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PERFORMANCE PREDICTIONS OF COASTAL DEFENCES USING STOCHASTIC DETERIORATION MODELLING

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Abstract. *Performance prediction of coastal defence structures becomes more challenging due to uncertainties arising from changing environments and deterioration processes; hence, requiring sophisticated time-variant reliability analysis in order to manage the risk of floods and erosions. This paper proposes a method for assessing failure probability of coastal defences with respect to their present condition grade. A Markov chain model is utilised to predict the transition probabilities between different condition grades of a coastal defence over time with respect to available maintenance plans. The deterioration level is categorised into 5 stages (each stage for an appropriate condition grade) in relation to the initial resistance, and then translated into a probabilistic framework in order to consider in the performance deterioration evaluation. A case study of a sea dyke section, located in Portsmouth, England, is employed to demonstrate the effectiveness of the proposed method. Finally, the time-variant failure probability are illustrated in order to provide a clear understanding of performance evaluation in the future. The results show that the failure probability of the sea dyke associated with overtopping failure mode will increase significantly due to deterioration processes.*

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1 INTRODUCTION

Coastal defence structures are the first lines to protect low-lying areas and their valuable assets against risks posed by flooding, coastal erosion and landslides. It is necessary to manage the risks effectively to avoid casualties and damages concerning the economic matters. However, coastal defence structures are often located in harsh and changeable environments; therefore, it becomes challenging to assess their future performance level accurately. It is necessary to inspect a coastal flood defence regularly to evaluate its current conditions including damage level. Environment Agency has been recording the inspection data since the 1990s and introduced Condition Assessment Manual in 2006 [1] to assess coastal defence general condition grade in a standard framework.

During last decades, many studies have been carried out on performance predictions of flood defences. Flikweert and Simm [2] have suggested estimating fragility curves for different condition grades defined by Environment Agency [1] as a new approach for performance prediction and risk assessment of flood defences. Simm et al. [3] have developed the mentioned method in 2009 to analyse reliability of flood defences using a condition-grading system. Many studies considered the deteriorating resistance and the uncertainties associated with the operating environment as major challenges to evaluate performance deterioration in the future (e.g. [4, 5]). Gouldby et al. [6] developed a methodology for assessing the flood risk under different deterioration scenarios in the future in a regional-scale model. However, the application of the condition-based system in the most studies is deterministic, and a grade-based stochastic deterioration model is not developed for coastal flood defence structures.

This paper aims to propose a stochastic performance analysis of coastal defence structures using a grade-based Markov model. Crest height degradation due to settlement is also considered for different condition grades. Time-dependent transition probability matrices are estimated by utilising the Markov model with Weibull sojourn times. Finally, the time-dependent failure probability of a sea dyke for its overtopping failure mode is presented for consideration of the future maintenance plans.

2 COASTAL DEFENCE CONDITION GRADING SYSTEM

Efficient management of assets at coastal areas is one of the main objectives for Environment Agency in the UK. Routine inspections of these assets help authorities to have essential information about the likely assets' performance and condition grade in order to make decision for future. For this purpose, Environment Agency published Condition Assessment Manual in 2006 in order to offer a standard framework for evaluating asset's condition grade [1]. Table 1 shows the definition of the condition grades defined by Environment Agency.

Grade	Rating	Description
1	Very Good	Cosmetic defects that will have no effect on performance.
2	Good	Minor defects that will not reduce the overall performance of the asset.
3	Fair	Defects that could reduce performance of the asset.
4	Poor	Defects that would significantly reduce the performance of the asset. Further investigation needed.
5	Very poor	Severe defects result in complete performance failure.

Table 1: Condition grades and descriptions adopted by Environment Agency [1].

In 2013, Environment Agency offered a series of asset deterioration curves for different types of coastal defences in order to estimate the residual life of an asset or structure related to with the condition grading system [7]. Deterioration curves predict the condition grade of assets associated with time, relying on historical data and expert judgment. The curves are explicitly focused on condition grades and do not necessarily provide information about structural deteriorations such as settlement. This paper uses the deterioration curves to predict the lifecycle performance of coastal defenses over time.

