Methods to Assess the Quality of Non-Destructive Testing in Civil Engineering Using POD and GUM for Static Calculations of Existing Structures

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Abstract. To draw reliable conclusions from results gained with non-destructive testing methods in civil-engineering (NDT-CE) it is important to know about the quality of results. Since recent times, the POD (probability of detection) according to MIL-HDBK-1823A and Berens Report is established in non-destructive testing in civil engineering (NDT-CE) to assess the reliability of qualitative testing problems. For determining the uncertainty of measurements of quantitative (metric) problems the Guide (Guide to the Expression of Uncertainty in Measurements - GUM) is used in NDT-CE.

Now, a new approach is to adapt both methods to get statistically secured measurement results with NDT-CE from existing structures such as prestressed bridges.

This paper introduces how calculations based on stochastic models can be used together with NDT-CE results analysed with POD and the Guide.

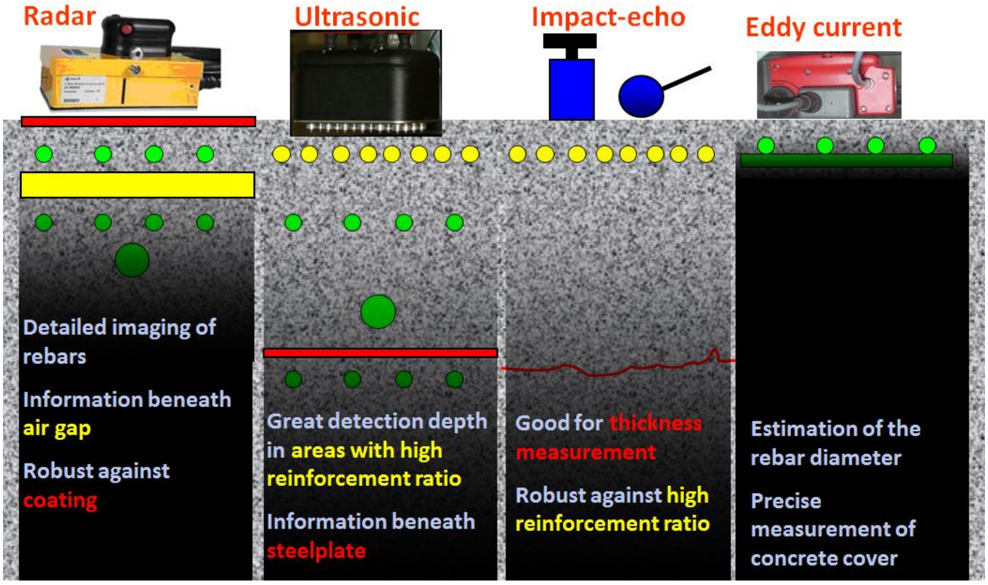
Introduction

This present article describes a new approach how statistic evaluated NDT results can be used in static recalculations of existing structures. After an introduction about the applied NDT methods in civil engineering and the existing bridge structures especially in Germany an overview of POD (Probability of Detection) [1], [2] and GUM (Guide to the Expression of Uncertainty in Measurement) [3] will be given. Afterwards the role of NDT results evaluated with POD and GUM “conditioned” for static calculations of bridges will be extracted.

