

Methodology for the validation of NDT-CE methods using transit time measurement

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Abstract

Validation is in many fields of technology state-of-the-art to furnish the proof that customer demands are fulfilled. Validation contributes to improve the application safety of a method and helps to leverage not standardised methods. A validation methodology has been developed with the three main steps “method characterisation”, “customer demands” and “customer fulfillment”. Starting with a universal approach, the methodology is specified for non-destructive testing methods (NDT) utilising transit time as measurand. The validation methodology can also be applied to other NDT-methods. The uncertainty of measurement plays a decisive role in method characterisation. The uncertainty of measurement is determined according to the Guide to the Expression of Uncertainty in Measurements (GUM). To furnish the proof of customer fulfillment, statistical standard methods (confidence interval and significance test) can be applied as well as methods of reliability theory used for the first time in NDT in civil engineering. This contribution rounds off with an application for a validation for the pile length measurement at bored concrete piles applying Low-Strain method.

Résumé

La validation sert déjà dans plusieurs domaines techniques pour vérifier, si les demandes des clients peuvent être réalisées. De plus, la validation aide à obtenir une meilleure certitude d'application, et fait avancer l'application des méthodes qui ne sont pas encore standardisées. L'article présente une méthodologie de validation comprenant trois principales étapes « caractérisation de la méthode », « exigences du client », « satisfaction du client ». Commencant d'abord par une approche globale, la méthodologie est spécifiée pour les contrôles non destructifs qui utilisent la mesure du temps de propagation du signal. Cette méthodologie peut être appliquée aussi pour d'autres contrôles non destructifs. La connaissance de l'incertitude de la mesure est essentielle pour la caractérisation de la méthode. Elle est calculée selon le GUM (Guide to the Expression of Uncertainty in Measurements). Pour répondre aux exigences des clients les méthodes statistiques classiques sont appliquées et, pour la première fois dans le domaine des contrôles non destructifs du génie civil, la méthode de la fiabilité est appliquée. L'article conclut avec un exemple de validation : La longueur des pieux du béton avec la méthode du Low-Strain.

Keywords

Validation, uncertainty of measurement, pile length measurement, low-strain method, ultrasonic, transit-time

1 Validation of NDT in Civil Engineering

In civil engineering only a few standards exist for non-destructive testing (NDT-CE). In the field of concrete repair regulations have affected quality in a very good way. For NDT-

CE methods the effect of a German regulation called RI-ZFP-TU [1] is very encouraging. It assures the high quality of tunnels and its inner shell construction. For quality assurance the contractor has to carry out non-destructive testing (ultrasonic-echo or impact-echo) to detect areas of reduced thickness in the inner shell of the tunnel to prevent cost intensive damages of the tunnel sealing that cause leakage. The exact description of the testing process (areas that have to be tested, measuring grid etc.) and the certification of the personnel staff have improved the application safety. The regulation is the result of an intensive characterisation of the ultrasonic-echo and impact-echo testing methods and the proof that the requirements of the building owner are satisfied. This process of successful validation encouraged BAM to validate the process for further testing tasks and to establish these testing methods in the construction process or damage assessment process. Furthermore, a general methodology for validation of NDT has been developed [2]. The results presented in this article follow this methodology.

To use the term of validation has become very common. But often it is unknown what is meant by true validation. By using this term in the sense of the DIN EN/ISO 17025 [3] the true meaning and the process of validation should be established in the field of civil engineering according to section 2.

2 Validation Process

Validation according to DIN EN ISO 17025 is the *confirmation by testing to furnish the proof that the requirements for a certain intended use can be fulfilled*. The client – in some cases together with the service provider – expresses his requirements considering all necessary boundary conditions. If a testing method – suggested by the service provider – succeeds to satisfy these requirements the validation process is completed. The validation process according to [3] consists of three steps:

- Characterisation of a testing method
- Requirements of the client
- Proof that the client's requirements have been fulfilled.

