Risk and Safety

in

Engineering

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- Theoretical Framework for Assessment
- Reliability Updating Techniques
- Decision Analysis for Reassessment
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General Philosophy for Reassessment

Structures are designed subject to given requirements :

- Purpose/use
- Safety to users
- Reliability in fulfillment of purpose/use
- Service life
- Durability subject to normal maintenance

An assessment of a structure is necessary:

if there is reason to doubt whether these requirements or the assumptions on the basis of which the structure was designed are valid.

General Philosophy for Reassessment

The main issues to be considered when assessing an existing structure are:

- The effect of possibly changed requirements to the structure on the structural performance
- Validation of design assumptions and assessing the effect of possible deviations from these assumptions on the structural performance
- Assessing the condition and residual capacity and service life of the structure

General Philosophy for Reassessment

Typical situations where the use/purpose of the structure is changed are:

- Increased loading (e.g. higher traffic volume and/or higher axle loads)
- Increased service life (the structure is still needed after the planned service life)
- Increased reliability (due to increased importance of the structure for society)
- Modification of the structure to accommodate modification in use (e.g. extra traffic lanes on a bridge)

General Philosophy for Reassessment

Typical situations where doubts may be raised with regard to the design assumptions are e.g.:

- The structure has not been inspected for an extended period of time (damages and unforeseen degradation might have taken place)
- Unexpected degradation has been observed (ASR, frost/thaw, fatigue, corrosion, etc.)
- The structure has been subject to an accidental or otherwise unforeseen extreme load (excessive load, fire, earthquake, etc.)
- Similar structure(s) exhibit unsatisfactory performance.
- New knowledge and revised design codes.

General Philosophy for Reassessment

In the assessment it is useful to look at the structure from the following perspective

Condition indicators:

Loads
Environment
Use
Accidents
Age
.

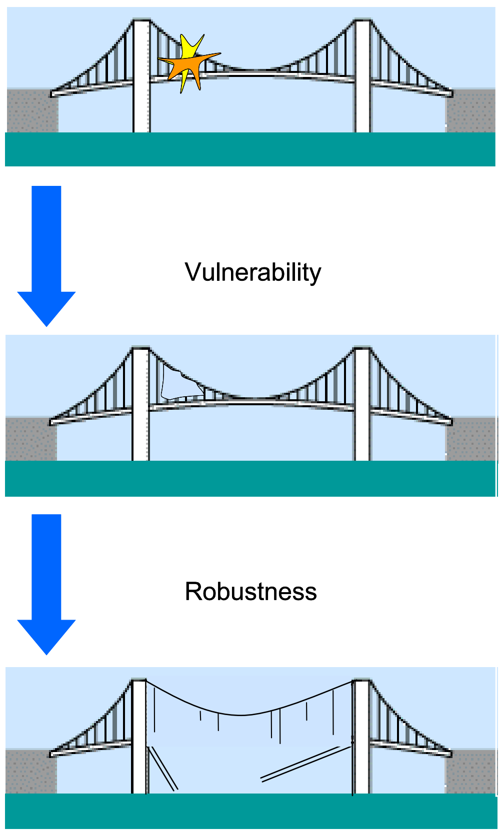
Design basis
Durability
.

Damages
Degradation
Response

Condition

Condition
Redundancy
Ductility
Insp./maint. strategy
Emergency prep. plans

Exposure



Vulnerability

Robustness

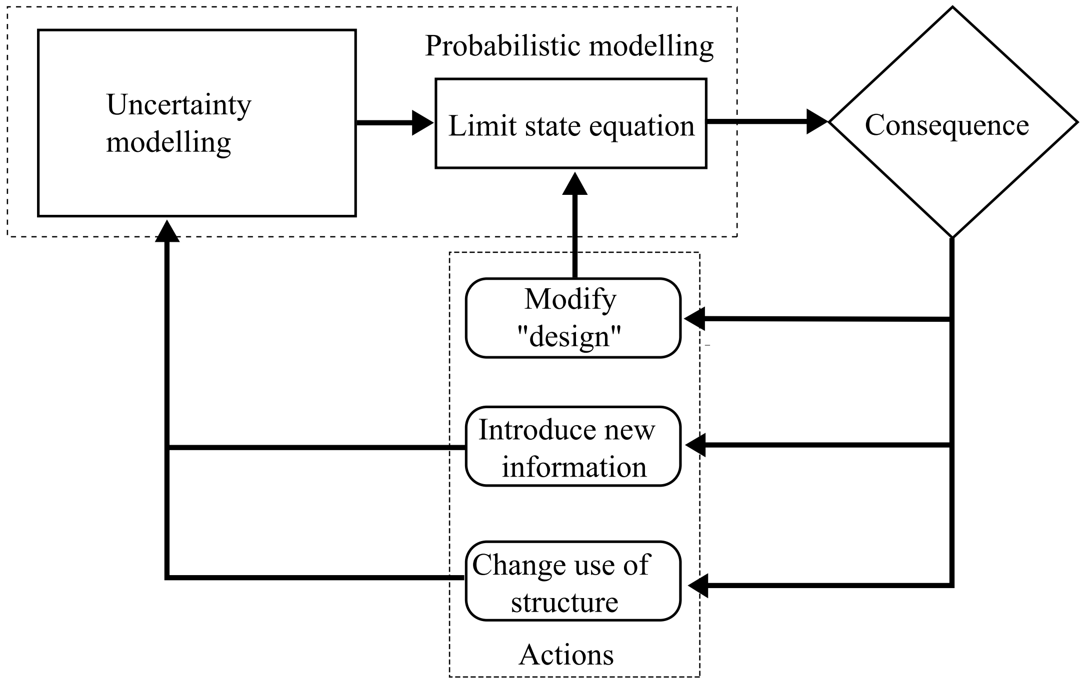
Exposures:
Wind loads
Traffic loads
Snow loads
Current loads
Earthquake loads
Ship/vehicle impact
Fire/explosions
Temperature loads
Water
Deicing salt
.