1 Non-Destructive Testing Methods in Civil Engineering

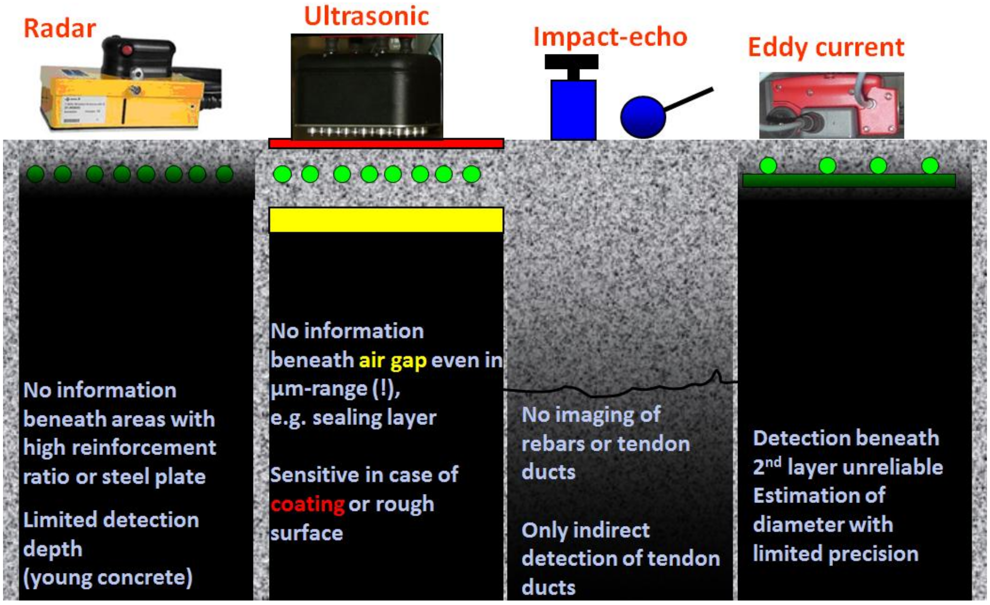
Techniques used in NDT-CE can be divided into classic and modern methods. The rebound hammer for estimating the concrete compressive strength, potential mapping for detecting areas with active corrosion or the concrete cover measurement with eddy current are representative classic methods. Examples for modern methods are ground penetrating radar

(GPR), often used for the detection of rebars and tendon ducts, ultrasound for the examination of honeycombs or the detection of tendons in higher depths or beneath an area of higher reinforcement ratio and impact-echo for thickness measurements. All above named methods have its strength and limitation. Pic. 1 contains an overview of the different strengths of four often used NDT-CE methods.



Pic. 1: Examples of NDT-CE methods with its strengths; according to [6]

The limitations of radar, ultrasonic, impact-echo and eddy current, which are also caused by the type of energy they transfer into the structure, are presented in Pic. 2.

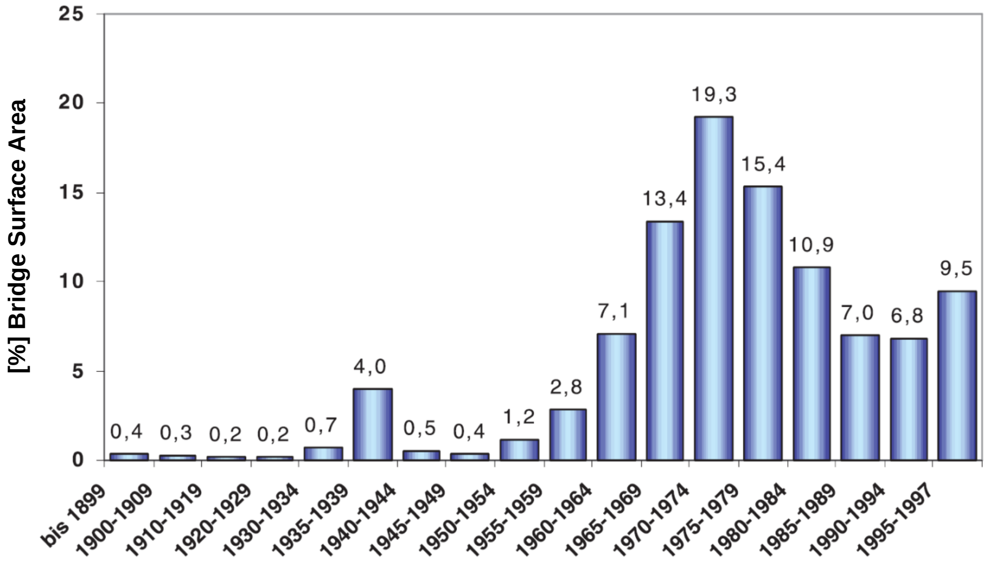


Pic. 2: Examples of NDT-CE methods with its limitations; according to [6]

For a safety application of different NDT-CE methods for solving different inspection tasks, its limits and uncertainties have to be well known.

