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MULTI-OBJECTIVE OPTIMIZATION APPROACH TO IMPROVE LEVEES CONSTRUCTIBILITY AND REDUCE THE FLOODING RISK

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ABSTRACT

More and more floods occurred over the last decade in the world, causing important damages and significant costs. Levee systems have been built to protect low-lying areas against high-floods in numerous rivers in the world over the long human history. However, when levees are not well designed, they hardly resist to major floods and can break easily. These failures increase flood consequences. Optimal design of a levee system for flood protection involves a set of objectives and constraints arising from political, economic and engineering aspects such as the protected area value, the levees construction cost, and the stability of levees. Designing flood protection levee respecting simultaneous these conflicting objectives, is very difficult using classical methods. In this paper a non-domination based genetic algorithm (NSGA-II) is used for solving the problem. It is combined with the response surface strategy (RSM) to automatically generate and compare multiple levee designs in a few seconds time. Several geometric parameters of levees are taken as operating parameters. Computational Fluid Dynamics (CFD) model is used to simulate the flood waters flow and water-levees interaction. Main inputs data necessary for such model are; 3-D Digital Terrain Model combined with 3D buildings model and upstream discharge hydrographs. This paper demonstrates that the multi-objective optimization method provides robust and acceptable solutions to the levees design

KEYWORDS: Urban Flood Propagation, Optimal Flood Levee Designs, 3D Modeling, Computational Fluid Dynamics (CFD), Multi Objective Optimization, Non-Domination Based Genetic Algorithm (NSGA-II), Response Surface Modeling (RSM) Introduction (Heading1)

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Original Article

INTRODUCTION

Flooding has long been recognized as the most damaging and costly natural hazard in many countries considering the frequency and influencing extent. Due to the global climate change and the rapid urbanization in the floodplains, the frequency of devastating floods tends to be higher and the loss of human lives and property show no sign of decreasing. Even with centuries of experiences on flood defense and tremendous amount of progresses have been achieved, flood still appears to enjoy being the main enemy of public in the category of natural disaster. Great majority of flood, related death and economic losses occurred in developing countries. In order to limit flooding impacts, and protect the urban area exposed to this risk, national and local governments are obliged to undertake structural flood control projects, such as levees systems, river improvements, dams, the construction of diversion channels, etc. These protection works are dedicated to protect the maximum lives and properties in urban areas, and at the same time they should not be a source of risk on these lands and communities, in case of breakage or damage. It's the reason that we have to construct levees, with the correct design. The financial resources available for the implementation of such hydraulic planning projects are often limited, and it is very difficult to set aside a special budget for a regular maintenance of these projects.

In the present study, levees are taken as the land use project against river flooding in urban area. In order to improve flood defense in urban area respecting the economic limits while maintaining the useful life of levees as long as possible, the main goal of this work is to find the optimal levees design able to respond effectively to such objectives. A levee, dike (or dyke), embankment, is an elongated naturally occurring ridge or artificially constructed fill or wall, which regulates water levels. It is usually earthen and often parallel to the course of a river in its floodplain or along low-lying coastlines [1]. Implementation of such project is often preceded by many questions asked by decision makers. The most important ones are:

Where can be the exact location of levees along the river to protect floodplain? What is their required length to protect the maximum areas? How we should design the levees to extend their useful life against the different damage mechanisms such as Erosion? How we can balance the losses of land value sacrificed for floodway expansion (encroachment) and flood damages caused by inadequate channel capacity? What is the economic levees size necessary to ensure an enough protection? At what cost?

Optimization technique has proven to be one of powerful tools, able to provide the satisfactory answers on such type of questions. So these methods should therefore be established to support the decision-making processes for an optimal flood protection. Over the last decade, optimization methods have been used to optimize and to design the flood defense system. These methods have been explicitly accounted in the design of various flood defense systems, such as storm sewer system [2], levees [3] dams and spillways [4], and storm surge protection [5].

