

# Some Aspects of Applying a Probabilistic Approach in Geotechnical Practice During Reconstruction

Oksana Kichaieva, Dietmar Adam

*Institute of Geotechnics, TU Wien, Austria, [oksana.kichaieva@tuwien.ac.at](mailto:oksana.kichaieva@tuwien.ac.at)*

**ABSTRACT:** Due to the increasing volume of building and structure reconstruction, there is a growing need to assess the reliability of solutions for strengthening structural elements and their bases. Modern European documents advocate for the application of a probabilistic approach in reconstruction, which allows for the consideration of many uncertainties associated with this task. One of the significant challenges is the implementation of a probabilistic approach to the “building – foundation” system in the context of reconstruction. While sufficient tools have already been developed for creating stochastic models in new construction, many specific features must still be accounted for in models for reconstructed objects. Reconstruction tasks are particularly interesting because each case is unique; there are no absolutely identical buildings, soil conditions, or operational circumstances. During reconstruction, the mutual influence of the components of this system on one another significantly increases, and accounting for this interaction is possible only through a computational model that adequately reflects the changes in the stress-strain state of the system during reconstruction. To automate the assessment of the stress-strain state of the “building – foundation” system, the finite element method (FEM) is actively employed, including the incorporation of probabilistic methods. Determining the risk of reaching a limit state based on the solution to the corresponding statistical dynamics problem presents particular complexity in reliability theory. Currently, the statistical testing method (Monte Carlo) is frequently used to address such problems. A comprehensive approach that combines FEM and probabilistic analysis enables monitoring and managing the reliability not only of individual elements but also of the entire “building – foundation” system as a whole.

**KEYWORDS:** Reliability assessment, degradation model, in-service building.

## 1 INTRODUCTION

In recent decades, Europe has witnessed a steady trend towards increasing the share of building and structure renovation compared to new construction. This trend is driven by several factors, including urban densification, the need to preserve the historical heritage, sustainable development goals, and the desire to minimize anthropogenic impact. However, the implementation of renovation requires a fundamentally different approach to engineering analysis, as each building subject to modernization represents a unique object with an uncertain level of residual reliability.

Unlike new structures, where design and geotechnical conditions are predetermined and can be precisely formalized, renovation faces multiple sources of uncertainty. These pertain to the condition of construction materials and foundations, the operational history, as well as the availability of design documentation. Conventional calculation methods generally do not fully account for such particularities and risks, which may reduce the accuracy and reliability of the engineering decisions made.

In response to these challenges, modern standards (EN 1990, EN 1997-1, ISO 13822) and recommendations from organizations such as JCSS emphasize the necessity of applying probabilistic methods for assessing the condition and reliability of existing structures. Of particular importance is the integration of stochastic approaches into the modeling of complex engineering systems, such as the “building – foundation” system, where internal interactions and accumulated damage amplify the system’s sensitivity to external influences.

Within the context of renovation, it is especially critical not only to assess ultimate limit states but to implement reliability management of existing structures over time, considering all risk factors and accumulated deterioration. This approach requires systematic and adaptive monitoring, enabling timely, well-founded engineering decisions aimed at extending service life and ensuring operational safety.

A key instrument for realizing reliability management is provided by contemporary normative documents, foremost among them the Eurocodes (EN 1990, EN 1997-1). These codes

establish the methodological foundation for probabilistic assessment of structural condition and the integration of knowledge levels regarding the technical state of the object into engineering calculations. The Eurocodes do not merely regulate design methods but offer a framework for systematic accounting of uncertainties, thereby enabling adaptive risk management at all stages of renovation – from initial diagnosis to strengthening and ongoing monitoring during operation.

Additional attention to the formalization of uncertainties is given in the New Technical Rules for the Assessment and Retrofitting of Existing Structures (DAfStb, 2012), which highlight the necessity of considering the level of knowledge about the structure as a key factor in calculations. This approach allows the introduction of supplementary adjustment factors reflecting the actual degree of confidence in the input data, thereby preventing both excessive strengthening measures and underestimation of risk.

