

Combined use of Simulation and Optimization Models for the Optimal Design of Harbor Breakwaters: Application at the Port of Thessaloniki

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Abstract

The optimal design of the dimensions of a harbor breakwater, is a very complex matter. The length of the breakwater must be long enough to protect the harbor but at the same time, small enough to reduce its cost. The approach presented in this paper includes the combined use of a simulation and an optimization model. The simulation model is used to determine the variation of the wave height in crucial areas of the port under different extensions in two directions, of the breakwater. The wave heights were produced using steady-length extensions of the breakwater in the two directions investigated. The optimization model, formulated in a linear programming form, aims to determine the minimum extension in these two directions that satisfies the operational constraints that were set concerning the acceptable wave heights. The two models are connected through a response matrix. This matrix is formulated by the results of the simulation model and is used to describe the constraints of the optimization model. The proposed methodology can be used and applied in a series of similarly structured construction design projects.

Keywords

optimization, decision making, harbor design, wave models

1. Introduction

Civil engineering is arguably the oldest engineering discipline. The built environment encompasses much of what defines modern civilization. Due to the advancement of technology and the present human needs civil engineers are constantly asked to solve complex construction problems, with greater accuracy and effectiveness. The field of marine engineering structures is of great importance, as harbors are examples of commercial and touristic power. More and more areas have been exploited to form there artificial harbors, with the support of many technical projects. However, optimization is an important criterion for the effective protection and operation of a harbor, without necessarily leading to uneconomic constructions.

So finding the optimal dimensions of a breakwater can offer maximum protection in a harbor, without providing prohibited cost. Throughout this process it is important to use a simulation model to determine the study area. The area of application of the simulation models, is limited in understanding the operation of the under study area, particularly in predicting wave heights, and

not able to determine the optimum dimensions of the breakwater. To investigate possible alternative scenarios, simulation models must be combined with optimization methods. The large number of alternative scenarios that may occur, are limiting the possibility of direct discrimination of the optimal solution. Using optimization model enables the selection of the best solution or a group of solutions that meet the requirements of the problem. Through an iterative process, scenarios are gradually reduced in order to give what best meets the expectations.

In the following sections, the description of the key characteristics of solving optimization problems by the response matrix technique is analysed. After the description of the study area for which the present research and mathematical simulation model is conducted, the basic characteristics and the solution process of optimization model are presented. Finally, the main results and their evaluation are presented along with suggestions for future process development prospects.

2. Response matrix technique

This method is based on the validity of the assumption of spatial and/or temporal linear superposition. Accordingly, a system is created consisted of incomings, which through a criterion that is defined in the form of a mathematical relationship, attribute desired output, minimizing the undesirables. Incomings define the decision variables, which are the requested value of the problem for which the optimal solution is sought. The mathematical relationship which is the criterion, according to which the desired results are obtained, is called the objective function. Finally, the conditions that define acceptable limits of values of the decision variables are the constraints of the optimization problem. According to this method an external mathematical simulation model is used to calculate factors, each of which correlates unit values of the decision variables at one point, with their effect on the constraints of the problem. The result of the organization of all factors arising is called response matrix, the dimensions of which depend only on the number of decision variables and the number of checkpoints, that define the constrains of the optimization model (Theodossiou, 1994; 2004; Psilovikos, 2006; Shirahatti and Khepar, 2007; Larroque et al, 2008; Theodossiou et al, 2014).

The validity of the assumption of linear superposition states that both the objective function and the constraints of the problem are linear functions of the decision variables. Apart from cases where there is actually a linear relationship, the response matrix technique can be even applied in cases where the linear relationship does not apply completely, imposing though much more strict application criteria. One can exploit the linearity that occurs in some areas by appropriately selecting the "unit" value for the calculation of the response matrix factors. If the "unit" value is selected close to the final value of the decision variables, then the deviation from linearity is small. This option can be either based on the experience of the manager or by a trial-and-error procedure.

