# PROBABILISTIC MODELS FOR PENSTOCK INTEGRITY ASSESSMENT

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# PENSTOCK DIAGNOSES AT EDF

- EDF operates more than 450 hydropower plants
- Cumulated length > 250 km
- **Average age > 60 years**
- Loss of thickness due to corrosion
- **Complete diagnoses with penstock assessment** are performed periodically
  - Visual inspections (internal & external) with thickness measurements
  - Evaluation of the residual Margin Factor


# PENSTOCK DIAGNOSIS & ASSESSMENT

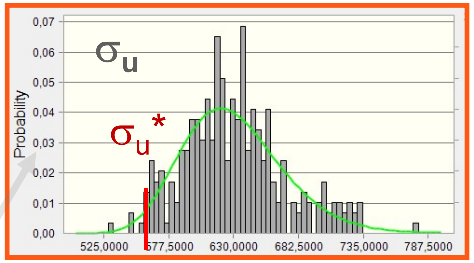
- Fitness for service of a penstock ⇔ ***Margin Factor ≥ 1***

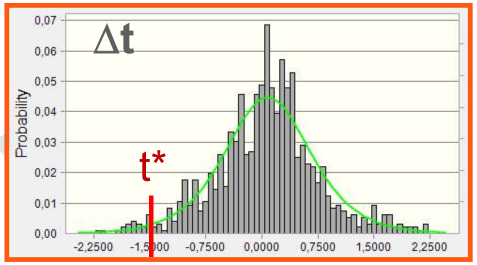
$$MF = \frac{f}{\sigma_C}$$

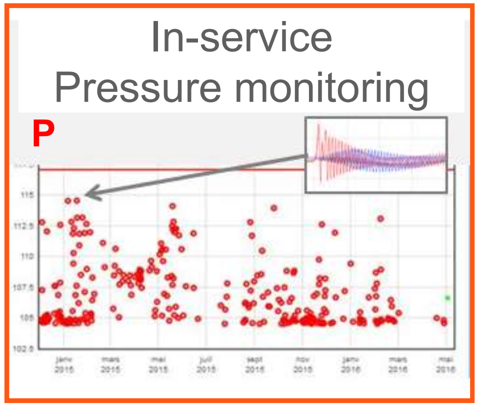
Allowable stress

Maximal in-service stress

- The Margin Factor depends on :
    - Steel mechanical characteristics :
      Yield Stress $\sigma_y$ & Ultimate Tensile Strength : $\sigma_u$
    - Residual Thickness : $t = t_{design} + \Delta t$
    - Maximal in-service Pressure **P** (monitored)



# PENSTOCK DIAGNOSIS & ASSESSMENT

- Diagnoses data show that $\sigma_{\mathbf{u}}$ and $\Delta\mathbf{t}$ scatter can be modelled by Normal or Log-Normal distributions
- The Margin Factor is calculated by taking a **calculation values** for Ultimate Tensile Strength $\sigma_{\mathbf{u}}^{*}$ and loss of thickness $\Delta\mathbf{t}^{*}$ at $\gamma$**=2 standard deviations** of their average values
- **Initial issue :** Search of minimal standard deviation multipliers $\gamma$ such that a Margin Factor ≥ 1 guarantees the annual failure probability to be lower than a given target threshold $P_{target}$

$P_{target} \sim 10^{-7}$ 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 corroded wall outside welded joints
- 2nd structural reliability model with generalized **Fracture Mechanics** failure criterion for welded joints with residual manufacturing flaws
- Extension of both models to pipes with a hydrostatic pressure test before commissioning : evaluation of **conditional failure probabilities**
- Evaluation of the upper bound of annual failure probabilities :
  - Large deterministic calculation grids (2 000 to 14 000) – Latin hypercubes
  - Probabilistic calculation grids
  - In-depth analysis for understanding the most influential factors

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# PLASTIC COLLAPSE MODEL (OUT OF WELDS) *(1/2)*

- Model with 4 random variables

| Variable | Description | Distribution |
|---|---|---|
| $\sigma_u$ | Ultimate tensile strength (MPa) | Lognormal |
| $\varepsilon$ | Deviation to the general correlation $\sigma_y$ - $\sigma_u$ | Normal |
| $\Delta t_{extra}$ | Manufacturing extra thickness (mm) | Normal |
| $\Delta t_{corr}$ | 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 : $t_N = t_{design} + \boldsymbol{\Delta t_{extra}} - \boldsymbol{\Delta t_{corr}}$
- Residual thickness – Year N+1 : $t_{N+1} = t_N - \Delta t_{annual}$

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# PLASTIC COLLAPSE MODEL (OUT OF WELDS) *(2/2)*

- **Failure criterion :** overcrossing of the flow stress $\sigma_f$ by the hoop stress $\sigma_C$ in the pipe wall

$$\boxed{\boldsymbol{\sigma_C > \sigma_f}}$$

$$\sigma_f = min\left(\frac{\sigma_y + \sigma_u}{2}; 0.85 \times \sigma_u\right)$$

- Annual failure probability :

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

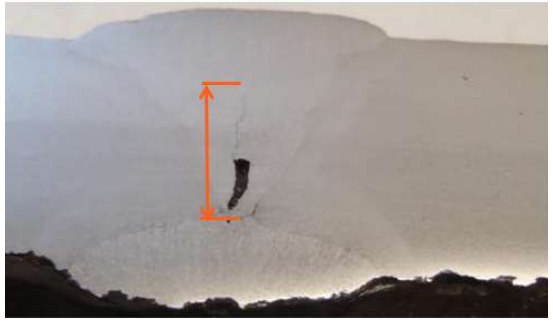
$$\Rightarrow \boldsymbol{P_{annual}(N) = \frac{P(G_{N+1} < 0 \cap G_N \geq 0)}{1 - P(G_N < 0)}}$$

  - No failure before year N : $G_N = \sigma_f - \sigma_{C,N} > 0$
  - Failure before year N+1 : $G_{N+1} = \sigma_f - \sigma_{C,N+1} < 0$

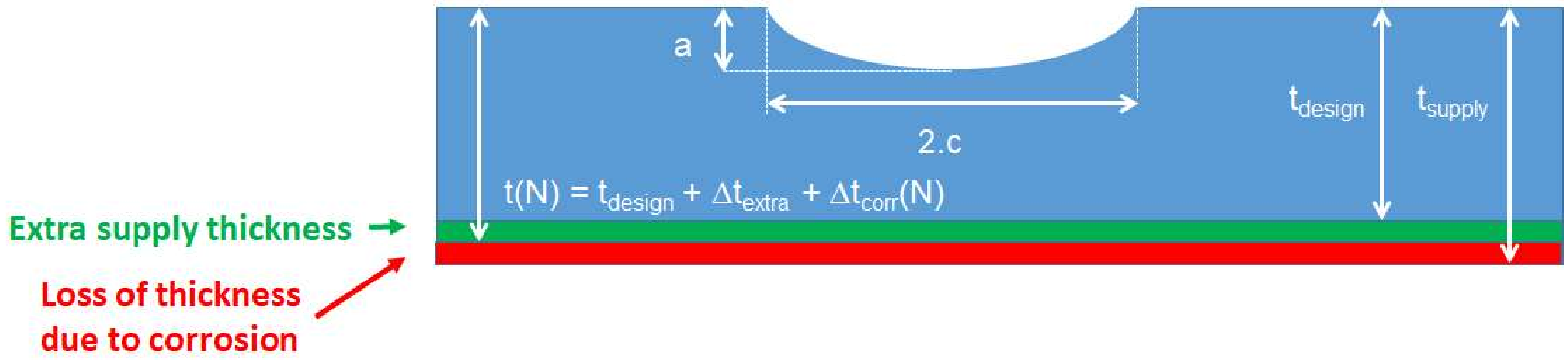
# FRACTURE MECHANICS MODEL FOR WELDS *(1/4)*

- Potential defects not detected by Non Destructive Testing

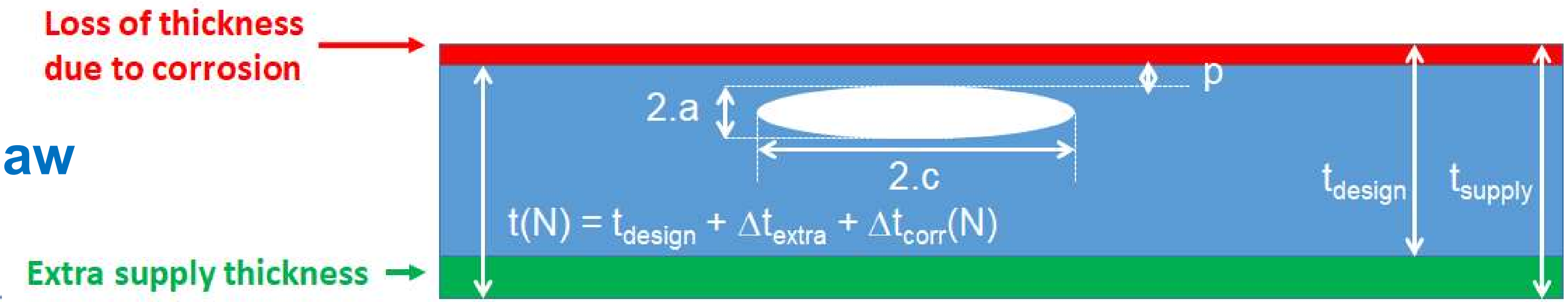
- Loss of thickness due to corrosion



## Surface flaw




## Embedded flaw

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# FRACTURE MECHANICS MODEL FOR WELDS *(2/4)*

