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A. H. El Hakea
American University in Cairo

S. Abu-Samra
American University in Cairo

Ossama Hosny
American University in Cairo, OHOSNY@AUCEGYPT.EDU

M. Iskander
Coastal Research Institute, Alexandria

H. Osman
Cairo University Faculty of Engineering

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Integrated Simulation Model for Maintenance and Repair Optimisation for Rubble Mound Coastal Structures, Using Markov Chains, Regression and Genetic Algorithms

A.H. El Hakea,[a] S. Abu-Samra [a], O. Hosny [a], M. Iskander [b], and H. Osman [c]

[a]Construction and Architectural Engineering Department, the American University in Cairo, Egypt
[b]Hydrodynamics Department, Coastal Research Institute, Alexandria, Egypt
[c]Structural Engineering Department, Faculty of Engineering, Cairo University, Egypt
E-mail: ayman.elhakea@aucegypt.edu, solimanamr_8@aucegypt.edu, ohosny@aucegypt.edu, coastal_alex@yahoo.com, hesham.osman@gmail.com

ABSTRACT

The significant increase in the world population living within close proximity to coastlines has assigned further importance to coastal protection structures. This importance has been even ascertained given the increasing risks posed by climate change. From this standpoint comes the importance of maintenance and repair strategies for coastal protection structures especially in low-lying coastal areas. This research provides an integrated model for the optimisation of maintenance and repair for rubble-mound breakwaters, revetments and groins under simulated climatic conditions. The model starts by establishing an Asset Inventory Database (AID), a Markov-Chain (MC) Deterioration Engine, and a Genetic Algorithm (GA) repair and maintenance Optimisation Engine. The AID includes the coastal structures within any particular study area, along with their design attributes and hydrodynamic data. The database divides coastal structures into structural reaches for ease of management. The MC deterioration engine predicts future condition of the structure based upon actual visual inspection results, while taking into account the single-time condition drop caused by seasonal storms. The GA Optimisation Engine includes a set of decisions that are triggered when the structure's Priority Index (PI) – a factor of the condition and the magnitude of failure impact- attains the defined threshold. MC deterioration patterns are expressed using best-fit regression to enable the integration between MC's and the GA Optimisation Engine. The case study consists of a group of rubble-mound structures in Alexandria, Egypt. The Optimisation Engine simulates repair and maintenance scenarios for various climatic conditions at a preset PI threshold, and results are compared and discussed.

Keywords – Simulation, Rubble-Mound; Coastal Structures; Markov Chains; Regression; Genetic Algorithms; Climate Change; Cost Optimisation

1 Introduction

This research presents an integrated model for the optimisation of maintenance and repair costs for rubble-mound coastal structures. In this section, the design concept of rubble-mound structures is briefly introduced, followed by the problem statement and the discussion of the need for optimizing maintenance and repair costs, especially in view of the implications of climate change.

1.1 Rubble-Mound Coastal Structures

Reference [1] classifies coastal protection structures into rubble-mound and non-rubble structures. From a design perspective, most rubble-mound structures typically consist of toe and core stone with a gradation between 10 and 300 kg, in addition to filter or under-layer stone with a gradation ranging between 300 and 800 kg [1] [2] [3]. The steepness of the seaside slope of rubble-mound structures is inversely proportional to the structure's ability to dissipate wave energy. Nevertheless, the weight, shape, porosity, and placement technique of armour stone is a major factor affecting the structural performance and deterioration under both regular and storm-condition wave attack. Armour stone can be either categorised into natural rock armour or engineered precast concrete armour units. Reference [3] provides a thorough review of rock armour types and properties while [1] and [2] include tabular representations of the properties of the various types of engineered precast concrete armour units. Non-rubble structures include a variety of structures featuring design principles built upon rigid vertical or curved concrete sections, and could include rubble-mound cross-sectional components. In the latter case they are given the term "Composite Structures" [4].

Rubble-mound structures could be classified by type into breakwaters, jetties, groins, and revetments. They could be also categorised by their relation with the shoreline as either shore-perpendicular or shore-parallel; in addition to being either semi-detached or detached. Considered the relation with still-water level, rubble-mound structures are classified into elevated, low-crest, and submerged structures [1] [2].