3. Case study

The problem addressed by this study concerns the construction of a new breakwater in the port of Thessaloniki. Given the expansion of the 6th pier and for the protection of the area, a breakwater is placed within 500 m of the front end of the extension, and then the provided protection of it is

examined, using combined simulation and optimization methods to determine the optimal length that ensures the highest protection of the area.

The Port of Thessaloniki has 6 piers that have 28 quays with total length 6,200 m. The port's 6th pier is the most important because it has the largest area, the deepest quays and the most modern infrastructure and equipment for container and cargo handling. The port's area covers the current operating needs, but is not enough to meet the future needs for bigger drafts to serve the new generation vessels and for more storage space for containers and bulk cargo. In order to meet the port's present and future needs, the extension of the 6th pier must be completed. With this extension the port will have the depths and land areas required to increase its current services and competitiveness.



Figure 1. The port of Thessaloniki today

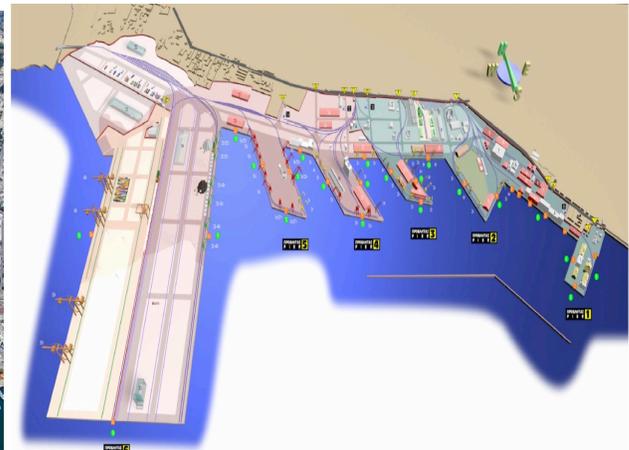


Figure 2. The port after the extension of the 6th pier

Piers 1, 2, 3 and 4, even though they have lower quay top surface levels, do not have wave problems because they are protected by the existing breakwater. Piers 5 and 6 have higher quay surfaces and are not protected by breakwaters. According to previous data, this new breakwater will provide the necessary safety, ensuring the proper operation of the port. In this study, a mathematical simulation of the waves generated by Southern (S), Southeastern (SE) and Southwestern (SW) winds towards the quays for various lengths of the placed breakwater, has been developed. To analyze this, the information needed to simulate the port, including the expansion of the 6th pier, was collected. Using these data, the new breakwater was placed with an initial length and then, wave disturbance for various expansions of the breakwater, left and right, were examined.

The wave height distribution, estimated by the wave simulation model, depending on a discretized increase of the length of the breakwater on either side, constituted the data of the unit response matrix. Subsequently, this matrix was imported in the optimization model, with the ultimate aim of finding the optimal solution defining the appropriate extension of the breakwater on either side, after many trials.

In the following paragraphs, the results produced through the application of the proposed methodology are presented, along with comments on the effectiveness and applicability and suggestions for further research, are presented

4. Simulation model

Due to its geographical position, the port of Thessaloniki is open to waves generated by Southerners (S), Southeast (SE) and southwest (SW) winds. In each scenario examined, waves, caused by the above three winds, were investigated. The procedure involves placing an original breakwater located 500 m to the south and parallel to the dike head of the 6th pier, and then derive its final optimum extension. The breakwater is of vertical forehead type, from armed concrete. It will, potentially, be extended on either side and its final position will allow seamless approach of ships to the port quays and especially in the quays of 5th and 6th pier. The determination of the location of the breakwater will not prevent any future additional extension of the 6th pier and quays of the port to the south, towards the sea. The depth of the seabed at the selected position is 16.5 m.

