Analysis of Existing Hydraulic Structures with Crack and Pore Water Pressure using Reliability Methods

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Abstract

The safety and reliability of German hydraulic structures, like ship locks, weirs, etc., have to be verified from time to time or for the decision of rehabilitation or renewal, This contribution presents a probabilistic methodology for the uncertainty quantification of relevant parameters and failure mechanisms for the evaluation of reliability levels of existing hydraulic structures. For a ship lock chamber wall, a gravity wall construction, a dominant action crack and pore water pressure is considered and its influence on the structural reliability is discussed. The case study is benchmarked for requirements posed by the latest European standards and German guidelines. For the application of the proposed methodology a typical structural geometry, material and load system for a ship lock wall is considered. Overturning and compressive strength have been investigated as the exemplary limit states. The results indicate a decrease in reliability levels in case of crack and pore-water pressure as an externally applied force. The differences are mostly influenced by the difference of levels of water within the chamber structure. Additional reliability based sensitivity analysis indicates that friction angle and concrete weight have the highest impact on the reliability for the considered parameter uncertainties and the limit states. The investigations are part of a research project in which probabilistic analyses for existing hydraulic structures shall promote a decision instrument so as to rehabilitate existing hydraulic structures and to support sustainability aspects in structural engineering.

Keywords: Hydraulic structures, Reliability analysis, Probabilistic modeling, Structural analysis, crack-pore water pressures.

1. INTRODUCTION:

Three main progressions are seen in structural engineering design for the evaluation of reliability and safety. These methods include allowable stress design (ASD), semi-probabilistic design (partial safety factors) and the latest full probabilistic design (fib 2016). Reliability can be regarded as a key element of the sustainability of a structure.

While assessing concrete hydraulic structures, it is often noticed that previous structural designs and verifications did not consider the crack and pore water pressure as an externally applied force (DIN 19702 2013). These forces can be considerable when global structural safety is considered in a critical section. This contribution reviews and applies an analytical formulation recommended by the German standard for solid hydraulic structures (DIN 19702, 2013) and guideline for the verification of existing hydraulic structures (BAW 2016) for a typical geometry and load combination on a ship lock structure and performs a probabilistic analysis. The relevant codes and standards recommend a minimum target reliability level of β_T =3.8 for Ultimate Limit State (ULS) and β_T =1.5 for Serviceability Limit State (SLS) which must be achieved for the assertion of safety and reliability for at least 50 years for buildings (EN 1990, 2010) and at least for 100 years for hydraulic structures (DIN 19702 2013). Although several Limit State Function (LSF) need to be fulfilled for a concrete hydraulic structure (Tahir et al 2016) in the first part of the research we have selected only two Ultimate Limit States (ULS) and two Serviceability Limit States (SLS) for the proof of the concept. First a LSF uncertainty quantification of parameters is conducted which serves as input into reliability analysis methods. Additionally, the analysis was conducted considering crack and pore water pressure formulations. To demonstrate the proposed methodology a case study was performed for a typical geometry and loading system for a ship lock water component for a predetermined cross section.

2. METHODS:

2.1 Structural design analysis of hydraulic structures:

For the evaluation of structural safety and reliability of existing hydraulic structures several different verification and limit state functions need to be fulfilled. The Eurocodes as European standards (i.e. EN1990 2010) classifies the limit state function (LSFs) into Ultimate Limit States (ULS) and Serviceability Limit States (SLS). These LSFs consider several possible failure modes are varying from stability, geotechnical to structure's internal stresses. This contribution considers only four of the recommended verifications in the guidelines (BAW 2016) for existing un-reinforced/lightly reinforced concrete hydraulic structure subjected to several loads and load combinations. These include overturning failure as a global safety measure (ULS), compressive failure for internal stress stability (ULS) as well as a joint opening stability where the joint opening must not exceed more than 50 % of base length (SLS), and see (BAW 2016). The figure 1 (left) indicates the LSFs for each ULS and SLS whereas the figure 1 (right) shows the force system for a typical ship lock gravity wall with earth pressure, groundwater and chamber water pressures. Section A-A was considered for structural and reliability analysis.

2.2 Crack and pore water pressure:

Components of the hydraulic structure remain in contact with water and are hence subjected to crack water pressures in cracks and open joints and pore-water pressures in the internal sections. The resulting additional forces and stresses from these water pressures have not been considered in previous design up to about 1980, therefore their inclusion is essential to update the safety levels of existing structures and to ensure their reliability for the remaining service life.