This paper describes the development and application of a new approach based on multi-objective optimization method aims to find quickly and with a quite accuracy the optimal levees designs to build along an urban river. The optimal design found, should be able to satisfy simultaneously several conflicting objectives:

- *Levee, should protect the maximum of urban area threatened by flooding, this implies that the value of its length, its height and / or its encroachment should be the highest possible to prevent water overtopping.*
- *Moreover in order to increase the levee life and its resistance against hydraulics and mechanics constraints such as erosion, it is recommended to increase some levee sizes. For instance: flattening the inside slope of the levee; widening the top of the levee and increasing the encroachment length.*
- *However, satisfy these objectives is not always economically feasible, that's why to keep the levee construction costs as low as possible, levee sizes should be as limited as possible.*

The results obtained indicate that there is potential for application of the Genetic Algorithm to levees designs optimization problems, where the objective function is nonlinear and other optimization techniques may be difficult to apply and find the global optimum. This approach is applicable on any river and urban area whatever the complexity of its topography.

DATA AND NUMERICAL METHODS

Methodology for 3D Modeling

For modeling flood plain problem on a real urban area, it is an important requirement that detailed topographical conditions are designed into the computational domain. For this purpose, a several GIS vector data (i.e. topographical map, Long and cross profiles of a river and the contours lines of buildings) have been used and intersected to obtain a full 3D model of study area (i.e. ground surface and 3D shape of buildings).

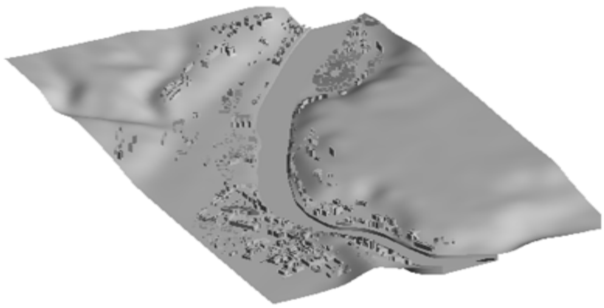

Figure 1: 3D Urban Area Modeling Based on the GIS Vector Data

Hydrodynamics and Erosion Model

In the present study, the Computational fluid dynamics (CFD) code ANSYS fluentis used to investigate the flow patterns in the river and its consequences on the levees failure by erosion phenomenon.The flow dynamics is modeled by numerically solving the Reynolds Averaged Navier-Stokes (RANS) equations for the water-air combination using a 3D unstructured mesh. Solving these equations system requires a turbulence model to set the Reynolds stresses turbulence closure is achieved through solution of the standard k-ε model [7].The free surface movement is tracked by the volume of fluid (VOF) method, for only one phase, water and void [8-9].

Erosion Model

There are three principal failure modes threatening the levees: internal erosion, external erosion and the mechanical instability. This paper is limited to study the third failure mode in order to model the mechanical instability by the shear effect (even if it is the least common cause for the levees broke).

The shear stress on the inside walls of the levees play an important role on the break. The lateral friction of solid particles (sediment) that the flow applied to the surfaces in contact with the water flow is not directly involved in the breakdown but is indirectly: the shear stress is the cause of erosion which may lead to the fall of the mechanical strength and instability of the floodwall-levees. The erosion rate is dependent of the levees design, construction material andflow pattern. In the current study tow powerful erosion models has been used [10-11].These models are available in ANSYS Fluent® for use in conjunction with the Lagrangian particle model.

Particle impact erosion model:

$$E_{impact} = AV_s^n f(\gamma_i)$$

With $f(\gamma_1)$ is a dimensionless function of the impact angle with respect to the surface tangent.

Erosion damage depends on impact parameters and mechanical properties of the material. The impact parameters include impact angle, impact velocity and size, shape and density of the particles under consideration.