2 Overview of the Existing Bridge Structure

The German road network contains around 38.000 federal highway bridges and around 120.000 bridges overall. Around 88% of all federal highway bridges are concrete or prestressed concrete bridges with approx.75 % of them 25 years and older [7] as shown in Pic. 3. Due to the advanced age of the bridges partial damages have been occurred so that the first maintenance activities have been carried out.



Pic. 3: age structure of federal highway bridges; cited from [7]

Due to a constantly increasing of traffic loads especially through the transport of goods, an increasing number of approved heavy load vehicles and the so called mega trucks or giga-liner the recent loads of bridges deviates from the specified load, for which the bridges were calculated. Considering the existing bridge damages, a static recalculation is partially essential.

When a realistic assessment of the bridge structures for a static recalculation is necessary or construction plans are missing, statistically evaluated results from NDT-CE measurements can be applied. But how can statistically evaluated results be achieved? Therefore, a new approach using POD and GUM and the advantages for the probability of failure of an existing construction are presented in the following chapter.

3 Approach for using NDT-CE in Static Recalculations

3.1 Introduction

To prepare the data gained from NDT-CE for static recalculation the following development is necessary. The first challenge contains the determination of the detection limits for a special inspection task by using the POD method. With the second step the uncertainty of this measurement will be established with the procedure described in GUM. Now a statistically verified result - e.g. concrete cover of a tendon duct measured with GPR with its uncertainty of measurement – may be applied in a static recalculation for the further calculation of the internal lever arm..

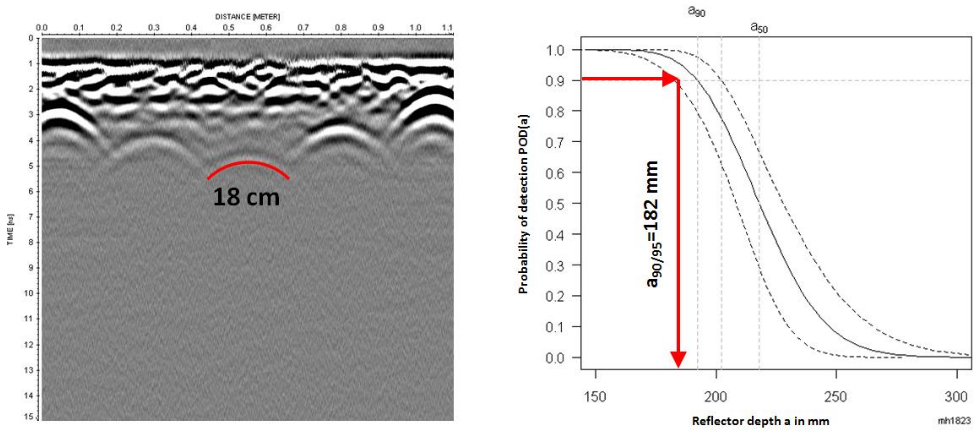
3.2 Determination of the Limits of Detection with the POD Method

The POD according to [1] and [2] has been established as a statistical tool to assess the reliability of a NDT system. Therefore, a POD curve provides an objective statement about the limits of detection for one special inspection task. After the verification of the four criteria for a valid POD calculation [4]