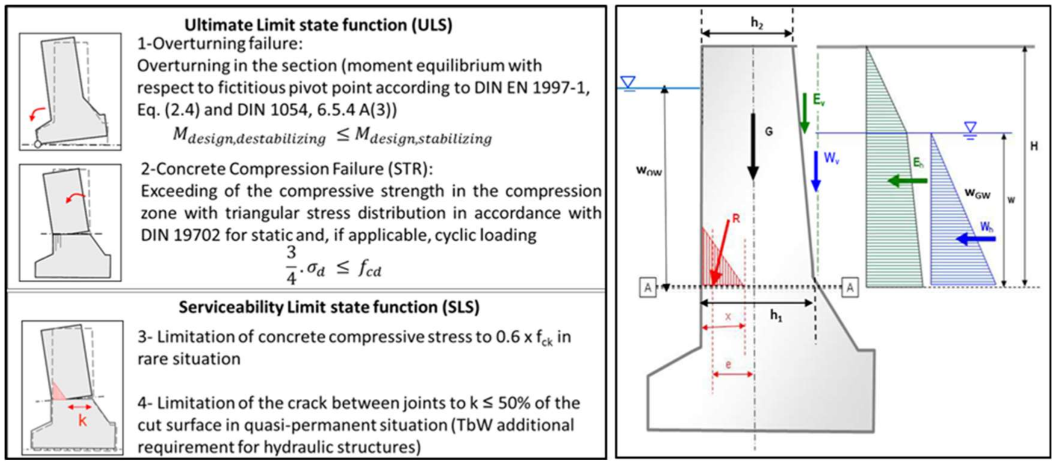

Figure 1: (Left) considered Limit state functions (ULS & SLS); (Right) Typical geometry and load system for a ship lock wall structure (adapted from (BAW 2016)

Figure 2 and the following equation indicate the stress distribution of crack and pore water pressures within a hydraulic structure with varying water levels on both sides of the section.

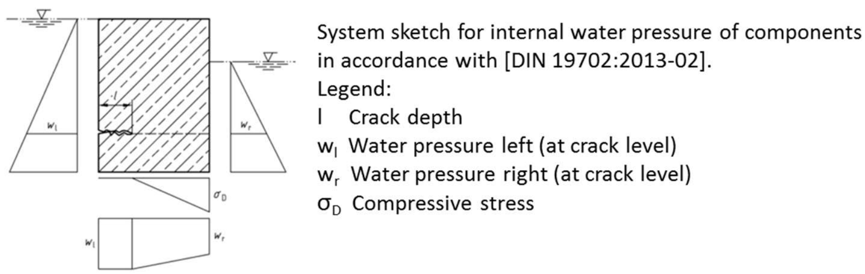

Figure 2: Stress distribution for water pressures in internal cross section, (DIN 19702 2013)

Equation (5) of DIN 19702 provides the depth of the pressure zone considering the internal water pressure, where x_{wd} is the depth of the cracked section equation (1) and e_d is the external eccentricity (Moment/Normal forces), h is section width and $\bar{\sigma}_{wd}$ is the ratio of the water pressure to the design normal force (drawn water pressure).

$$\frac{x_{wd}}{h} = 3 \cdot \left(\frac{1}{2} - \frac{\frac{e_d}{h}}{1 - \overline{\sigma_{wd}}} \right) \quad \textbf{(1)}$$

Equations (6) and (7) of DIN 19702 provides the resulting modification factor for design internal forces considering the internal water pressure, for modified design normal force (N_{wd}) equation (2) and modified design moment (M_{wd}) across a section equation (3).

$$N_{wd} = \left(1 - \overline{\sigma_{wd}} \cdot \left(1 - \frac{1}{2} \cdot \frac{x_{wd}}{h} \right) \right) \cdot N_d \quad \textbf{(2)}$$

$$M_{wd} = \frac{1}{1 - \overline{\sigma_{wd}}} \cdot \frac{N_{wd}}{N_d} \cdot M_d \quad \textbf{(3)}$$

2.3 Reliability analysis:

The vital part of a reliability assessment is the calculation of the probability of failure P_f related to a specific loading situation and a limit state function equation (4) It is defined as

$$P_f = \Pr\left[g(\underline{\mathbf{X}}) \leq 0\right] = \int_{g(\underline{\mathbf{X}})\leq 0} f_{\underline{\mathbf{X}}}(\underline{\mathbf{x}})d\underline{\mathbf{x}} \quad (4)$$

where *X* is a random vector of input parameters with joint probability density function $f_X(x)$ and *g()* is the limit state function (LSF). Probabilistic modelling of important parameters in a limit state is an essential part of the evaluation of the reliability levels. Following probabilistic models for parameters were considered using literature indication for the case study.