Erosion Model based on Wall Shear Stress

Due to high solid loading the particles travel nearly parallel to the wall surface and hence erosion due wall shear stress is more dominant than erosion due to particle impact.

$$E_{shear} = AV_s^n \tau_{ws} \frac{\alpha_s}{\alpha_{sp}}$$

Where A is an empirical Constant, $\tau_{ws}$is a solid phase wall shear stress, $V_s$is a solid phase velocity, n is a velocity exponent, $\alpha_s$is a volume fraction of solid phase and $\alpha_{sp}$is a packing volume fraction

Computational Domain and Boundary Conditions

The study area model is discretized using an unstructured tetrahedral mesh comprising of approximately 700,000 elements. Ten layers of prismatic elements were used at the walls to provide better resolution of the wall boundary layer. Mesh controls are used to refine the mesh near the water/air interface. The surface mesh and computational domain are shown in Figure 2. A polynomial function for water level versus time steps is developed and then used to specify the water level evolution at the inlet boundary (upstream).

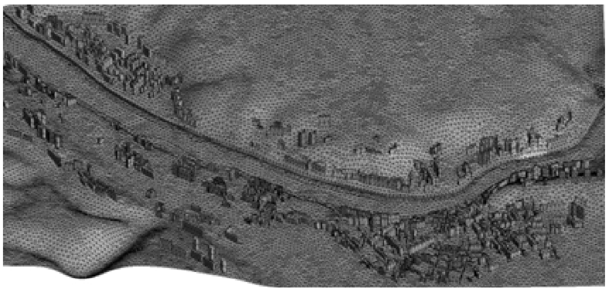

Figure 2: Computational Domain and Surface Mesh

A uniform distribution of velocity is set at the inlet boundary. The particles transported with the flow are assumed to be randomly distributed at the inlet and, due to the low Stokes number, the particle velocity distribution was assumed to be identical to that for the fluid phase. The particle size distribution was specified between 0.063 and 2mm. A zero gradient condition was applied at the outlet. The free surface condition is based on a volume of fluid method on the free surface. Standard no-slip wall functions were applied at all solid surfaces for the fluid phase except the levees walls roughness (river side) is set to 0.2 mm and the coefficient of restitution for the particles was left at the default value of 1.0. Using a more accurate figure was not considered important because the low Stokes number indicated that wall interactions would not be important in the flow. The next section describes the employed methodology, including geometry parameterization and optimization strategies.

METHODOLOGY

Geometryparameterization

The first step of an optimization procedure is the choice of the quantities required to completely parameterize the levee design. This is a very important phase of the optimization, since it is the most affected by the engineer's knowledge of the problem. Two opposite requirements have to be satisfied at the same time: the number of parameters should be kept as low as possible to speed up the optimization computation, whilst the design of the levee should be exhaustively described with all involved features, and thus with a large number of parameters. The result of the final parameterization is then a trade-off between the aforementioned conflicting requirements.

Design Parameters

The description of the levee contains design parameters to be optimized. These design parameters are defined as input variables. They are shown in this section together with the bandwidth (minimum and maximum values) by which they may vary.

The current variables in the description of the levee are (x_4) the levee length, (x_2) the levee height, (x_5) the width of the crest, (x_3) the riverside slope of the levee (assumed to be the same for the outer and inner Levee), (x_1) the length of the encroachment, (x_6) the number of levees on the first riverside (x_7) the number of levees on the second riverside, (x_8) the location of levees on the first riverside and (x_9) the location of levees on the second riverside. They are drawn in Figure 3.