Direct consequences to the structure:
Component failure
Corrosion damage
Erosion
Fatigue
Spalling
Wear
Yielding
Cracks
.

Indirect consequences to the structure:
Collapse

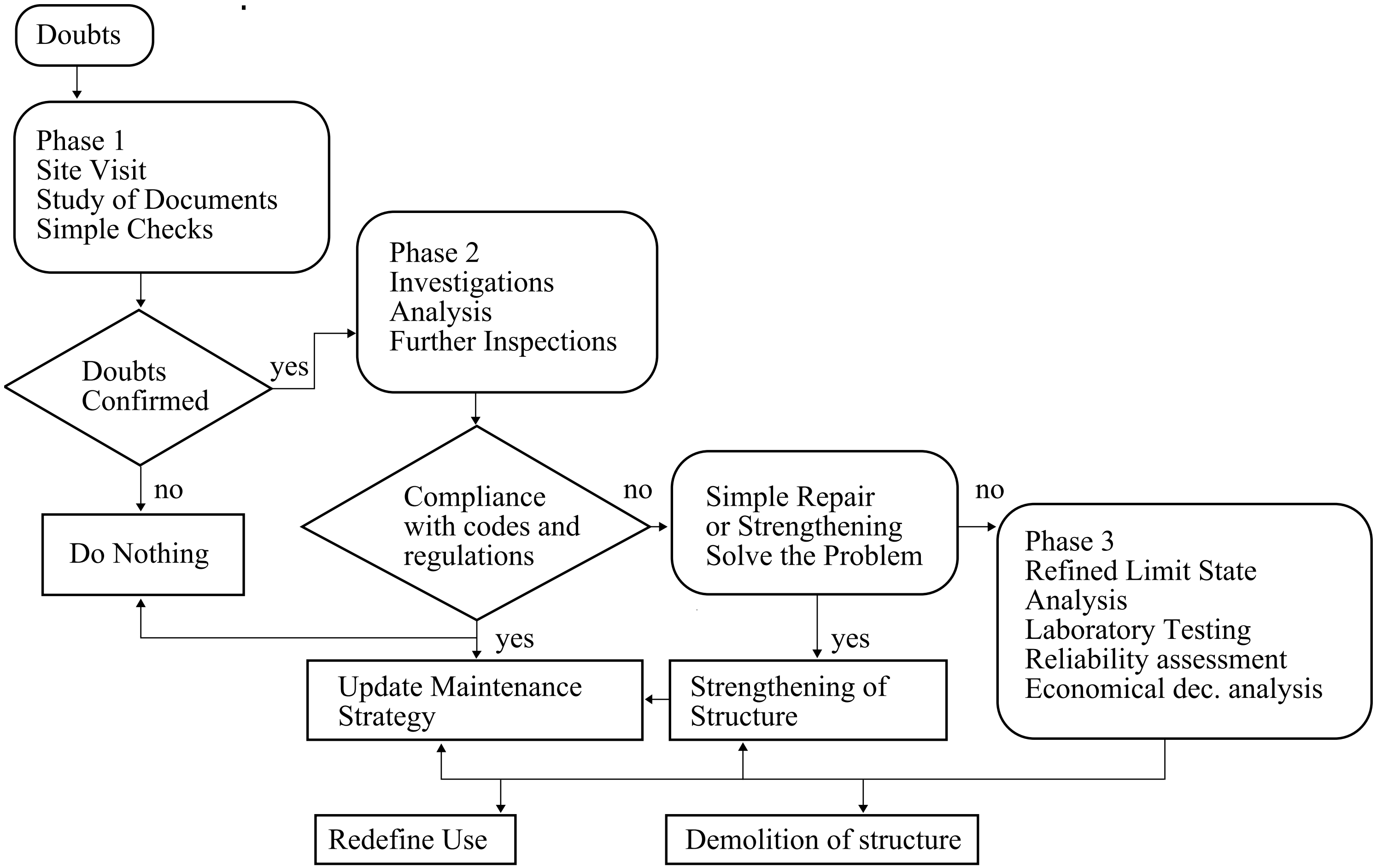
Theoretical Framework for Assessment

The framework for assessment can be represented in the following general way:



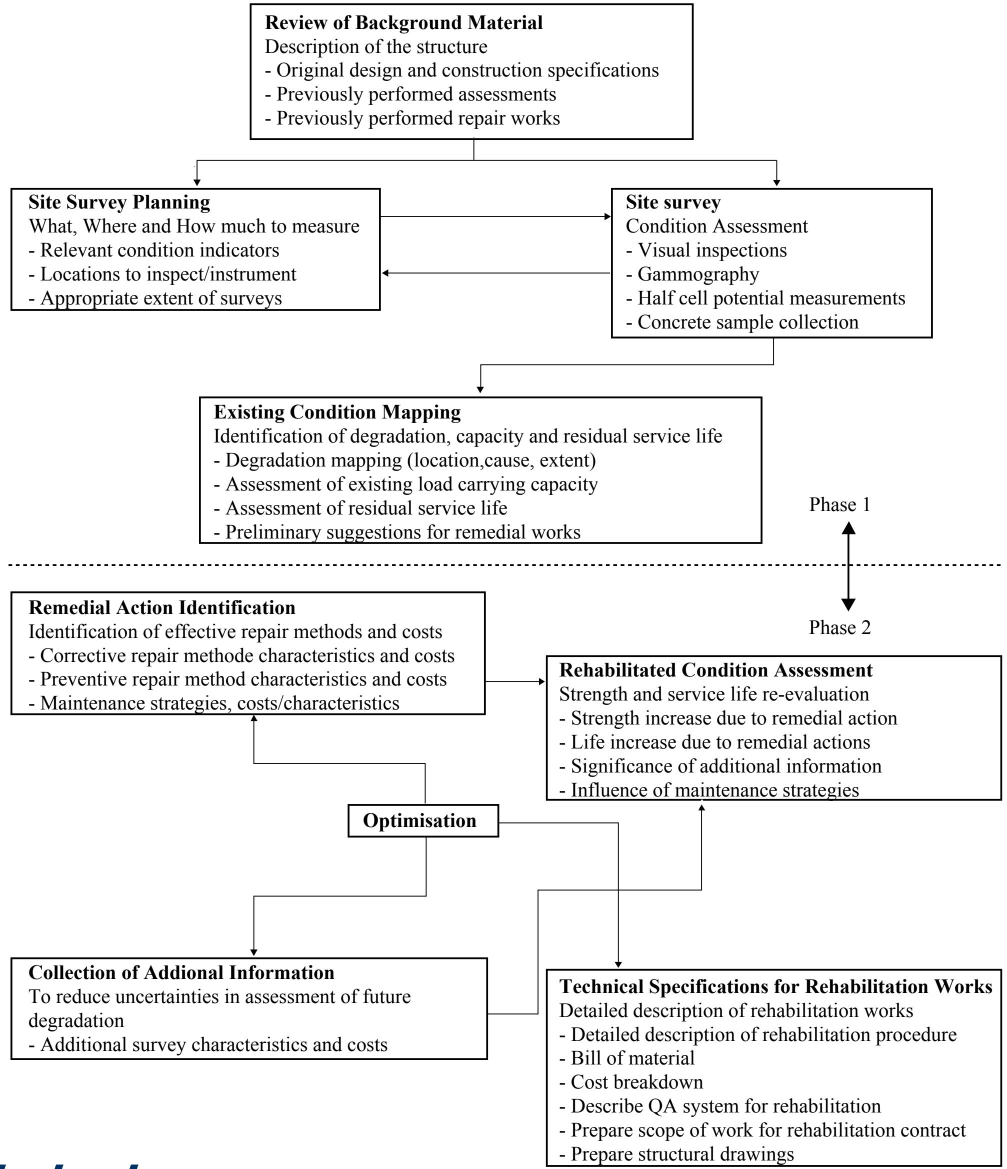
General Philosophy for Reassessment

The assessment process should be performed in an adaptive manner:



General Philosophy for Reassessment

For the assessment of concrete structures the following procedure might be helpful:



Reliability Updating Techniques

Updating may be performed whenever new information is obtained.