1.2 Problem Statement

When dealing with coastal structures in general, it is essential to consider that the long-term structural deterioration patterns may differ between various structures within the same geographical region based upon a multitude of design, environmental, and anthropogenic factors. The need for optimisation of maintenance and repair costs for coastal structures is hence evident in view of such highly uncertain variables.

From a design point of view, and considering rubble-mound structures; the grading of the core stone, toe, and filter layer; as well as the armour stone design and material properties; are all decisive factors that impact the deterioration pattern of the structure. Equally important is the method of laying the armour stone, whether pell-mell or regular placement. Environmental factors include still-water depth at the toe of the structure, seabed properties and bathymetry, wave properties, and intensity of design and intermediate storm reflected in the significant wave height "H_s" and significant wave period "T_s". It is established that for the same storm, the single-time sudden drop in the condition state of the structure will vary from one structure to another based upon the design and environmental attributes. Anthropogenic factors include the past history of maintenance, repair, and rehabilitation, and extend to include another crucial dimension: maintenance and repair policies along with their associated implementation agencies, and the budgets allocated for the execution of such policies. Furthermore, coastal protection structures are classified in terms of their priority of intervention in accordance with the level of criticality associated with the assets and populations they protect.

In view of the above, the aim of this research is the provision of a decision-support model for asset-managing agencies that enables the guided management of maintenance and repair intervention policies for rubble-mound coastal structures. The objective of the model is to minimise the total maintenance and repair cost over a preset future forecast interval, while maintaining the predefined Priority Index (PI) threshold for each structure within the desired study area. PI's are factors of both the structural condition at any given year, and the risk impact upon failure expressed in a numerical scale, as shall be discussed in the following sections. As will be discussed in the next section, the main observed research gap is the timely integration between condition indices, climate change effect, risk exposure limits, and repair and maintenance investments.

2 Literature Review

2.1 Estimating Future Deterioration

The traditional approach for determining future deterioration and damage progression until failure for rubble-mound coastal structures is built upon armour stability empirical formulae, which are in their turn stemming from experiments conducted on structure prototypes in laboratory test flumes. This approach tackles deterioration in stormy conditions, and is followed in extensive literature most notably in [5], [6], [7], [8], [9], and [10]. The typical failure modes of rubble-mound structures are presented for the purpose of illustration in [11].

While these empirical armour stability formulae provide a simulation of real-life deterioration and damage accumulation following various sets of timely wave attack, they vary according to the armour shape, necessitating separate formulae for each type of engineered concrete armour units, in addition to different equations for breakwater rounded head and trunk sections. Reference [12] even questions the reliability of tests conducted on prototypes of structures with the aim to simulate or predict the damage progression patterns. This criticism is based upon the multitude of factors making such prediction highly uncertain, and is further ascertained in [13] and [14].

Furthermore, a statistical approach for modelling damage progression on rubble-mound breakwaters is followed in [15] and [16], and was further extended in [14]; but again, this statistical approach is built upon the Damage Parameter "*S*" established in [9] and used since then in all literature featuring armor stability empirical formulae [17].

Limited research considered the adoption of Artifical-Intelligence (AI) tools and techniques in modeling of timely deterioration of coastal structures. While [18] presented the use of Artificial Neural Networks (ANN's) in estimating future deterioration of rubble-mound breaklwaters, [19] adopted a MC deterioration approach for both rubble and non-rubble structures. Reference [20] compared three sets of ANN models and a Fuzzy Logic model considering their accuracy in predicting future deterioration of rubble-mound breakwaters and jetties.

Moreover, [21] compared MC and ANN detrioration modeling for the same set of coastal structures, and suggested that the stochastic MC modeling approach is more accurate than the detrministic ANN approach in modeling future deterioration for the case of single inspection point. Reference [21] also adopted a backward MC approach between this single inspection point and the year of construction or last major repair, and utilised the obtained trend to simulate future deterioration patterns. Neither of the AI-based modeling approaches considered the sudden drop in the condition index of structures resulting from single-time storm events.