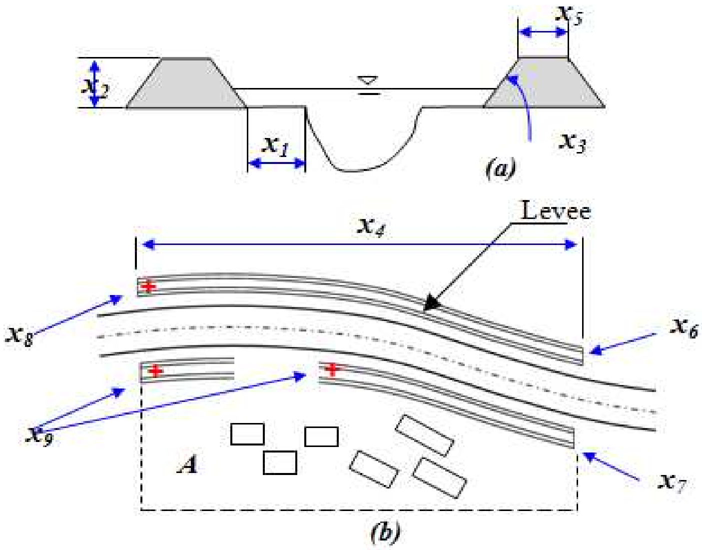

Figure 3: Geometry Sketch and Design Parameters Employed for the Optimization. (a) Front View and (b) Top View

The range in which the variables vary was limited to reduce the solution space and thereby reduce the computational costs. It was defined according some levees design guidelines. In addition, a number of logical borders are also set. Some Input variables are linear dependent and some variables are not. An overview of the variables with the maximum and minimum values is given in Table 1.

Table 1: Bandwidth of the Parameters

Var	Description	Unit	Min	Max
x_1	Encroachment	meter	1	10
x_2	Height	meter	3	10
x_3	Inside slope	Coef (H:V)	2:1	6:1
x_4	Levee length	meter	100	3000
x_5	Crest width	meter	1	4
x_6	Nbr of levee /1st S	-	1	5
x_7	Nbr of levee /2nd S	-	1	5
x_8	Location of levee/1st S	-	1	200
x_9	Location of levee/2nd S	-	1	200
A	Protected area	meter^2	-	-

Optimisation Objectives

The levee design optimization is performed with the aim of minimizing three objective functions, namely, (i) ConstructionCost (levee construction cost), (ii) ErosionRate (levee failure) and (iii)FloodLevel (the volume of flood waters having reached the protected urban area). In the following section, the mathematical expressions of these objectives are given.

- **Construction Cost**

The construction cost of the levee is assumed to depend on the volume of the levee body only. It is given in Euros (€). The equation expressing the construction cost is:

$$\text{ConstructionCost} = \sum_{i=1}^{k} \text{Vi} \cdot \text{Co}_v$$

$$\text{With } V_i = x_{2(i)} \cdot x_{4(i)} \cdot \left(x_{2(i)} \cdot \cot(x_{3(i)}\right) + x_{5(i)})$$

in which :

V_i : volume of levee (m^3).

cot (x_3): cotangent of the slope (inner and outer levee).

Co_v: construction cost per unit volume (€/m^3).

k = $x_{6\,+}\, x_7$: total number of levees along the river.

The construction cost is minimized by minimizing the total volume of levee.

- Erosion Rate

In order to account for both erosion mechanisms (wall shear and impact based erosion), the combined effects of both the models were considered:

$$E_{total} = E_{impact} + E_{shear}$$

- Flood Level

In this study the flood level is assumed as a function of flooded area and average flood depth, it is calculated using equation 10:

$$\text{FloodLevel} = p_w \cdot A_f$$

A_f : Flooded area (m^2);

p_w: Average water depth (m);

The value of surface protected of urban area is depending of levees length, height and encroachment length. The flood damages are limited if the river levee is designed taking into account these parameters.

The general mathematical model of the present optimization problem can be formulated as:

$$\min\,(f_1 : \text{ErosionRate}, f_2 : \text{ConstructionCost}, f_3 : \text{FloodLevel})$$

$$\text{subject to}: \begin{cases} x_{1min} \le x_1 \le x_{1max} \\ x_{2min} \le x_2 \le x_{2max} \\ x_{3min} \le x_3 \le x_{3max} \\ x_{4min} \le x_4 \le x_{4max} \\ x_{5min} \le x_5 \le x_{5max} \\ x_{6min} \le x_6 \le x_{6max} \\ x_{7min} \le x_7 \le x_{7max} \\ x_{8min} \le x_8 \le x_{8max} \\ x_{9min} \le x_9 \le x_{9max} \end{cases}$$

Optimization Strategy

- Optimization cycle

To solve the problem, a general optimization approach based on the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) is proposed as illustrated [12]. The NSGA-II optimization algorithm was used for the present work as it is based on a fast and elitist multi-objective evolutionary algorithm.