- linearity of the parameter â and a

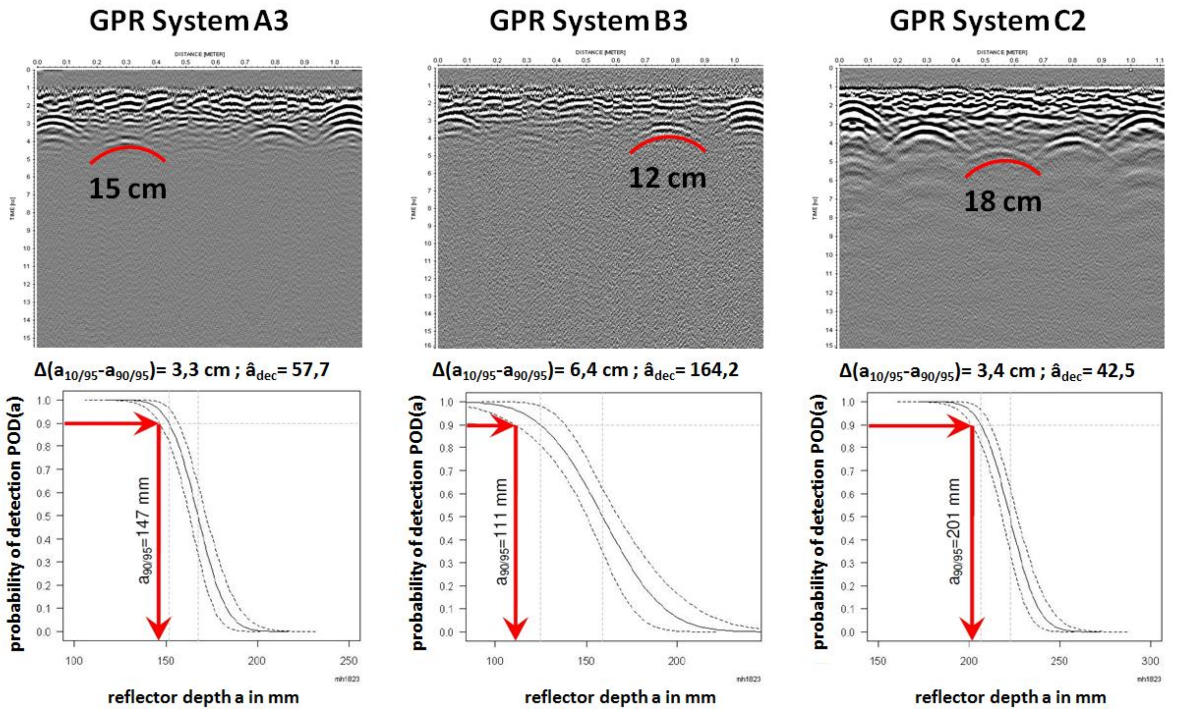
- uniform variance of the system responses â
- uncorrelated observations â
- multivariate normal distribution of the â errors

For this GPR investigations a decision threshold $\hat{a}_{dec}$ has to be determined e. g. by analysing the noise using the software mh1823 POD [1]. An objective value $a_{90/95}$ is the result of this POD calculation and describes the capability of the used NDT system for the certain inspection task (Pic. 4).



