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POD and GUM
Universal Methods for Making Safety Measurable

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Abstract

Various non-destructive testing (NDT) methods such as ultrasounds (UT) or eddy current (ET) have been established for in-service inspections (ISI) or for condition assessment in different kind of industries such as in the nuclear or aerospace business. Another example for a common NDT inspection task is the detection of tendon ducts in the field of civil engineering (CE) using Ground Penetrating Radar (GPR) as well as the determination of its lateral and depth position. Therefore, the detection limits of the used inspection system, which depends on the depth position and the number of tendon ducts and distances between them, has to be well known. One approach to determine the limits of detection is the application of the POD method (probability of detection) as a universal procedure, which excludes the human factor and calculates the $a_{90/95}$ value and other characteristic parameters. With this information, different inspection systems can be compared objectively to choose the most suitable NDT-system for each individual inspection task. To distinguish between a real variation in the tendon duct position and the accuracy of the inspection system, the knowledge about the uncertainty of measurement is required. To determine the accuracy of the selected NDT-system, the GUM procedure (guide to the expression of uncertainty in measurement) has been established and provides a statistical evaluated result in form of the measurement result and its expanded uncertainty. This article introduces a procedure using the example of tendon duct detection (POD) and depth position description (GUM) in concrete with Ground Penetrating Radar (GPR). Finally, the universal application of both methods (POD and GUM) in different fields of industries is illustrated by some examples.

Keywords: Non-destructive Testing in Civil Engineering (NDT-CE), NDE Reliability, Probability of Detection (POD), Guide to the Expression of Uncertainty in Measurement (GUM), Ground Penetrating Radar (GPR)

1. Introduction

Across many industries, the knowledge about the structural condition as well as the description of potential damages like cracks, honeycombs or delaminations is indispensable. Therefore, different NDT methods have been established to locate wall thickness variations due to corrosion processes, to detect service induced flaws or for other in-field applications. Especially for concrete structures, the detection of rebars and tendon ducts are common inspection tasks, which associated with the NDT method Ground Penetrating Radar (GPR) due to the fast speed of data collection and the wide range of field applications on the one hand (DGZFP - Deutsche Gesellschaft für zerstörunsgfreie Prüfung, 2008; Kind & Maierhofer, 2004; Kind & Wöstmann, 2012; Kind, Feistkorn, Trela, & Wöstmann, 2009; Kind, Kurz, Taffe, & Wöstmann, 2013; Streicher, Taffe, & Boller, 2010; Trela, Kind, & Günther, 2015).

On the other hand, 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 approximately 75% of them 25 years and older (Naumann, 2014) as shown in Figure 1. Among the condition assessment, the re-creation of missing construction drawings is one essential task, for which NDT methods are used to provide important information such as material parameters or the number and position of rebars and tendon ducts. This NDT-generated information can also be taken into account for static recalculations of bridges, which are required due to the increasing number of approved heavy load vehicles and the so called mega trucks or giga-liner, which leads to a constantly increasing daily traffic volume with rising numbers of axles and allowable load per axel. In summary, the recent loads of bridges deviates from the specified loads, for which the bridges were statically verified. Considering additionally the actual bridge condition including all existing damages, a static recalculation is partially essential based on statistically evaluated results from NDT-CE measurements. But how can statistically evaluated results be achieved? Therefore, the POD method and the GUM procedure could be used and will be introduced in the following chapters.

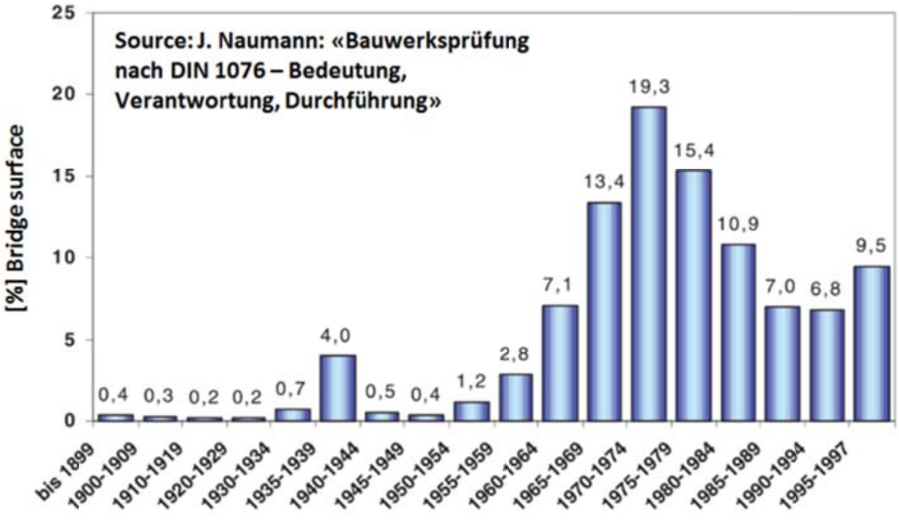

Figure 1. Age structure of bridges in Germany (Naumann, 2014)

To determine the limits of detection for metallic reflectors using GPR (issue: up to which depth it is reliable to detect a metallic rebar?) the POD method has been transferred to concrete in a PhD study (Feistkorn, 2012) based on (Department of Defence, 2009) and (Berens, 1989) conducted at BAM (Federal Institute of Materials Research and Testing). For the description of measurement uncertainties of different NDT methods on concrete (issue: how precise can the depth position of metallic reflectors be specified?) the GUM method (ISO/IEC Guide 98-3, 1995) has been established in civil engineering (Taffe, 2008).