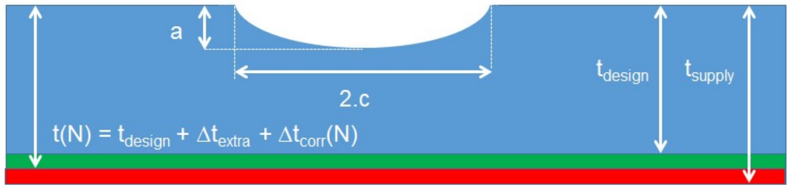
- Model with 6 random variables

| Variable | Description | Distribution |
|---|---|---|
| $\sigma_u$ | Ultimate tensile strength (MPa) | Lognormal |
| $\varepsilon$ | Deviation to the general correlation $\sigma_y$ - $\sigma_u$ | Normal |
| $\Delta t_{extra}$ | Manufacturing extra thickness (mm) | Normal |
| $\Delta t_{corr}$ | Thinning due to corrosion (mm) | Normal |
| **a** | Flaw maximum height (mm) | Uniform [0; $a_{max}$] |
| $K_{IC}$ | Steel toughness (MPa.$m^{1/2}$) | Weibull |

- + 1 new parameter : Residual stress $\sigma_{res}$ in welds

# FRACTURE MECHANICS MODEL FOR WELDS *(3/4)*

- New parameters depend on the manufacturing & NDT processes
  - Residual stress $\sigma_{res}$ depends on the relief process
    - **No stress relief ("as welded")** $\sigma_{res} = 0.8 \times \sigma_y$
    - **Partial mechanical relief** $\sigma_{res} = 0.4 \times \sigma_y$
    - **Post welding Heat Treatment** $\sigma_{res} = 0.2 \times \sigma_y$
  - Height $a_{max}$ of residual manufacturing flaws depends on the detectability performance of Non Destructive Test (NDT)
    - **$S_1$ :** Magnetic Particle (MP) on machined welded joint $a_{max}$ = 1,0 mm, $2.c_{max}$ = 5 mm
    - **$S_2$ :** Liquid Penetrant (LP) on "as welded" joint $a_{max}$ = 1,5 mm, $2.c_{max}$ = 10 mm
    - **$S_3$** : Poor quality test $a_{max}$ = 4,0 mm, $2.c_{max}$ = 20 mm



# FRACTURE MECHANICS MODEL FOR WELDS *(4/4)*

- Failure criterion (BS-7910)

$$\boldsymbol{G = K_R - f(L_R) \ < 0}$$

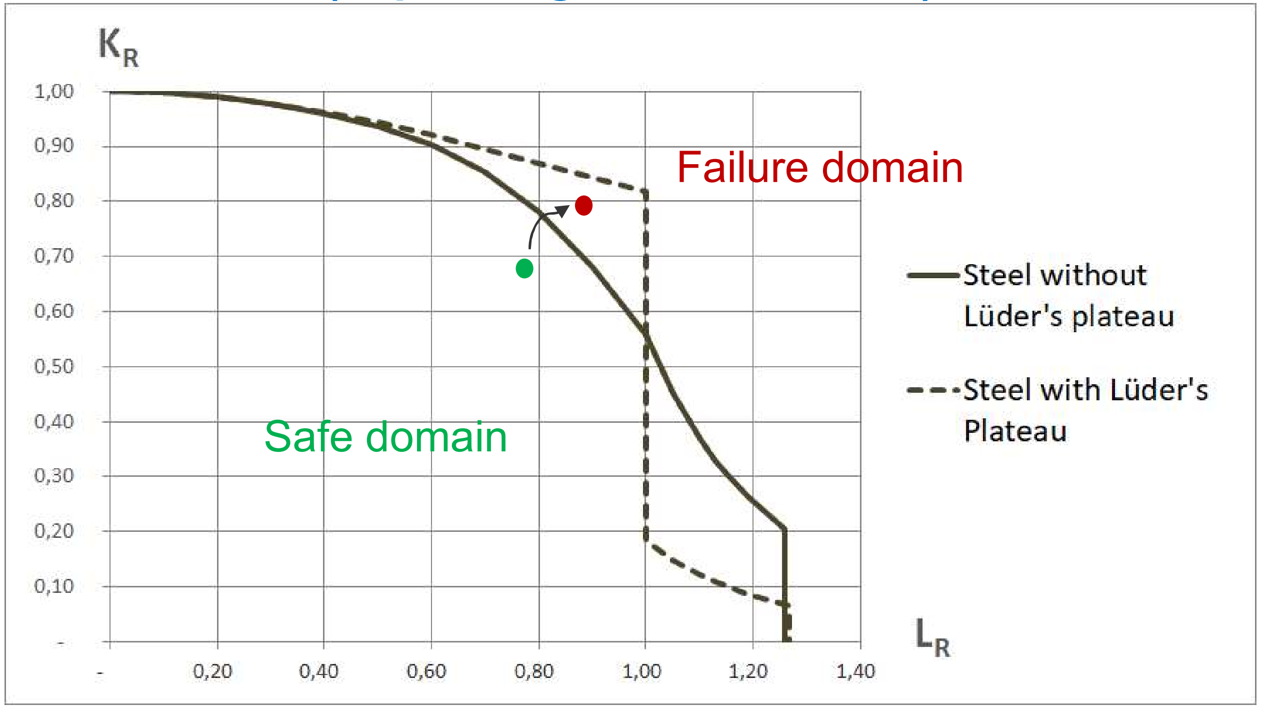
- with :

$$L_R = \frac{\boldsymbol{\sigma_C}}{\sigma_y}$$

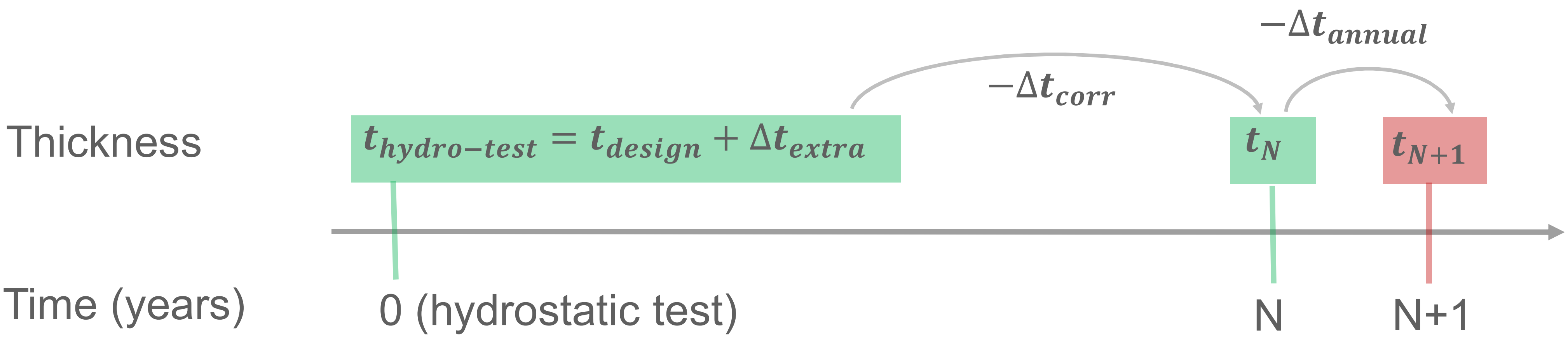
$$K_R = \frac{M \cdot (\boldsymbol{\sigma_C} + \sigma_{rés}) \cdot \sqrt{\pi \cdot a}}{K_{IC}}$$

$$\boldsymbol{\sigma_C} = \frac{f}{MF} \cdot \frac{t^*}{\boldsymbol{t}}$$

**Failure Assessment Diagrams (depending on the material)**



# CONDITIONAL FAILURE PROBABILITIES KNOWING A SUCCESSFUL HYDROSTATIC TEST




- Conditional annual failure probability :

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

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

# PLASTIC COLLAPSE MODEL : DETERMINISTIC DESIGN OF EXPERIMENTS (DoE)

- > 2 000 penstock configurations (Latin hypercube)

| Variable | Mean value | Variation Coefficient or standard-deviation |
|---|---|---|
| $t_{design}$ | 5 mm to 30 mm | - |
| $\sigma_u$ | 320 to 750 MPa | C.V. : 5% to 10% |
| $\varepsilon$ | -50 to +50 MPa | C.V. : 2% to 5% |
| $\Delta t_{appro}$ | 0 to 1 mm | S.D. : 0.25 to 0.50 mm |
| $\Delta t_{corr}$ | 1 to 3 mm | S.D. : 0.25 to 1.00 mm |

- In depth analysis of results :
  - Estimation of the upper bound of annual failure probability (for calculation values taken at $\gamma$ = 2 or $Q_{2,5\%}$)
  - Identification of the major influent factors