The procedure of the application of the response matrix technique as a method to connect the simulation and optimization models is as follows. From the wave simulation model (Karambas, 2012, Christopoulos et al., 2012) the wave height will be calculated initially by placing a breakwater of 800 m length. Then, the breakwater will be extended only to the right side, with a constant increment of 30 m. Thereafter, it will be extended only to the left side, with a constant increment of 50 m. The results of the wave height, as already mentioned, will be used for the optimization process that will follow. For each scenario, Southern (S), Southeast (SE) and Southwest (SW) winds are investigated. Wind speed is considered to be 11 Bf (30 m/s) with 10 hrs duration (being conservative consideration).

The significant wave height H_s and the period of maximum energy density T_p are calculated by applying the JONSWAP method (given the fetch length, wind speed and duration).

The next step will be the discretization of the field in order to generate a depth file, while defining the areas where there is land with the use of appropriate software (Karambas, 1999; 2004). The output files of this procedure will constitute the input files of the wave model. From the wave model, the wave height in every point of the grid will be calculated, for every length of the breakwater. To make a visual presentation of the model Surfer program by Golden Software was used.

5. Application of the optimization model

Via the process of optimization, the optimal length of the breakwater is sought (Clauss and Birk, 1996; Manguez et al, 2006; Isebe et al, 2008). This goal is achieved, starting with the selection of an initial length of the breakwater and then progressively increasing it with steady-length extensions in the two directions investigated. Thus arises the need to define the decision variables, the objective function and the constraints that define the problem. The aim of the whole process is the selection of an optimal length of a breakwater, for which wave heights within the harbor area, do not exceed a maximum limit, thus contributing to the normal operation of the harbor and protecting it from extreme weather events.

The selection of the original length of the breakwater as the only factor which defines the decision variables, emerged after thorough investigation. The height, width, construction materials, and layout of the harbor, define components of the problem which lead to more

complex analyzes and could be investigated in future research works. Also, in order to resolve the problem, the choice of a stable original position of the breakwater that provides maximum protection to the quays of the 4th, 5th and 6th pier, existing and new, helps to retain the whole process in reasonably complex level.

The optimization is performed by connecting only the variation in the length of the breakwater to the change of wave height at each observation point, assuming that other elements do not affect the process. It was decided to manage the optimization problem with the use of linear programming to highlight its features. At the same time this was an opportunity to demonstrate the fact that through the appropriate procedure, easy to solve methods like linear programming can be used to analyze complex non-linear problems as he one investigated in this paper. This was achieved with user interventions introducing the understanding of the physical problem and the experience in optimization, to compensate with non-linearities.

The method used for the solution of the optimization problem, was the well-known Simplex Method through the application of the Linprog software [Tolikas, 2000].

Two decision variables were selected for the problem in order to define the response matrix X_1 and X_2 , which symbolize the extensions to the right and left of the initial length of the breakwater with steady-length increment. The dimensions of the response matrix depend only on the number of decision variables and checkpoints of the harbor. Based on its definition, as decision variables, X_1 and X_2 , are set the right and left extension. The unit values that were chosen, was 30 meters for the right-side extension and 50 meters for the left-side extension. Each of the decision variables examined for three indicative length scenarios. From these scenarios, factors will be extracted, each of which correlates unit values of the variable decision at one checkpoint with the effect of these sizes that define the constraints of the problem. The result of the organization of all factors arising, is called response matrix, and is included in the management model as a substitute of the simulation model.

The set of points at which the wave heights are estimated by the simulation model, is extremely large and unmanageable and thus it was decided that the most critical points affected by the placement of the new breakwater, should be checked. These cover the area around the piers 4, 5, 6, the existing breakwater and points in front and behind the position of the new breakwater, for the three wind cases, resulting in a total of 45 checkpoints.