2. Limitations of a specific NDT inspection task - Probability Of Detection (POD)

According to (Erhard, 2007) the fundamental objectives of non-destructive testing are the avoidance of disadvantages to humans and the environment, the optimization of manufacturing processes and the determination of material properties and geometric dimensions. To gain information about the limitations of an NDT inspection system, an objective criterion for its reliability is essential. The POD method, based on the “â vs. a” approach according to (Department of Defence, 2009) and (Berens, 1989), has been established as a statistical tool to assess this required reliability of an inspection system in the traditional field of NDT for metallic components providing objective information in form of so-called POD-curves. In this context, the term “reliability” was defined as “the degree up to which an NDT system is capable of achieving its purpose regarding detection, characterization and false calls” (Müller, et al., 2002).

Within the POD methodology, the “â vs. a” model shown in Figure 2 left plays a key role. Applying this model to GPR on concrete, the independent variable “a”, plotted on the horizontal axis, represents in the actual case the reflector depth of a rebar in concrete. The system response “â” is plotted on the vertical axis as a function of this reflector depth. Consequently, the black data points in Figure 2 left represent the pairs of reflector depth “a” and the corresponding system response “â”. In addition, the probability density functions [POD(a_1); POD(a_2); POD(a_3)] of the system responses “â” are also plotted in Figure 2 left.

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With an increasing reflector depth "a", the system responses "â" will decrease due to the attenuation in concrete and the divergence of the electromagnetic waves. In result, the regression line, connecting the mean values of the probability density functions, has a negative slope.

In addition, this "â vs. a model" has to satisfy the following four criteria for a valid POD calculation (Department of Defence, 2009):

- linearity of the parameter â and a
- uniform variance of the system responses â
- uncorrelated observations â
- normal distribution of the â errors

To calculate the detection probabilities POD(ai), a decision threshold âdec, displayed as a horizontal black dotted line in Figure 2 left, is required. In this regard, the decision threshold âdec separates the responses of the used GPR-system into signal and noise. Consequently the decision threshold âdec can be considered the "key value" in any POD analysis. If the response of the GPR-system is above âdec, it is treated as signal, whereas if the value of the response is below the âdec value, the response will be considered noise. If the decision threshold âdec in Figure 2 is shifted upwards, the false call rate and the a90/95 value decrease, when shifting âdec downwards, the false call rate and the a90/95 value increase. After determining a decision threshold âdec (e.g. by noise analysis), the POD curve with its characteristic value a90/95 is calculated as shown in Figure 2 right, here by using the software mh1823 POD (Department of Defence, 2009).

The $a_{90/95}$-value of 14.7 cm of the example shown in Figure 2 right above describes the reflector depth "a", in which a rebar will be detected with GPR in this particular case with a probability of 90% in 95 out of 100 cases (or in other words: 95% confidence bound). This value $a_{90/95}$ states, that up to this depth it is very unlikely to miss a metallic rebar (FN: False Negative result).

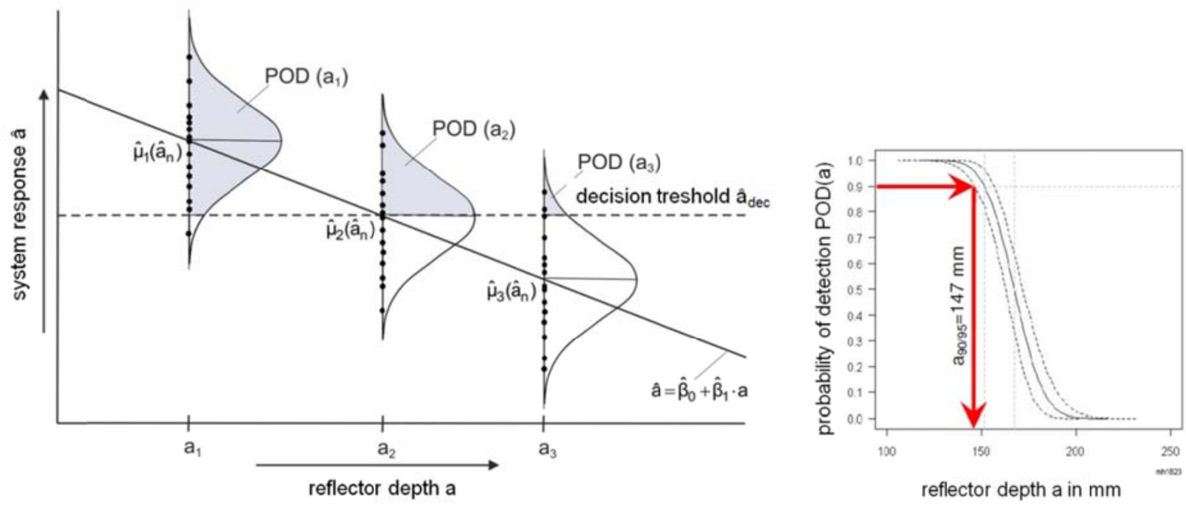

Figure 2 left. Example of the "â vs. a" model – correlation between the reflector depth "a"