3 MARKOV MODEL

A Markov model is a memoryless stochastic process that evolves over time or space, and the future of the process is only conditional on the current condition of the system or asset [8]. Let $X = \{x_1, x_2, \dots, x_M\}$ be a set of finite states of a flood defence asset. A Markov process on a flood defence is defined once its transition probability matrix and initial condition state $X_0(t)$ at time $t \geq 0$ are specified, where $X_0(t) = \{\alpha_1^t, \alpha_2^t, \dots, \alpha_M^t\}, \sum \alpha_i^t = 1$ and $\alpha_i^t \geq 0$. A discrete-time Markov property for a stochastic process X^t at time $t, (t > 0)$ is expressed as [8]

$$p_{ij}^{t,t+1} = \Pr(X^{t+1} | X^1, X^2, \dots, X^t) = \Pr(X^{t+1} = x_j | X^t = x_i) \tag{1}$$

where conditional probability $p_{ij}^{t,t+1}$, with constraints $p_{ij}^{t,t+1} \geq 0$ and $\sum_{j=1}^{M} p_{ij}^{t,t+1} = 1$, denotes the transition of the asset from condition grade i to j during a given period of time. It is assumed that the structure can deteriorate only one state at a time (with consideration of an appropriate transition period).

3.1 Transition probability matrix

As discussed earlier, coastal defence structures are categorised into 5 condition grades, where condition grade 1 denotes good as new and condition grade 5 denotes failure. Hence, if a structure is in condition grade 5 under no-maintenance plan, then cannot transit to a higher (worst) state, and always remains in condition grade 5. The one-step transition probability matrix under do-nothing maintenance plan is expressed here as

$$P^{t,t+1} = \begin{bmatrix} 1-p_{12}^{t,t+1} & p_{12}^{t,t+1} & 0 & 0 & 0 \\ 0 & 1-p_{23}^{t,t+1} & p_{23}^{t,t+1} & 0 & 0 \\ 0 & 0 & 1-p_{34}^{t,t+1} & p_{34}^{t,t+1} & 0 \\ 0 & 0 & 0 & 1-p_{45}^{t,t+1} & p_{45}^{t,t+1} \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

In a Markov process, a state space remains in a particular state for a given length of time, then transits to another state. Let $\{T_1, T_2, \dots, T_M\}$ be random variables denote the sojourn time in states $\{x_1, x_2, \dots, x_M\}$, respectively. Their corresponding probability density function (PDF), cumulative distribution function (CDF), and survival function are denoted $f_i(t), F_i(t)$ and $S_i(t)$, respectively. Thus, $T_{i,i+1}$ is the time from state i to state $(i+1)$. If the deterioration process is in state i at time t, then the conditional probability that the structure transits to the next state in one time-step is expressed as [9]

$$p_{i,i+1}(t) = \Pr\{X^{t+1} = x_{i+1} | X^t = x_i\} = \frac{f_{1\to i}(t)}{S_{1\to i}(t) - S_{1\to(i-1)}(t)} \quad , \quad i = \{1,2,3,4\} \tag{3}$$

where the transition probability $p_{i,i+1}(t)$ is time-dependent and non-homogenous. Assume that the waiting time T_i follows Weibull distribution. The CDF (F), PDF (f), and survival S function of Weibull distribution are expressed, respectively, as [10]

$$
\begin{aligned}
&F_i(t, \theta_i, \beta_i) = 1 - \exp(-\theta_i t)^{\beta_i} \quad , \qquad t > 0; \quad (F(t) = 0 \; for \; t \leq 0) \\
&f_i(t, \theta_i, \beta_i) = \theta_i \beta_i (\theta_i t)^{\beta_i - 1} \exp-(\theta_i t)^{\beta_i} \quad , \qquad t > 0 \\
&S_i(t, \theta_i, \beta_i) = 1 - F_i(t, \theta_i, \beta_i) = \exp(-\theta_i t)^{\beta_i}
\end{aligned}
\tag{4a,b,c}
$$

where θ_i and β_i are scale and shape parameters, respectively. Hence, under the specification of Weibull parameters, the probability of the transition from state i to state $(i+1)$ can be estimated. For example the transition probability from state 4 to state 5 at time t is expressed as