2.2 Integrated Coastal Management Frameworks

Since the beginnings of the 1990's, the US Army Corps of Engineers has launched the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) program with the aim to establish an integrated life-cycle management of all coastal protection and navigation infrastructure across the United States. The REMR scheme indcluded a series of publications most notably [22], [23], [24], and [25]. The REMR framework according to [23] starts by condition inspection and rating, then logging of the inspection data onto the asset database computerised system, analysis of maintenance and repair alternatives and associated costs, and finally the production of condition reports, budget reports, and maintenance records. While all of these work focus on inventory management and condition rating procedures and forms; reference [24] stand out in the way they introduced the first computer program intended to facilitate the process of life-cycle management of coastal and navigational infrastructure. Envisaging the same process flow of the REMR scheme, [24] introduced the Breakwater™ software, a simple DOS-based coastal asset inspection, condition rating, and budget allocation program.

Furthermore, [3], [11], [23], and [26] all discussed the various inspection, maintenance, and maintenance and repair cost optimisation methods for coastal structures. The main methodology in all of these studies is to establish a pattern simulating the gardual decline in the structural condition index, before moving into choosing the optimum set of intervention decisions. With the exception of [26], these works however did not expand into the associated maintenance and repair costs. Reference [26] intorducted mathematical functions that calculate the total life-cycle cost of rubble-mound structures but based upon empirical armour stability degradation forecast, without including climate change effect.

3 Research Methodology

The general research methodology is illustrated in Figure 1. The formulation of the methodology features four major components: (1) The AID; (2) the Inspection and Condition Rating Module; (3) the MC Deterioration Engine, including the supplementary Storm Simulator; and (4) the Maintenance and Repair Optimisation Engine. Each of these components is discussed in the coming sections.

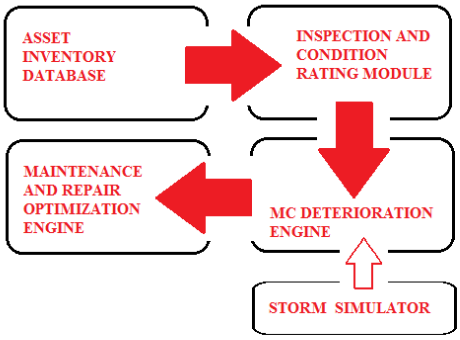

Figure 1. General research methodology formulation.

3.1 Asset Inventory Database (AID)

In accordance with the REMR procedures, rubble-mound structures are sub-divided into sub-reaches and reaches based upon the cross-section attributes (i.e. rounded head, trunk, and root in case of breakwaters and groins). In cases of revetments, where the cross-section is constant, the subdivision of reaches and sub-reaches is carried out by dividing the structure into equal segment ranging between 50.00 m and 150.00 m. For semi-detached breakwaters, jetties, and groins, the typical divisions of the structure would be as follows: (1) Root; (2) Inshore Trunk; (3) Offshore Trunk; and (4) Rounded Head. The sub-reaches would then be further subdivisions of each of these reaches according to the length, taking into account that the rounded heads due to their negligible length are not subdivided into sub-reaches. For revetments for instance, the structure would typically consist of a single reach, which is in its turn divided into equidistant sub-reaches.

The design and environmental attributes of all sub-reaches belonging to all structures under the management scope are listed in the AID, along with the past record of intervention. The associated costs of intervention policies for every reach per LM are included in the AID.

3.2 Inspection and Condition Rating Module

The inspection and condition rating procedures followed in this research are based upon the REMR scheme for rubble-mound structures. The aim of the Inspection and Condition Rating Module is the establishment of a unified numerical condition scale for rubble-mound structures. Such scale is divided into 7 categories: (1) Excellent; (2) Good; (3) Fair; (4) Marginal; (5) Poor; (6) Very Poor; and (7) Failed; and ranges between 0 to 100; o being the Failed condition lower limit, and 100 being the Excellent condition upper limit. These categories of rating ate applied while rating the condition of cross-sectional components, sub-reaches, reaches, and entire structures. Typical cross-sectional components for rubble-mound structures, as shown in Figure 2, include the crest or cap, the seaside slope, the rounded head, and the leeside slope. The REMR procedures deal with the rounded heads of breakwaters in the same manner as the seaside slopes, given the fact that rounded heads are the areas subjected to the highest damage level [1]. Using this configuration, each of the rating fields corresponding to each of the cross-sectional components is assessed against specific rating tables outlined in [22] and [23], which list the sets of observations corresponding to each of the condition rate categories, for each type of the cross-sectional component distresses shown in Figure 2. Having completed the distress ratings under each cross-sectional component, the cross-sectional component index is then calculated as per the REMR guidelines, whereby the Cross-Sectional Component Index (CSCI) value is designed to be very near to the lowest distress type rating. After computing the CSCI, the next step is to compute the Sub-Reach or Reach Index (RI).

