Compliance Assessment for Plugs and Seals in Germany

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Within the German programme a quantitative approach to compliance demonstration has been developed. This strategy is a semi-probabilistic, reliability-oriented concept using partial factors and is based on the internationally recognized Eurocodes. The general principle of the assessment method is described and an application example for one of the required individual assessments is given for a vertical emplacement borehole seal.

Introduction

The primary objective of repository research is to establish a scientific and technological basis for a safe disposal of high-level radioactive waste. In addition to the technical feasibility, one major goal is the feasibility of suitable safety assessments. In this context, the safety assessments of the multi-barrier system, which consists of the geologic barrier and the necessary geotechnical barriers, e.g., containers and drift or shaft seals, are of major importance. These individual components of the sealing concept, which often are arranged in parallel, are to ensure the safe long-term isolation of the radioactive waste.

Regarding design and safety assessment, the use of a uniform concept for all types of geotechnical barriers is considered to yield the best results. The following sections give an introduction to the partial factor concept. The methodology as relevant to a safety analysis is described quantitatively using exemplarily a sealing element and an abutment for a seal concept for an emplacement borehole recently developed within the scope of the German R&D project ANSICHT.

Compliance Assessment Method

The German strategy for demonstrating compliance of the seal designs with the design basis has been developed by DBE TECHNOLOGY GmbH (Müller-Hoeppe et al. 2012). It is a semi-probabilistic, reliability-oriented concept that uses partial factors and is based on the internationally recognized Eurocodes (EC-JRC 2008). The Eurocodes are a series of ten European standards that each consist of several parts. In engineering, they can thus be considered as state of the art for demonstrating the load-bearing capacity of a structure, i.e. the ability of a structure to perform to the required standards under induced loads.

In this approach, specific requirements are considered to have been met if the designs meet criteria (limiting values) evaluated by means of “assessment cases” (or load cases). The term “assessment cases” was chosen analogous to the term used in long-term safety assessments as, in addition to the load, other parameters need to be taken into account as well. The assessment cases are derived from the combinations of loads on a structure and from the specific system characteristics. Figure 1 shows the general principle of the assessment method called the “partial safety factor method”.