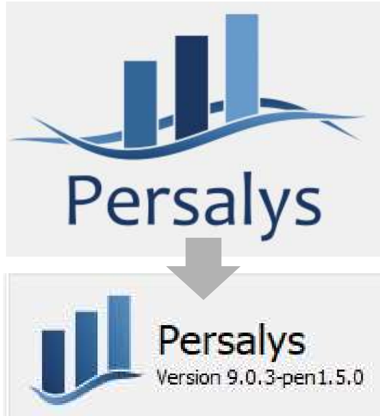
# MODEL IMPLEMENTATION *(1/2)*

- Very large number (thousands) of probability configurations to be performed
- System event probabilities calculated (System reliability)
  - Annual failure probability: **double intersection**
  - Conditional probability (given a successful initial Hydraulic Testing): **triple intersection**
  - For Fracture Mechanics, limit state function is locally non differentiable and can be discontinuous material with Lüder's plateau) ⇨ Convergence problems may occur
- This industrial need initiated an evolution in OT (V 1.14)
  - **System event** definition and reliability calculation
  - All the classical reliability methods available for single events have been adapted for **system events** :
    - FORM
    - FORM-IS
    - Subset Simulation
    - Directional Simulation / Adaptive directional Stratification
  - OpenTURNS is now ahead of other UQ tools, for System Events (UQLAB (ETH Zurich) uses only System-FORM)

# MODEL IMPLEMENTATION *(2/2)*

- **Implementation of the models in Persalys software**

  → **Persalys-Penstock** becomes the 1st dedicated tool based on Persalys




- **Adaptation of reliability methods developed in Persalys**
  - Subset Simulation
  - Directional Simulation
  - Adaptive Stratified Sampling

- **Development of specific methods, not yet included in OpenTURNS**
  - Multi-constraint-FORM-IS : necessary for conditional probability calculation
  - FORM-IS-Best Algorithm : iterative selection of a satisfactory optimization algorithm (6 possibilities)

  → **Persalys-Penstock** includes enhanced reliability methods (not yet in OT or in Persalys)

- **Comparative performance analysis of the methods is underway (R&D/PRISME)**

- **Treatment of large size DoEs (>> 1 000) is possible :**
  - Optimized parallel computing
  - Large reduction of the computational time (CALIBRE: ratio 4,5)

- **Probabilistic DoEs are also possible**

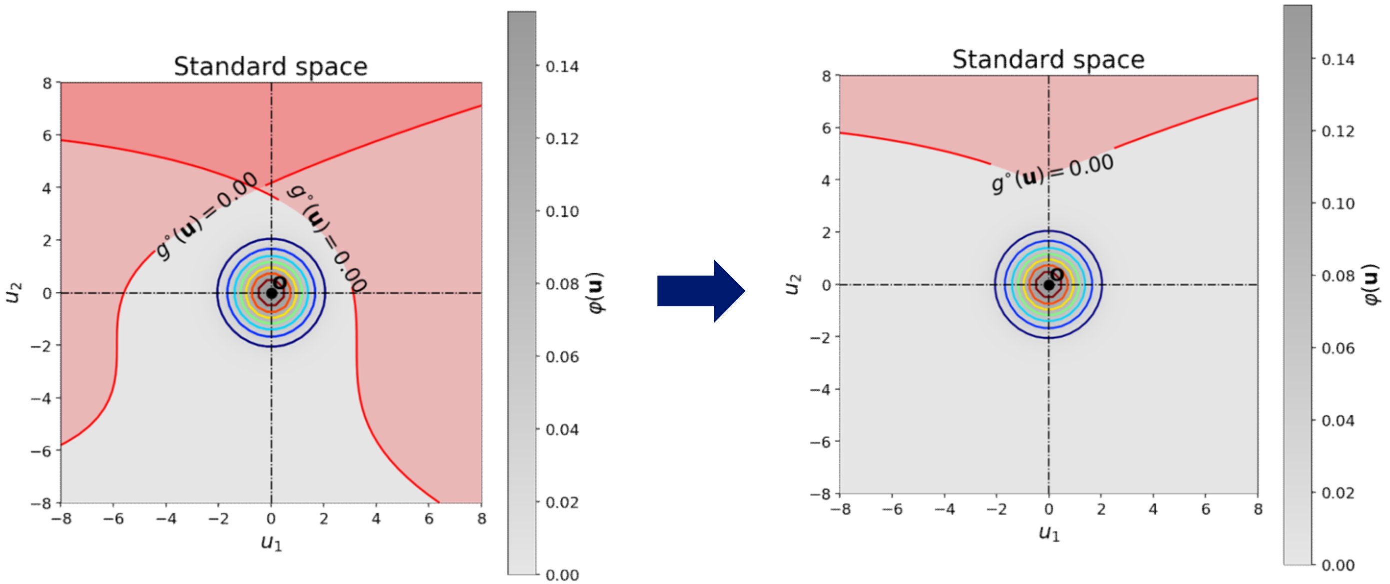
# EVENTS INTERSECTION PROBABILITY

- **Failure probability :**

$$p_f = P\left(\bigcap_{i=0}^{N} g_i(\boldsymbol{X}) < 0\right)$$

$g_i$ = limit state functions

- **Example in dimension with 2 limit state functions :**
  - $p_{f,Monte\ Carlo} = \mathbf{1,24 \times 10^{-5}}$ (818 000 samples, coefficient of variation = 10%)



# INTERSECTION PROBABILITY EVALUATION *(1/3)*

V 1.14

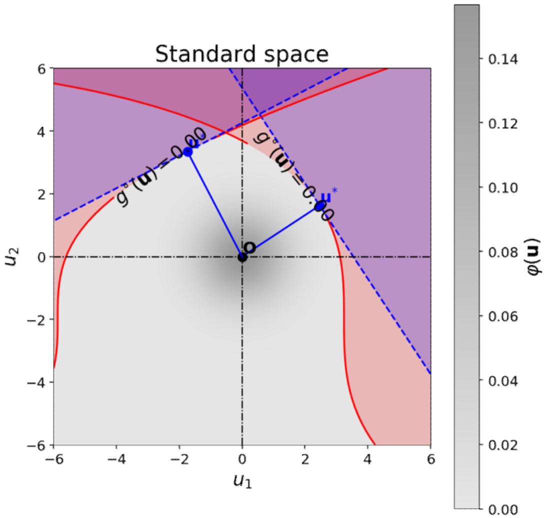
Persalys
Version 9.0.3-pen1.5.0

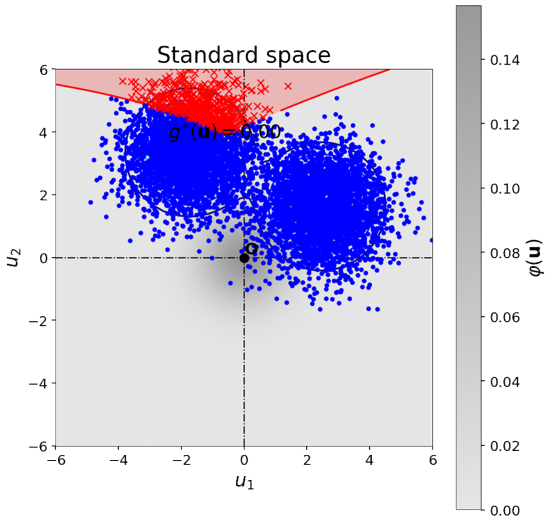
- General approach : FORM + Importance Sampling

## 1. Classical method : System-FORM

- FORM on each limit state function + sampling around the N design points U*
  (instrumental density = mixture of the N densities centered around the U* points)

- **FORM :** $p_{f,FORM\ systeme} = P\left(\bigcap_{i=0}^{N} g_i(\boldsymbol{X}) < 0\right) = \Phi_N(-\boldsymbol{\beta}, [\rho]) = 4{,}21 \times 10^{-7}$
- **FORM-IS :** $\boldsymbol{P_{f,IS} = 1,42 \times 10^{-5}}$ (6 530 samples, CoV = 10%)




**Problem:** depending on the relative position of the limit-state surfaces, the sampled values may not be centered around the right point

⇨ Poor computational efficiency

# INTERSECTION PROBABILITY EVALUATION *(2/3)*

- General approach : FORM + Importance Sampling

V 1.14

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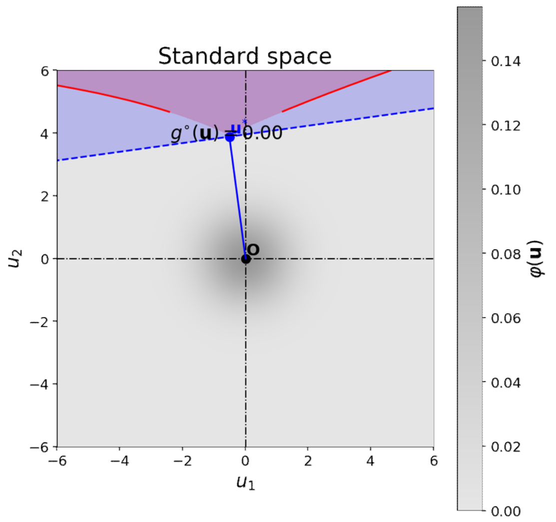
Version 9.0.3-pen1.5.0

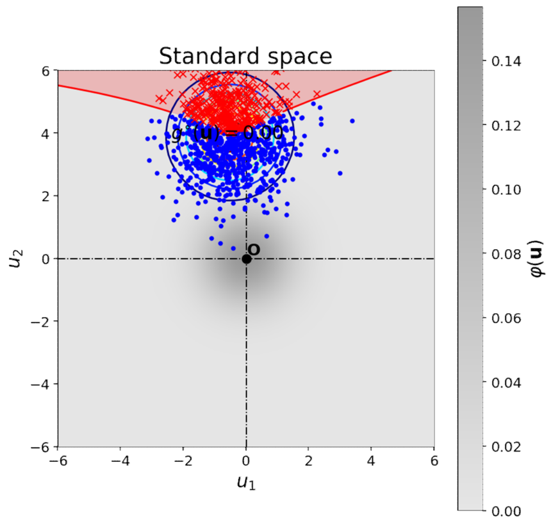
## 2. Multi-constraints FORM

- Multi-constraint optimization problem
- 4 optimization algorithms issued from NLOPT

$$Min \sum_i u_i^2$$
$$s.t. \quad \{g_i(U) = 0\}_{i=1,\dots,N}$$

- **FORM-IS :** $\boldsymbol{P_{f,IS} = 1,42 \times 10^{-5}}$ (970 samples, CoV = 10%)