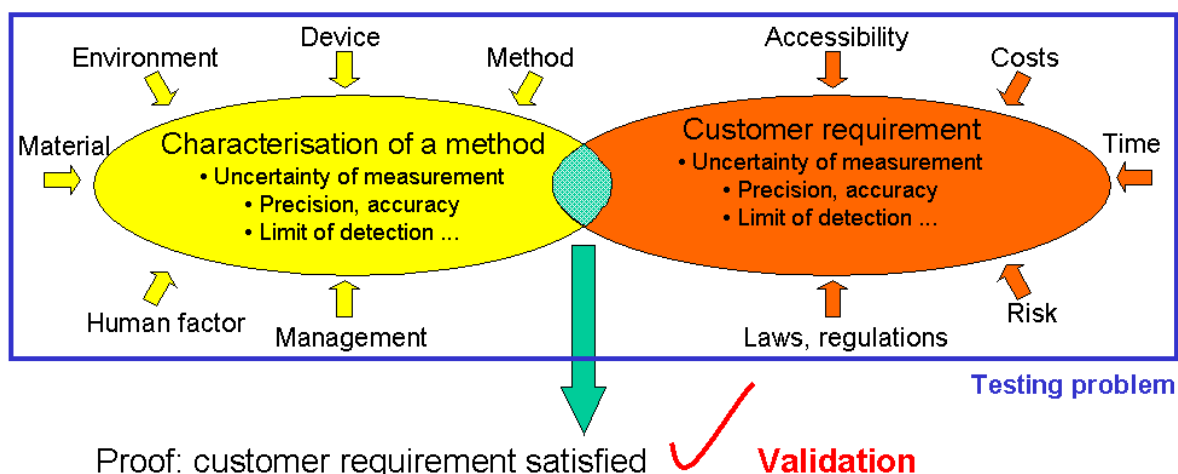


Figure 1. Validation process according to [2] developed from [3]

Figure 1 from [2] visualises this process: characterisation is done by regular testing in research and development and evaluating the results. Calculating the uncertainty of

measurement, determining the precision, accuracy and limit of detection etc. are possibilities to characterise a method under certain boundary conditions (method, device, environment etc.). Also the customer requirements are expressed by the properties mentioned before. They are influenced by time, cost, accessibility etc. All these together form the individual testing problem. A testing method under the characterised methods that is suitable for the testing problem is marked by the intersection of characterisation and customer requirement. The validation is at the end of the process if the proof is furnished that customer's requirements are satisfied.

3 Uncertainty of Measurement according to GUM

As shown in Figure 1 the determination of the uncertainty of measurement plays an important role in the characterisation of a method. This will be carried out according to the Guide to the Expression of Uncertainty in Measurement (GUM) [5]. It has internationally been accepted in the meantime and has normative character. The GUM easily describes how to evaluate the quality of a result. Its all-purpose formulation allows easy transfer to civil engineering. The GUM shows the necessity and the success of a standardised and transparent process that should also be developed for the validation process.