In situations requiring prompt and substantiated engineering decisions – especially when working with operational structures – the adoption of integrated approaches combining finite element methods, degradation models, and probabilistic analysis becomes increasingly indispensable. These approaches emphasize not only the prediction of ultimate limit states but also the management of reliability over time, taking into account operational, geotechnical, and informational conditions.

The objective of the present work is to develop a substantiated methodology for the quantitative assessment of reliability in renovation contexts, incorporating key risk factors and enabling adaptive management of the residual service life of structures.

## 2 A PROPOSED FRAMEWORK FOR THE RELIABILITY ASSESSMENT OF IN-SERVICE BUILDING

Contemporary degradation models occupy a fundamental position within engineering analyses aimed at assessing the durability and operational reliability of rehabilitated building structures. These models provide a quantitative framework for characterizing the progressive deterioration of the physical and

mechanical properties of materials and structural components under the influence of a multifaceted array of factors, including service loads, aggressive chemical and atmospheric agents, cyclic and dynamic deformations, as well as climatic effects. These factors typically act in a coupled manner, generating complex damage mechanisms that necessitate the use of models capable of accurately capturing multiphysical and multifactorial degradation processes.

Over recent decades, a variety of methodological approaches to modeling these phenomena have been established in both scientific literature and engineering practice. Particular emphasis has been placed on models of reinforcement corrosion, which account for electrochemical reactions leading to cross-sectional loss of metallic elements and consequently a reduction in the load-bearing capacity of reinforced concrete structures. Similarly, fatigue degradation models for concrete and metals have been developed to describe the accumulation of microcracks and the gradual deterioration of structural properties under repeated cyclic loading. A critical component of these efforts involves crack initiation and propagation models, which enable the prediction of critical damage thresholds and the timely forecasting of ultimate serviceability limits.

Furthermore, models describing creep and shrinkage of concrete merit distinct attention, as these processes induce slow but significant deformations that can markedly alter the stress-strain state of structures over extended periods. Weathering and erosion phenomena, which result in surface material degradation due to environmental exposure, are also intensively studied, particularly with regard to façades and other exposed structural elements.

Modern approaches to degradation modeling emphasize not only isolated phenomena but also their interactions, which is especially crucial when evaluating structural conditions in service environments where synergistic effects may significantly accelerate deterioration rates. The employed models range from deterministic formulations grounded in classical physico-mechanical principles to stochastic frameworks that incorporate uncertainties inherent in input data, parameter variability, and operational conditions.

The integration of degradation models with finite element methods and probabilistic analyses facilitates the prediction of temporal evolution of structural condition and enables quantitative assessment of residual service life, accounting for accumulated damage. This comprehensive methodology gains particular relevance in rehabilitation contexts, where initial data are often incomplete or uncertain. In such cases, adaptive degradation models supported by structural health monitoring systems represent an effective instrument for reliability management, allowing optimization of reinforcement strategies and extension of service life while minimizing associated risks.

### 2.1 Foundation Concepts of the Model

Consider the reliability of the "building – foundation" system at time  $t$ . The overall reliability outcome is influenced not only by the system's degradation but also by several critical factors, including the extent of knowledge regarding the existing structure, the designed service life, and the prevailing operational conditions. The proposed functional relationship is defined as follows:

$$P(t) = P_b \cdot P_f \cdot \exp\left(-\frac{K_1 \cdot K_2 \cdot g(t)}{T_d \cdot KL}\right) \quad (1)$$

where  $P_b$  and  $P_f$  are the initial reliability values of the building (or structure) and the foundation soil, respectively, in accordance with their assigned Consequence Classes;

$T_d$  is the service life of the building (or structure), measured in years.