New information could concern:

- The structure has survived
- Material characteristics from different sources
- Geometry
- Damages and deterioration
- Capacity by proof loading
- Static and dynamic response to controlled loading

Reliability Updating Techniques

In principle two different types of information can be optained:

- *information of the **equality** type*
  - e.g. the stress in a given location is equal to 200MPa
  - the concrete compression strength is equal to 45MPa

- *information of the **inequality** type*
  - the depth of de-passivation is smaller than 20mm
  - possible fatigue cracks are smaller than 2mm
  - the load bearing capacity is larger than 45 T

equality type: $h(\mathbf{x}) = 0$

inequality type: $h(\mathbf{x}) < 0$

Reliability Updating Techniques

Updating of random variables:

$$f_X(x) \quad f_Q(q) \quad \hat{x}$$

Prior model + data

$$f_Q''(q \mid \hat{x}) = \frac{f_Q'(q)\, L(q \mid \hat{x})}{\int_{-\infty}^{\infty} f_Q'(q)\, L(q \mid \hat{x})\, dq}$$

Posterior model

$$f_X^U(x) = \int_{-\infty}^{\infty} f_X(x|q)\, f_Q''(q \mid \hat{x}) dq$$

Predictive model

Reliability Updating Techniques

Updating of probabilities of events:

$$P(F|I) = \frac{P(F \cap I)}{P(I)}$$

F : failure event

I : inspection result

$$P(F|I) = \frac{P(M(\boldsymbol{X}) < 0 \cap h(\boldsymbol{X}) < 0)}{P(h(\boldsymbol{X}) < 0)}$$

Decision Analysis for Reassessment

Decision alternatives in assessment and maintenance planning should take basis in a life-cycle perspective:

$$E\left[C_T(t_{inst})\right] = P_I C_I + P_f C_f + C_R P_R = E\left[C_I\right] + E\left[C_f\right] + E\left[C_r\right]$$

Decision Analysis for Reassessment

Prior decision analysis:

A steel bar is considered.

The loading on the steel bar will be increased by 10%

The question is: should the steel bar be exchanged with a steel bar with an 10% increased cross section?

Two events are possible

1) The strength of the steel bar is larger than the loading
2) The strength of the steel bar is smaller than the loading

Decision Analysis for Reassessment

Prior decision analysis:

The load effect *s* is equal to 2765 kN.

The resistance *R* is assumed to be Normal distributed with:

Mean value equal to 3500 kN
Coefficient of variation equal to 10%.

Decision Analysis for Reassessment

Prior decision analysis:

The *prior* probabilities can then be determined e.g. by FORM/SORM analysis as:

$$P'\left(\theta_0 \left| a_0\right.\right) = P(R - s > 0) = P(R - 1.1 \cdot 2765 > 0) = 1 - 1.15 \cdot 10^{-2}$$

$$P'\left(\theta_1 \left| a_0\right.\right) = 1 - P'(\theta_0 \left| a_0\right.) = 1.15 \cdot 10^{-2}$$

$$P'\left(\theta_0 \left| a_1\right.\right) = P(1.1 \cdot R - s > 0) = P(R - 2765 > 0) = 1 - 1.33 \cdot 10^{-4}$$

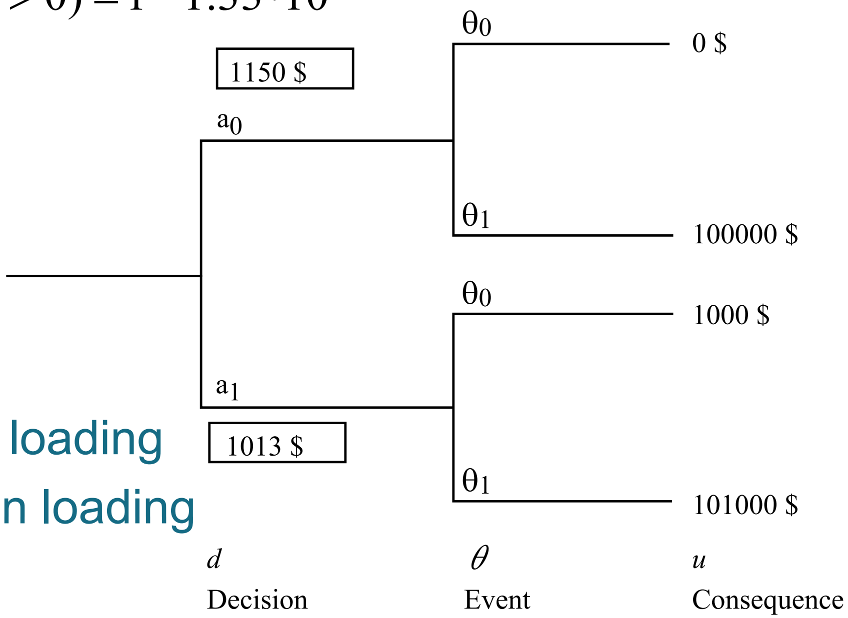
$$P'\left(\theta_1 \left| a_1\right.\right) = 1 - P'(\theta_0 \left| a_1\right.) = 1.33 \cdot 10^{-4}$$