Table 1: Probabilistic models of random parameters for LSFs

	Parameter	Distribution	Mean (μ)	Coefficient of variation	Standard Deviation (σ)	Source
1	Concrete strength (f_{ck})	Lognormal	12	15%	1.80	(JCSS 2001)
2	Concrete weights (γ_B)	Normal	23	5%	1.15	(JCSS 2001)
3	Soil weights (γ_{BG})	Normal	20	5%	1.00	(JCSS 2001)
4	Friction angle (φ)	Lognormal	35	8%	2.8	(JCSS 2001)
5	Groundwater level (GWL)	Lognormal	5	10%	0.5	Field Data

First Order Reliability Method (FORM)

Currently, several methods are used for the evaluation of the reliability which could be classified into approximated methods and Monte-Carlo based simulation methods. This contribution will employ the approximation based method i.e. the First Order Reliability Method (FORM), (Rackwitz and Fiessler 1978), also known as first-order second moment approximation. The two main advantages of employing FORM is its numerical robustness and the allocation of reliability based sensitivity analysis as a byproduct without additional calculation. Essentially FORM defines a Taylor series expansion of the limit state function g(x) to the first order at the design point. This enables an efficient solution for estimating the reliability index β. This could be visualized in figure 3 (a) below, where the joint probability distribution of two random variables and the limit state function g(x) = R-E define the safe and the failure regions. Figure 3 (b) indicates the process of searching the failure point and hence the reliability index (β).

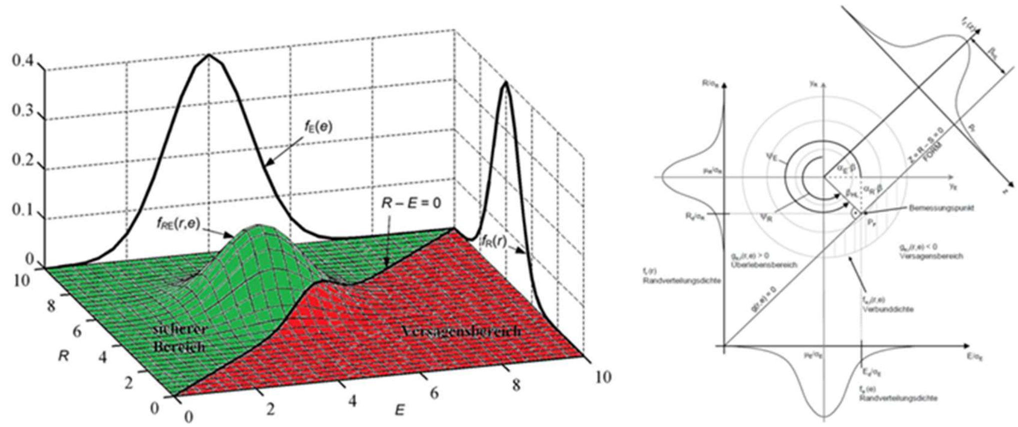

Figure 3: (Left) Representation of the Joint PDF with limit state function R - E = 0 and failure region (red) (Hausmann 2007) (Right) Design point, reliability index β_{HL} and Joint probability density of E and R in the standard normal space (Braml 2010).

3. CASE STUDY AND RESULTS:

As discussed in the sections earlier the reliability analysis using FORM method was conducted for a typical unreinforced (plain) concrete ship lock chamber wall , loads and limits states (ULS and SLS) as indicated in Figure 1. The analysis was conducted for a wall thickness of 3m, a wall height of 8 m, a groundwater level at 5 m height, varying water levels in the chamber and for two major load cases, with and without considering crack and pore water pressures, see figure 4. For Ultimate Limit State (ULS) it was observed that reliability levels are (nearly) achieved without crack and pore water pressures (PWP), considering the target safety level ($\beta_T = 3.8$) by (DINEN1990 2010), indicated in Figure 4 (A), whereas a decrease is seen when PWP was considered in the cross-sectional analysis. The difference varies with changing the water level in the chamber and the limit state function as indicated in Figure 4 (C). A difference of 100 % is seen since cases with chamber water levels less than 5 m show failure for gaping joint SLS verification. Regardless of ULS or SLS verifications an exponential increase of reliability is seen for cases where the water level is greater than 5m. This could be contributed to the fact that considered groundwater level is at 5m and since water in the chamber is a stabilizing force, the load cases with higher chamber water level have significantly higher structural safety. The same reasoning could be applied to the reduction in the difference in reliability levels for cases with and without PWP as indicated in Figure 4 (C). Further investigation shows that this point could be due to the limitation of the analytical method prescribed by the existing crack and pore water methodology in codes and guidelines.