and the GPR-system response "â"(Braml, Taffe, Feistkorn, & Wurzer, 2013)
Figure 2 right. Example for a POD curve; reliable detection depth $a_{90/95}$ of metallic reflectors in concrete; black solid line: calculated POD curve as the result of the conducted experiment; black dotted lines: upper and lower 95%-confidence bounds depending on the variance of the system responses â (Braml, Taffe, Feistkorn, & Wurzer, 2013)

In summary, the POD curve is a cumulative normal distribution and represents the percentage of area of the signal responses above the specified decision threshold âdec (grey shaded areas in Figure 2 left) in different reflector depths "a". With a POD curve as shown in Figure 2 right an objective criterion to describe a GPR-system is given. If POD curves are determined for different GPR-systems under the same conditions, the GPR-systems to be investigated can be compared objectively with different parameters such as the shape of the curve, the a90/95 value or the decision threshold âdec, if this value is determined based on the same noise analysis in all cases (further explanation is given in Feistkorn (2012)). Such comparison of different GPR-systems will reveal the most suitable one in an objective way for the analysed specific inspection task.

3. Uncertainties of a specific inspection task - Guide to the expression of Uncertainty in Measurement (GUM)

To calculate the size of the inner lever arm at a certain point of the concrete structure for a static recalculation due to the increased traffic loads as described in chapter 1, the detailed position of tendon ducts can be obtained normally from construction drawings. If these construction drawings are incomplete or totally missing, measurement results from NDT-CE methods such as GPR have to be taken into account to determine in field the real position of tendon ducts. In this case, the uncertainty of the used GPR inspection system has to be well known to distinguish between a real position variation of the tendon ducts and the accuracy of the NDT-system for the following structural recalculation. This uncertainty of measurement cannot always been quantified by carrying out multiple measurements and calculating the standard deviation. Therefore, the Guide to the Expression of Uncertainty in Measurement (ISO/IEC Guide 98-3, 1995) provides a uniform and internationally accepted procedure for expressing measurement uncertainties and for combining individual uncertainty components (influence quantities expressed as statistic variables X_i in Figure 3) into a single total uncertainty u_c of the quantity of interest (such as the measured transit time or tendons depth position; expressed as measurand Y). The procedure becomes transparent, helps to quantify knowledge in a statistical way and the results will be comparable (Braml, Taffe, Feistkorn, & Wurzer, 2013).

Standard deviations can either be evaluated by statistical methods or can be derived from expert knowledge, e.g. when the upper and the lower limit of a quantity is known. Applying the Gaussian uncertainty propagation and evaluating the correlation between different influence quantities (e.g. measurement of the propagation velocity of the electromagnetic waves and the later conversion in the depth position by using the same GPR device) a combined standard deviation can be calculated. If one quantity has changed, e.g. a more

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precise GPR device (increased precision under repeatability conditions) is used, the updated standard deviation will be used in the calculation and its effect on the total uncertainty can be evaluated once a model equation f_M has been set up. So the GUM approach helps to avoid the repetition of the whole measurement (Braml, Taffe, Feistkorn, & Wurzer, 2013).

The GUM-procedure according to Figure 3 will be shown for the example of a tendon duct concrete cover determination. The measurand Y is the depth position of a tendon duct and its expanded uncertainty on a certain level of confidence is of interest for further static recalculations. The model equation f_M for the concrete cover (left part of Figure 3) contains the propagation velocity v of the electromagnetic waves and the measured transit time t_{Meas} multiplied and divided by two in case of an echo-arrangement of the GPR antenna (transducer and receiver on the same side). The δ-values in f_M just indicate random errors of each influence quantity; they will be quantified as standard deviation u_{Xi} and put in the equation of $u_c(y)$ shown in the right part of Figure 3. Though the model equation f_M is very simple in that example, the equation for $u_c(y)$ gets more complicated the more influence quantities will be regarded. One basic influence quantity is the repeatability of the GPR equipment, which can be evaluated as standard deviation of the measured transit-time under repeatability conditions. Another influence quantity of great importance is the propagation velocity of the electromagnetic waves with random error due to variance in the concrete quality. A further influence quantity of the measured concrete member might be its unevenness, which can be quantified according to GUM as a standard deviation from an upper and a lower limit (Braml, Taffe, Feistkorn, & Wurzer, 2013).

