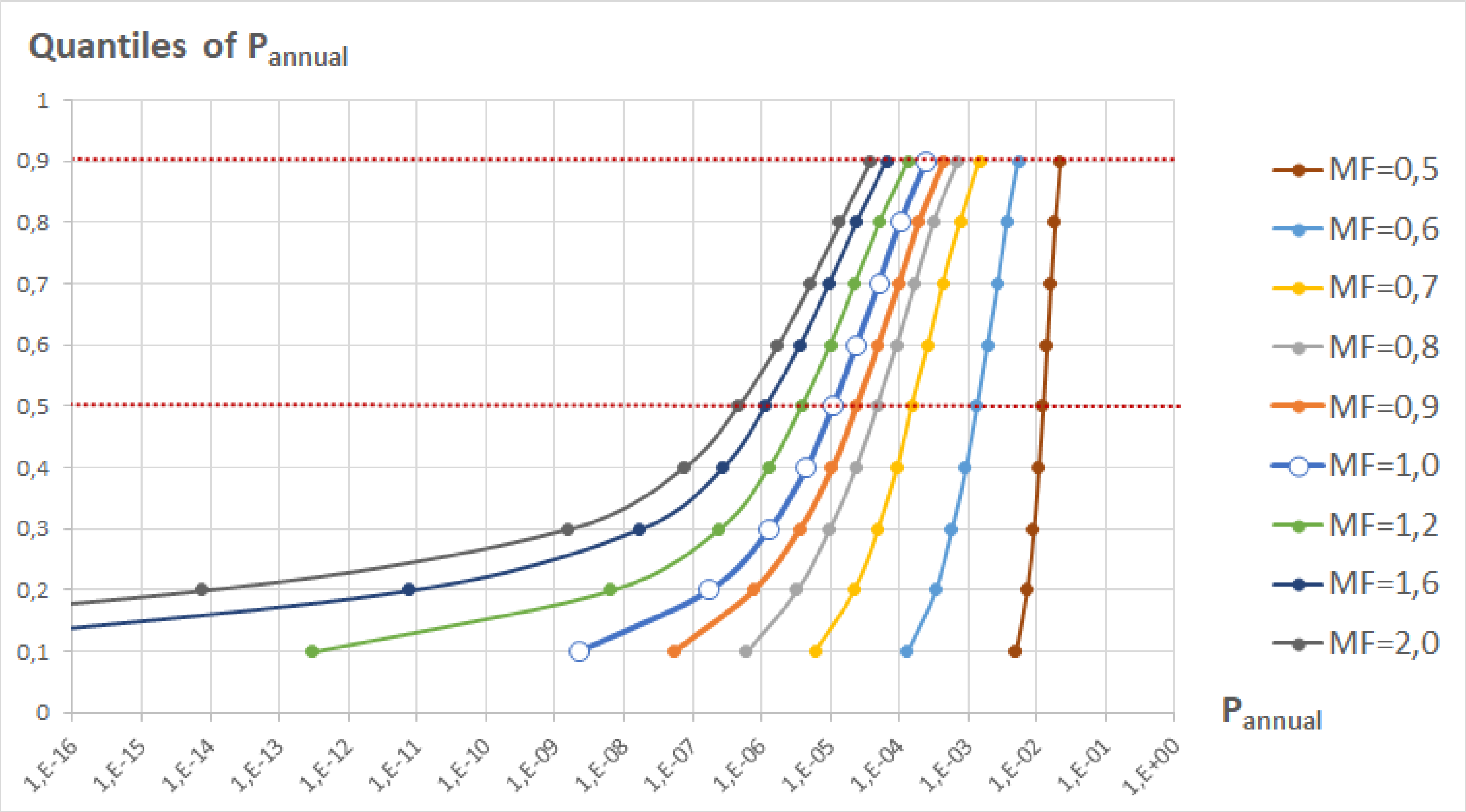
- Calculation of failure probability for Margin Factor (MF) in [0.6 ; 1.4]