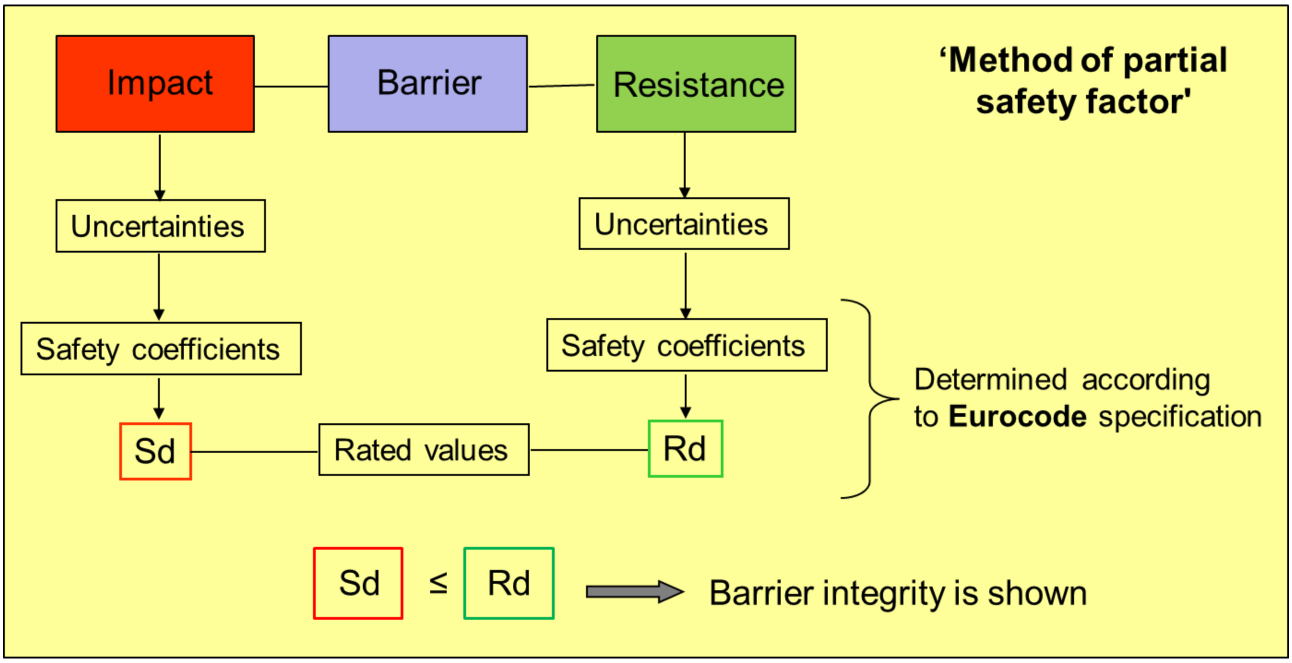

Figure 1: General principle of the partial safety factor method.

The demonstration of compliance is carried out by conducting a limiting value evaluation of the loads on a structure and the resistance of the structure to those actions, e.g., the (existing) stresses are compared with the nominal design stresses which can be calculated from the material strength. Both loads and resistances are determined from distribution functions. The limit state describes the state of the structure where it just barely meets the requirements. If this state is exceeded, the structure no longer complies with the design requirements. Accordingly, in order to meet the design requirements, the resistances need to be sufficient to withstand the loads (actions) on the structure.

The following individual assessments are essential for demonstrating compliance with the design basis according to the state of the art in technology:

- Demonstration of sufficient hydraulic resistance (demonstration of tightness)
- Demonstration of sufficient load bearing capacity (structural integrity)
    - Demonstration of structural stability
    - Demonstration of crack limitation
    - Demonstration of deformation limitation
    - Deformation of filter stability
    - Demonstration of durability

These assessments are essential for demonstrating the effectiveness of a sealing construction and thus the compliance with the design basis. Furthermore, the

- Feasibility

needs to be assessed and demonstrated. Figure 2 shows the individual assessments and their connections to the overall demonstration of functionality. In addition to applying the method of partial factors, a reliability assessment based on empirical data needs to be carried out in order to quantify the reliability of using probabilistic methods.