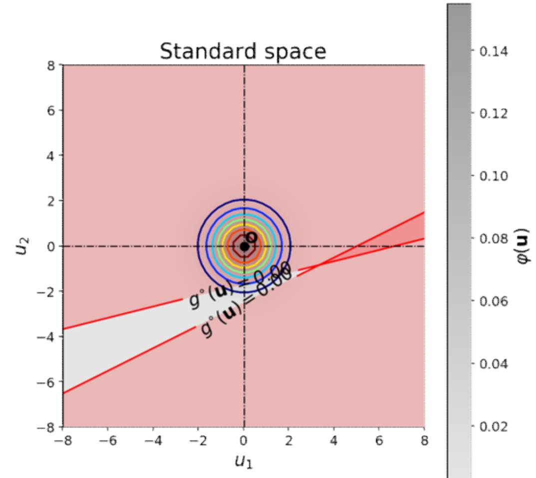



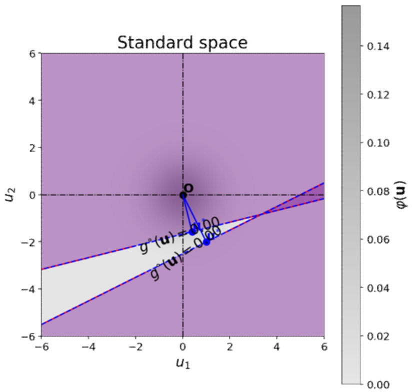

**Problem:** The search algorithm for the U* point may not converge

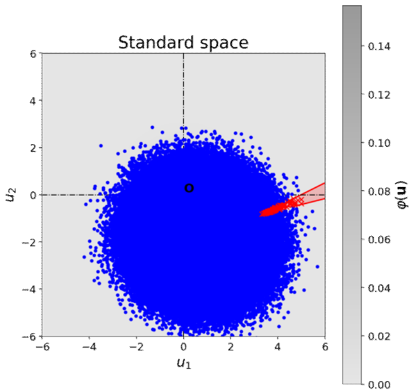
But computational efficiency is generally increased

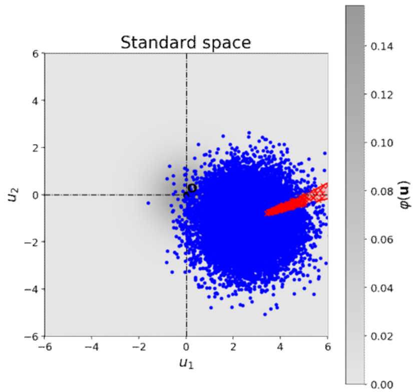
# INTERSECTION PROBABILITY EVALUATION *(3/3)*

- **For penstock conditional failure probability with successful hydro pressure test, the intersection can be located far from the U* points**
  - Monte-Carlo (reference probability): $\boldsymbol{p_{f_{reference}} = 9 \times 10^{-6}}$
  - System-FORM (samples centered on the 2 U* points):
    $\boldsymbol{P_{f,IS} = 1,1 \times 10^{-5}}$ (1 074 000 samples, CoV = 10%)
  - Multi-constraint FORM (samples centered on the intersection point)
    $\boldsymbol{P_{f,IS} = 9,1 \times 10^{-6}}$ (17 580 samples, CoV = 10%)