Parameter	Notation	Unity	Variation interval
Nominal Design Thickness	t_{design}	mm	[5 mm ; 30 mm]
Average loss of thickness	$\mu(\Delta t_{corr})$	mm	[0 ; 3]
Loss of thickness standard deviation	$\sigma(\Delta t_{corr})$	mm	[0,2 ; 0,8]
Average ultimate tensile strength (UTS)	$\mu(\sigma_u)$	MPa	[360 ; 800]
Coefficient of variation of UTS	$COV(\sigma_y)$	-	[0,05 ; 0,10]
Coefficient of variation of σ_y for a given σ_u	ω	-	[0,02 ; 0,05]
Shift of σ_y-σ_u vs. general correlation	$E_c(\varepsilon)$	MPa	Normal (μ=0; σ=28 MPa)
Maximal size of residual flaw	a_{max}	mm	[1 ; 4]
Maximal length of residual flaw	$2.c_{max}$	mm	[$3.a_{max}$; $6.a_{max}$]
Average toughness	K_{IC}^0	$MPa.m^{1/2}$	[70 ; 120]
Welding residual stress	σ_{res}/σ_y	-	[0 ; 1]

- For each Margin Factor : $\mathcal{N}$ **= 2.4 x 10^6 simulated configurations**

Design of Experiments

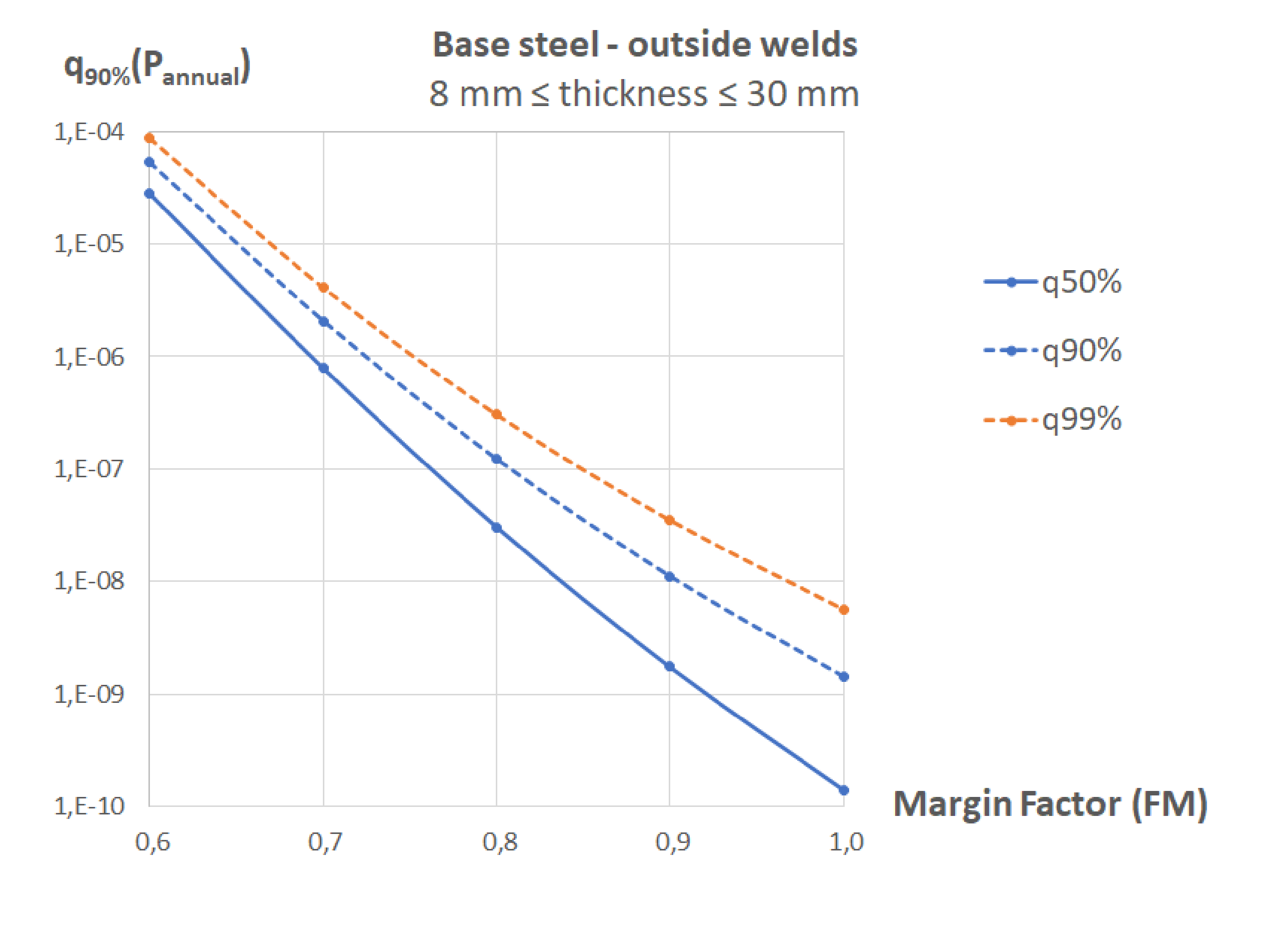
- The calculations allow an estimation of **quantiles of the annual failure probability** for different values of the Margin Factor – Example obtained from a sub-DoE



