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Armor stone displacements at German inland waterways: An approach to schedule inspections coupling reliability analysis with Markov chains

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Abstract: The German Federal Waterways and Shipping Administration (WSV) maintains about 7235 km of waterways whose shores are mainly secured by loose or grouted armor stones. To enable the WSV to make optimal use of its resources, taking into account boundary conditions such as economic efficiency and nature protection requirements, an extension of the current German design concept towards maintenance is required. In this paper a "classical" reliability analysis is conducted to investigate the probability of armor stone displacements along German inland waterways. Subsequently, it is proposed to use the obtained probabilities of armor stone displacement in Markov chain simulations to relate the former to the number of ship passages and time. Eventually, this may allow estimating maintenance intervals in regard to actual traffic density. The methodology is illustrated with traffic observations along four artificial inland waterways in Germany. The results are discussed in relation to the consequences for embankment maintenance and applicability in practice.

Keywords: bank revetments; armor stone displacement; FORM; Monte-Carlo simulation; Markov chains.

1 Introduction

To promote inland waterway transport in Germany, a broad navigability of the waterways network has to be provided taking into account economic and ecological boundary conditions. This requires an integral analysis of the stability of revetments in regard to traffic, observed damage, and critical damage patterns, which also encompasses different waterways subjected to various loading, ecological and maintenance conditions.

Bank revetments at German inland waterways are mainly secured by loose or grouted armor stones on a geotextile or mineral filter layer. In Germany, the design of revetments is currently conducted according to BAW Code of Practice: Principles for the Design of Bank and Bottom Protection for Inland Waterways (GBB, 2010). The design consists of a hydraulic and a geotechnical design. While the hydraulic design defines the minimum armor stone diameter necessary to withstand (ship-induced) waves and currents, the geotechnical design is required to evaluate embankment stability taking into account excess pore pressures caused by a fast, ship-induced water level drawdown.

From expert interviews (Sorgatz et al. 2018) it was deduced that armor stone displacement is the most significant damage pattern. Yet, damage progresses slowly. Minor impairments can be observed up to 15 years before an intervention will become urgent. Hence, for efficient resource management and budgeting, it would be advantageous if a method was available for scheduling optimal maintenance intervals.

The first section briefly explains the proposed methodology. In the second section, four exemplary, yet real datasets are introduced and analyzed. Finally, the results of the reliability analysis and Markov chain simulation are presented and discussed.

2 Methodology

2.1 Damage classification

To describe damage of revetments by means of a Markov chain, a damage classification is required. Sorgatz et al. (2018) distinguish between four main damage categories. In Figure 1, damage develops from left to right. In S1, few armor stones are eroded. In S2.1, the filter layer is almost uncovered. Maintenance measures are to be initiated before S2.2, where the filter is exposed. In S3, the filter is destroyed. Finally, the soil is subjected to loading and subsequent erosion (S4). Unfortunately, and as confirmed by expert interviews (Sorgatz et al., 2018), damage of armor stone revetments progresses differently after initial damage has occurred. Thus, the present Markov model allows forecasting initial (S0 → S1), but not progressing damage (S1→ S4).

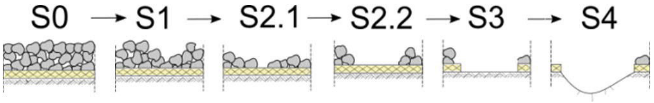

Figure 1. Development of damage for loose armor stone revetments.

2.2 Limit state function

The hydraulic model (hydM) computes the minimum armor stone diameter necessary to withstand (ship-induced) waves and currents. The term ‘model’ refers to the mathematical formulation of the limit state function g which is defined by

$$g = D_{50,ist} - D_{50,\mathrm{erf}}\left(v_{\mathrm{rueck}}, u_{\max}, H_{\mathrm{u,Heck}}, H_{\mathrm{Sek}}\right) \leq 0, \tag{1}$$

with the variables return flow velocity v_{rueck}, supply flow velocity $u_{\max}$, sternal wave height $H_{\mathrm{u,Heck}}$ and secondary wave height H_{Sek}. The calculated mean armor stone diameter $D_{50,\mathrm{erf}}$ required to resist erosion can then be compared to the mean in-situ armor stone diameter $D_{50,\mathrm{ist}}$. Failure is described by

$g \leq 0$. Figure 2 displays the equations to be solved, whose mathematical formulations may be reviewed in GBB (2010).