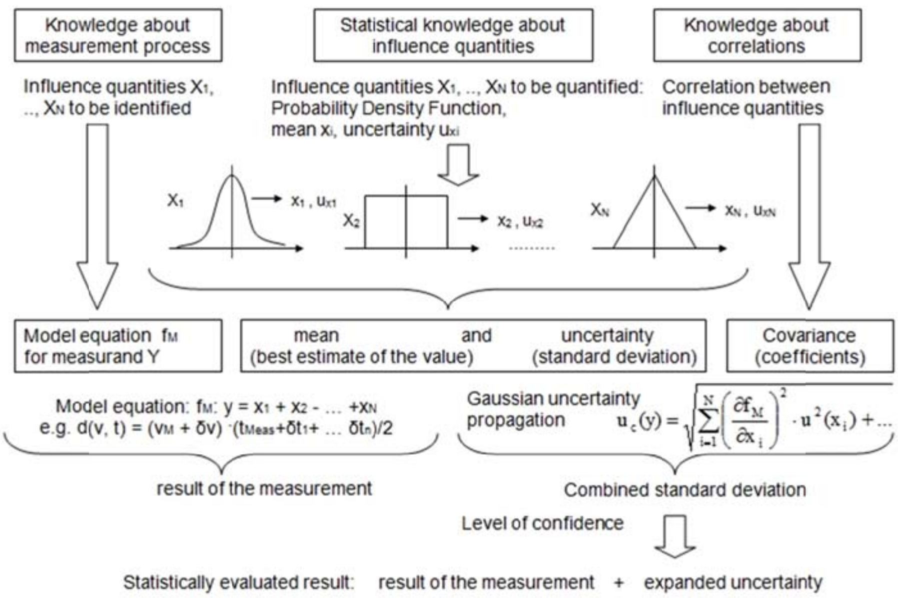
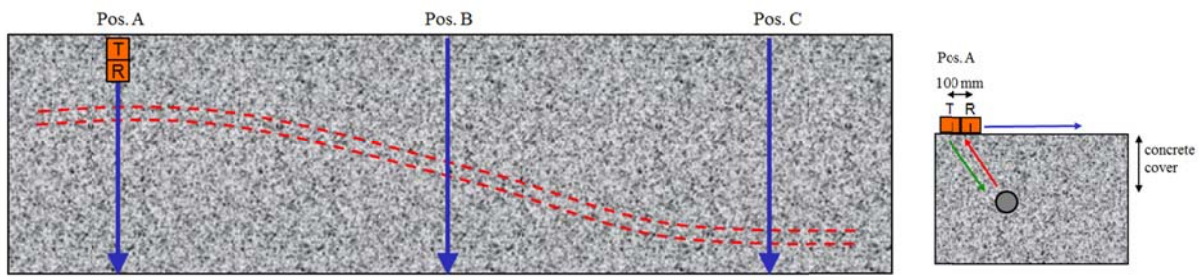


Figure 3. Flowchart according to GUM (ISO/IEC Guide 98-3, 1995) and Sommer & Siebert (2006): Knowledge about the measurement process and quantities influencing the results will be quantified. A statistical evaluated result at the end of the process allows drawing reliable conclusions. (Taffe, 2008), (Taffe & Gehlen, 2010)

In the introduced example of the uncertainty in tendon duct positions, the probability density function in Figure 4d represents the total standard deviation s of all influence quantities described above as well as the real position variation of the tendons in the bridge main girder.

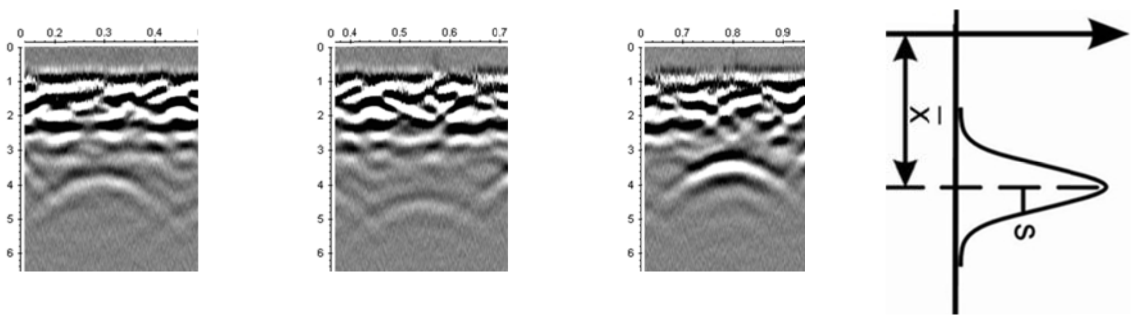
The calculated uncertainty gained from measurements on a tendon duct in the estimated depth position of 50 mm is only valid for this particular case (GPR equipment, concrete member, construction). If each standard deviation s_i has been quantified separately, a combined standard deviation s can be calculated with the equation for $u_c(y)$. It contains all influence quantities, which also can be visualized in an uncertainty budget. This budget reveals, which quantities have the main influence and which quantities can be neglected. For the data analyst it becomes obvious, which quantity he has to accept (e.g. unevenness, variation of pulse velocity) or which one can be influenced (e.g. precision of the GPR equipment). At the end of the process in Figure 3 is the statistically evaluated result, which defines a specified level of confidence, in which the true but always unknown value of the tendon duct position is located with a certain probability (e.g. 95%) This result is an import value for the static recalculation based on a probabilistic analysis.