Estimated annual failure probabilities in base steel

Estimated annual failure probability outside the welds

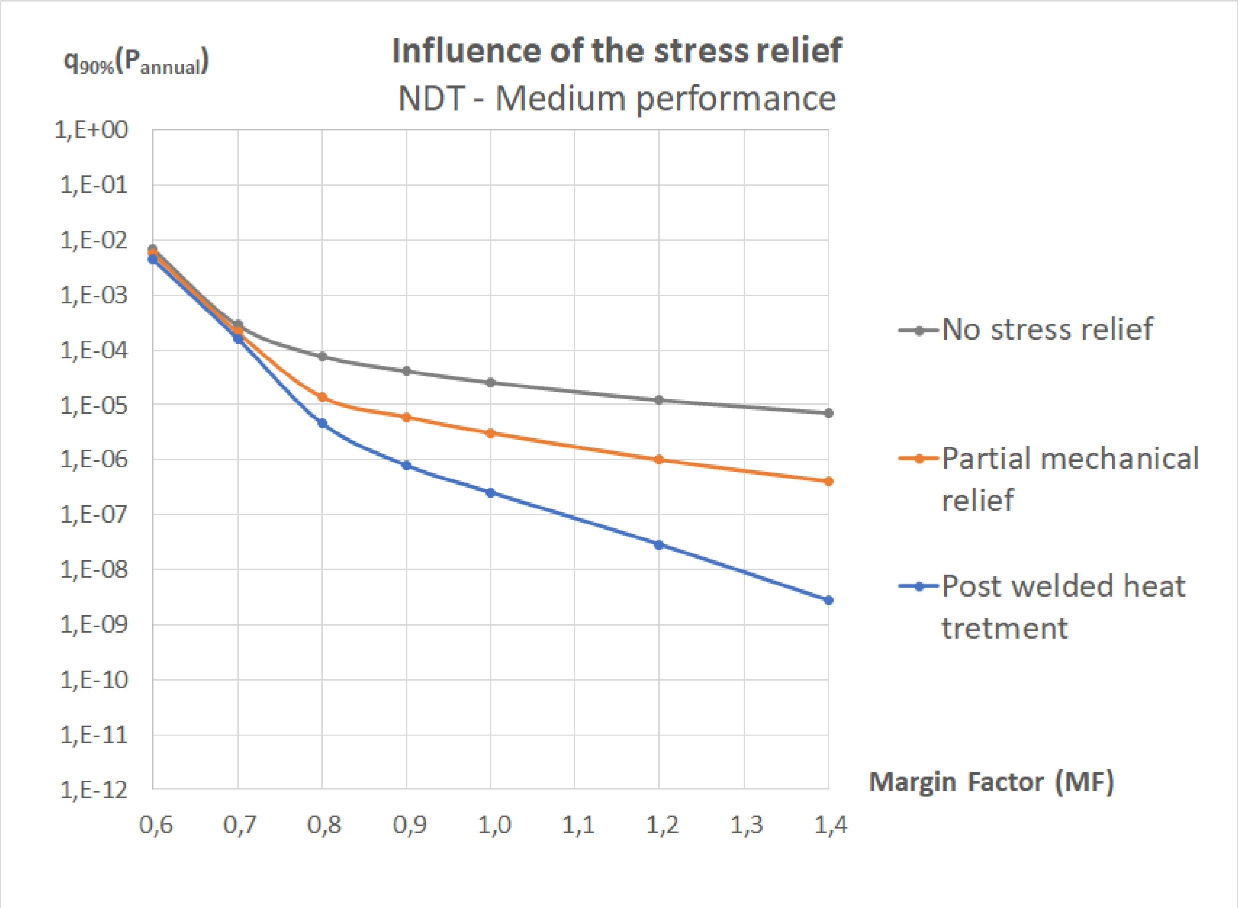
- For 1 elementary pipe
- For a default envelope corrosion rate : Δt_{annual} = 100 µm/year