As part of the comprehensive assessment of the condition and structural reliability of the in-service "building – foundation" system, three fundamental coefficients are employed:  $K_1$ ,  $K_2$ , and  $KL$ . Each of these parameters characterizes a distinct and critical dimension influencing the long-term performance, durability, and safety of the structure.

Geotechnical Conditions Coefficient  $K_1$ . This coefficient quantifies the influence of subsurface complexity on structural degradation. Based on the geotechnical categorization adopted in Eurocode 7 (EN 1997), the following representative values are considered in this study:

- 1.0 for Geotechnical Category 1 (GC1);
- 1.2 for Geotechnical Category 2 (GC2);
- 1.4 for Geotechnical Category 3 (GC3).

The increasing values reflect escalating geotechnical complexity and associated uncertainty in subsoil behavior.

Operational Conditions Coefficient  $K_2$ . This coefficient captures the degree to which the structure's usage and maintenance regimes conform to normative requirements:

- 1.0 – operation strictly in accordance with regulatory standards;
- 1.05 – operation with minor procedural deviations (e.g., minor non-compliance with maintenance schedules);
- 1.1 – absence of a structured maintenance framework, implying a lack of routine inspections and preventive interventions.

Knowledge Level Coefficient  $KL$ . This parameter reflects the comprehensiveness and currency of the available data regarding the structural system, as defined by the *New Technical Rules for the Assessment and Retrofitting of Existing Structures*:

- 0.8 – limited knowledge base (fragmentary or outdated technical information);
- 0.9 – standard knowledge level (typical documentation supported by partial condition assessments);
- 1.0 – exhaustive knowledge (detailed diagnostics, continuous structural health monitoring, and up-to-date technical records).

A combined use of these three coefficients enables a comprehensive and risk-informed evaluation of the structural system's reliability throughout its service life.

In equation (1)  $g(t)$  is the degradation model, proposed as a piecewise linear function that simulates the change in the condition of the structure throughout its service life. It is assumed that degradation progresses slowly during the first half of the service life, and then the degradation rate accelerates closer to the end of the service life:

$$g(t) = \begin{cases} 0.2 \cdot \frac{t}{0.5 \cdot T_d}, & t \leq 0.5 \cdot T_d \\ 0.2 + 0.8 \cdot \frac{t - 0.5 \cdot T_d}{0.5 \cdot T_d}, & t > 0.5 \cdot T_d \end{cases} \quad (2)$$

where  $t$  is the service time (operating time), measured in years. In our opinion, such a function models the gradual aging of the structure, where degradation progresses slowly at the beginning and accelerates as it approaches the strength limit.

### 2.2 Modeling and analysis

For each of the coefficients  $K_1$ ,  $K_2$ , and  $KL$ , discrete probability distributions were defined to capture the inherent uncertainty and variability associated with real-world operating conditions and the structural system's actual state.

Geotechnical Conditions Coefficient  $K_1$ : the values {1.0, 1.2, 1.4} are assigned probabilities {0.25, 0.5, 0.25}, respectively. This distribution reflects the assumption that moderately complex geotechnical conditions (1.2) occur most frequently in practice, while both simple (1.0) and highly complex (1.4) conditions are encountered less often and with equal likelihood.

Operational Conditions Coefficient  $K_2$ : the possible values {1.0, 1.05, 1.1} are distributed with probabilities {0.7, 0.25, 0.05}, respectively. This reflects the practical observation that most structures are operated in compliance with regulatory requirements, while deviations and the complete absence of maintenance are considerably less frequent.

Knowledge Level Coefficient  $KL$ : the values {1.0, 0.9, 0.8} are associated with probabilities {0.75, 0.2, 0.05}, respectively, indicating that a normal level of available information (0.9) predominates in practice, whereas cases of either complete (1.0) or limited (0.8) information occur less frequently.

These probability distributions were selected based on engineering judgment and practical experience, allowing for a realistic yet tractable representation of actual conditions. Where statistical data derived from inspections and structural health monitoring are available, these distributions may be refined to enhance the accuracy and reliability of the assessment.