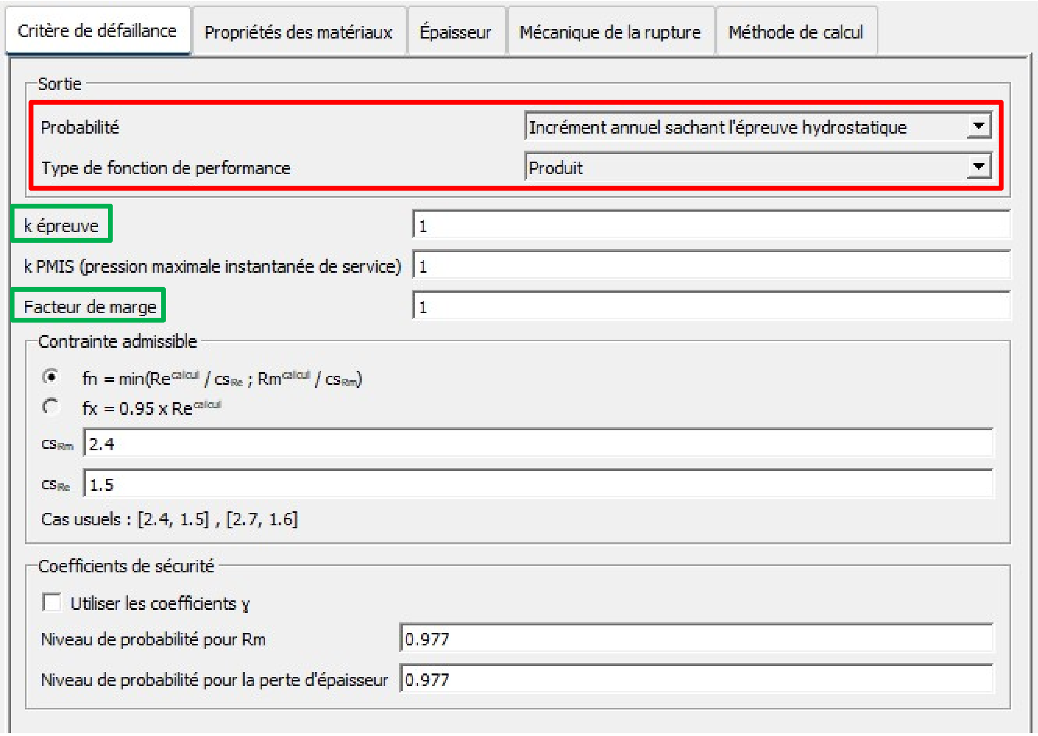



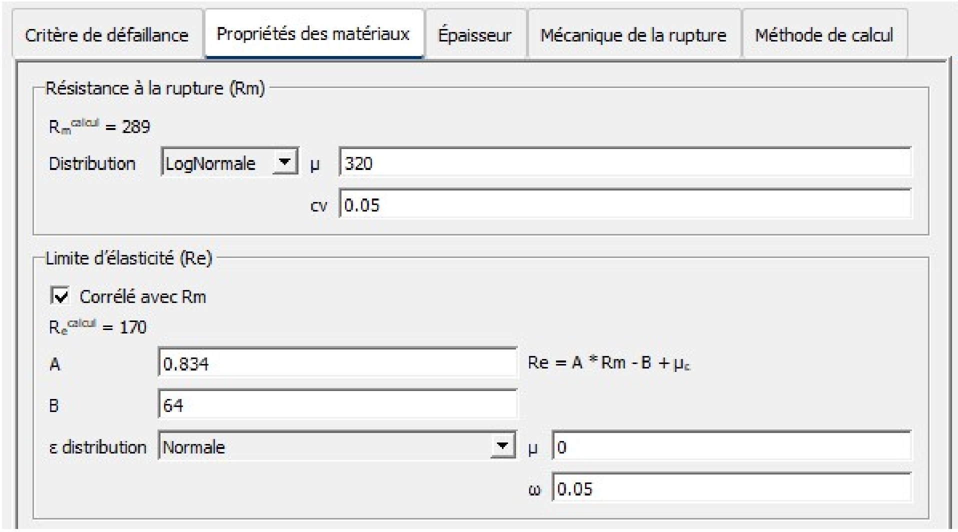
# PERSALYS-PENSTOCK INTERFACE *(1/2)*

## Failure criterion

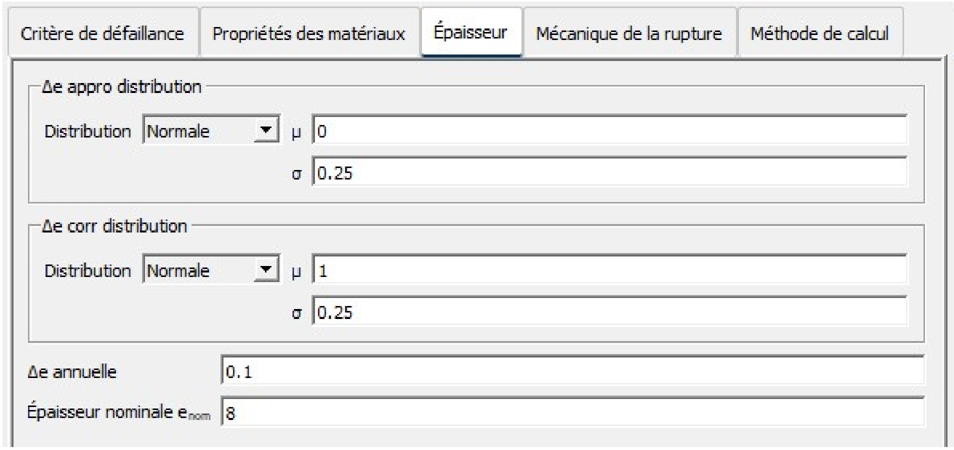




## Material properties

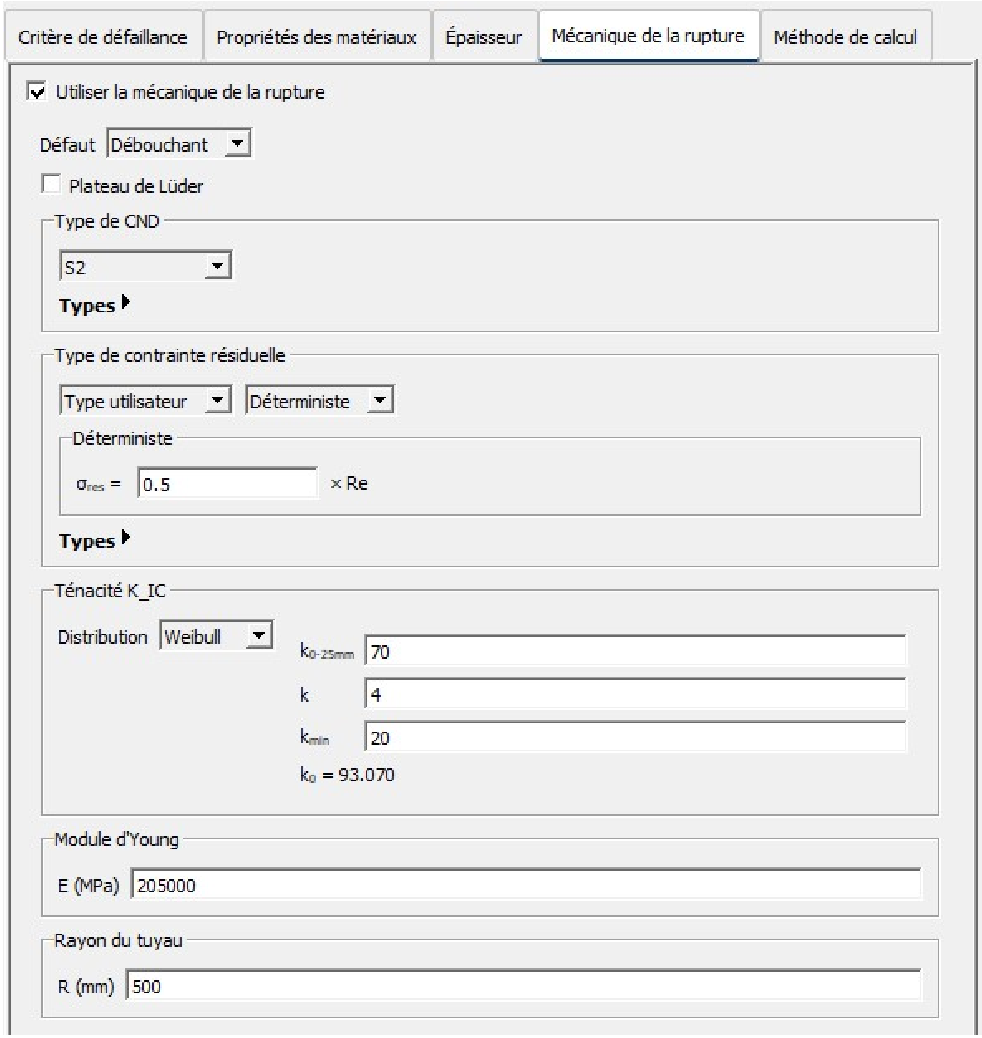



## Thickness

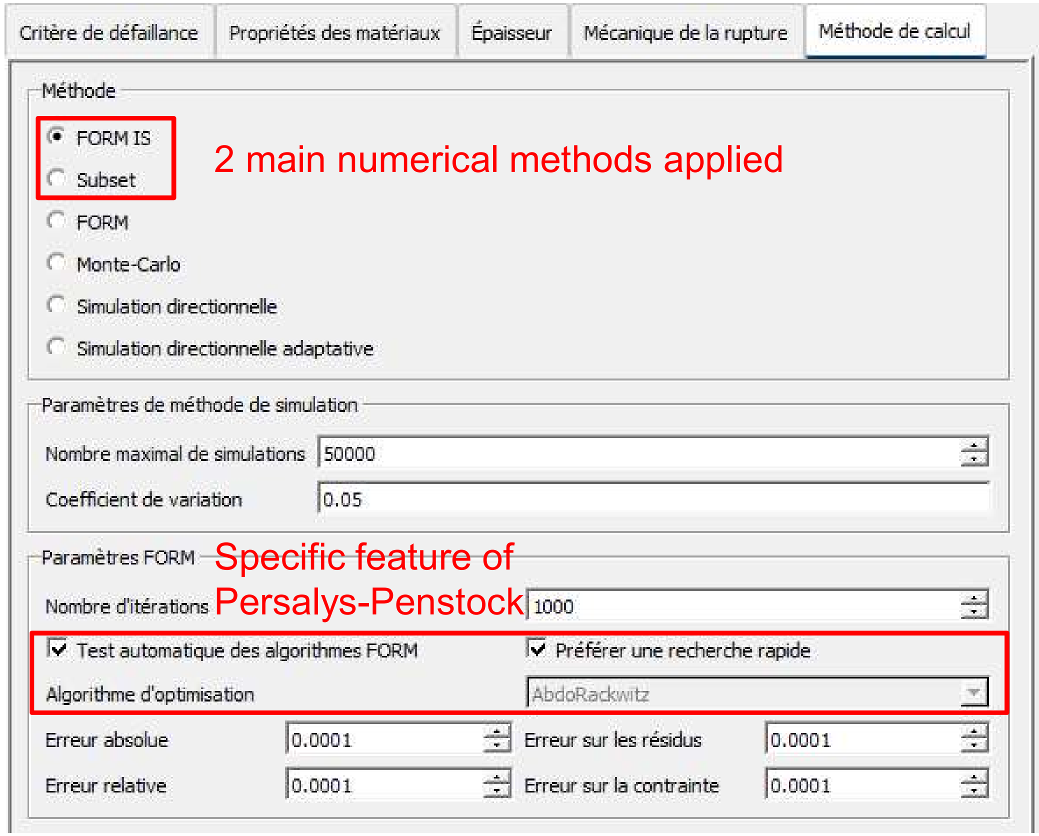


# PERSALYS-PENSTOCK INTERFACE *(2/2)*

## Fracture Mechanics




## Numerical method

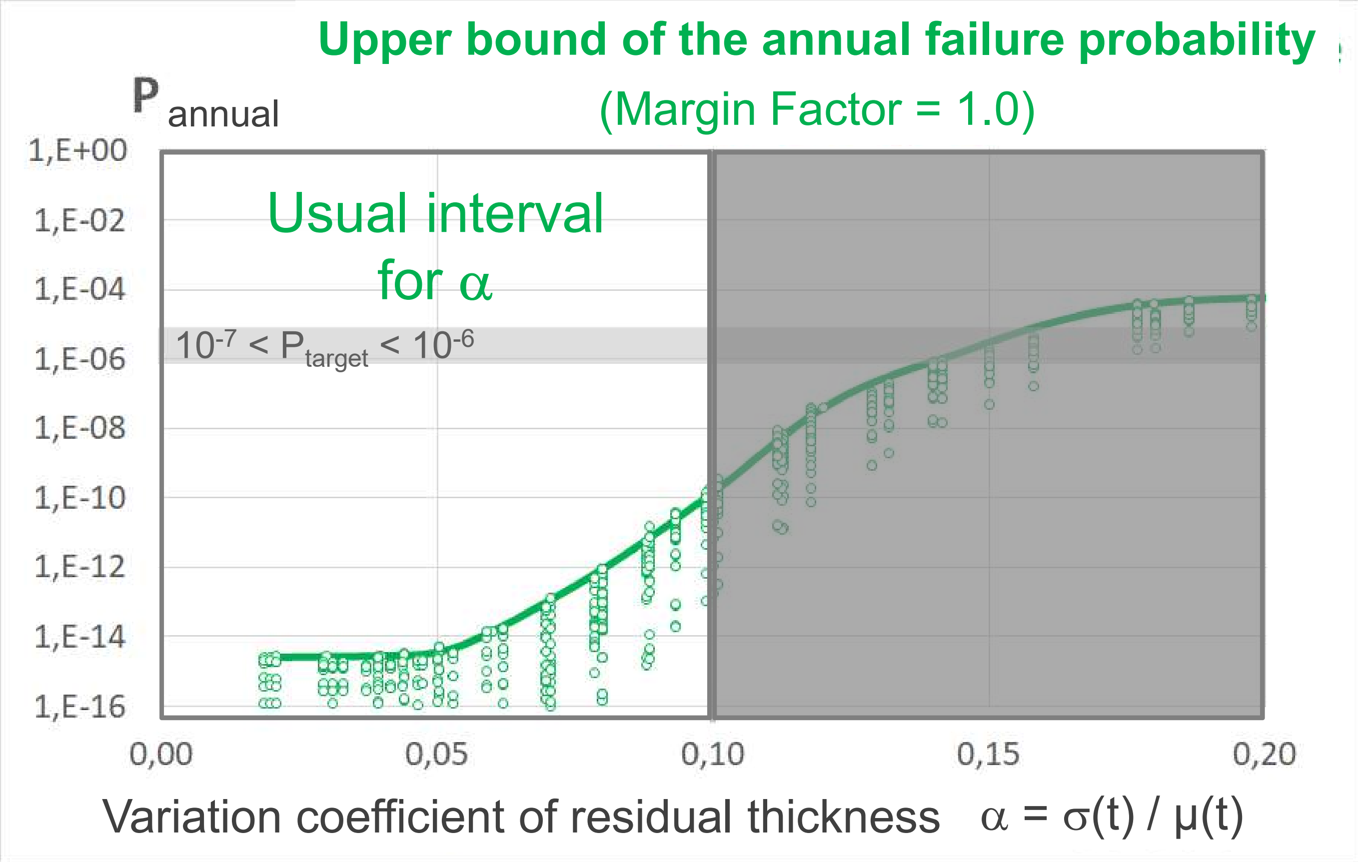



Persalys
Version 9.0.3-pen1.5.0

# PLASTIC COLLAPSE MODEL : UPPER BOUND OF ANNUAL FAILURE PROBABILITY (DETERMINISTIC DoE)

- The upper bound of annual failure probability increases with the variation coefficient of residual thickness