Computer software such as GUM-Workbench from metrodata makes it very easy to set up a model equation. Each influence quantity will be recognized automatically and has to be added with statistical parameters. A matrix allows the input of correlation between different quantities. In summary, the procedure according to GUM offers a very flexible and uniform method to quantify uncertainties for a later use of i.e. basic variables in the general limit state equation.



a) example of a bridge main girder (top view); red lines = tendon duct position b) side view of the bridge

Pos. A Pos. B Pos. C



c) B-Scans d) standard deviation

Figure 4. Example for the description of uncertainties in measurements;
a) example of a bridge (top view) with tree different positions for GPR measurements;
b) side view of the bridge main girder in Pos. A (T: Transducer; R: Receiver);
c) B-Scans (Radargrams) with clear reflections from tendons in form of hyperbolae and its corresponding transit times in [ns] in Pos. A, B and C;

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d) the standard deviation s quantifies the uncertainty of measurement in case of concrete cover measurements of tendon ducts by moving the antenna in different positions; the mean of the depth position (x□) can be derived from NDT results

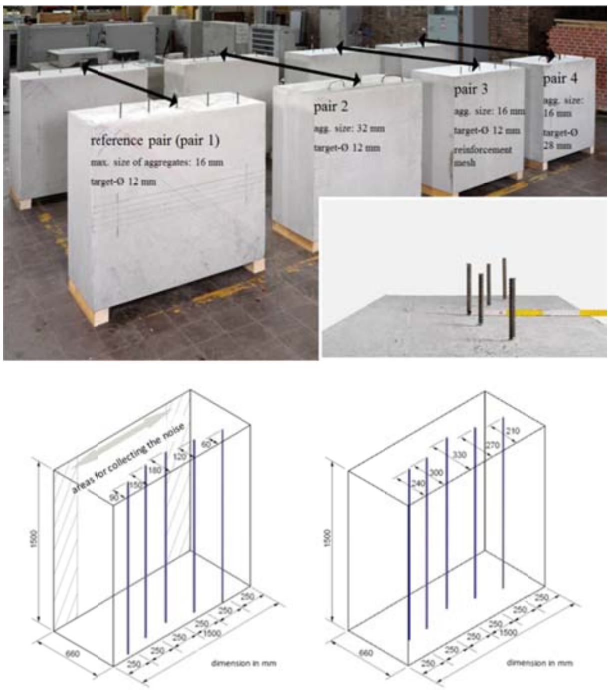
4. Example for the practical application of POD and GUM using GPR on concrete

4.1 Limitations of tendon duct detection

For a structural analysis or a static recalculation, the number and position of tendon ducts has to be well known due to the calculation of the inner lever arm. Therefore, the detection limitations - up to which depth it is possible to detect tendon ducts reliable - of the selected GPR inspection system has to be determined. In (Feistkorn, 2012) the reliability of different GPR-systems was analyzed under different conditions by varying the concrete age, the maximum size of aggregates, the reflector diameter, the density of a near reinforcement mesh and the GPR-systems itself.

To select a GPR-system, which provides the required reliable detection depth $a_{90/95}$, Table 1 could be used as a reference. It has to be taken into consideration, that the presented results were obtained on metallic rebars with diameter of 12 mm (Table 1) respectively 28 mm (Table 2), whereas the diameter of tendon ducts are in the region of 80 mm.

Table 1. Reliable detection depths $a_{90/95}$ (right side) for all investigated GPR-systems collected on reference specimens (left side) with a reflector diameter of 12 mm over a period of 336 days



reliable detection depths $a_{90/95}$ in cm **of a metallic reflector (ø 12 mm) for GPR-system**								
concrete age	**A1**	**B1**	**C1**	**A2**	**B2**	**A3**	**B3**	**C2**
7 days	23.2	18.6	18.2	17.4	15.7	8.1	6.1	14.5
13 days	27.0	19.3	20.4	18.6	17.1	10.1	7.0	15.1
28 days	30.0	21.9	22.2	20.3	17.2	13.2	9.3	17.3
42 days	31.5	24.6	27.4	20.5	17.8	13.8	10.1	19.1
57 days	31.9	25.6	29.3	24.0	18.2	14.1	10.2	19.9
113 days	35.9	31.8	31.0	27.2	21.8	15.7	12.1	20.5
203 days	34.6	32.1	31.9	29.8	23.2	16.0	12.0	20.8
286 days	36.5	31.8	32.8	31.5	23.5	16.6	11.5	22.0
336 days	41.4	34.1	32.5	30.3	22.8	17.2	12.3	22.5