By performing pairwise multiplication of the discrete values of the coefficients  $K_1$ ,  $K_2$ , and  $KL$ , a total of 27 unique combinations of the resulting generalized coefficient  $K$  were obtained. Each combination corresponds to a specific probability, calculated as the product of the probabilities associated with the respective individual coefficients.

As a result, a discrete distribution of 27 values of the generalized coefficient  $K$ , each with its corresponding probability, was constructed. This distribution enables the application of stochastic analysis in subsequent stages of the assessment to evaluate the risk and reliability of the "building – foundation" system.

Reliability calculations for the building (structure) with a service life of 100 years were performed using the Mathcad software suite at reference points of 0, 20, 40, 60, 80, and 100 years. The initial reliability value for the building was taken as  $P_b = 0.9999$  (failure probability  $P_{fb} = 10^{-4}$ ), and for the foundation –  $P_f = 0.999$  (failure probability  $P_{ff} = 10^{-3}$ ). The coefficients  $K_1$ ,  $K_2$ , and  $KL$  were varied across the entire range of their values.

The calculation result is presented in the form of a surface plot (fig.1), where the relationship  $K$  is defined as follows:

$$K = \frac{K_1 \cdot K_2}{KL} \quad (3)$$

The approximation of the obtained distribution of logarithms by a log-normal distribution enabled the transition to a continuous stochastic model. Subsequently, new values of the coefficient  $K$  were generated via inverse transformation from the logarithmic scale, thereby ensuring a realistic simulation of parameter variability under conditions of uncertainty. As a result, an array of  $10^5$  values of the coefficient  $K$  was formed, characterized by a mean of 0.037 and a standard deviation of 0.053. These statistical characteristics are consistent with the parameters of the original distribution and demonstrate that the stochastic generation accurately reproduces the variability of the coefficient  $K$ , thereby providing a realistic representation of its uncertainty.

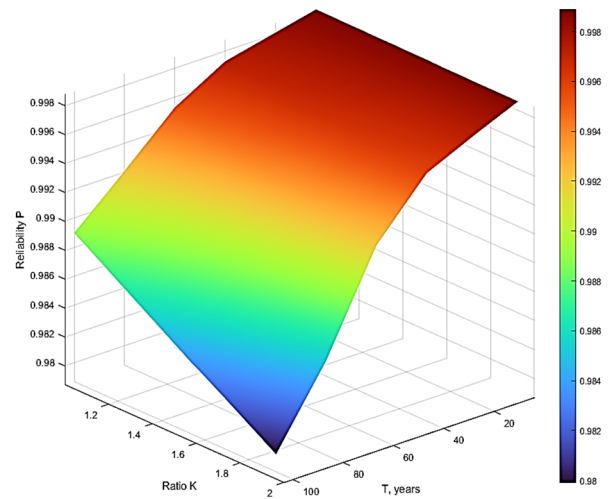


Figure 1. Surface plot illustrating the variation of reliability as a function of time  $t$  and the combined coefficient  $K$ .

To estimate the probability of failure, the method of statistical trials (Monte Carlo method) is employed, utilizing computational results obtained via the Mathcad software package according to the following procedure (with  $N = 10^5$  trials conducted):

- The following probability distributions for the input parameters are adopted: the reliability random variable  $P_i(t)$  is modeled as a normally distributed variable with mean  $\mu = 0.9986$  and standard deviation  $\sigma = 2 \cdot 10^{-4}$ .
- The limiting reliability random variable  $P_{lim}(t)$ , corresponding to the threshold reliability value, is also assumed to follow a normal distribution with parameters  $\mu_{lim} = 0.9995$  and  $\sigma_{lim} = 1 \cdot 10^{-4}$ , as prescribed by relevant regulatory guidelines.
- Random samples of system reliability for the "building – foundation" system are generated.
- For each iteration, the condition  $P_i(t) \leq P_{lim}(t)$  is evaluated.
- Upon completion of all  $N$  trials, the failure probability over the design service life is computed as the ratio of trials in which  $P_{lim}(t) - P_i(t) < 0$  to the total number of trials. In the present study, this probability is found to be  $P_f = 1 \cdot 10^{-4}$ .