The optimization process start by vary the set of design parameters from the input variables using random as a DOE algorithm. Levee design parameters (x1 to x9) are defined as input variables (i.e. the quantities which can be modified to obtain the optimal solution).

The geometric parameterization of levee should be correctly made before the optimization step, so that the changing of the levee design is done automatically by optimization process. ANSYS®fluent solver is used for both floodplain and levee erosion modeling. A cycle of optimization is performed as follow: The NSGA-II runs ANSYS®fluent in batch mode by feeding it with the current geometric file which is meshed and next used in fluent solver. The evolution of water level in the model and levee erosion rate versus time are calculated and defined as CFD outputs. Then, the objective functions are calculated from the expressions defined in the previous section and saved to be evaluated and compared with the next cycle results. The NSGA-II repeat this cycle for the whole of the initial generated population, and evaluates the objective functions at each cycle, in order to generate new populations trying through several generations to find an optimal combination of levee design parameters able to satisfy simultaneously the problem objectives. However, this optimization process requires a large number of objective function evaluations, making this strategy unusable for intensive computation time problems, such as flood propagation problem in urban area, case of our study.

This large number of evaluation functions can be greatly reduced by replacing a large part of these evaluations by approximations constructed from a meta-model also called Response Surface Method (RSM) [13] and the computational time is considerably reduced. The designs generated during optimization make up the tradeoff surface (Pareto-frontier).

RESULTS AND DISCUSSIONS

Response surface modeling (RSM) creation and input space exploration.

Kriging algorithm was selected to create RSMs because of its good accuracy value on interpolation error over the output variables. A response surface is created for each outlet and objective. After the RSMs have been built, it is possible to use the surrogate model to evaluate the performance of levee, instead of real solver (i.e. ANSYS®fluent). Since the design evaluation using RSMs is very fast, a massive optimization of the design space using NSGA-II is performed by using the response surface (see Figure 4).

Thus, virtual optimization is the optimization carried out by running the problem on the surrogate model. At the end of the virtual optimization, the best so far designs (those belong to the Pareto-frontier) are calculated by running the real solver. This process is named validation of the response surface. More precisely, five Pareto points are selected by using Kriging RSM and then evaluated using ANSYS®fluent in order to obtain a measure of the interpolation error between real and virtual points. The accuracy of the initial set of response surfaces is fairly low; therefore, a new interpolation function is needed.

For this purpose, the results given by the real CFD analysis allow one to update the existing database with fifteen more designs. At this point, a new RSM training is carried out by using Kriging algorithm once again.