Through the recording of these values on reference specimens, a transfer to practical applications is needed. Therefore, the reliable detection depths $a_{90/95LF}$ (low frequent GPR-systems) and $a_{90/95HF}$ (high frequent GPR-systems) will be calculated as mean values of the experimental setup on reference specimens with a rebar diameter of 28 mm to be as close as possible in the diameter range of tendon ducts. As the determined reliable detection depth is only valid in the experimental environment of the designed test blocks, the reliable detection depth will be reduced by 20% to take into account potential in-field variations such as different concrete recipes as well as different tendon duct diameter (Feistkorn & Algernon, 2015).

Table 2. Reliable detection depths $a_{90/95}$ of different GPR-systems; concrete age of ~ 200 days

reliable detection depth $a_{90/95}$ in cm of a metallic reflector (ø 28 mm) for different								
specific value	**low frequent GPR-systems with an antenna frequency f_m ~ 1 GHz**					**high frequent GPR-systems with an antenna frequency f_m ~ 2 GHz**		
$a_{90/95}$	26.9	26.3	31.2	27.5	21.4	20.1	11.1	14.7
a_{50}	32.1	31.7	36.3	30.0	26.0	22.4	15.9	16.7
$\hat{a}_{90/95}$	26.7					15.3		

Based on the conducted experiments with a 28 mm rebar in concrete, the following reference values for reliable detection depths of tendon ducts will be recommended (Feistkorn & Algernon, 2015):

- low frequent GPR-systems with an antenna mid frequency of ~ 1 GHz:
  feasible detection depth: $a_{90/95LF}$ = 21.4 cm
- high frequent GPR-systems with an antenna mid frequency of ~ 2 GHz:
  feasible detection depth: $a_{90/95HF}$ = 12.2 cm

The conducted investigations lead to the conclusion, that it would be possible to detect a tendon duct in a depth of 21.4 cm reliable with a probability of 90% in the 95% confidence bound with low frequent GPR-systems without considering the human factor. Disadvantageous in-field conditions, such as high concrete moisture content, can reduce the reliable detection depth. Another example for the decrease of the reliable detection depth is the presence of near surface reinforcement meshes, depending on the GPR-system and the density as well as the lateral position of the mesh relative to the tendon ducts. For example, the near surface reinforcement mesh Q188A leads to a reduction between 3% and 27% of the reliable detection depth (Feistkorn, 2012).

4.2 Uncertainty of Measurement for the depth positioning of tendon ducts

The concrete cover of near surface reinforcement can be described very precise with a maximum deviation of +/- 2 mm up to a concrete cover of 60 mm by using magnetic inductive methods (Deutscher Beton- und Bautechnik-Verein, 2002/2011). High density of reinforcement or reinforcement in larger depths like tendon ducts makes it necessary to use alternative methods such as GPR. Therefore it is important to know the accuracy of the used inspection system. In (Streicher, Taffe, & Boller, 2010) the model equation based on GUM

(ISO/IEC Guide 98-3, 1995) was set up with the objective to clarify, if scanning measurements with a defined air gap between the GPR antenna and the concrete surface leads to an acceptable uncertainty of measurement. Due to the constant offset of 100 mm between Transmitter (T) and Receiver (R) it has to be considered, that this systematic error as well as the constant air gap between the antenna and the surface has to be corrected in the result of the measurement. Only the random error in the distance between the antenna and the concrete surface (air gap) has to be included in the calculation of the measurement uncertainty according to the GUM procedure (ISO/IEC Guide 98-3, 1995).

The calculated results of the measurement uncertainty using the software GUM-workbench in the case of a precise location of a tendon duct in the depth of 50 mm are displayed in Figure 5. Therefore, the random errors in various parameters, such as the “permittivity ε” (propagation velocity of the electromagnetic waves in concrete), the “air gap”, the “GPR lead-time”, the “GPR-system” (precision under repeatability conditions) and the resolution of the “time axis”, which influences the uncertainty of measurement, will be considered and entered in the model equation, but not discussed in detail in this article (see uncertainty budget in Figure 5 and Taffe & Feistkorn (2013) and Streicher, Taffe, & Boller (2010)).

If the systematic error in form of the transit time extension due to the constant distance of 100 mm between Transmitter and Receiver is corrected, the standard deviation is 2.2 mm if the antenna is coupled with the concrete surface. Further, the standard deviation increases only to 2.6 mm, if the air gap between the GPR antenna and the concrete surface is between 0 mm and 20 mm assuming a rectangular distribution in case of rough and uneven surfaces (Streicher, Taffe, & Boller, 2010). Although this value of 2.6 mm is above the required maximum threshold according to Deutscher Beton- und Bautechnik-Verein (2002/2011), it should be considered as acceptable to determine larger concrete cover values precisely with the GPR method instead of magnetic-inductive methods. This fact also leads to the conclusion, that scanning measurements, where always an air gap is necessary between the antenna and the surface, provides enough accuracy for the concrete cover determination of tendon ducts. Only a gap between 0 and 40 mm will be the dominant influence parameter in the budget of uncertainty (see Figure 5).