- **Annual failure probability is proportional to :**
  - Section length (number of elementary pipes)
  - Corrosion rate
- **Margin Factor decreases of 0.1 → Annual failure probability ~ x 10**

Estimated annual failure probabilities in welds

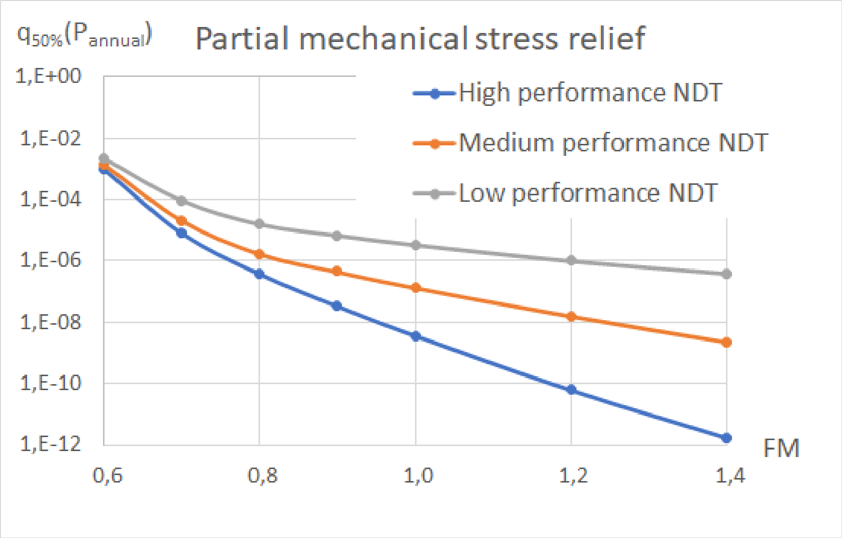
Sensitivity to stress relief

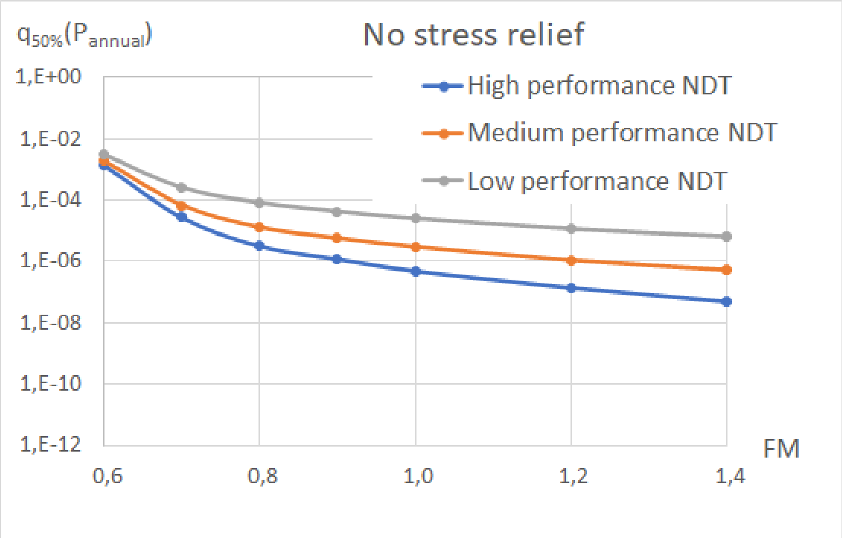


- **For low margin Factors (0.6 to 0.7) :**
  - Preponderant failure mode is plastic collapse
  - Small influence of residual stress
- **For higher Margin Factors :**
  - Brittle fracture failure mode becomes preponderant
  - Residual stress level becomes a more influent parameter
- **For medium Margin Factors (0.9 to 1.1) :**
  - Failure probability may increase of 1 decade when the residual stress increases
    - Absence of stress relief vs. partial mechanical stress relief
    - Partial mechanical relief vs. PWHT