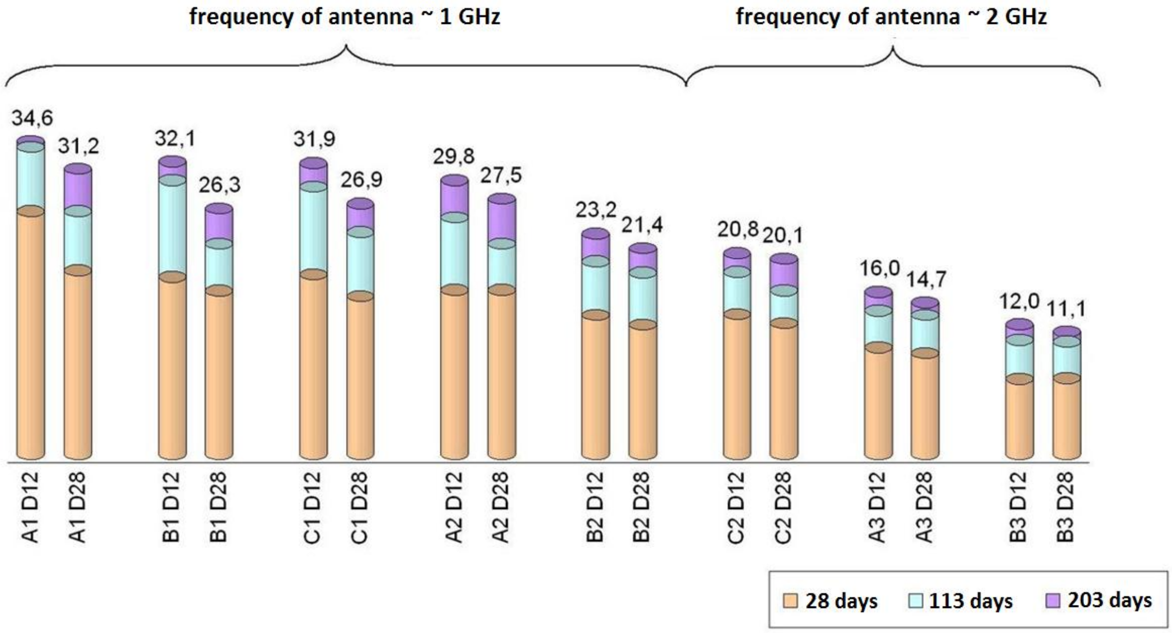
Pic. 4: POD curve with the reliable detection depth $a_{90/95}$ of a metallic reflector in concrete using GPR left: B-Scan recorded with GPR; right: calculated POD curve with $a_{90/95}$ of approx. 18 cm, cited from [4]

A comparison of different NDT-CE inspection systems is the second way using a POD calculation to choose the appropriate system for one specific inspection task. According to Pic. 5, which represents a comparison of different NDT systems, differences between the $a_{90/95}$ value, the decision threshold $\hat{a}_{dec}$, which is based on the system noise and the variance of the responses â which are reflected in the slope of the POD curve can be read out.



Pic. 5: comparison of different GPR systems with nearly the same antenna frequency (2 GHz), cited from [4]

To understand and determine the influence of different parameters on a certain NDT-CE result POD curves can be used, too. One result, which is shown in Pic. 6, is presented in a bar diagram established of eight pairs of bars. One pair stands for one GPR system. A pair of bars compares one GPR system concerning the reliable detection depth $a_{90/95}$ calculated by a rebar diameter of 12 mm against a diameter of 28 mm in a concrete age of 28 days, 113 days and 203 days. The left pair of bars compares the results of different rebar diameter recorded with the GPR system A1. Here the left bar represents the reliable detection depth $a_{90/95}$ calculated using the data collected on the specimen with the 12 mm diameter (A1 D12). The right bar of the left pair shows the $a_{90/95}$ value calculated with the recorded data on the specimen with the 28 mm diameter (A1 D28).