a_0 : Do nothing

a_1 : Strengthen the steel bar

θ_0 : Strength of steel bar larger than loading

θ_1 : Strength of steel bar smaller than loading



Decision Analysis for Reassessment

a_0 : Do nothing
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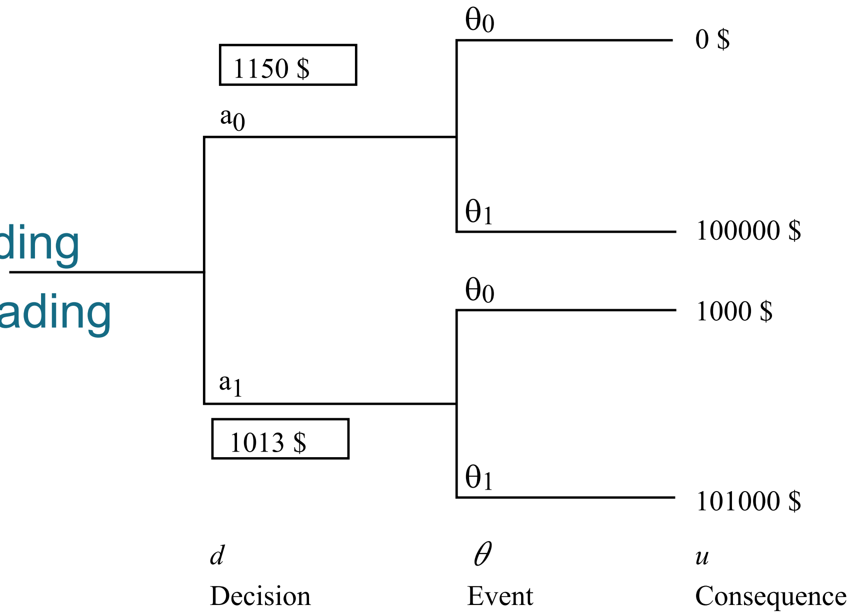


$$E'[u] = \min\{P'(\theta_0|a_0)\cdot 0 + P'(\theta_1|a_0)\cdot 100000,\ P'(\theta_0|a_1)\cdot 1000 + P'(\theta_1|a_1)\cdot 101000\}$$

$$= \min\{(1-1.15\cdot 10^{-2})\cdot 0 + 1.15\cdot 10^{-2}\cdot 100000,\ (1\text{-}1.33\cdot 10^{-4})\cdot 1000 + 1.33\cdot 10^{-4}\cdot 101000\}$$

$$= \min\{1150, 1013\} = 1013$$

Typical Reassessment Problems

We may utilize reliability updating for decision analysis using indirect information

Assume that we have two steel bars made by the same manufacturer but of steel from two different batches

The mean value and standard deviation of the resistance of the steel from the two batches are the same **μ = 3500 kN , σ = 175 kN**

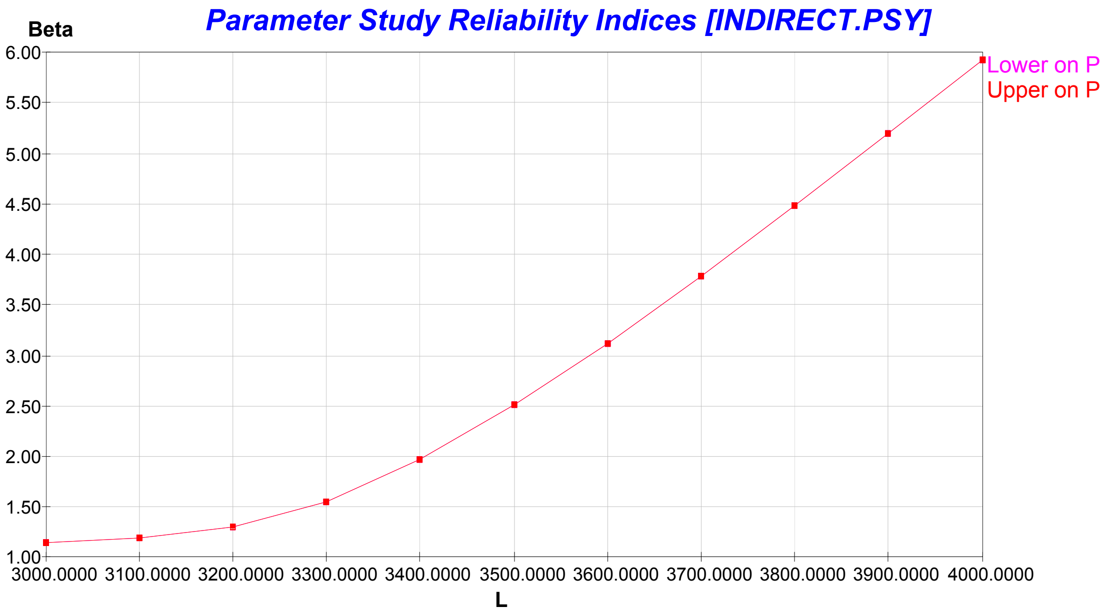
From tests it is further known that the resistances of the steel from the two batches are correlated with ρ **= 0.8**.