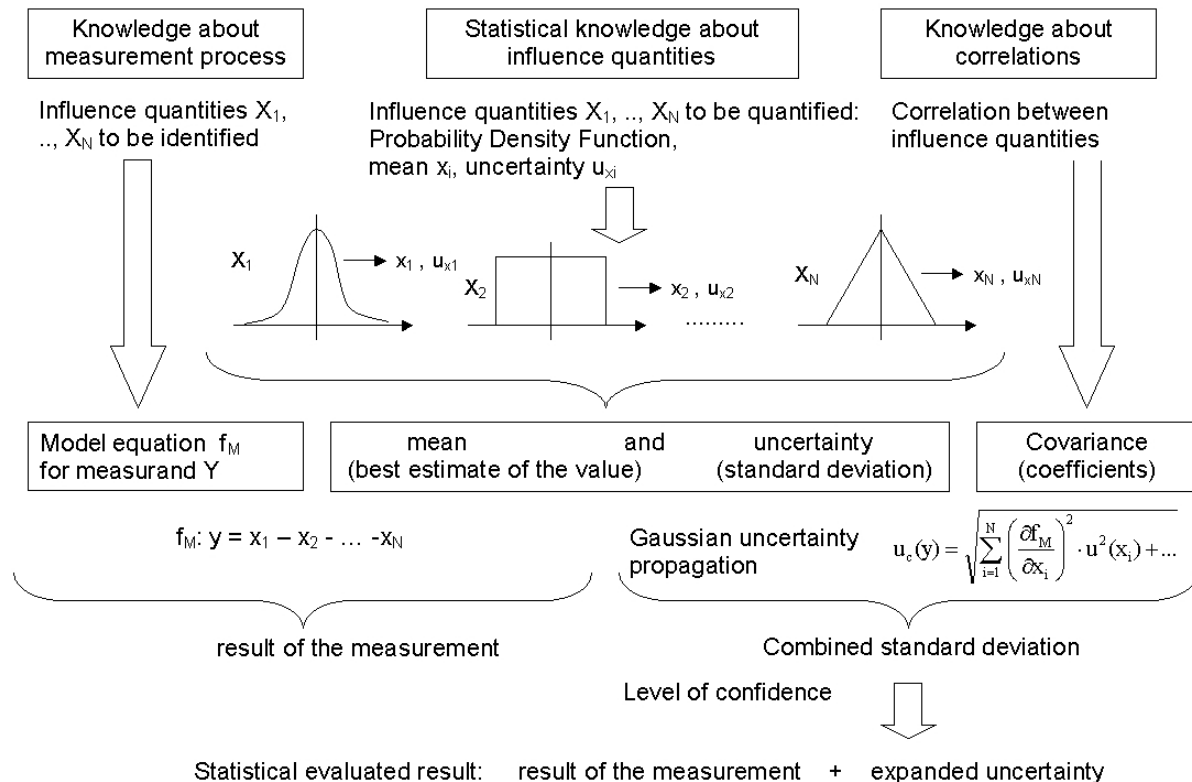


Figure 2. Flowchart according to GUM [5] and Sommer [6]: Knowledge about the measurement process and quantities influencing the results will be quantified. A statistical evaluated result at the end of the process allows drawing reliable conclusions.

Knowledge about the measurement process is represented by the identification of quantities influencing the results as shown in Figure 2. These influence quantities (e.g. variance of the device, of the wave speed and unwanted changes of the thickness or unevenness) have to be quantified by statistical methods. They occur in the model equation giving the result of the measurement and in the formula for the combined total standard

deviation. At the end of the process, there is a statistical evaluated result that allows drawing reliable conclusions about the testing problem.

In the following chapter it will be shown for the testing task “pile length measurement and reliable embedding in load bearing layer” what influence quantities are relevant and how they are quantified.

4 Testing Task: Pile length measurement with reliability theory

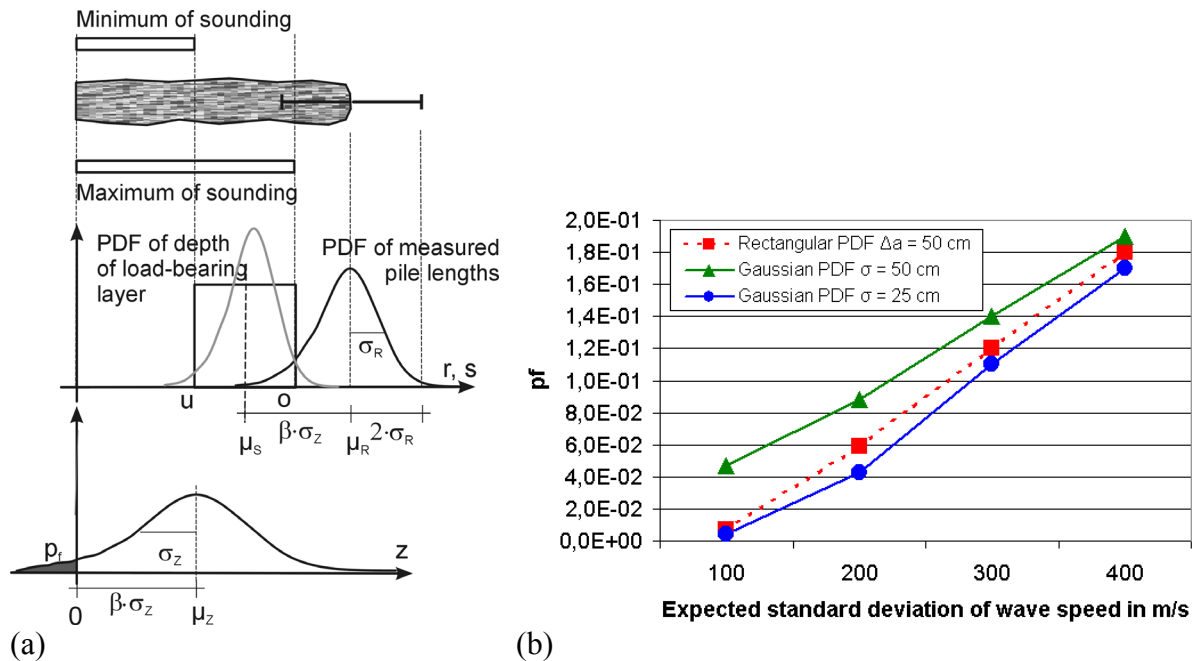


Figure 3. (a) Application of reliability theory to pile length measurement: The rectangular distribution represents the low level of knowledge about the real depth distribution of the load-bearing layer in the subsoil. The Gaussian distribution represents deeper knowledge from validation testing. p_f gives the probability that the measured pile does not reach the load-bearing layer in the subsoil. (b) Probability of failure p_f indicates the probability of the pile not being embedded in the load bearing layer. p_f depends on 1) the knowledge about the depth of the load bearing layer (poor knowledge: rectangular PDF with $\Delta a = 50$ cm; precise knowledge: Gaussian with $\sigma = 25$ cm) and 2) the deviation of the wave speed.