$$p_{4,5}(t) = \frac{f_{1\to4}(t)}{S_{1\to4}(t) - S_{1\to3}(t)} \tag{5}$$

3.2 Parameter estimation

The scale θ_i and shape β_i parameters are estimated based on historical observations and condition assessments, which are available via Environment Agency publications as discussed in Section 2 (e.g. [7]). Deterioration curves are developed by experts to predict the condition grade of assets associated with time according to their environment, material, deterioration rate and maintenance regime. For example, a deterioration curve for a specific asset describes that the structure remains in condition grade i for T years. After selecting an appropriate deterioration curve for the case study, a two-state Markov chain is utilised to estimate the transition probability for condition grade i. The one-step transition matrix is expressed here as

$$TP_{ii} = \begin{bmatrix} p_{ii} & 1 - p_{ii} \\ 0 & 1 \end{bmatrix} \tag{6}$$

where TP_{ii} is a discrete-time and homogenous Markov transition matrix; and p_{ii} is the probability of being in condition grade i at time-step (year) one. Transition probability that the coastal defence goes from condition grade i to next condition grade in n steps is called n-step transition probability, and is calculated from the n^{th} power of the transition matrix TP_{ii}. Let τ be the time-step (year) that the structure remains in the same condition grade with probability of $p_a = 50\%$. From Equation 4(c), gives

$$\exp(-\theta_i \tau)^{\beta_i} = p_a = {p_{ii}}^{\tau} \tag{7}$$

Also, it was assumed that the survival function at condition grade i follows a Weibull survival function S_i, as expressed in Equation 4. A non-linear least squares method is suggested to find the scale θ_i and shape β_i parameters by minimising the difference between two functions. The scale θ_i and shape β_i parameters can be estimated by solving the minimization, together with Equation 5, as

$$minimise \; \sum_i (S_i(t) - {p_{ii}}^t)^2 \;\; ; \qquad i = \{1,2,3,4\} \tag{8}$$

where $S_i(t) = \exp(-\theta_i t)^{\beta_i}$ is the Weibull survival probability at time (year) t.

4 SEA DYKE PERFORMANCE ASSESSMENT

The reliability of coastal flood defence structures depends on two main factors, the hydraulic conditions and the structural resistance. The resistance of the structures decreases over time due to the deteriorating processes such as settlement. If $R(t)$ denotes as the resistance over time, and $S(t)$ denotes as the loading, then the limit state function $Z(t) = R(t) - S(t)$ describes the reliability of the system over time. Therefore, the structure fails if the loading is equal or more than the resistance [3]. The probability of failure p_f can be expressed as

$$p_f(t) = \Pr\{Z(t) \leq 0\} \tag{9}$$

In this paper, reliability analysis is carried out for one major failure mode; the overtopping over the dyke crest. The limit state function for overtopping Z_q over time t is given as [4]

$$\mathrm{Z}_q(t) = q_{cr} - \chi_q q(t) \tag{10}$$

where q_{cr} is a predefined mean overtopping discharge; χ_q is model uncertainty coefficient associated with overtopping parameters; $q(t)$ is average overtopping discharge over time and can be calculated by using Eurotop manual [11], given here as

$$\frac{q(t)}{\sqrt{g \cdot H_{m0}{}^3}} = \frac{B_1}{\sqrt{tan\,\alpha}} \cdot \gamma_f \cdot \varepsilon_{m-1,0} \cdot \exp(-B_2 \frac{R_{c,i}(t)}{\varepsilon_{m-1,0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot H_{m0}}) \tag{11}$$

with a maximum of:

$$\frac{q(t)}{\sqrt{g \cdot H_{m0}{}^3}} = B_3 \cdot \exp(-B_4 \frac{R_{c,i}(t)}{\gamma_f \cdot \gamma_\beta \cdot H_{m0}}) \tag{12}$$