We know that a steel bar made of steel from one batch has survived a load of l and would like to re-assess the reliability of a steel bar made of steel from the other batch subjected to a load of **3300 KN**.

Typical Reassessment Problems

Depending on the intensity of the load l the reliability may be updated and written as:

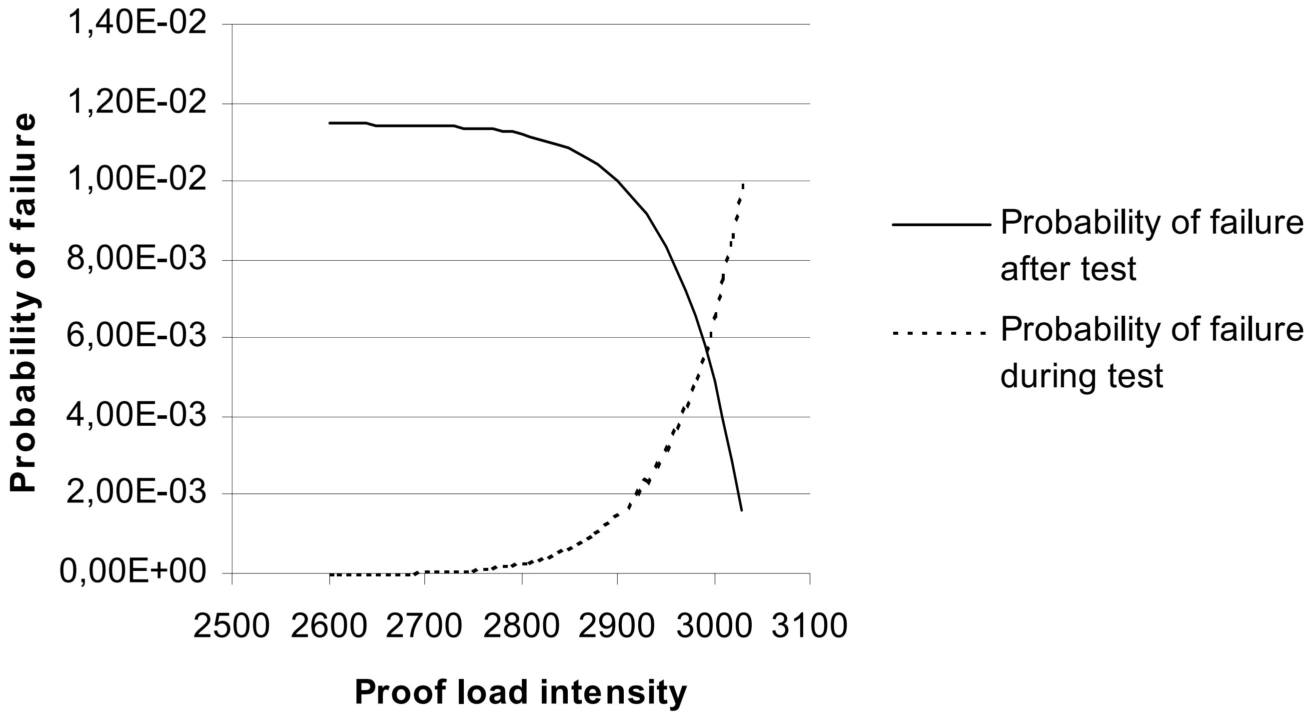
$$P_F^U = P(g_1(X) \le 0 | g_2(X) > 0) = \frac{P(R_1 - 3300 \le 0 \cap l - R_2 \le 0)}{P(l - R_2 \le 0)}$$



Typical Reassessment Problems

We may also perform reliability updating by **proof loading**

$$P_F^U = P(g_1(X) \leq 0 | g_2(X) > 0) = \frac{P(R_1 - 3041 \leq 0 \cap l - R_1 \leq 0)}{P(l - R_1 \leq 0)}$$