$$\alpha = \sigma(t) / \mu(t)$$

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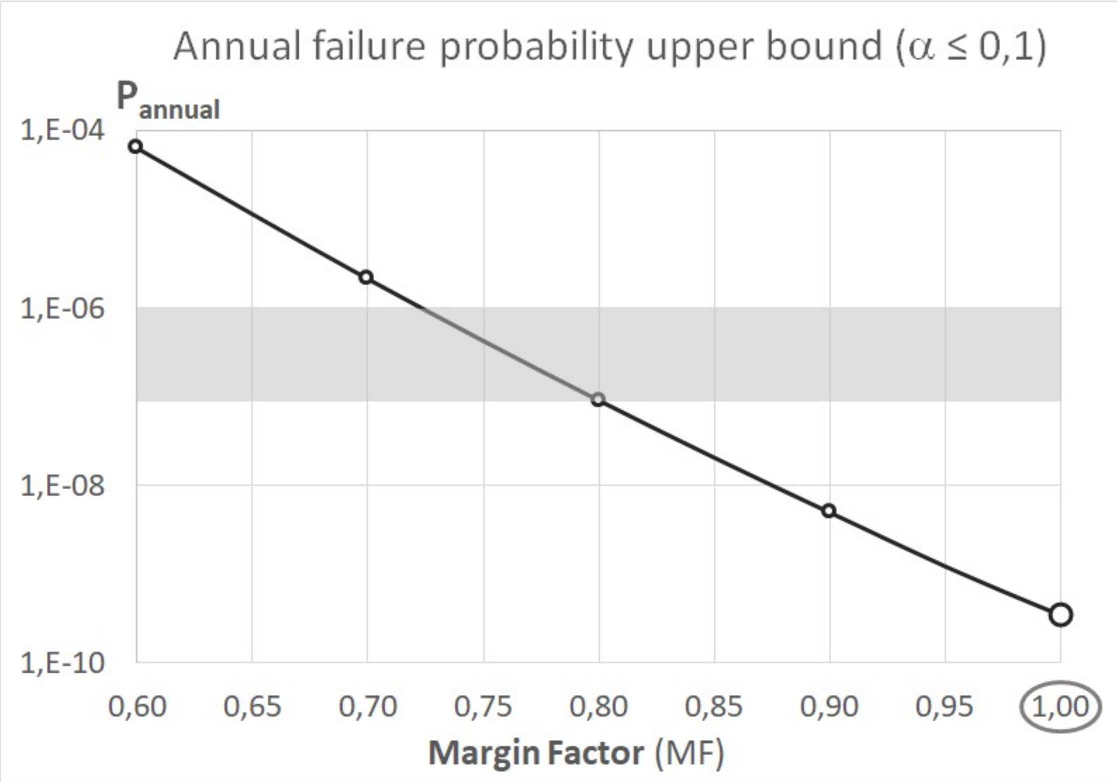
# PLASTIC COLLAPSE MODEL : $P_{ANNUAL\text{-}MAX}$ = f (MARGIN FACTOR) (DETERMINISTIC DoE)

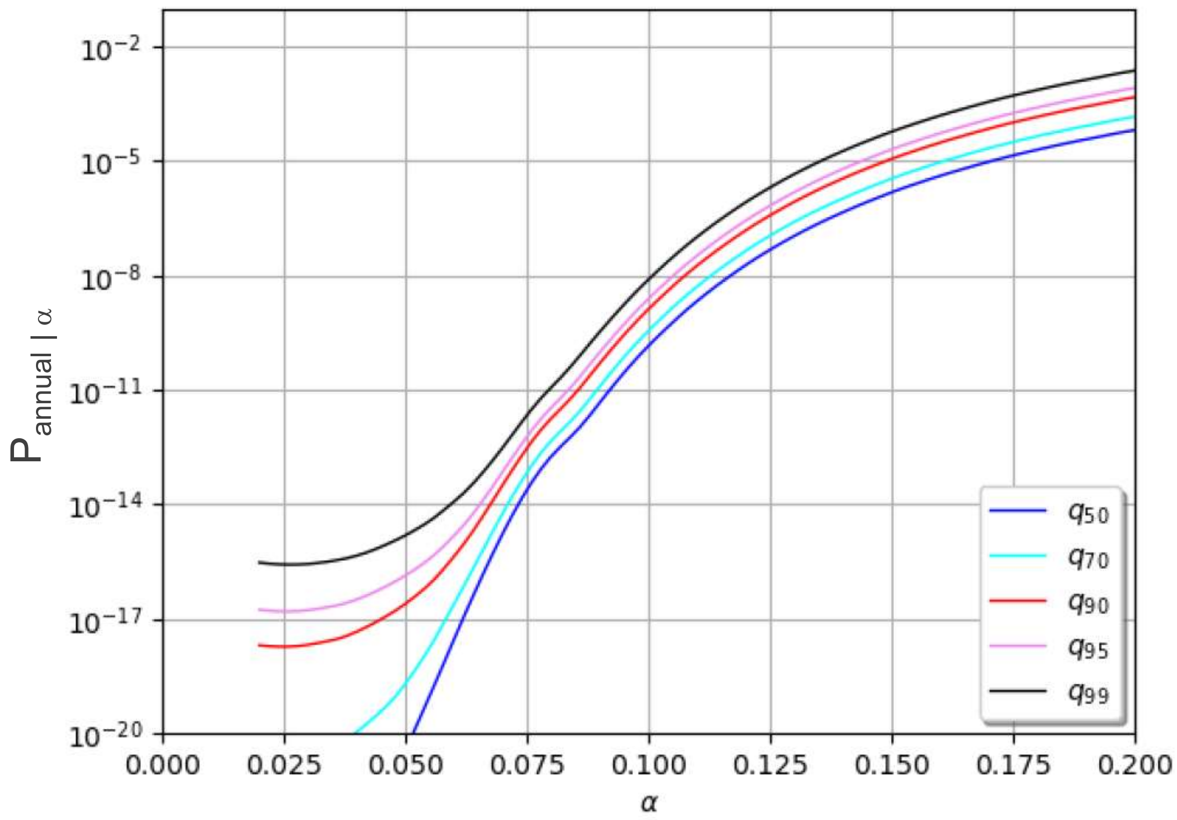



- Margin Factor = 1 (calculated with $\gamma$ = 2)
- $\alpha \leq 0.1$

⇨ $P_{annual\text{-}max} < 10^{-9}$ pipe$^{-1}$.year$^{-1}$

# PLASTIC COLLAPSE MODEL : EVALUATION OF ANNUAL FAILURE PROBABILITY (PROBABILISTIC DoE)

- Parameters of the random variables modelled by uniform distributions
- Application of a Monte-Carlo scheme to generate random parameters combinations for the calculation grid (instead of Latin hypercube)
- Estimation of the distribution of $P_{annual}$ and of the marginal distribution $P_{annual\,|\,\alpha}$