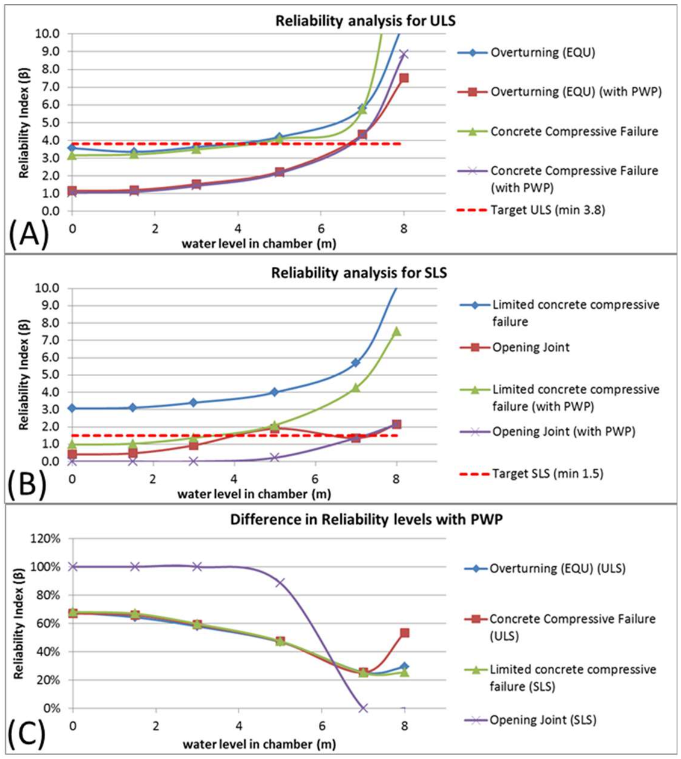

Figure 4: Results of Reliability analysis for ULS and SLS, with/without PWP

One of the most significant advantages of the FORM method is the ability to provide sensitivity analysis without any additional computational effort. The so called alpha values, indicate the extent of the sensitivity of the parameter on the reliability. The performed sensitivity analysis for the limit states "Overturning" indicates friction angle, concrete weight whereas and groundwater are the critical parameters as shown in Figure 5.

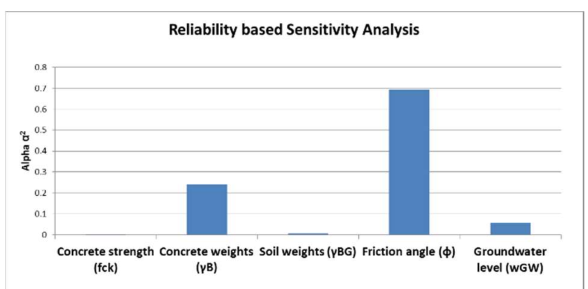

Figure 5: Reliability-based sensitivity analysis of Overturning (EQU) as ULS

4. CONCLUSIONS:

The contribution presented a methodology to incorporate crack and pore-water pressures, a hydraulic structure specific load into reliability assessment framework. An analytical method developed by BAW was employed and the effect on reliability levels of ULS and SLS were investigated using FORM method. It could be concluded that consideration of crack-pore water pressures decreases the overall reliability of the structure. The difference in reliability levels with and without inclusion of pore pressures decreases with decrease in difference of water levels in ground and chamber. FORM based sensitivity analysis indicated friction angle, concrete weight and groundwater level have the most influence on reliability for overturning ULS. A certain asymptotic relationship is seen in reliability levels after the water levels in chamber and ground are equal. This trend requires more research, for which the authors suggest a validation through non-linear iteration based method rather than analytical approach. The current study presented a workflow and case study for an idealized system, application to actual structures is expected in future work with additional limit state functions and field data.

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