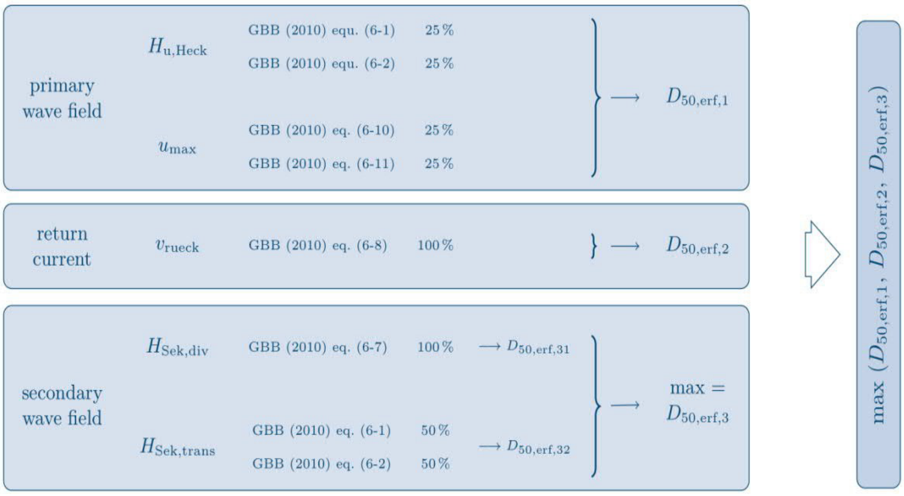

Figure 2. Hydraulic model (hydM). Schematics to determine the armor stone diameter as outlined in GBB (2010).

2.3 Reliability analysis

Uncertainties are categorized as aleatoric and epistemic uncertainties. This work deals with the former by introducing load and resistance parameters as random variables (i. e. v_s, $H_{\mathrm{u,Heck}}$, v_{rueck}, D_{50}). Epistemic uncertainties, e. g. model errors, are not taken into account. In the future, they may be included; however, more research in this area is required.

The theory of reliability-based methods and their application in geotechnical engineering is well-known, although rarely applied in practice (Lacasse et al., 2013). A description of the mathematical basics is therefore not given in this paper. Reference is made to literature, e. g. Baecher and Christian (2003). Therefore, following the introduction of the datasets, this paper directly outlines the distribution analysis, correlations and a sensitivity analysis. The goodness-of-fit of a distribution is evaluated in *RStudio* by means of the "fitdistrplus" package (Delignette-Muller et al., 2017). The subsequently presented reliability analyses are conducted with OpenTURNS (Baudin et al., 2015) in Python. Due to the limit state function, see eq. (1), the obtained probabilities of failure (POF) may also express the probabilities of armor stone displacement.

2.4 Markov chain model

To predict damage initiation for riprap revetments, the probabilities of armor stone displacement are employed in Markov chain simulations. A similar approach has been outlined by Possan and Andrade (2014) for the service life of reinforced concrete structures. A simpler application of Markov chains to bank revetments was proposed by Kayser (2015).

Figure 3 visualizes the current Markov chain model. The initial system without damage, S0, is characterized by the state vector $v^{(0)} = [1, 0]$. The probability of the system moving to the next state, in this application S1, is given by the probability of failure (p_{01} = POF). The reliability, on the other hand, represents the probability of the system staying in the current state (p_{00} = 1 - POF). It is assumed that the system cannot return to a previous state without maintenance (p_{10} = 0, p_{11} = 1). The transition probabilities are summarized in a transition matrix $P = \begin{bmatrix} p_{00} & p_{01} \\ p_{10} & p_{11} \end{bmatrix}$ The evolution of the system for n steps is defined by eq. (2). Details on the theory of Markov chains may be reviewed in Rubinstein and Kroese (2016).

$$v^{(n)} = v^{(0)} * P^n \tag{2}$$

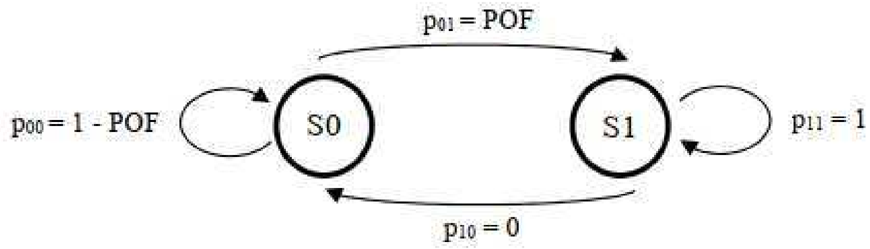

Figure 3: Markov chain transition probabilities.