The format of the objective function of the problem is:

$$X_1 + X_2 = \text{minimum}$$

The form of restrictions will be the following:

$$(A \times X_1) + (B \times X_2) \geq C \text{ where}$$

A, B: the factors of the decision variables representing the right and left extension of the breakwater, and the average of all possible combinations of variation of wave heights for each extension, always subtracting the wave height of the longest breakwater from that of shorter length. Thus, the positive sign indicates a decrease in wave height at the checkpoint, while the negative sign, an increase in wave height.

C: the allowable increase / decrease in wave height at each checkpoint than the permitted limit. The allowable increase is indicated by the negative sign and the decrease by the positive sign.

Figure 3 presents the distribution of wave heights around the study area, for the original length of the breakwater, resulting from a South wind (a), Southeastern wind (b) and Southwestern wind (c). These results were set as a base distribution of the wave heights used for the investigation of the variation of the wave heights as a result of the extension of the breakwater on either side.

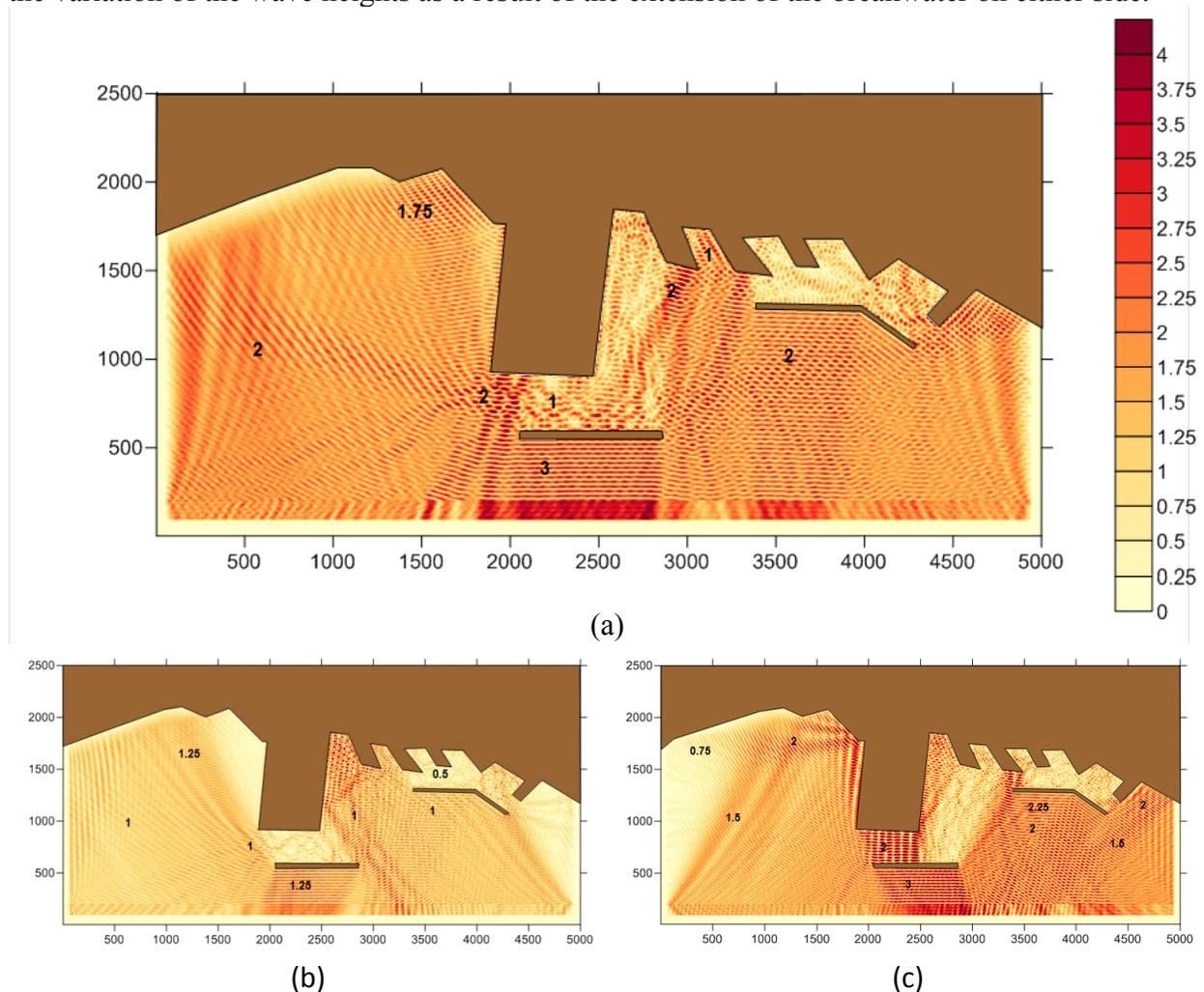


Figure 3. Simulation of the distribution of wave heights resulting from a South (a), a Southeastern (b) and a Southwestern (c) wind, along the harbor for the initial breakwater length

In order to find a solution with the optimization model, the goal is to reduce gradually the number of constraints. In the beginning, all the constraints that include positive values of the A, B and C factors are removed, as they already meet the target. To exclude further constraints, a graphical process was followed. Each constraint inequality is illustrated by a straight line of the corresponding equation. In every checkpoint, a comparison was made between the lines and in any case only the lines that had the same design format (ascending / descending) and inclination but were in the lower value range, and overlap by one or more of that checkpoint, were excluded while otherwise the constraints were retained. This procedure eliminated a significant number of constraints. Of course for every result that will be presented, all the eliminated constraints were checked in order to confirm that are actually fulfilled.

6. Results and discussion