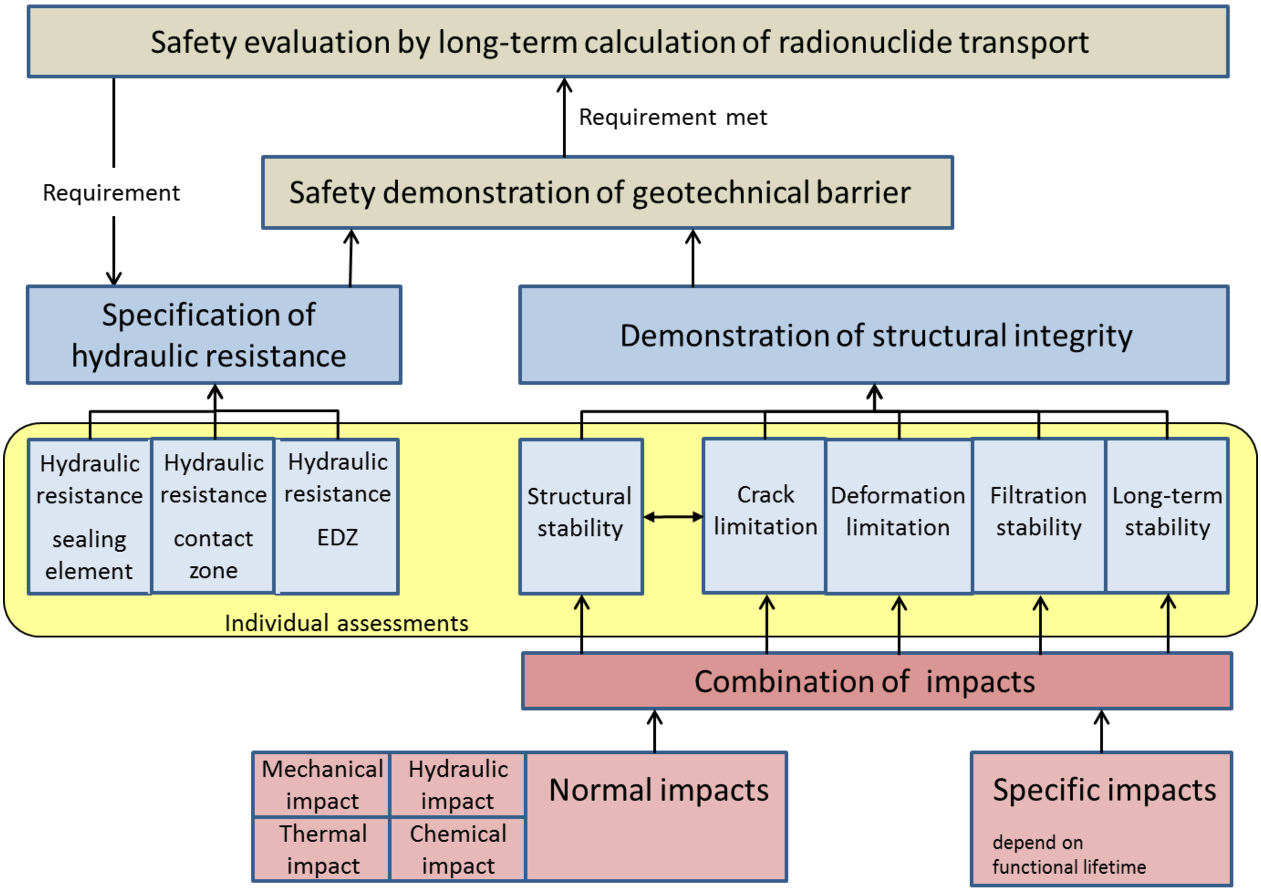

Figure 2: Connection of hydraulic long-term calculations in a long-term safety assessment with the individual, function-related assessments (after Müller-Hoeppe et al. 2012).

The design values for the individual assessments are derived from the characteristic values of the actions on and the properties of the barrier combined with the related partial factors. When applying the method of partial factors, actions and resistances, i.e. the parameters of the targeted relation, are allocated partial factors. The effects of actions are multiplied by partial safety factors and, thus, increased, whereas resistances are divided by partial factors and, thus, decreased. This method and the application of partial factors generally account for uncertainties in the representative values of the actions and uncertainties in the properties of the structure.

Application example

The current German repository design for disposal of heat generating high active waste and spent fuel in huge Jurassic clay formations includes the emplacement of canisters in short vertical boreholes. Each borehole is equipped with different components such as an inner and outer liner, a buffer, and a seal (Figure 3). The seal is located at the top of the borehole consisting of a bentonite element and a concrete abutment. The dimensions of the abutment correspond to the borehole cellar, which is needed for the emplacement. The diameter of the bentonite seal is 2.5 m, with a height of 5 m.