Estimated annual failure probabilities in welds

Sensitivity to NDT performance





- **For low margin Factors (0.6 to 0.7) :**
  - Preponderant failure mode is plastic collapse
  - Small influence of NDT performance
- **For higher Margin Factors :**
  - Brittle fracture failure mode becomes preponderant
  - NDT performance becomes a more influent parameter
- **For medium Margin Factors (0.9 to 1.1) :**
  - Failure probability increases of 0.5 to 1 decade if the NDT performance decreases
    - from HIGH to MEDIUM
    - from MEDIUM to LOW

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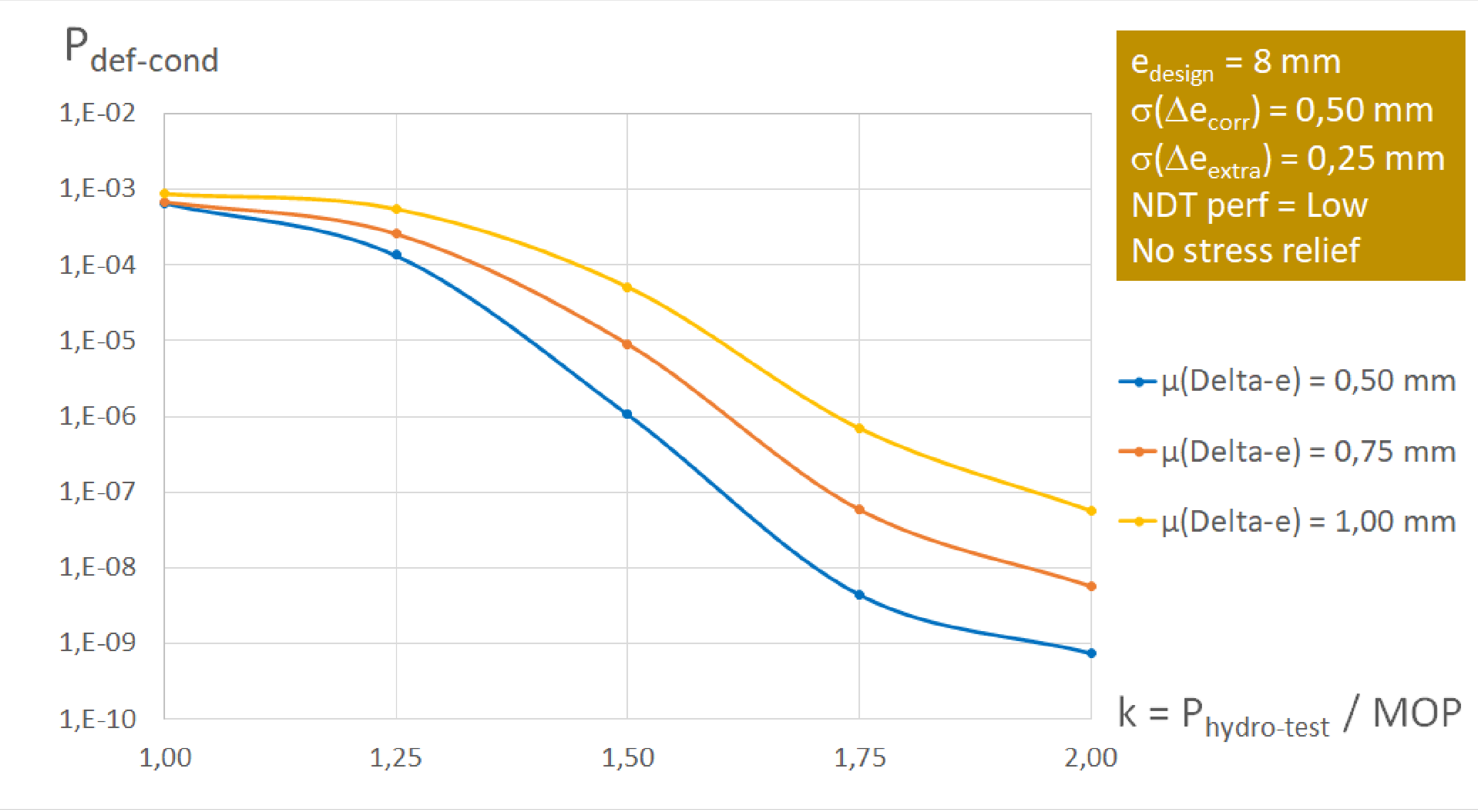
Estimated annual failure probabilities in welds