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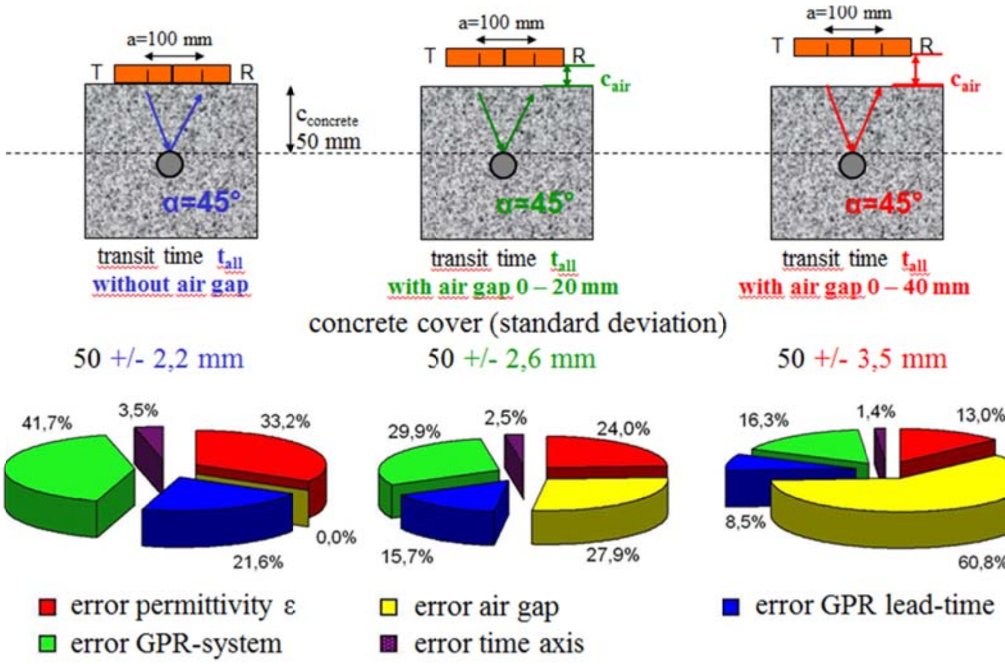

Figure 5. Measurement of concrete cover for tendon ducts using the GPR-method: Distance of transducer (T) and receiver (R) 100 mm, 45° angle, concrete cover 50 mm. Budget of uncertainty: without air gap between antenna and surface (left), air gap between 0 and 20 mm (middle) and air gap between 0 and 40 mm (right), based on (Taffe & Feistkorn, 2013)

For larger concrete cover values, the influence of the "permittivity ε" will increase while the influence of the "time axis" as well as the influence of the "GPR-system" and the "GPR lead-time" has a lower impact for the uncertainty of measurement budget.

5. Conclusions

An objective quality assessment of a specific NDT inspection task on concrete using the GPR method was introduced in this article. First, the limits of detection for tendon ducts with different concrete cover were determined with the POD approach on different specimens for the later in-field application. In a second step, the accuracy of the selected GPR-system was calculated. This determination of measurement uncertainty according to the GUM procedure provides a statistically evaluated measurement result including its expanded uncertainty as well as the associated budget of uncertainty. The so-processed measurement data can be used i.e. for static recalculations and lead to a more reliable evaluation of the structure resistance. Some other inspection tasks, where the application of POD and GUM could have a positive effect for establishing various NDT-CE methods in practice are listed in Taffe & Feistkorn (2013) and Feistkorn & Taffe (2014). Also both methods are applicable to specific inspection tasks in other industries such as aerospace or nuclear. The POD method could be support the decision, whether if a new specific inspection system provides better detection rates than the one previously used or if a new detection criterion can be achieved. If material parameters such as surface or coupling conditions have changed, the influence on the detection rate can also be analysed by using the POD method. One important field for the application of the GUM procedure could be the discrimination between the specific uncertainty of an inspection system and real crack growth with regard to in-service inspections (ISI). Furthermore, effects of modifications concerning the inspection system or the material and environment conditions on the uncertainty of measurement or the uncertainty budget can be calculated by applying the GUM procedure to the adapted inspection situation.

In summary, due to the variable and universal application of POD and GUM, both methods can be used in other industries for a wide range of inspection tasks to analyse them objectively in terms of performance and accuracy and to quantify any condition changes.

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References

Berens, A. P. (1989). *NDE Reliability Analysis, Reprinted from Metals Handbook Volume 17, 9th Edition: Nondestructive Evaluation and Quality Control.* University of Dayton Research Institute.