The main function of the borehole seal is the reduction of brine movement inside and out of the borehole. The seal is made of an in-situ compacted mixture of pellets and lose bentonite, in regard to the good experiences collected at Salzdetfurth experiment (Breidung 2002). One pellet has a volume of approximately 10 cm². Overall the pellets create 70 to 80 mass-% of the mixture. The lose bentonite has a grain size smaller than 3 mm. Both components are mixed and compacted in-situ by vibration-compactors. This technology creates dry bulk densities between 1600 and 1800 kg/m³. The final type of bentonite is not known yet. The selection depends on different criteria such as the chemical compatibility to the host rock and the pore water, the needed swelling pressure or the needed permeability. Up to now the Ca-bentonite type Salzdetfurth is considered as reference material. (Lommerzheim & Jobmann 2015)

The bentonite seal must fulfil the evidence of a sufficient high hydraulic resistance, the evidence of crack limitation and the evidences of long-term and filtration stability. The feasibility is already demonstrated by comparable large scale in-situ experiments like the German Salzdetfurth experiment (Breidung 2002) or the Belgian RESEAL experiment (van Geet et al. 2009).

The demonstration of a sufficient high hydraulic resistance includes the specification of the permeability of the seal and the comparison to the design situations. Those create the impacts to the seal. The major design situations are the steady state case, the transient case, extraordinary situation and an earth quake. The exact assessment cases are defined in regard to the site specific FEP-list. The following sections give a brief overview of the demonstration method of partial factors for determination of the permeability at the sealing location.

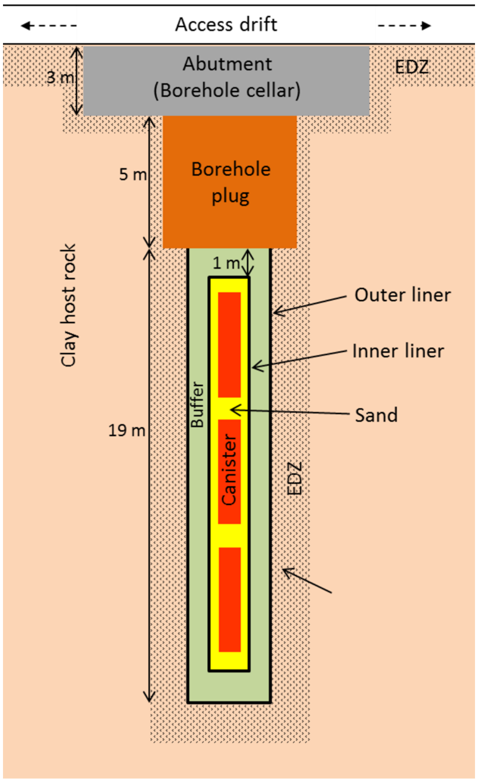

Figure 3:Conceptual design of a vertical emplacement borehole and seal

The specification of the permeability (K) at the sealing location includes the seal (S), the contact interface (C) and the EDZ. The permeability of all three parts is called integral permeability (K_{int}) of the seal location:

$$K_{int} = \frac{K_S * A_S + K_C * A_C + K_{EDZ} * A_{EDZ}}{A_S} \qquad \text{Eq. 1}$$

This demonstration method bases on a sufficient amount of necessary data. Within this exemplary evidence a data set is created from different references (see Figure 4). From those data the permeability of the seal can be calculated in dependency of the dry density.