3 Datasets and their uncertainty

3.1 Traffic observations

The data specifying the random variables required for reliability analysis originates from measurement campaigns conducted by the Bundesanstalt für Wasserbau (BAW). A campaign commonly lasted between one to two weeks and resulted in the raw data, the processed measurements such as wave heights and flow velocities, as well as reports on the boundary conditions. For the purpose of reliability analysis, the four most recent campaigns are chosen (Ingenieurbüro Schmid, 2006, 2007a, 2007b, 2015) covering waterways of various traffic densities and maintenance conditions (see Table 1). Although they are comparable in regard to the employed measurement devices and data processing, the data itself is partly heterogeneous and/or incomplete, and therefore requires pre-processing in terms of completeness and validity. For instance, the supply flow velocity $u_{\max}$ is hardly quantifiable in field observations and was thus not included in any dataset. The return current velocity was only observed in KuK-2015. The missing parameters are evaluated using the equations of GBB (2010) and solved for each observed vessel passage individually.

Table 1: Example originated from recent field campaigns conducted by BAW.

Campaign	waterway information		measurements	
	vessel passages / year	description (Sorgatz et al., 2018)	vessel passages	validated data points
Dortmund-Ems-Kanal (DEK-2006)	15 000	Damage occurs regularly in not expanded sections and at constructive weak points. Ship-induced loads and pack ice are the main damage causes.	298	260
Küstenkanal (KuK-2015)	2 500	The channel shows considerable damage. In particular, armor stone displacements are observed frequently, either due to a lack of maintenance in the past or an insufficient design.	47	46
Silokanal (SiK-2007)	10 000	The channel was expanded only recently and is well maintained. Damage refers to single armor stone displacements, often caused by vandalism.	318	96
Wesel-Datteln-Kanal (WDK-2007)	20 000	At the channel damage is rare. Rarely occurring extreme ship-induced loads and vandalism are identified as the main causes of damage.	751	396

The in-situ armor stone class is specified based on field reports. Sampling a large number of armor stones in the field for distribution fitting is very ineffective. Therefore, a general statistical description valid for different armor stone classes is derived from a grain-size analysis of two armor stone classes.

To identify the most significant parameters that should be modelled as random variables, the hydM is studied using Sobol indices (Sobol, 2001; Saltelli, 2002). In general, the number of random variables depends on the model, the required accuracy of the analysis and the available data. For reasons of limited space, the results are only briefly described. The sensitivity analysis suggests that $H_{\mathrm{u,Heck}}$, v_{s}, v_{rueck} and $D_{\mathrm{50,ist}}$ contribute considerably to the output variance. H_{Sek} shows little influence, most likely due to the small wave height of the secondary waves. Therefore, H_{Sek} is defined as a deterministic campaign specific maximum. Additionally, it was observed that the cross sectional area influences the significance of a variable.

3.2 Distribution analysis

The use of parametric distributions and their approximation by Maximum Likelihood Estimate and Method of Modified Moments proved to be the most robust and, above all, most reproducible way to assess the probability density functions, taking into account fluctuating sample sizes. Visual and hypothesis tests are utilized to evaluate the goodness-of-fit of each distribution. $H_{\mathrm{u,Heck}}$ is best described by a three-parameter shifted Log-normal distribution LG (λ, ζ, γ) which suits particularly heavy skewed data. In addition to the shape λ and scale ζ parameter, it features a shift parameter γ. The variables v_{s} and v_{rueck} are approximated by Gaussian distributions N (μ, σ). The armor stone diameter $D_{\mathrm{50,ist}}$ is due to the measurement method, commonly sieving, a discrete quantity. It is fitted by a Poisson distribution P(λ) and then transferred to a Gaussian distribution, an approach valid for large sample sizes. Table 2 summarizes the distributions.

The current fitting implies that the distribution type depends utterly on the variables, not on a particular waterway. It is, however, emphasized that visual and hypothesis tests solely indicate the most likely distribution type. Depending on the sample size and quality, there is always uncertainty related to that choice.