where $B_1 = 0.067$, $B_2 = 4.30$, $B_3 = 0.20$, and $B_4 = 2.30$ are empirical coefficients for deterministic uses, and normally distributed stochastic parameters with means of $B_2 = 4.75$ and $B_4 = 2.60$ and standard deviations of 0.50 and 0.35, respectively, are taken for probabilistic calculations; H_{m0} is significant wave height at the toe of structure; g is the acceleration due to the gravity; $\varepsilon_{m-1,0}$ is breaker parameter; γ_b, γ_f and γ_β are correction factors for berm, roughness and oblique wave attack, respectively; α is the angle between overall structure slope and horizontal line; and $R_{c,i}(t)$ is crest freeboard (over still water level) of the structure at time t given is in condition grade $i \in \{1,2,3,4,5\}$. The future freeboard $R_{c,i}(t)$ at time t is described here as

$$R_{c,i}(t) = R_c(0) - \Delta L_{Z,i}(t) \tag{13}$$

where $R_c(0)$ is initial freeboard at initial time; and $\Delta L_{Z,i}(t)$ is the deterioration of crest level (Z direction) associated with certain condition grade at time t. In order to characterise the deterioration level $\Delta L_{Z,i}$ regarding the initial freeboard, the table below is suggested (Table 2). Table 2 suggests the variation of the lifecycle phases according to condition grade scheme based on the crest level elevation loss.

Grade	Crest level loss, $\Delta L_{Z,i}$, (m)	Distribution of deterioration intensity
1	$0.00 \leq \Delta L_{Z,i} < 0.05$	Lognormal
2	$0.05 \leq \Delta L_{Z,i} < 0.10$	Normal
3	$0.10 \leq \Delta L_{Z,i} < 0.20$	Normal
4	$0.20 \leq \Delta L_{Z,i} < 0.40$	Normal
5	$0.40 \leq \Delta L_{Z,i}$	Lognormal

Table 2: Suggested crest level loss (Z direction) deterioration for a sea dyke related with condition grade system.

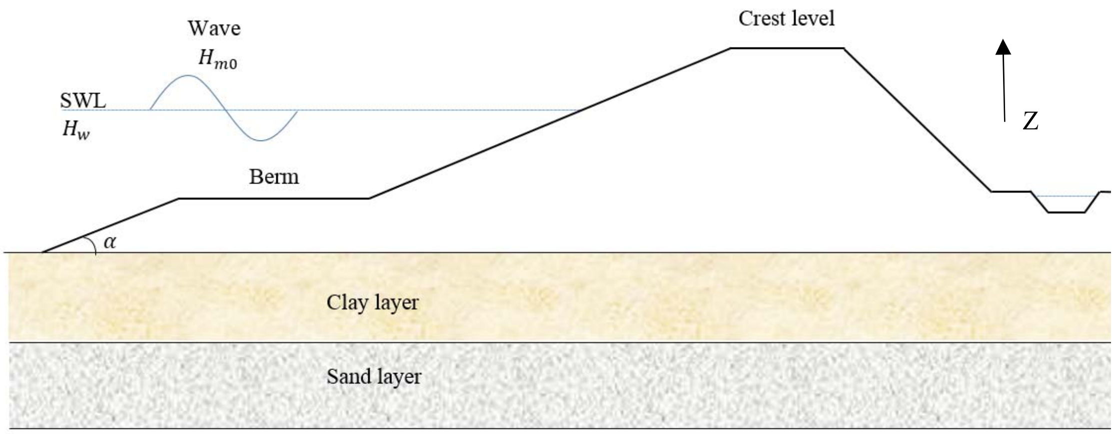

Figure 1: Sketch of numerical example of the earth sea dyke section. SWL: still water level.

The crest level loss is defined based on the erosion at a specific condition grade, and it is available in Quantitative Assessment Methods [12]. To translate the condition grades into probabilistic parameters, it is assumed that erosion over time is linear and the deterioration intensity is normally distributed. The distributions are normal except the first and last condition grades, which are assumed to be lognormal, as the dyke will not improve due to deterioration (condition grade 1), and more deterioration considers as the functional failure (condition grade 5).