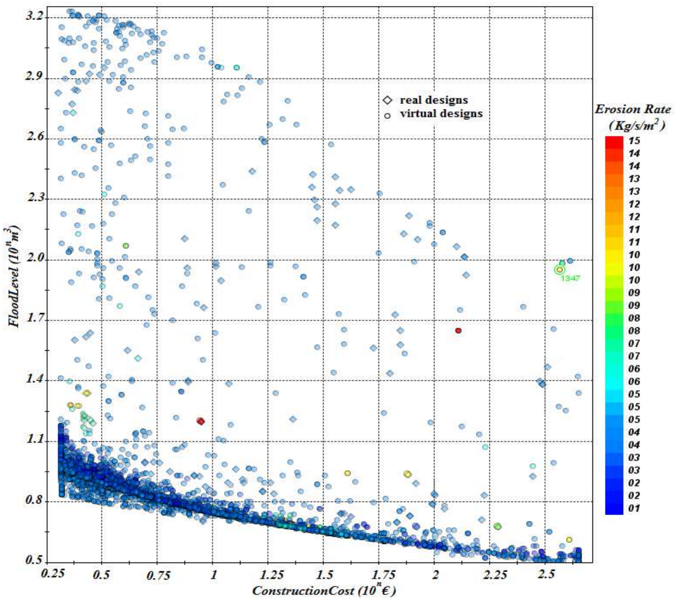

Figure 4: The Use of the RSM Allows Wide Exploration of the Domain Space

As a result, a new set of response surfaces is created with a reduced interpolation error, compared with the initial one. A new optimization phase subsequently takes place by using response surface as virtual solver with a NSGA-II algorithm set as scheduler. As previously, five Pareto points are selected and then validated with ANSYS®fluent. This recursive task stops once the accuracy level of the response surface becomes acceptable for the designer. Following this approach, six consecutive RSM trainings in total are needed so as to reach a sufficient accuracy of the definitive response surface. Once the latter has been built, a very effective tool is available to accomplish the whole Pareto-frontier wherein the best solutions are selected.

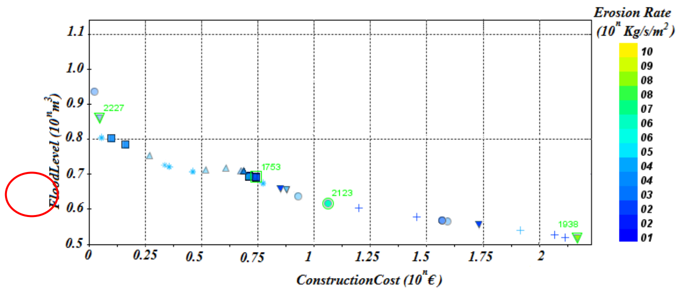

Figure 5: Pareto-Frontier of Predicted Points after Validation

Figure 7 shows the results of the validation of the predicted solutions by response surface for each of the three attempts. It can be seen that all the designs after validation belong to the Pareto-frontier.

Analysis of the Optimal Levee Design

Figure 8 summarizes the variational trends as well as the inter dependency between the objective functions and design variables by means of a scatter matrix. The lower triangular part of the matrix represents the correlation coefficients whereas the upper one shows the corresponding scatter plots. Diagonal elements represent the probability density charts of each variable. The correlation coefficients vary from−1 to 1. Two variables are strongly dependent when their correlation coefficient is close to−1 or 1 and independent when the latter is null. From Figure 6.

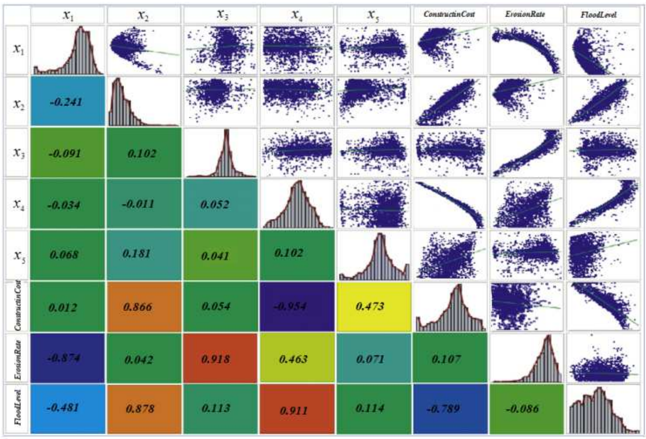

Figure 6: Scatter Matrix for Objective Functions and Design Parameters

- Construction Cost and Flood Level are strongly dependent and negatively correlatedas the correlation coefficient between them is equal to −0.789.
- The correlation of Erosion Rate with Construction Cost and Flood Level is very low as the corresponding correlation coefficients are equal to 0.107 and −0.086, respectively.
- x2 and x4 have strong and direct correlation with Flood Level (0.878, 0.911, respectively) whereas they have strong and inverse correlation with Construction Cost (0.866, −0.954, respectively).
- Erosion Rate is very sensitive tox1 and x3 where their correlation coefficients are equal to −0.874 and 0.918 respectively.
- x5 has very weak or unpredictable relations with respect to all objectives and parameters.