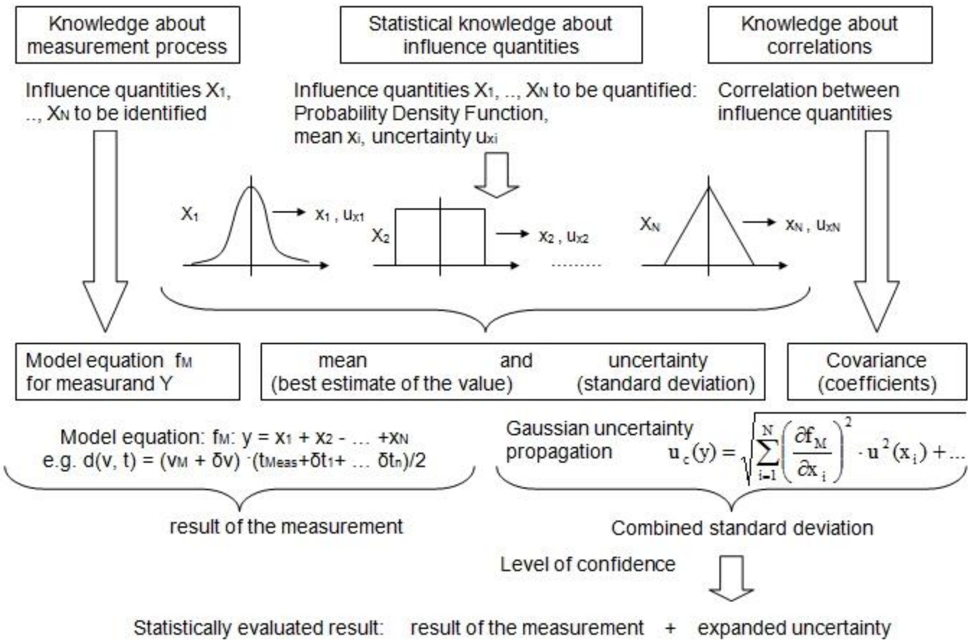


Pic. 6: Comparison of reliable detection depths $a_{90/95}$ from different GPR systems A, B, C to assess the influence of different rebar diameter, cited from [4]

As shown in the objective POD results in Pic. 6 a rebar with a 28 mm diameter will be detected in lower depths than a reflector with a diameter of 12 mm. The difference between both reliable detection depths using the GPR system A1 is approx. 3 cm in a concrete age of 203 days, when comparing the values with the collected data of the GPR systems B1 and C1, the difference is even approx. 6 cm. A possible reason of that result could be the displacement of electricity of conductors to their surface (skin effect). Due to that effect, the induced conduction current through the antenna spreads to a larger surface of the rebars when investigated the specimen with the 28 mm diameter. So the induced conduction current emits more indirectly to the GPR transmitter as the induced conduction current of a 12 mm rebar. That is different to the rebars with a small concrete cover arranged near to the surface. In this case, the larger diameter of 28 mm appears as a “metal plate” and so the signal amplitudes in comparison with a 12 mm rebar are much higher.

3.3 Determination of the Uncertainty in Measurement with the GUM Method

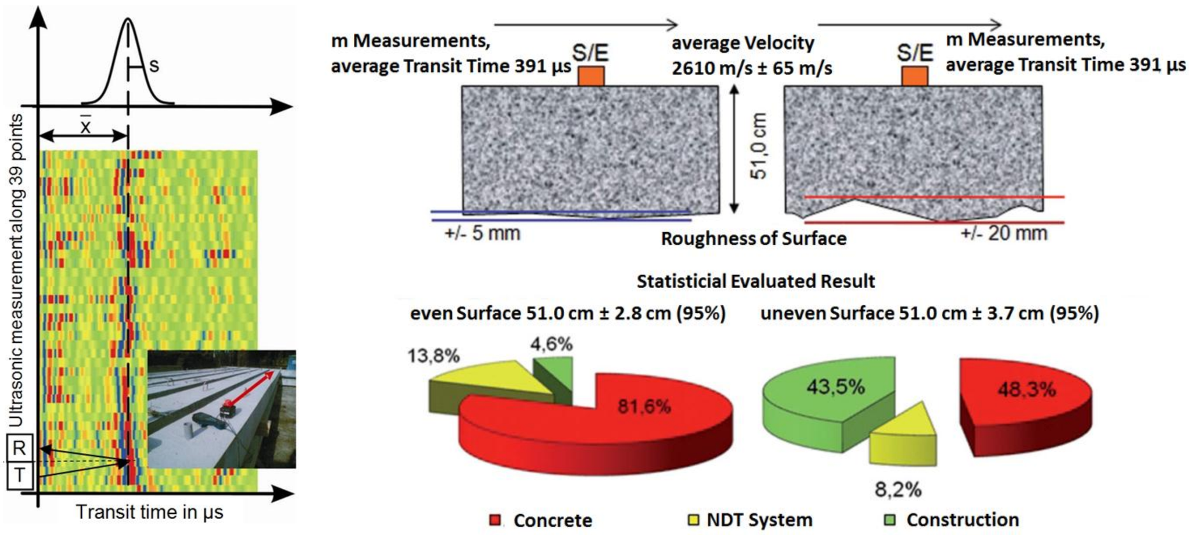
When the reliable detection depth $a_{90/95}$ of a rebar is known, the information about the uncertainty of this measurement is required. Therefore the GUM provides a uniform and internationally accepted procedure for expressing the uncertainty of measurement. With this method the knowledge about the measurement process and quantities influencing the result will be quantified. Pic. 7 represents the flowchart according to GUM [3] and Sommer [8].