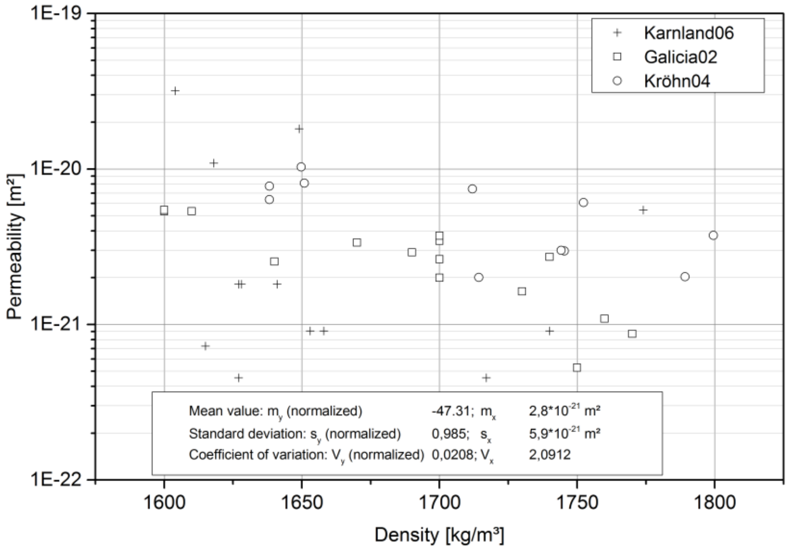

Figure 4: Permeability of the saturated bentonite samples in dependency of the dry density, based on (Jobmann et al. 2016)

The data set allows the estimation of the design value (X_d). The Eurocode (EN 1990) provides the determination of the design value by the characteristically value as the preferred method (Eq. 2). This approach includes the assumption that the data are normally distributed. The determination is realized with a logarithmically normalized data set. Uncertainties are covered by the use of a partial factor (γ_m) and the fractile factor (k_n). The conversion factor (η_d) considers uncertainties out of the data transmission between different scales (laboratory, half or full scale).

$$X_d = \frac{\eta_d}{\gamma_m} * e^{[m_y - k_n * s_y]} \qquad \text{Eq. 2}$$

In addition the Eurocode describes the method for determining the design value directly or as an estimation of the average value using a high confidence interval of 95% (see Eq. 3 and 4).

$$X_d = \eta_d * e^{[m_y - k_{d,n} * s_y]} \qquad \text{Eq. 3}$$

$$X_d = \frac{\eta_d}{\gamma_m} * \left[m_x - \frac{t_{(n-1)}^{0,95} * s_x}{\sqrt{n}} \right] \qquad \text{Eq. 4}$$

Due to the absence of reliable exploration data the expanse and the permeability of the EDZ have to be estimated, too. Wagner (2005) gives a simple approach for the estimation of the EDZ`s depth. Here it is expected to be 0.8 m. This corresponds to an area of 9.6 m². The permeability of the EDZ was deduced from Major et al. (2005). Table 1 summarizes the individual and integral permeability based on the different calculation methods.

Table 1: Overview of the design values based on the different determination methods

Design value by…	**Seal**	**Contact area**	**EDZ**	**Total**
…characteristical value	$1.2 \cdot 10^{-20}$	neglected	$9.2 \cdot 10^{-19}$	$\mathbf{2.5 \cdot 10^{-20}}$
…direct determination	$6.9 \cdot 10^{-20}$	neglected	$1.7 \cdot 10^{-15}$	$\mathbf{2.5 \cdot 10^{-17}}$
…estimation of the average value	$3.4 \cdot 10^{-21}$	neglected	$1.7 \cdot 10^{-19}$	$\mathbf{5.9 \cdot 10^{-21}}$

The expected permeability at the seal location is almost comparable with the permeability of the undisturbed host rock. This allows the conclusion that the seal will have a sufficient low permeability. Nevertheless, the exemplary demonstration includes several assumptions. A reliable assessment calls for a sound data base which is not yet available and a comprehensive knowledge of the rock at the seal location. The comparison of the three determination methods shows a significant difference between the direct determination method and the other two methods. This results mainly from the limited data available for the EDZ and the currently high fractile factor $k_{n,d}$.

Conclusion

The German strategy for demonstrating compliance of the seal designs with the design basis is a semi-probabilistic, reliability-oriented concept that uses partial factors and is based on the internationally recognized Eurocodes. Specific requirements are considered to have been met if the designs meet criteria (limiting values) evaluated by means of “assessment cases” (or load cases). The assessment cases are derived from the combinations of loads on a structure and from the specific system characteristics. The demonstration of compliance is carried out by conducting a limiting value evaluation of the loads on a structure and the resistance of the structure to those actions. The application example regarding the seal tightness shows how the compliance assessment method works but also that a sound data base is required to yield consistent and reliable result.

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