Typical Reassessment Problems

Reliability updating by inspection

It is assumed that a structural detail is subjected to fatigue loading

It is assumed that the annual number of load variations is $1 \cdot 10^5$

The expeced value and standard deviation of the Normal distributed stress ranges are

$$\mu_S = 30MPa, \ \ \sigma_S = 5MPa$$

A simple one-dimensional crack growth model is assumed

$$a(n) = a_0 \exp(C\pi s^2 n)$$

$$C = 5 \cdot 10^{-10}$$

$$\mu_{A_0} = \sigma_{A_0} = 1 \ mm$$

Typical Reassessment Problems

Reliability updating by inspection

Failure is assumed if the crack exceeds 40mm

Inspections are possible

The Probability of Detection (POD) of cracks is assumed Exponential distributed with

$$\mu_{POD} = \sigma_{POD} = 1\ mm$$

It is assumed that the reliability requirement for the fatigue failure mode is a maximum failure probability of 10^{-4} per annum.

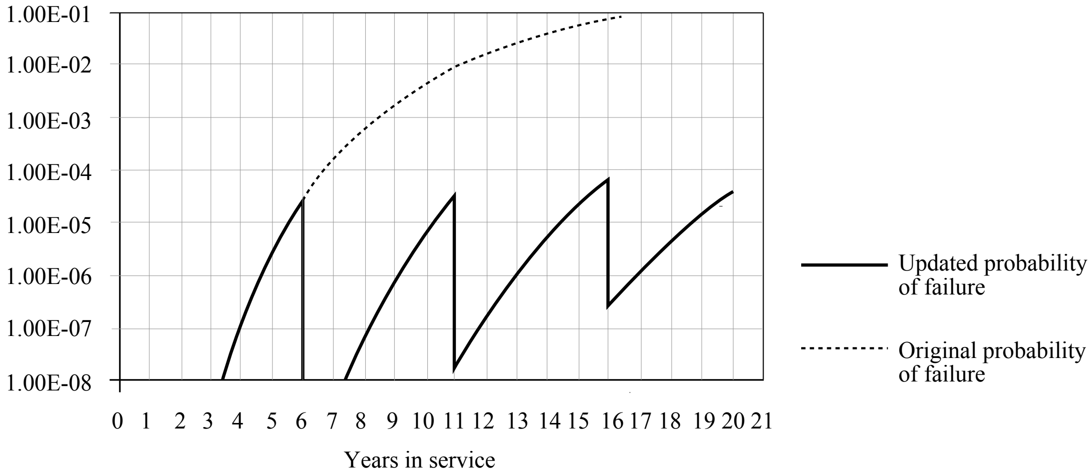
Typical Reassessment Problems

Reliability updating by inspection

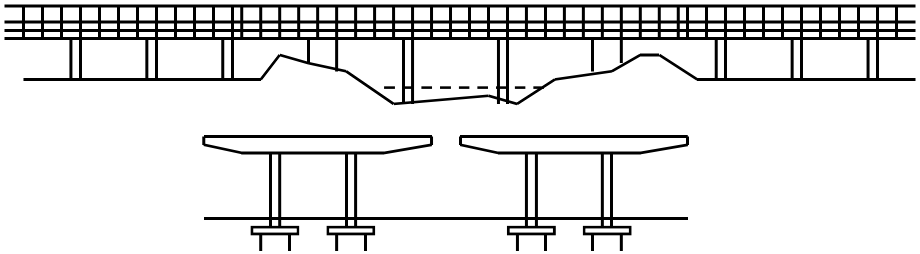
Assume that an inspection is carried out after 6 years

The updated probability of failure is estimated as

$$P(a_{crit} - a(n) \leq 0 \,|\, a(n) - POD \leq 0) = \frac{P(a_{crit} - a(n) \leq 0 \cap a(n) - POD \leq 0)}{P(a(n) - POD \leq 0)}$$



Upgrading of the Gudenaa Bridge



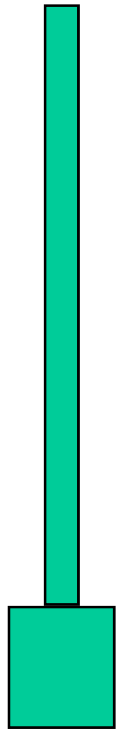
- The bridge was built in 1974
- Concrete slap bridge founded on 300 piles
- Length = 400 m
- Width = 26 m
- Spans around 15 m

Problem (1993):

- A bridge classification for 100T traffic is required
- From standard calculations it is only possible to verify a class 40 T – problems with the foundation
- Assessed costs for repairs and strengthening estimated to be 10 million SFr
- It is known that the bridge has been subjected to class 100T traffic several times
- The bridge appears to be in a very good conndition