From the procedure described above, the following results were produced. In order to result to acceptable solutions, further reduction of the number of the constraints was made in order to simplify the optimization procedure. The concept of this practice was to identify solutions that do not actually satisfy all the constraints of the optimization problem and provide the manager a series of alternative solutions. The meaning of these solutions is that the longer the breakwater the better the results concerning the wave heights in the harbor area. Of course, the longer the breakwater, the higher the cost. So the manager has the option to select the more appropriate among the alternatives minimizing the cost and at the same time accepting that under extreme conditions, and specific wind directions, in some areas (known through the application of the proposed methodology) the wave heights will exceed a safe level. Some of the solutions produced through this procedure are indicatively presented in the following (Kralli, 2014).

1 st Solution (47 constraints)	decision variables	value	This solution provides a total length of the breakwater, of 1900 meters and there were 6 constraints that could not be fulfilled.
	X ₁	14.782	
	X ₂	13.145	

2 nd Solution (20 constraints)	decision variables	value	This solution provides a total length of the breakwater, of 1555 meters and there were 9 constraints that could not be fulfilled.
	X ₁	16.167	
	X ₂	5.406	

3 rd Solution (9 constraints)	decision variables	value	This solution provides a total length of the breakwater, of 1220 meters and there were 12 constraints that could not be fulfilled.
	X ₁	7.624	
	X ₂	3.828	

It must be noted that the number of constraints represents a specific number of checkpoints and that every constraint is created for a certain wind scenario, therefore there are only a few points where the wave height exceeds the maximum limit. Also the frequency of occurrence of each wind is different and this reduces even more the possibility of high waves. All these combined with the protective measures taken and temporary prohibition of docking of ships until recovery of the extreme phenomena at these points is an effective way of addressing the problem. So this whole approach results to the achievement of smooth operational conditions along the port, without problems as a result of a good protection provided by the breakwater.

The problem can become even more complicated if one takes into account more parameters that affect the problem. But this requires more complex calculations and use of non-linear methods, to achieve greater accuracy. However this approach demonstrates how a complex nonlinear problem can be addressed through assumptions of linear methods and based on the experience of the engineer to provide both a sufficient reference guide to resolve, and also become a medium for verifying an optimum outcome. Further research on this subject can evolve this methodology and also be a good and reliable example of connecting simulation and optimization models for better addressing similar problems.

7. References

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