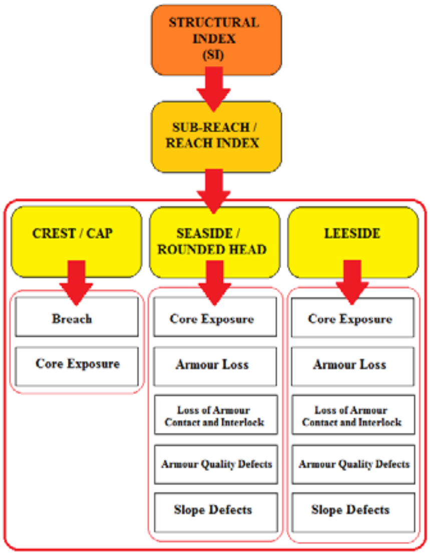

Figure 2. General research methodology formulation.

The calculation of the Structural Index (SI) is accordingly carried out as a function of all RI values corresponding to the structure.

According to [3] and [25] inspections and condition assessments should be both event-dependent (i.e. immediately after storm occurrence or significant damage events), and time-dependent (i.e. every 2-3 years).

3.3 MC Deterioration Engine

3.3.1 Backward MC Engine

The MC Deterioration Engine is built on the assumption of a single inspection point. This is intended in order to solve the commonly-occurring issue of lack of previous inspection and condition rating records. In this single inspection point, CSCI, RI, and SI values are determined for all structures within the scope of the study. The other condition state known point is at the date of construction or the date of last major repair or rehabilitation. At that year SI is 100%. Equation (1) provides the MC formulation utilised in this research to simulate the backward deterioration between the last point in time where SI was equal to 100%, and the other point in time where the SI was actually calculated based upon visual inspection and condition assessment:

$$\begin{bmatrix} \%\ Excellent \\ \%\ Good \\ \%\ Fair \\ \%\ Marginal \\ \%\ Poor \\ \%\ Very\ Poor \\ \%\ Failed \end{bmatrix} = \begin{bmatrix} 1-P1 & 0 & 0 & 0 & 0 & 0 & 0 \\ P1 & 1-P2 & 0 & 0 & 0 & 0 & 0 \\ 0 & P2 & 1-P3 & 0 & 0 & 0 & 0 \\ 0 & 0 & P3 & 1-P4 & 0 & 0 & 0 \\ 0 & 0 & 0 & P4 & 1-P5 & 0 & 0 \\ 0 & 0 & 0 & 0 & P5 & 1-P6 & 0 \\ 0 & 0 & 0 & 0 & 0 & P6 & 1 \end{bmatrix}^{t} x \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

Where: (1) The left parameter of the equation represents the current structural condition matrix of the reach or sub-reach based upon field inspection, such that in each row of the matrix the percentage of the reach or sub-reach length belonging to each condition rating range is listed; (2) "*P1*" through "*P6*" are the transition probabilities between each two successive deterioration grades in the Deterioration Transition Matrix (DTM); (3) "*t*" is the period of time in years separating the date of construction or that of last major repair or rehabilitation from the date of the last condition rating; and (4) the right parameter of the equation is a single-column matrix representing the condition state at the year of construction, or at the time of the last major repair or rehabilitation. This configuration is based upon the work done in [19] and [21]. Solving Equation 1 for P1 through P6, and taking into account the typical ranges of these transition probabilities based upon expert consultation, the characteristic DTM's for each reach and sub-reach were obtained.