Pic. 7: Flowchart according to GUM [3] and Sommer [8]: Knowledge about the measurement process and quantities influencing the results will be quantified. A statistically evaluated result at the end of the process allows drawing reliable conclusions. ([5], [9]), cited from [11]

After compiling the model equation and determining the quantities which influence the result of a measurement, the statistical knowledge (probability density function with mean and uncertainty) of this parameters has to be quantified. With the known correlations between the influence quantities the covariance coefficients can be calculated. The final result of this procedure is a statistically evaluated result in form of the measurement result and its expanded uncertainty e.g. the 95% confidence level.

An example for determining and analysing main influence quantities on the uncertainty of measurement is shown in Pic. 8.



Pic. 8: Uncertainty of thickness measurement with ultrasound as a quantitative inspection task, according to [10] and [12] left: variance of the backwall reflection; right: pie charts with main influences on the expanded measurement uncertainty

Quantities influencing the trueness and precision of the thickness measurement are e.g. the measurement variance from the NDT-system through coupling, the concrete quality through different compaction and unwanted thickness variation through the construction process. Analysing those parameters with software packages such as STRUREL or the

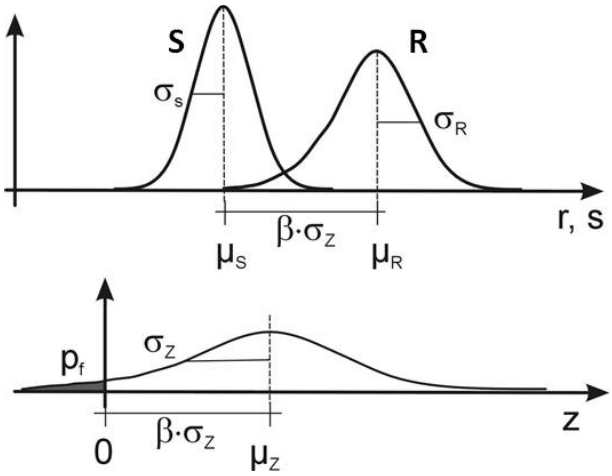
GUM Workbench as shown in Pic. 8 the influence of the construction on the uncertainty of thickness measurement is 43.5% when investigating a concrete member with an uneven surface (variance of ±20 mm). The expanded measurement uncertainty (95% confidence bound) in this inspection task is ±3.7 cm. The expanded measurement uncertainty will be reduced to ±2.8 cm when the surface variance is only ±5 mm. In this situation, the main influence with 81.6% is the different ultrasound velocity through different compaction.

As it can be seen on the explained quantitative inspection task the uncertainty of one specified inspection task can be established with the GUM procedure. Additionally the influence of different parameters on the expanded measurement uncertainty can be determined and minimized by analysing the pie charts.

Now the statistic evaluated measurement result can be applied for static recalculations.

3.4 Static Recalculation with Statistic Verified Measurement Result Gained from NDT-CE

The general principle of a static calculation is displayed in the upper part of Pic. 9. Therefore, two random variables R and S with a statistical distribution are used to oppose the stress S with the resistance R, where the random variable S is defined by the loads which occur to a structure like dead load, wind load or snow load. The resistance R contains the knowledge about a structure and depends on material parameters, geometrical dimensions, the positions of the tendon ducts and the reinforcement.