Existing piles have been measured with low-strain method (commonly known as pile-integrity testing). For the re-use of these piles the conclusion should be drawn how reliable they are embedded in the load-bearing layer of the subsoil (Figure 3a). **Knowledge about the variance of the depth of the load-bearing layer** exists as well as **knowledge about the testing method**. It has to be quantified and put in to a **model equation** at the left side with index s (for “stress” in dependence on reliability theory used in civil-engineering for the design of concrete structures) and index r (for “resistance”). In this case d_s represents in Eq. 1 the **varying depth of the load-bearing layer** with the mean depth d_M and its deviation δd .

$$d_s = d_M + \delta d \quad (1)$$

A reliable embedding of the piles in the load-bearing layer is given if $d_s < l_R$. l_R is the **varying measured pile length** due to deviations caused by the testing method. Eq. 2 gives the model equation for the pile length measurement with the variation of the wave speed δv (varying concrete quality over all piles), limited resolution of the time axis of the device δt_T

and the varying testing conditions of the low-strain method δt_{LS} (hammer blow, surface roughness etc.):

$$l_R = (\bar{v} + \delta v) \cdot (t_M + \delta t_T + \delta t_{LS}) / 2 \cdot 10^6 \quad (2)$$

Eq. 1 and 2 are implemented in the STRUREL Computer software for reliability calculation. For every variable a mean and/or a standard deviation are to be chosen. This is the case when the variables can be represented by Gaussian distribution (details in [2]). All variables are summarised in Table 1.

Table 1. Summary of the variable in Eq.1 and 2

Variable	Unit	Mean value	Standard deviation	PDF
d_M Mean value of the depth of load-bearing layer	m	9.0	-	-
δd Deviation of the depth of the load-bearing layer	m	0	(1) $\Delta a = 0,50$ (2) $\sigma_S = 0,50$ (3) $\sigma_S = 0,25$	Rectangular Gaussian Gaussian
v Wave speed in concrete (result of calibration)	m/s	4.156	-	-
δv Deviation of the wave speed (Knowledge from measurements)	m/s	-	<i>100 ... 400</i>	Gaussian
t_M Measured transit time of device (result at one certain pile)	μs	4.799	-	-
δt_T Deviation due to limited resolution of time axis (depends on device)	μs	0	$\Delta a = 20$	Triangle
δt_{LS} Deviation caused by method (Knowledge from measurements))	μs	0	52	Gaussian

The varied parameters are highlighted in grey and written in italics.

With the STRUREL calculation the influence of the more or less precise **knowledge about the deviation of the depth of the load bearing layer** (PDF rectangular or Gaussian with σ either 0.50 m or 0.25 m) and the **knowledge about the deviation of the wave speed** (Standard deviation between 100 and 400 m/s, approx. 2.5 – 10%) should be deduced.

Figure 3b indicates the influence of the knowledge

- about the depth of the load bearing layer. Poor knowledge about the varying depth is indicated by a rectangular probability density function (PDF) with $\Delta a = 50$ cm. Precise knowledge is indicated by a Gaussian PDF with $\sigma = 25$ cm.
- about the deviation of the wave speed that varies from one pile to the other.

The probability of failure p_f indicates the **probability of the pile not being embedded in the load bearing layer**. It becomes obvious that the expected deviation of the wave speed has great influence on p_f . The poor knowledge about the varying depth of the load bearing layer indicated by an upper and lower boundary is compared to the “better” knowledge of a Gaussian distribution (e.g. results from three or four soundings) not of great influence. That means that profound expert knowledge often given by an upper and lower boundary together with a rectangular PDF can be more precise than knowledge from statistical

evaluation. This expert knowledge not taken from statistical evaluation is used according to GUM [5] as “GUM Type B”. GUM Type A knowledge is drawn from statistical evaluation.

The more uncertain the expected deviation of the wave speed gets the less is the influence of the knowledge about the depth of the load bearing layer. Data from pile test sites where the standard deviation of the wave speed has been estimated show a standard deviation more at 100 m/s than at 300 or 400 m/s. Calculating with a deviation of wave speed of 100 m/s the probability of the pile not being embedded in the load bearing layer is between 0.5% (in case of good knowledge) and 5% (in case of poor knowledge). A reliability of the pile being embedded in the load-bearing layer between 95% and 99.5% allows drawing a conclusion about further re-use of the pile or not.

5 Conclusions

This work presents that a validation is at the end of a three step process furnishing the proof that the customer's demands are fulfilled. Using the uncertainty of measurement according to GUM (Guide to the expression of uncertainty in measurement) and reliability theory the quality of the results can be quantified and reliable conclusions can be drawn for further decisions.

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