3.3.2 Forward MC Engine

Taking from where the Backward MC Engine process ends and using the characteristic DTM's peculiar to sub-reaches and reaches, it became possible to forecast the future deterioration trends for rubble-mound structures using the same Equation (1), but this time solving for the left parameter of the equation given that *P1* through *P6* are known from the backward MC model, and considering that the value of *t* corresponds to the age of the structure at the year of the forecast. In fact the work published in [21] has reached this exact stage; however, the addition this research presents is the expression of the forward MC deterioration trends in terms of mathematical functions using best-fit regression. Equation (2) provides an example of the typical deterioration curves obtained through the regression of MC deterioration patterns, for a rubble-mound breakwater:

$$SI_{Oij} = -2 \times 10^{-6} (Y_j - Y_{oi})^3 + 0.003 \times (Y_j - Y_{oi})^2 - 0.0101 (Y_j - Y_{oi}) + 0.5452 \quad (2)$$

Where: (1) "SI_{Oij}" is the initial SI for structure "i" at year "j" in case no storms take place and also in case no intervention; (2) "Y_j" is the current year of SI calculation; and (3) "Y_{oi}" is the structure "i" year of construction or its year of last major repair, whichever is more recent.

3.3.3 Storm Simulator

This research features the single-time impact of design and intermediate storms, which appear a sudden drop in the SI value upon the storm occurrence. The numerical drop in SI value for various combinations of armour shapes, armour weights, seaside slope angles, significant wave heights, still-water depths, and freeboards, were obtained in this research using expert feedback. The return periods of intermediate storms used in this paper are 25 years and 15 years, respectively, to represent the normal and stringent climatic condition. Nevertheless, the chosen return periods for design storms are 50 years and 30 years to represent both the normal and the stringent climatic conditions, respectively.

3.4 Maintenance and Repair Optimisation Engine

3.4.1 Objectives Function, Decision Variables, and Constraints

The Maintenance and Repair Optimisation Engine for rubble-mound structures is designed with the objective function to minimise the total cost spent on all assets during the forecast interval for maintenance, repair, and rehabilitation. The formulation of the objective function is displayed in Equation (3)

$$\sum_{i=1}^{n} \sum_{j=0}^{m} [M_{Uij} (1 + I) (Y_j - Y_o)] L_i \quad (3)$$

Where: (1) "M_{Uij}" is the intervention policy unit cost for structure "i" at age "j"; (2) "I" is the inflation rate taken as 12%; (3) "Y_j" is the current year; (4) "Y_o" is the starting year of the optimisation run, which is 2013 for the case study; (5) "L_i" is the length of structure "i"; (6) "n" is the total number of structures within the scope of the optimisation; and (7) "m" is the total number of years under the optimisation scope.

The decision variables are the unit costs of the given set of intervention policies corresponding to rubble-mound structure maintenance and repair. Such unit costs are particular to every structure within the group of assets under study, and the inflation rate is applied to such rates for future forecasts. The model constraints are represented by the maximum PI threshold, the triggering SI ranges for each of the intervention policies, and the maximum number of interventions per year for the entire study area, and for each individual structure. The PI concept is further discussed in the following section. At the convenience of the end user, the model features the preset budget constraint, which can be either applied to specific structures or to the entire number of structures taken into consideration. Meanwhile, the years of occurrence of design and intermediate storm and their effect of the deterioration are all determined by the Storm Simulator feature, and are fixed for each cost optimisation run.

3.4.2 Priority Index (PI)

PI's for all structures in the desired study area are obtained using data obtained from both literature and expert opinion. They are taken as the product of multiplying the probability of failure of the structure by the impact level of the structure's failure. The probability of failure is taken as *(1-SI)*, such that a scale from 1 to 4 is also used to quantify the levels of impact; with1 being the lowest impact and 4 being the highest. This is further explained by Equation (4), using the same concept of reliability-based maintenance as outlined in [26].

$$PIij = (1 - SIFij) * (RF) \quad (4)$$

Where: (1) "PI_{ij}" is the Priority Index for structure "i" ay year "j"; (2) "SI_{Fij}" is the adjusted Structural Index of structure "i" at year "j" after taking into account the climatic and intervention policy effect; and (3) "*RF*" is the Risk Factor, which is an numerical value between 0 and 4 representing the ascending risk scale upon the structure's failure