5 NUMERICAL EXAMPLE

A case study for a simplified model of earth sea dyke (see Figure 1) at Portsmouth, England described by Taylor et al. [13] is employed to demonstrate the applicability of the proposed method for reliability assessment of coastal defence structures using condition-grading system. The structure has a crest height of 3.60 mOD, a seaside slope of 1: 8, and landside slope of 1: 5. The structure has a bermed slope and it is protected by pitched stones. The earth dyke rests on a layer of impermeable clay soils, and below the clay layer is 5.00 m of water conductive sand layer overlaying impervious bedrock.

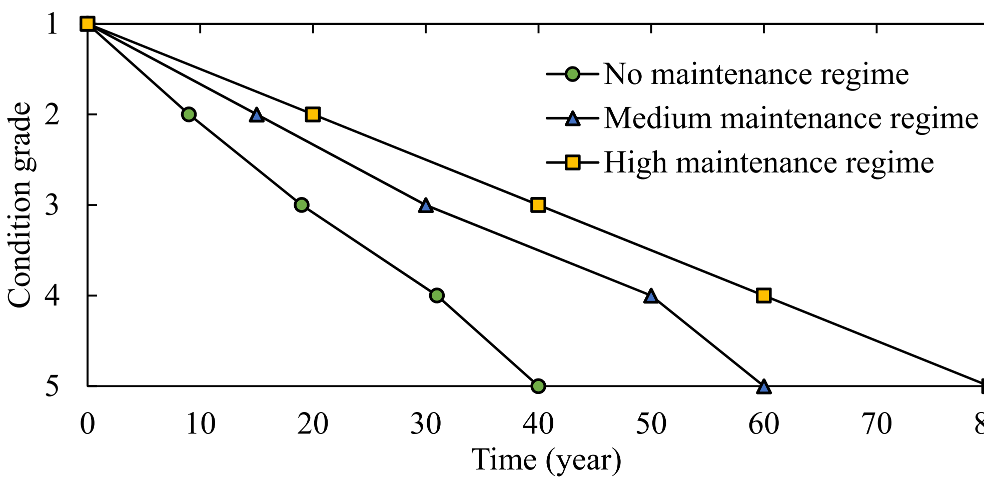

Figure 2: Deterioration curve for sea dykes with medium expected deterioration rate under different maintenance regimes [7].

The extreme water level height during storm surges and high tides is at a level of 1.50 mOD. Significant wave height in deep water is 2.30 m with a return period of 1000 years. The critical design value of the wave overtopping discharge is considered 2 l/s/m. It is assumed that the structure is in good condition with the initial condition vector of $X_0(0) = (1,0,0,0,0)$. Figure 2 shows appropriate deterioration curves for this case study under medium deterioration rate, and subjected to three different maintenance regimes. Medium maintenance regime means regular maintenance including minor repair to sea dyke for surface cracking, rutting and erosion. High maintenance regime is similar to medium maintenance regime but with increased frequency and more stringent criteria for repair [7].

	No maintenance				Medium maintenance				High maintenance			
	year				year				year			
Grade	τ	β_i	θ_i	SSE	τ	β_i	θ_i	SSE	τ	β_i	θ_i	SSE
1(→ 2)	4	3.061	0.221	2.1e-7	11	7.916	0.086	1.2e-7	13	5.774	0.072	1.8e-7
2(→ 3)	6	4.814	0.154	2.4e-7	12	7.929	0.086	1.6e-7	13	5.774	0.072	1.8e-7
3(→ 4)	7	4.734	0.132	8.8e-8	11	4.152	0.083	1.8e-7	13	5.774	0.072	1.8e-7
4(→ 5)	4	3.061	0.221	2.1e-7	7	7.032	0.135	1.5e-7	13	5.774	0.072	1.8e-7

Table 3: Parameter estimation for three different scenarios. τ: years after initial date that the sea dyke is in the same condition grade with 50% probability. SSE: sum of squares due to error (Goodness-of-Fit test).