Table 2: Summary of the probability distributions for a hydraulic revetment design in compliance with GBB (2010). LogNorm $LG(\lambda, \zeta, \gamma)$; Gaussian $N(\mu, \sigma)$.

dataset	v_s in ms^{-1}	$H_{\mathrm{u,Heck}}$ in m	v_{rueck} in ms^{-1}	$D_{\mathrm{50,ist}}$ in mm
DEK-2006	**Gaussian** (2.535, 0.520)	**LogNorm** (-0.783, 0.245, -0.228)	**Gaussian** (0.810, 0.357)	**Gaussian** (150, 12)
KuK-2015	**Gaussian** (2.410, 0.433)	**LogNorm** (-1.254, 0.263, -0.078)	**Gaussian** (1.115, 0.376)	**Gaussian** (150, 12)
SiK-2007	**Gaussian** (3.180, 0.614)	**LogNorm** (-1.520, 0.351, -0.091)	**Gaussian** (0.341, 0.169)	**Gaussian** (150, 12)
WDK-2007	**Gaussian** (2.834, 0.404)	**LogNorm** (-1.530, 0.350, -0.004)	**Gaussian** (0.708, 0.192)	**Gaussian** (180, 12)

3.3 Correlation analysis

Physical considerations imply a dependency of the ship-induced variables v_s, $H_{\mathrm{u,Heck}}$ and v_{rueck}. Thus, the correlation is analyzed with the Pearson coefficients. Different parameters and waterways yield different coefficients. In particular, the flow velocities display a wide variation emphasizing the importance of thorough data pre-processing. For now, a simplified approach is adapted using one correlation matrix valid for different waterways (see Table 3).

Table 3: Correlation matrix for the random variables of the hydM.

	v_s	$H_{\mathrm{u,Heck}}$	v_{rueck}	$D_{\mathrm{50,ist}}$
v_s	1.00	0.30	0.40	0.00
$H_{\mathrm{u,Heck}}$	--	1.00	0.70	0.00
v_{rueck}	--	--	1.00	0.00
$D_{\mathrm{50,ist}}$	--	--	--	1.00

4 Results and Discussion

4.1 Reliability analysis

The results of the reliability analyses are summarized in Table 4. For each waterway, the probability of failure (POF) is evaluated by FORM with the Abdo-Rackwitz algorithm and Monte Carlo (MC) simulations. The POF vary strongly between the waterways and, in the case of SiK-2007, also between the methods. The latter may be caused by an insufficient number of MC runs. However, for SiK-2007, the deviations result from the FORM that yields a local maximum as confirmed by the Strong Maximum test (Dutfoy, Lebrun, 2007). FORM approximates a design point at a high vessel velocity and wave height but a low return flow velocity. This combination is physically doubtful, since fast vessels cause high flow velocities, too.

Compared to the target values for the design of concrete and steel structures (JCSS, 2001; DIN EN 1990:2010-12) or breakwaters (PIANC, 1989) the assessed POF are rather high. There are several reasons for this: (1) The analysis does not refer to newly erected constructions. The admissibility of larger vessels and/or cargoes than considered in the original design may lead to undersized revetments according to the present design code GBB (2010). (2) The GBB (2010) assumes a factor of safety equal to 1 without any partial safety factors. (3) The GBB (2010) permits minor damage as few displaced armor stones do not propose a risk to the embankment stability. Thus, larger POF may be acceptable with sufficient maintenance. Finally, it is emphasized that the analyses are valid for a specific cross section of each waterway. They do not represent the overall state of that waterway. Yet, the findings are confirmed by expert interviews (Sorgatz et al., 2018).

Table 4: Probability of failure (POF) and design points evaluated by means of OPENTURNS using MC simulations and FORM (Abdo-Rackwitz algorithm). The FORM / MC deviations for SiK-2007 are colored in gray.

	MC simulation	FORM	FORM design point			
Dataset	POF = p_{01}	POF	v_S in ms^{-1}	$H_{u,Heck}$ in m	v_{rueck} in ms^{-1}	$D_{50,ist}$ in mm
DEK-2006	5.012E-03	4.439E-03	3.01	0.44	1.59	145
KuK-2015	4.773E-02	4.419E-02	2.66	0.36	1.64	130
SiK-2007	8.135E-05	2.293E-07	4.53	1.09	0.95	134
WDK-2007	1.784E-05	2.083E-05	2.99	0.86	1.22	173

4.2 Prediction of initial damage

The probability of damage initiation can be visualized with regard to vessel passages or time. The time is derived from the average number of ship passages over one year (see Table 1). The calculations assume that the loads used for reliability analysis, and thus the POF, represent the typical annual behavior.