Pic. 9: General principle of a static calculation, cited from [14]

In the context of a valid static calculation of a new construction or a recalculation of an existing structure the resistance R has to exceed the stress S, otherwise the structure collapses. This is defined in the general limit state equation (1):

$$Z(R,S) = R - S = 0 \tag{1}$$

When both random variables R and S are normally distributed, the parameter μ_z and σ_z of the probability density function Z shown in the lower part of Pic. 9 can be calculated as:

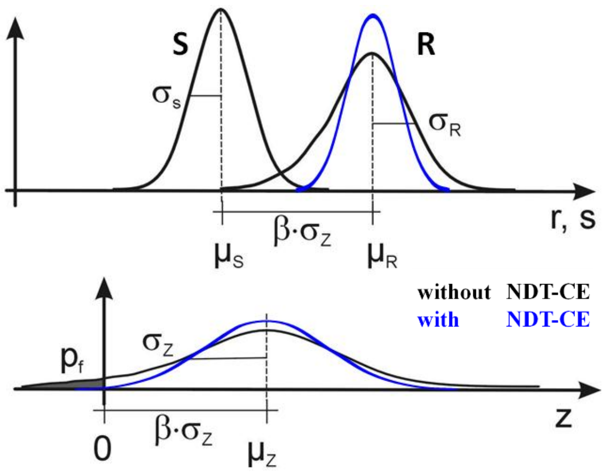
$$\mu_Z = \mu_R - \mu_S \tag{2}$$

$$\sigma_Z = \sqrt{\sigma_R^2 + \sigma_S^2} \tag{3}$$

With the parameter μ_z and σ_z, the reliability index β and the probability of failure p_f, which is defined as the probability, that the stress S exceeds the resistance R (Pic. 9) are calculable:

$$p_f = p(Z < 0) \tag{4}$$

The advantage of using statistically evaluated results from NDT-CE for a static recalculation is illustrated in Pic. 10. With a more precise knowledge of the resistance R of an existing construction, for example a more precise estimation of the concrete compressive strength through rebound hammer, the variance of R decreases and leads to a narrower probability density function. This has a positive effect on the probability of failure p_f, which decreases and on the reliability index β (see Pic. 10) because both are enhanced by an increasing variance σ_R (see Equation (3)). It is now the challenge to establish appropriate limit state equations containing the knowledge of the as-built structure and to quantify measured results as statistic variables.



Pic. 10: improvement of the reliability by using statistic evaluated NDT-CE results

4 Conclusion

An objective quality assessment of NDT methods in Civil Engineering by using the POD and GUM method was introduced in this paper. For the application the results in static recalculation, first, the limits of a special inspection task have to be determined with the POD method. After establishing the limits of a method or an inspection task, the uncertainty of measurement has to be calculated according to the GUM procedure. This so-processed measurement data can be used in a static recalculation and leads to a more reliable evaluation the resistance of the structure.

Some inspection tasks allowing the application of POD and GUM have a positive effect on the probability of failure p_f as listed below:

Qualitative Inspection Tasks:

- Detection of reinforcement/tendon ducts/backwall
  (Maximum of concrete cover of detectable reinforcement/tendon ducts)
- Detection of Fractured Strands in Tendon Ducts
  (Smallest number of fractured prestressed strands)
- Detection of Indications (Honeycombs, Flaws…)
  (Minimum size of detectable defects)

Quantitative Inspection Tasks:

- Thickness of the Structure
  (Accuracy of the component thickness for the deadweight calculation)
- Cover of Near Surface Reinforcement/Tendon ducts
  (Accuracy of the concrete cover for corrosion risk analysis or calculation of the inner lever arm)
- concrete compressive strength
  (Accuracy of the rebound number for the concrete compressive strength)

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