3.4.3 Intervention Policies

The intervention policies are listed as follows:

1. Monitoring and inspection. This policy is both event-dependent and time-dependent as discussed in the Inspection and Condition Rating Module.
2. Routine Maintenance, with a total cost per structure equal to 2% of the initial construction cost. This policy involves the compensation of lost armour units.
3. Repair, with a total cost of 6% of the initial construction cost. This policy includes extending the toe in the seaward direction and the laying of additional armour to strengthen the original degraded armour layer. It may include the re-arrangement of existing armour in a pell-mell fashion rather than being uniformly placed, in order to increase wave energy dissipation and decrease wave run-up.
4. Rehabilitation, with a total cost of 100% of the initial construction cost. This policy involves the removal of the entire armour layer, the re-shaping and compensation of the degraded filter or core stone, the replenishment and extension of the toe including dredging of the seafloor as may be necessary, and the replacement of the entire armour layer. It may also include the reinstatement of the crest, cap, or crown-wall of the structure.

4 Case Study and Discussion of Results

4.1 Case Study Overview

The case study location is Alexandria, Egypt, as shown in Figure 3. The study area extends over a distance of 18.5 km of shoreline, and houses 36 rubble-mound structures; 19 of which could be classified as rubble-mound breakwaters and groins, and the other 17 structures are classified as rubble-mound revetments. The total seaside length of these structures is approximately 14 km. Among the breakwaters and groins category, 4 structures are submerged and 1 structure is a low-crest structure. The AID includes all of the design attributes, environmental data, and past history of maintenance and repair pertaining to all structures within the study region. In addition, owning agencies and bodies, repair and maintenance contractors, and construction costs are included for all structures as part of the AID. For the purpose of inspection, all structures were divided into reaches and sub-reaches using fixed surveying stations. For underwater structures, it was not possible to conduct visual inspection and come up directly with an SI value.

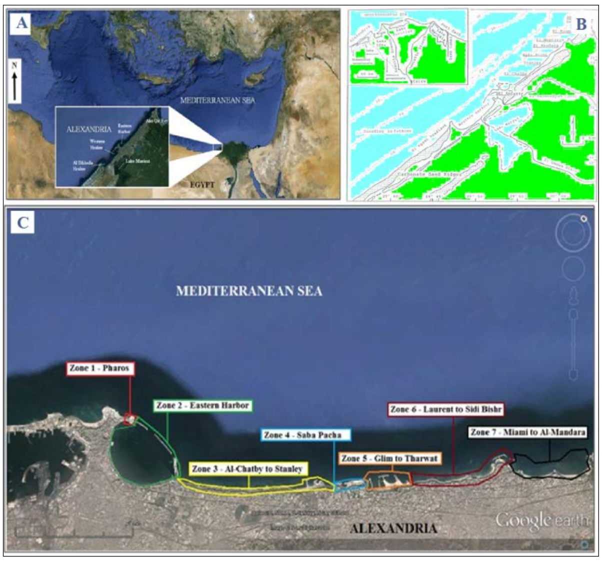

Figure 3. Maps showing: (A) Location of Alexandria in the Eastern Mediterranean Basin; (B) Location of Alexandria in the Nile Delta region; and (C) Coastal asset zones of Alexandria.

As such, the REMR guidelines as outlined in [23] and [24] for functional rating of coastal structures were followed. Hence, the obtained functional condition index is taken as the equivalent of SI. Thus, SI values for all structures were calculated based upon the single-inspection performed in 2013. Risk areas in Alexandria were identified in [4], such that PI values for all structures were obtaining using expert opinion and validated against the findings of past literature.