Sensitivity to hydro-test pressure - example

- **Margin Factor = 1**
- **Initial hydro-pressure test : between MOP and 2 x MOP**
- **Moderate loss of thickness since the commissioning**



- Above 1.5 x MOP, the hydraulic pressure test allows to decrease drastically the conditional failure probability
- However, this decrease depends on the average loss of thickness since the commissioning

Conclusion

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Conclusion

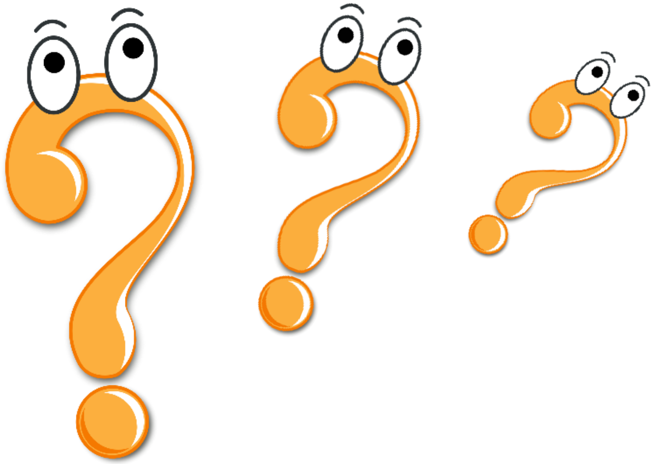
The Persalys-Penstock mechanical probabilistic model leads to estimate

- Annual failure probability distribution of a penstock section, knowing its Margin Factor, its main manufacturing data and its corrosion rate
- Instantaneous failure probability distribution of a penstock section resulting from an overpressure
- The effect of hydraulic pressure test at commissioning

This model allows to quantify the evolution of failure probability

- Its decrease rate in relation to the residual Margin Factor
- Its dependance on manufacturing conditions : NDT performance, welding stress relief
- It can be used to calibrate semi-quantitative rating scales for hazard studies

Thank you !



References (1/2)

EDF Publications on penstock reliability models

Logiciel Persalys-Penstock pour l'estimation de la fiabilité des conduites forcées soumises à la corrosion : développements et applications

Philippe Bryla , Emmanuel Ardillon , Antoine Dumas , Anne Dutfoy-Lebrun

Lambda-Mu 23 Conference (2022) https://hal.science/hal-03878042v1

Probabilistic Models for Penstock Integrity Assessment

Bryla Philippe, Ardillon Emmanuel, Dumas Antoine

ESREL European Safety and Reliability Conference (2020) https://www.rpsonline.com.sg/proceedings/esrel2020/html/4172.xml

Penstock reliability assessments: some results and developments

Ardillon Emmanuel, Bryla Philippe, Dumas Antoine

ICOSSAR 13th International Conference on Structural Safety and Reliability (2022)

Software

https://persalys.fr/

https://openturns.github.io/www/index.html

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Standards

BS 7910 (2019). Guide to methods for assessing the acceptability of flaws in metallic structures. British Standard Institute

ISO 2394 (2015). General principles on reliability for structures. International Standard

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I. Hadley, P. Moore, Fracture case studies for validation of fitness-for-service procedures, TWI Report n°850/2006, Mai 2006

M. Lemaire (2009). Structural Reliability. Wiley - ISTE