Conditional quantiles of $P_{annual\,|\,\alpha}$ as function of $\alpha$

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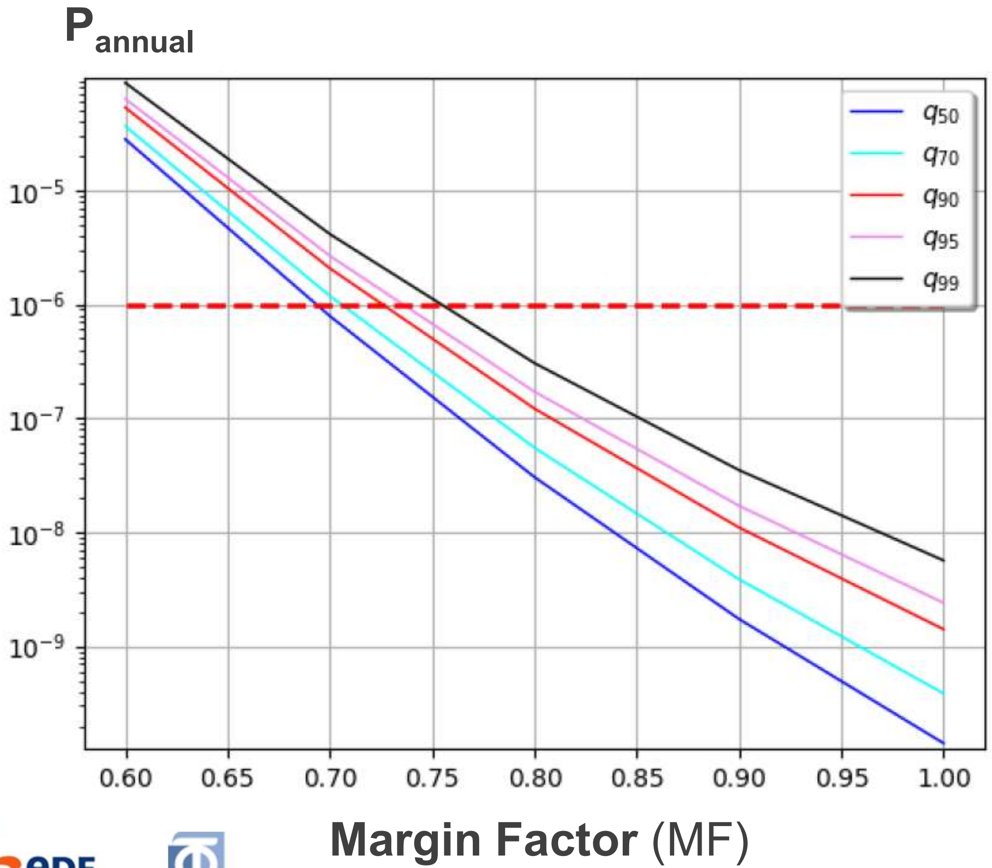
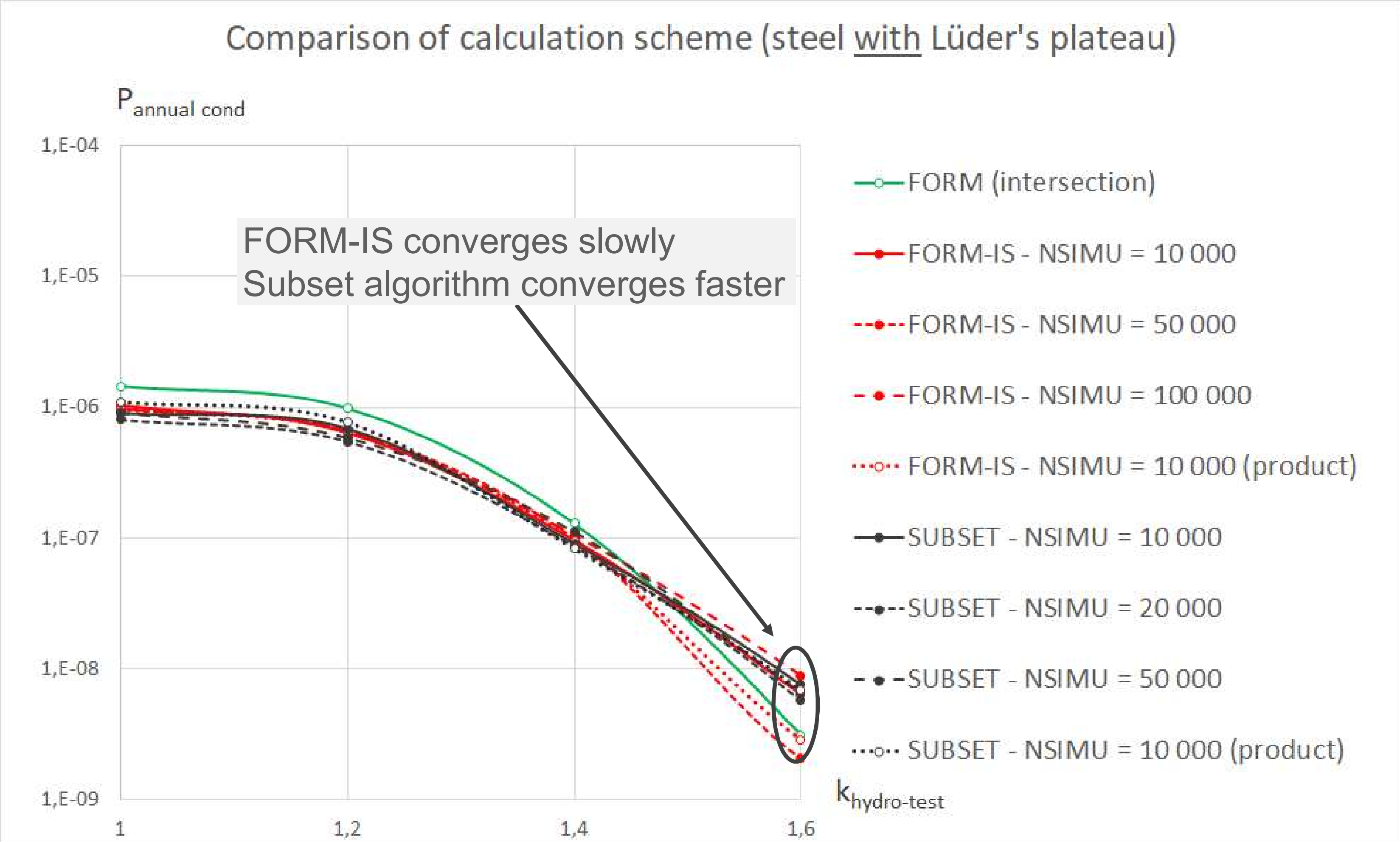
# PLASTIC COLLAPSE MODEL : $P_{ANNUAL}$ = f (MARGIN FACTOR) PROBABILISTIC DoE (~ 1.7 X $10^6$ SAMPLES)




- Margin Factor = 1 (calculated with $\gamma$ = 2)
- $\alpha \leq 0.1$

⇨ $P_{annual} \ll 10^{-8}$ pipe$^{-1}$.year$^{-1}$

# COMPARISON OF NUMERICAL METHODS *(1/2)*



# COMPARISON OF NUMERICAL METHODS *(2/2)*

**Mean CPU time per elementary probability calculation, <u>with fracture mechanics option</u>**

| Numerical method | Intersection calculation | Max. simulations | Annual probability increment | Conditional annual probability (successful hydro-test) |
|---|---|---|---|---|
| FORM | Intersection | - | 0,5 s | 0,5 s |
| FORM-IS | Intersection | 20 000 | 8,0 s | 16,0 s |
| | Product | 20 000 | 8,0 s | 11,3 s |
| | Difference | 20 000 | 1,2 s | - |
| SUBSET | Intersection | 20 000 | 6,5 s | 13,5 s |
| | Product | 20 000 | 3,2 s | 10,3 s |
| | Difference | 20 000 | 5,4 s | - |

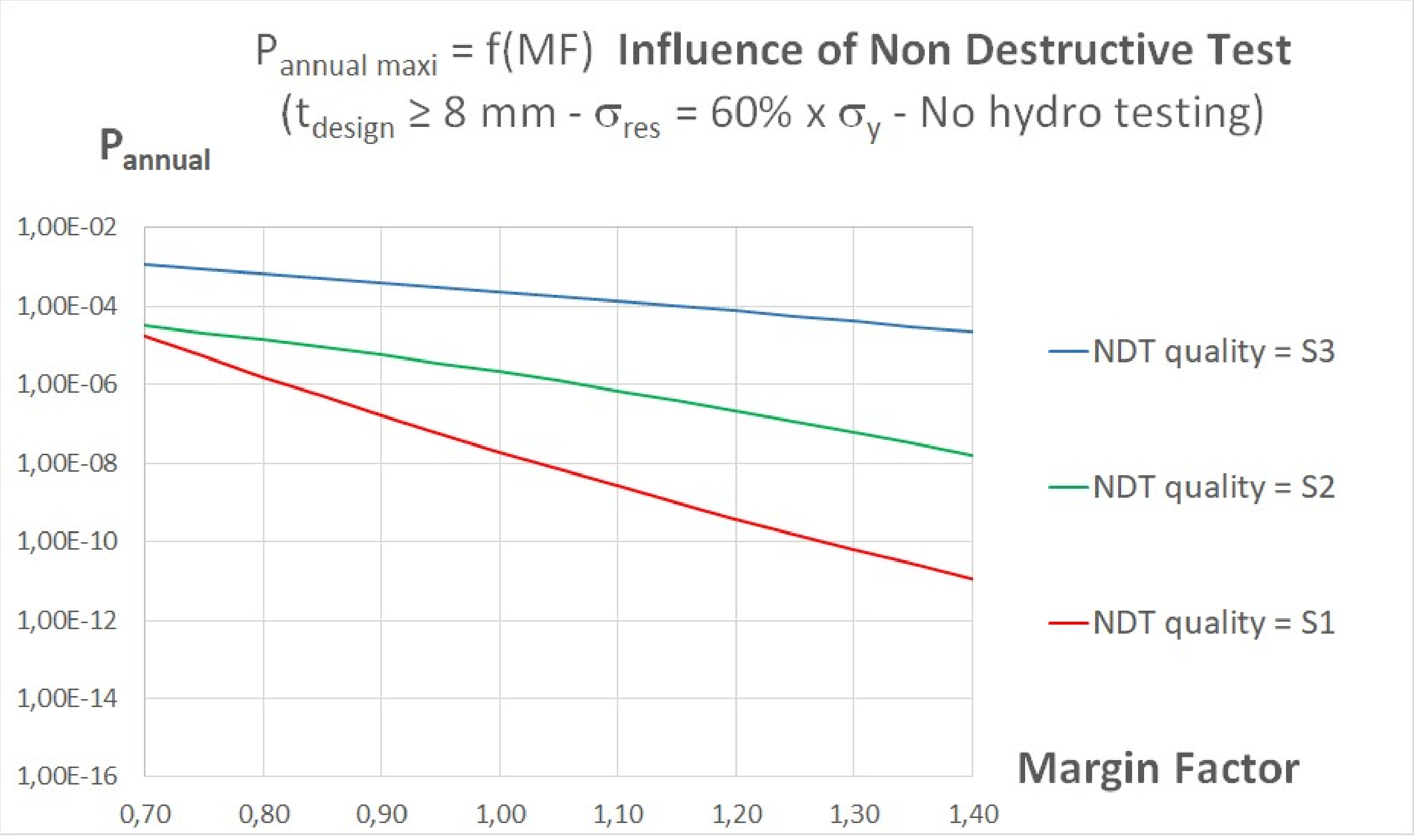
**Typical large calculation grid (fracture mechanics) :**