Figure 2 illustrates histograms of the obtained reliability values  $P_i(t)$  and the threshold reliability  $P_{lim}(t)$ , whereas Figure 3 depicts their corresponding probability density functions.

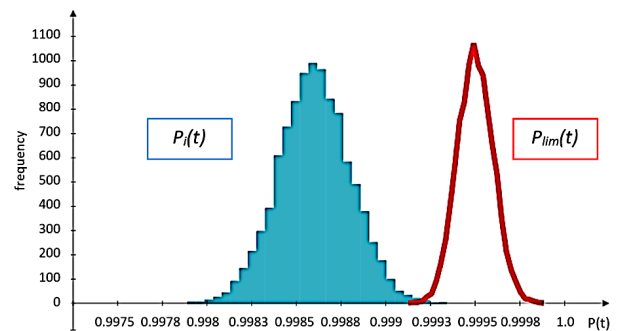


Figure 2. Histograms of the simulated reliability values  $P_i(t)$  and the threshold reliability values  $P_{lim}(t)$ .

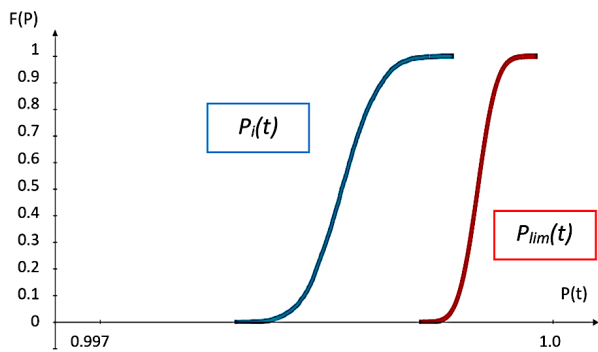


Figure 3. The distribution functions of the random variables  $P_i(t)$  – the blue curve, and  $P_{lim}(t)$  – the red curve.

### 3 CONCLUSIONS

The proposed reliability assessment model for the "building–foundation" system holds significant practical value by providing a comprehensive approach that accounts for the diverse factors influencing the technical condition of the structure throughout its entire service life. Unlike conventional degradation models, this approach integrates a broad spectrum of key parameters, including the complexity of geotechnical conditions, service life duration, as well as the heterogeneity and uncertainty of the initial structural data. Such comprehensiveness enables a more realistic and detailed depiction of system behavior under uncertainty, thereby mitigating the risk of both overly conservative and underestimated assessments of strength and safety.

The model's flexibility substantially broadens its applicability across various stages of the structure's life cycle. It is effectively employed for the technical and economic justification of design decisions and reinforcement measures, assisting engineers and stakeholders in balancing safety, operational performance, and costs. Furthermore, the model is applicable to monitoring the technical condition, auditing, and residual life evaluation of existing buildings and structures, thereby facilitating sustainable asset management. Its compatibility with probabilistic methods, such as Monte Carlo simulations, further enhances its functionality by providing reliable quantitative uncertainty assessments and supporting adaptive management under conditions of incomplete or evolving information.

The model offers capabilities for visual representation of results, presented as a three-dimensional surface illustrating the dependence of reliability on service time and an aggregated condition coefficient  $K$ , which synthesizes the main influencing factors. This form of representation allows for rapid reliability evaluation under varying input parameters, sensitivity analysis, and identification of critical parameter combinations.

Thus, the proposed model makes a significant contribution to the advancement of probabilistic reliability assessment methods for "building – foundation" systems in the context of reconstruction, technical operation, and reliability management. Its integrative approach and broad practical applicability render it a valuable tool for both scientific research and engineering practice, promoting the long-term reliability and safety of buildings and structures throughout their entire life cycle.

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