Figure 4 illustrates the probability of initial damage and the transition from S0 to S1 as a function of time and vessel passages. The results do not indicate a failure of the embankment. A 50 % likelihood of initial damage may be observed after 200 vessels or 3 days for DEK-2006, 11 vessels or 2 days for KuK-2015, 9 000 vessels or 250 days for SiK-2007, and 50 000 vessels or 900 days for WDK-2007. Thus, inspections may be scheduled more frequently for DEK-2006 and KuK-2015 than for SiK-2007 and WDK- 2007. The results emphasize the necessity to include traffic densities to schedule inspection intervals. For instance, although DEK-2006 and KuK-2015 are characterized by similar POF, a larger traffic density increases the likelihood of observing initial damage in an equal time period.

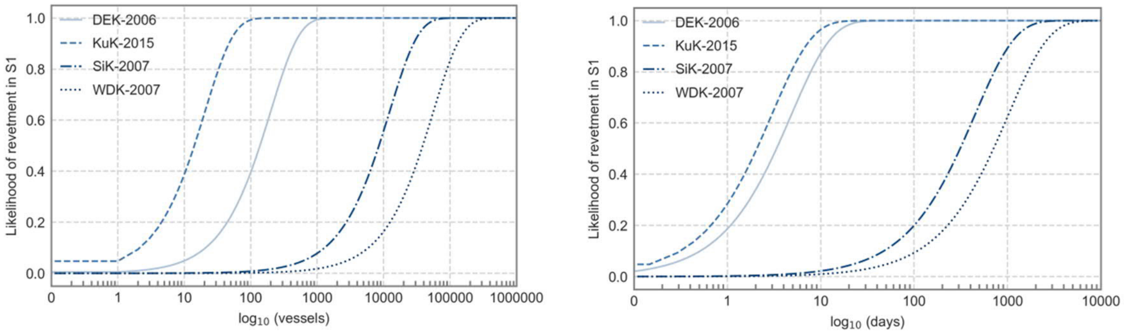

Figure 4: Likelihood of displaced armor stones or of the revetment being in S1 for different example datasets. The left figure displays damage initiation per ship. On the right graph, the damage initiation per day is shown.

Altogether, the results reflect field observations well. Nevertheless, the following drawbacks are to be mentioned. (1) The model can only represent damage induced by overloading. Vandalism, collisions or material degradation may also cause damage. Expert interviews, though, have shown that these are less frequently observed (Sorgatz et al., 2018). (2) The Markov chain approach assumes that the current load distribution, established from measurements lasting one to two weeks, represents the annual traffic. However, for the examples, the data representativeness varies. (3) As outlined in section 3.1, few load parameters are determined with the GBB (2010) equations leading to a conservative estimate. (4) Additionally, the measurement of hydraulic parameters still depends on the expert in charge. (5) Finally, homogenous discrete- state Markov chains imply an exponential progressing damage. This assumption may not be suitable to relate damage to a large number of individual events. Summarizing, these drawbacks may cause an overestimation of the POF and/or inspection intervals, likely observable for DEK-2006 and KuK-2015.

5 Conclusions

This paper outlines a reliability analysis of the hydraulic design of revetments. The model, parameter distributions and parameter values are presented. The evaluated probabilities of failure are employed as transition probabilities to predict initial damage by means of a Markov chain.

The proposed approach can aide in scheduling inspection intervals based on the estimated time or number of ship passages to initial damage. The greatest value, though, is the identification of parameters with the highest influence on failure and the complementary evaluation of failure probabilities. The Markov chain allows a simple interpretation of failure probabilities by visualizing the probability of initial damage in regard to traffic or time. Since no target probabilities exist for the design of revetments, and target reliabilities of other engineering structures cannot be transferred on a one to one basis, the presented methodology may allow failure probabilities to be classified leading to the definition of possible target values.

More research is required to link progressing damage with traffic. Initial damage may be more severe for highly frequented waterways. Moreover, the results highlight the necessity to gather representative datasets. It is, thus, recommended to extend the duration of measurement campaigns, and to standardize measurements and field observations. Finally, the Markov chain assumption of exponentially progressing damage initiation may be overly conservative. An extension of the current model, for instance towards a non-homogenous Markov chain, is desirable. Yet, as long as hydraulic loads, damage and maintenance are not documented comparably, this advancement will be challenging.

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