- 14 400 conditional annual probability
- Computation time ~ 100 000 s CPU

Intel(R) Core(TM) i5-8350U CPU @ 1.70GHz 1.90 GHz

8,00 Go (7,84 Go utilisable)

# FRACTURE MECHANICS MODEL : INFLUENCE OF NON DESTRUCTIVE TESTING ON THE ANNUAL FAILURE PROBABILITY

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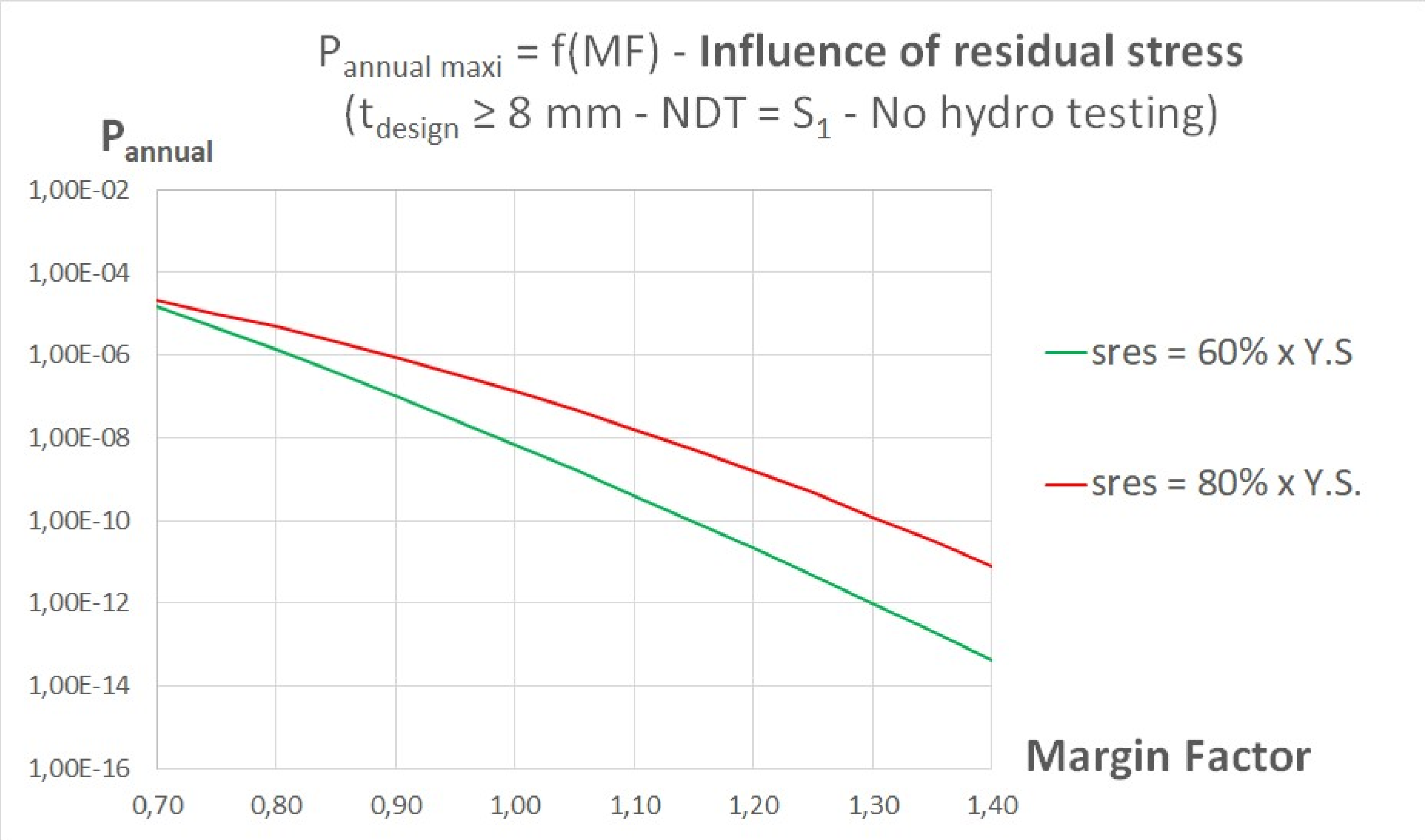
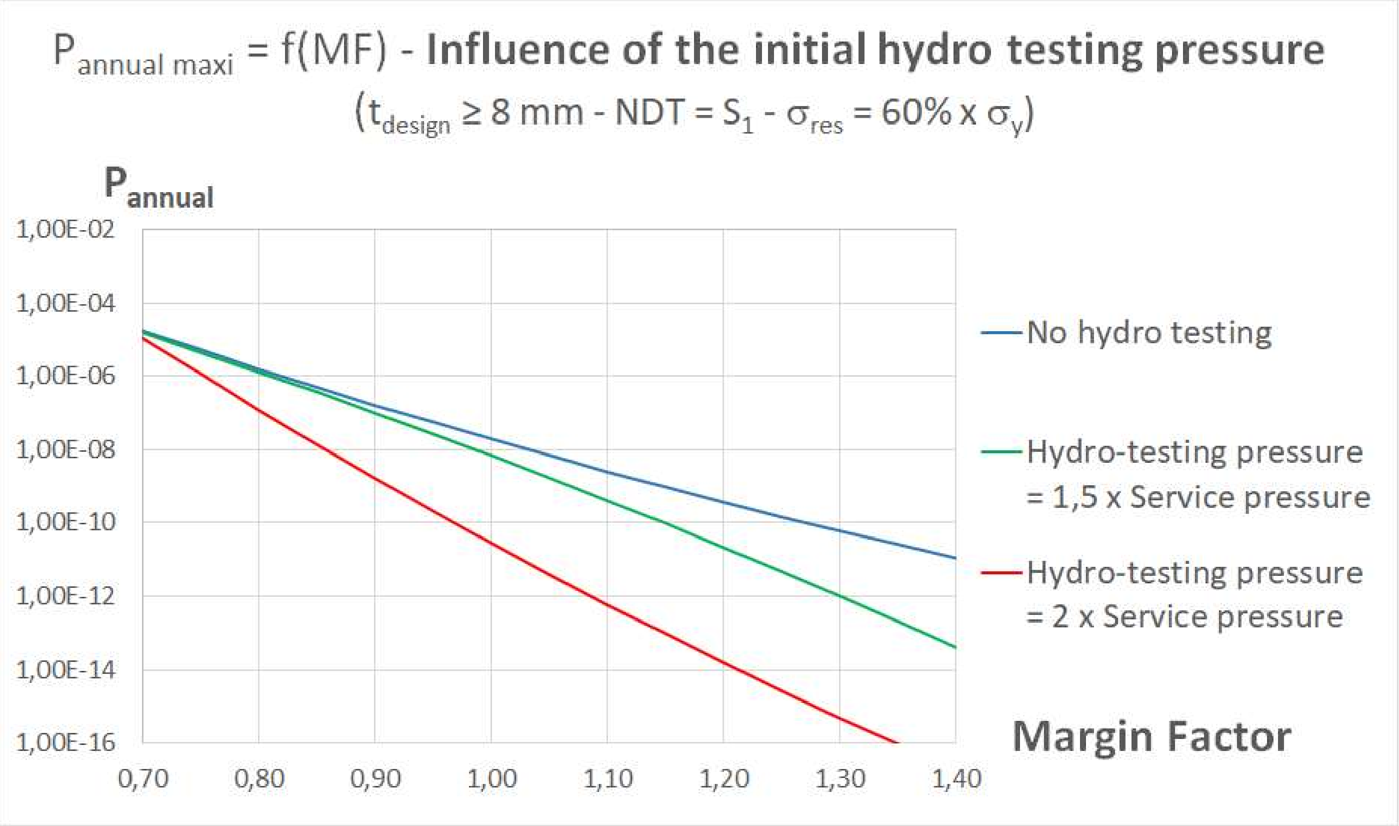
# FRACTURE MECHANICS MODEL : INFLUENCE OF MANUFACTURING PROCESS ON THE ANNUAL FAILURE PROBABILITY



# FRACTURE MECHANICS MODEL : INFLUENCE OF INITIAL HYDRO TESTING ON THE CONDITIONAL ANNUAL FAILURE PROBABILITY



# CONCLUSIONS

- The probabilistic models allowed to assess the sensitivity of the upper bound of annual failure probability with regard to the Margin Factor of a penstock
  - For plastic collapse criterion (out of welds, without planar flas)
  - For fracture mechanic criterion (in welds with potential planar flaws)
- These models have been implemented in **Persalys-Penstock**
- Specific innovative numerical methods have been specifically developed and tested in order to calculate the probabilities corresponding to intersection of events
- **Persalys-Penstock** allows to solve – deterministic or probabilistic – large calculation grids
- Its application highlights that the annual failure probability depends on 4 major influencing factors :
  - The coefficient of variation of residual thickness
  - The relief of residual stress in welds
  - The detectability performance of Non destructive Tests
  - The initial hydrostatic pressure test leads to a significant reduction of the annual failure probability since the average cumulated corrosion thinning is moderate


TANK YOU !
QUESTIONS ?