4.2 Optimisation Scenarios

The cost optimisation for repair and maintenance was performed for the time window between 2013 and 2050. The intervention policies for every structure at each year between 2014 and 2050 are represented by the integer values 0, 1, 2, 3, in the same order of policies outlined in the Research Methodology Section of this paper. Budget constraint is taken as equal to 2% of initial total construction cost per year for all structures. Further constraints featured a maximum of 1 replacement per structure, and a maximum of 10 interventions per structure throughout the optimisation timeframe. Another constraint dictates a maximum of 10 interventions per year for the entire study area. Nevertheless, the maximum PI threshold is taken as 2.00 based upon expert opinion. The climatic scenarios are considered for all structures as shown in Table 1. The optimisation is run using MS Excel^{TM} Evolver evolutionary algorithm tool, with a population of 200, and a crossover to mutation rate of 80% to 20%.

Table 1. Climatic scenarios for maintenance and repair cost optimisation

Climatic Scenario	Intermediate Storm Date	Design Storm Date
1	2016, 2041	2018
2	2016, 2031, 2046	2018, 2048

4.3 Discussion of Results and Conclusions

Figure 4 displays the cumulative repair and maintenance cost between years 2013 and 2050 for all structures, considering the climatic Scenarios 1 and 2. It is observed that the stringent climatic condition represented by Scenario 2 was more costly in order to maintain the PI threshold.

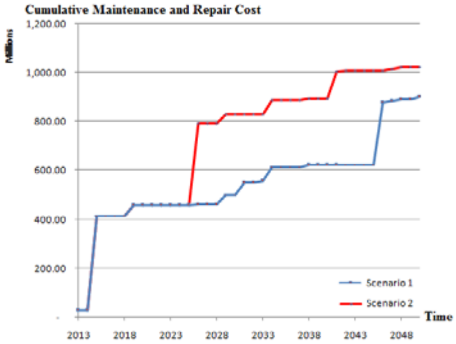

Figure 4. Cumulative repair and maintenance cost for Scenario 1 (normal climatic condition, and Scenario 2 (stringent climatic condition).

Furthermore, Figure 5 displays the change in the maximum PI amongst all structures relative to the maximum PI threshold, for both Scenarios 1 and 2. It is observed that in the stringent climatic condition, whenever a storm occurs, the rate of increase in PI value, i.e. the risk level, increases at as faster rate than in the normal climatic condition.

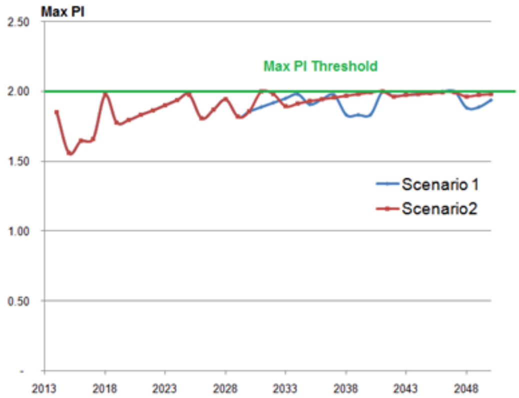

Figure 5. Timely change of the maximum PI value.

Comparing Figures 4 and 5, it is further concluded that Scenario 1 was able to achieve less PI value, i.e. less risk exposure limit, with significantly less expenditures than Scenario 2, where the stringent climatic conditions have aggravated the need for extensive intervention to maintain the ever-increasing PI values below the desired threshold.

5 Recommendations for Further Studies

Recommended future enhancements and research areas are plenty. Inspections could be improved by virtue of modern inspection tools and technologies, especially for under-water portions of coastal structures, and more important, for submerged and low-crest structures. Underwater inspections will provide more reliable figures for actual condition indices, and hence increasing the accuracy of the deterioration forecast. A future area of work also lies in the conduction of another round of visual inspection and condition rating of the study area to refine and retune the findings of the Backward MC Engine, obtained using a single-inspection point. Thus, the MC deterioration forecast model can be systematically upgraded with every new inspection. Furthermore, various runs for the optimisation module could be carried out using different sets of storm return periods and inflation rates. For instance, the inflation rate taken in this research case study is 12% annually. This is viewed as an essential need for sensitivity analysis and long-term management planning for coastal assets, especially in light of the ever-increasing environmental impacts of global climate change. Nevertheless, it is finally suggested that other scenarios would be run for different budget scenarios such that there is no PI constraint, with aim to study the impact of both budget availability and budget deficiency on risk exposure levels to life and property.

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