The parameters of the Weibull function are estimated using Equations 7 and 8. Trust-Region algorithm is utilised to solve the minimisation function to estimate the parameters for different condition grades, and results are presented in Table 3. Figure 3 shows the cumulative survival distributions of the transition process and their changes over time under no maintenance plan. For example, the sea dyke at age of 15 is about 6% to be in condition grade 2, about 56% to be in condition grade 3, about 24% to be in condition grade 4, about 13% to be in condition grade 5, and less than 1% to be in condition grade 1. The same procedure is considered to estimate cumulative survival functions for sea dyke under medium and high maintenance regimes. Then, the time-dependent transition probabilities are generated using Equation 3.

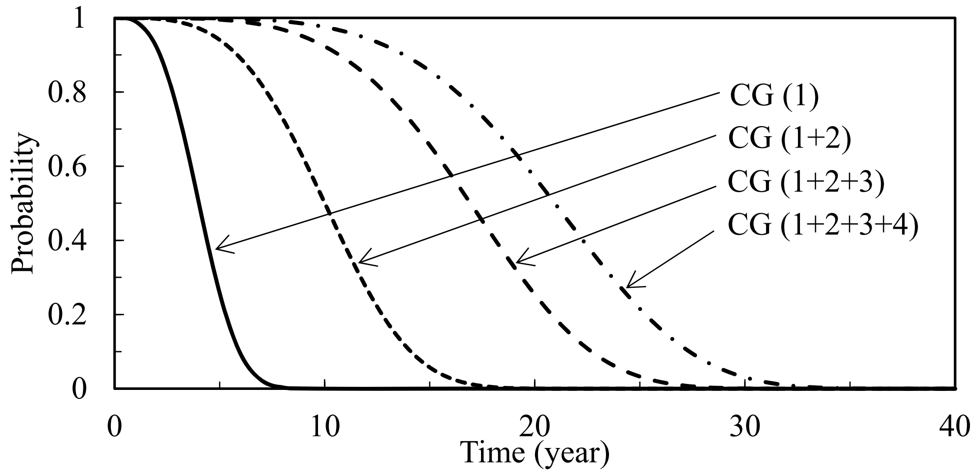

Figure 3: Survival functions of cumulative waiting times in different condition grades (CG) subjected to no maintenance regime.

Figure 4 shows the probability density distribution of crest level loss associated with different condition grades according to Table 2. The distributions of the loss are lognormal for condition grade 1 and 5, and are normal distributions for condition grades 2, 3 and 4. The mean and standard deviation of the distributions are calculated using the proposed method by Ang and Tang [14]. It is assumed that the accuracy of distributions are 90% of all the inspection results, for example, the mean value for the probability distribution of condition grade 3 is 15.0 cm with the standard deviation of 3.20, assuming 10% of all observed values belong to another condition grades.

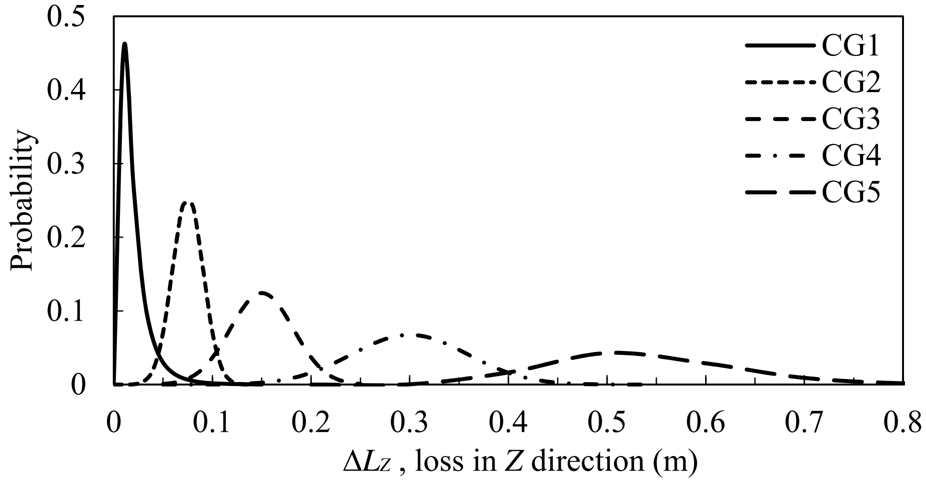

Figure 4: Probability density distribution of the sea dyke crest level loss associated with condition grade (CG).