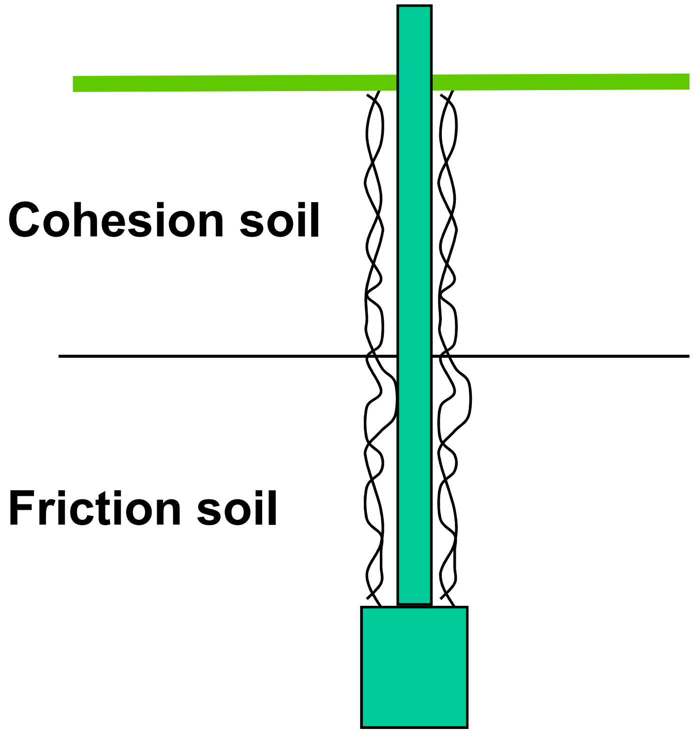
Upgrading of the Gudenaa Bridge

The piles were of the **foot pile** type



Upgrading of the Gudenaa Bridge

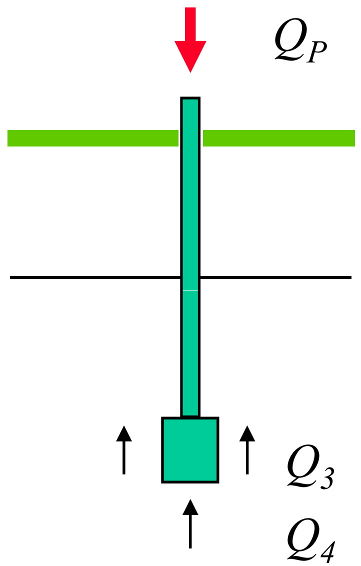
- The piles were driven to a depth between 20 and 40 m
- The upper part of the piles was positioned in cohesion soil and the lower part in friction soil
- Traditional calculations taking basis in pile driving literature indicated that 40 piles should be strengthened
- The assumption that the soil around the pile shafts since the original installations had rehabilitated could not be quantified



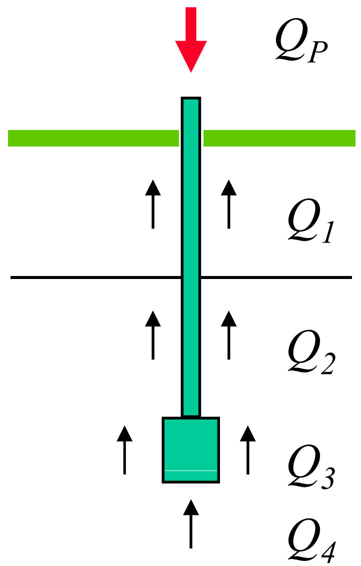
Upgrading of the Gudenaa Bridge

Probabilistic models for the pile capacity were formulated for two situations

The situation corresponding to 1 month after driving – at which time 4 piles were tested



The assumed situation after 28 years



Upgrading of the Gudenaa Bridge

- With basic soil profiles and other tests probabilistic models for Q_1, Q_2 and Q_3 were formulated

$$Q_1 = c_u \cdot A_{cf}$$
$$Q_2 = S_u \cdot A_{fs} \cdot N_m$$
$$Q_3 = S_u \cdot A_{ff} \cdot N_m$$

- The relation between the capacity assessed on the basis of the pile driving Q_{DDR} and Q_P was established from the four tests results using MLM

$$Q_P = Q_3 + K \cdot Q_{DDR} + \Sigma$$

K : Bias Factor

Σ : Noise Factor

- A probabilistic model was established for each individual pile

$$Q_P = Q_1 + Q_2 + Q_3 + K \cdot Q_{DDR} + \Sigma$$

Upgrading of the Gudenaa Bridge

- A-priori models for the pile capacity were developed for each pile for the following situations:
  - after one month
  - after 28 years
- Posterior models were then established by Bayesian updating using three new experiments
- Based on the probabilistic models and the additional 3 experiments the piles could be upgraded and the bridge could be verified for class 100T traffic.