Braml, T., Taffe, A., Feistkorn, S., & Wurzer, O. (2013). Assessment of existing structures using probalilistic analysis methods in combination with non-destructive testing methods. *Structural Engineering International - Journal of the International Association for Bridge and Structural Engineering (IABSE), SEI Volume 23, Number 4*, 376-385.

Department of Defence. (2009). *MIL-HDBK-1823A Nondestructive Evaluation System Reliability Assessment.*

Deutscher Beton- und Bautechnik-Verein. (2002/2011). *DBV-Merkblatt: Betondeckung und Bewehrung.* Berlin: Eigenverlag.

DGZFP - Deutsche Gesellschaft für zerstörunsgfreie Prüfung. (2008). Merkblatt B10 über das Radarverfahren zur Zerstörungsfreien Prüfung im Bauwesen. Berlin.

Erhard, A. (2007). Aufgaben und Abgrenzung der Zerstörungsfreien Prüfung. *DGZfP-Jahrestagung 2007 DGZfP BB 104-CD.* Fürth.

Feistkorn, S. (2012). *Gütebewertung qualitativer Prüfaufgaben in der zerstörungsfreien Prüfung im Bauwesen am Beispiel des Impulsradars* (Bd. Heft 603). (D. A. Stahlbeton, Hrsg.) Berlin: Beuth Verlag.

Feistkorn, S., & Algernon, D. (2015). Reliability and uncertainty for relevant GPR inspection tasks in field (with TFB Switzerland for FEDRO). *unpublished*.

Feistkorn, S., & Taffe, A. (2014). Methods to assess the quality of non-destructive testing in civil engineering using POD and GUM for static calculations of existing structures. *Materials Testing, Volume 56*, 611-616.

ISO/IEC Guide 98-3. (1995). *Uncertainty of measurement - Part 3: Guide to the expression of uncertainty in measurement GUM.*

Kind, T., & Maierhofer, C. (2004). Das Impulsradarverfahren - ein Verfahren zur zerstörungsfreien Strukturaufklärung in Bauwerken. In E. Cziesielski, *Bauphysik-Kalender 2004* (S. 333-341). Berlin: Ernst und Sohn.

Kind, T., & Wöstmann, J. (April 2012). Kombinierte Radar und Ultraschalluntersuchungen zum schadfreien Kernbohren im Zuge einer Verstärkung. *Beton- und Stahlbetonbau 107*, S. 255-261.

Kind, T., Feistkorn, S., Trela, C., & Wöstmann, J. (Dezember 2009). Impulsradar für schadensfreie Kernbohrungen an Spannbetonbrücken. *Beton- und Stahlbetonbau 104*, S. 876-881.

Kind, T., Kurz, J., Taffe, A., & Wöstmann, J. (2013). Ortung und Unterscheidung von Querspanngliedern hinter schlaffer Bewehrung mit dem Radarverfahren in einer Fahrbahnplatte. *DGZfP-Jahrestagung 2013 Berichtsband DGZfP BB 141*. Dresden.

Müller, C., Elaguine, M., Scharmach, M., Redmer, B., Ewert, U., Schaefer, L., & Wilrich, P.-T. (2002). Reliability investigation of NDT systems by modular analysis of recorded data. *8th ECNDT Proceedings - European Conference on Nondestructive Testing*. Barcelona.

Naumann, J. (2014). *Bauwerksprüfung nach DIN 1076 - Bedeutung, Verantwortung, Durchführung*. Von https://tu-dresden.de/bu/bauingenieurwesen/imb/ressourcen/dateien/veranstaltungen/dbbs/14_DBBS/02_download/14bbs_02.pdf abgerufen

Sommer, K.-D., & Siebert, B. R. (2006). Systematic approach to the modelling of measurements for uncertainty evaluation. *Metrologia 43*, 200-210.

Streicher, D., Taffe, A., & Boller, C. (2010). Quantitative Ermittlung der Leistungsfähigkeit von Radar an Stahl- und Spannbetonbauteilen. *DGZfP-Jahrestagung 2010 Berichtsband DGZfP BB 122-CD*. Erfurt.

Taffe, A. (2008). *Zur Validierung quantitativer zerstörungsfreier Prüfaufgaben im Stahlbetonbau am Beispiel der Laufzeitmessung* (Bd. Heft 574). (D. A. Stahlbeton, Hrsg.) Berlin: Beuth Verlag.

Taffe, A., & Feistkorn, S. (2013). Methoden zur Gütebewertung von ZfPBau-Verfahren. *Beton- und Stahlbetonbau 108*, 237-251.

Taffe, A., & Gehlen, C. (2010). Methodology for the validation of NDT-CE methods using transit time measurement. *7th International Symposium on Non Destructive Testing in Civil Engineering NDT-CE 09*, (S. 997-1002). Nantes.

Trela, C., Kind, T., & Günther, M. (2015). Ground penetrating radar in reflection vs transmission mode for void detection in concrete structure. *International Symposium Non-Destructive Testing in Civil Engineering (NDT-CE)*. Berlin.