A reliability analysis carried out for overtopping failure mode for the structure of the sea dyke section shown in Figure 1. Reduction factors for berm γ_b and slope roughness γ_f are considered 0.85 and 0.90, respectively. Figure 5 shows the failure probability caused by wave overtopping over 80 years after the initial construction date under three maintenance regimes. It is demonstrated that the probability of failure increases over time due to deterioration process and crest level settlement. The failure risk of overtopping varys with the type of maintenance regime that is undertaken over time, as expected. For example, the risk of failure at age 30, is high (about 67%) for the sea dyke under no maintenance regime, while it is about 30% and 9% for the sea dyke under moderate and high maintenance regime, respectively.

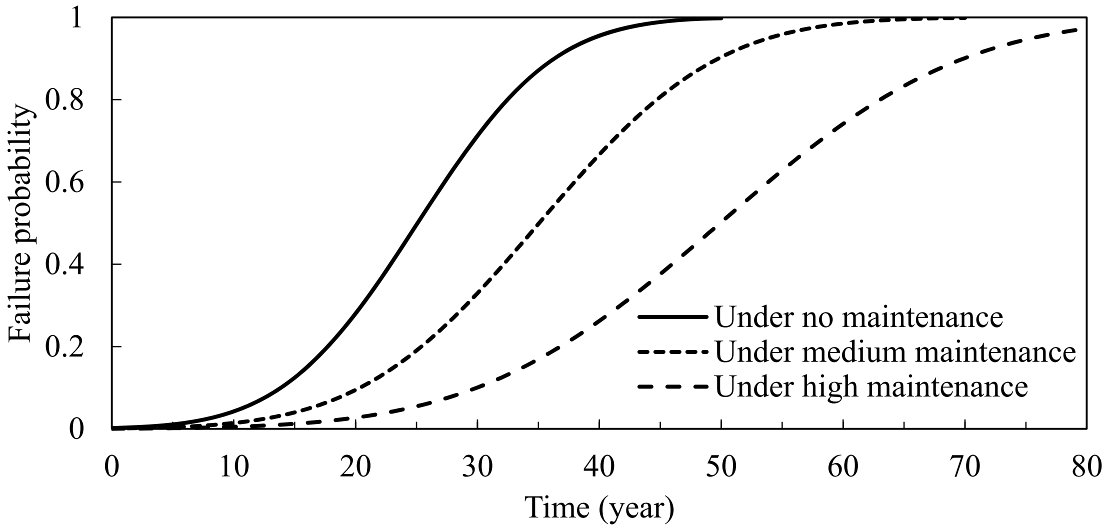

Figure 5: Overall probability of failure caused by wave overtopping with different maintenance scenarios.

6 CONCLUSION

This paper proposes a method to assess failure probability for coastal defence structures by utilising a stochastic time-dependent Markov model with respect to condition grading scheme. The probability of condition grades for the sea dyke during the lifetime is determined by using transition probability matrices estimated from Markov process with Weibull model waiting time at each condition grade. Reliability analysis for overtopping failure mode is carried out, and the structural resistance deterioration due to crest level settlement is considered in the limit state equation for each condition grade. The crest level settlement is categorised into 5 lifecycle stages (each lifecycle for an appropriate condition grade) in relation to the initial resistance, and then translated into a probabilistic framework to consider in the performance deterioration evaluation. A case study is utilised to show the applicability of the proposed method, and the following conclusions are noted.

The Markov model is useful to assess the transition of condition grades over time with respect to the maintenance plans in order to predict the future performance evaluation. The Markov model can estimate distinct transition matrix at each time-step with consideration of undertaken maintenance regime. The deterioration of sea dyke (e.g. crest level settlement) can be defined into condition grading system, and then is translated into a probabilistic framework. Estimating deterioration level with respect to condition grading system through the time-dependent transition probabilities gives a more accurate evaluation of the future performance prediction. Overtopping failure probabilities largely depend on sea dyke's resistance level; hence, failure risks are expected to be increased over time due to deterioration processes. The dyke crest level settlement increases significantly the risk of overtopping failure of the sea dyke in the future.

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