After the optimization, 3D Pareto frontier has been selected from the entire design space and four interesting solutions have been highlighted (see Figure 7) as follows; ID 2227 the solution having the lowest construction cost, ID 1938the solution having the lowest level of flood, ID 1753the solution having the lowest erosion rate and ID 2123a solution that is a good compromise for the three conflicting objectives. Figure 9 highlights the CFD modeling results for the set of selected solutions, where the relationship between design parameters and erosion rate as objective is showed.

Thus the ID 2123 is chosen as trade-off solution because it balances between different objectives (Figure 8). In this case to balance between the levee construction cost and flooded area (flood level) we choose not to fully protect the urban area near the river but only protect some areas characterized by high urban density.

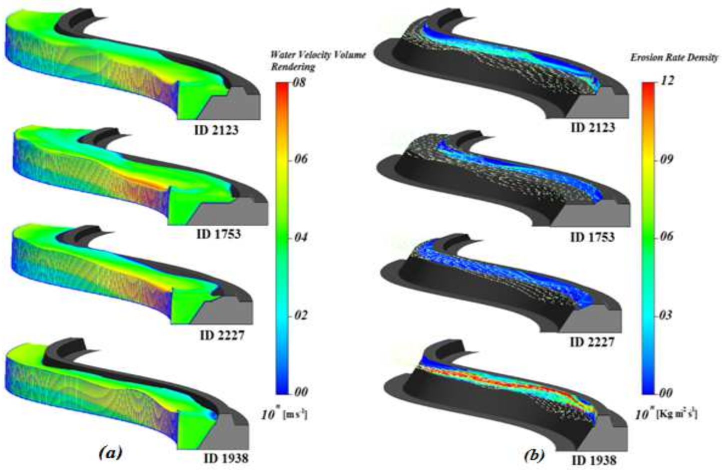

Figure 7: Interesting Pareto Solutions (a) Volume-Rendered Velocity Magnitude (b) Erosion Map

A comparison between the trade-off solution ID 2123 and a dominated one ID 1347 (not optimal) is summarized in table 2. The case of flood propagation without levees protection is also presented to provide a reference for these solutions.

Table 2: Comparison between the Trade-Off Solution and a Dominated One

Solutions	Erosion Rate [kg/s/m^2]	Flood Level [m^2]	Construction Cost [€]
Trade-off ID 2123	5.3	0.64	1.07
Dominated ID 1347	9.68	1.93	2.6
Reference simulation	-	5.58	-

Both solution ID 2123 and ID 1347 clearly show a reduction in flood level of 48% and 76%, respectively compared to the reference one without protection. In case of the dominated solution ID 1347 levees are built along almost the entire river in order to protect the maximum urban area, however this solution increases systematically the levees construction cost. Moreover the encroachment value (x_4) in this solution is very low, which increases the water flow and pressure against levees, increasing consequently the levees erosion rate. Regarding the solution ID 2123 we note that it meets all three objectives simultaneously, where the values of both construction cost and erosion rates is low, even if some parts of the urban area (less dense) are flooded.

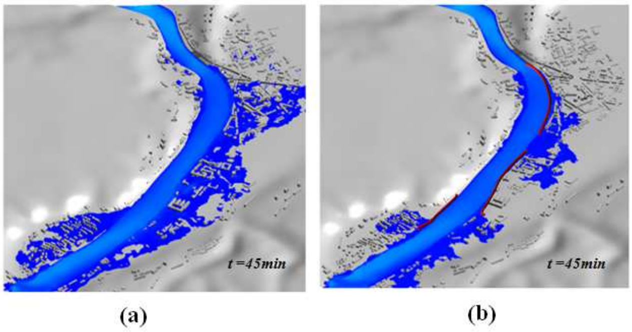

Figure 8: Flood Propagation versus Time (a) not Protected, (b) Partially Protected by Optimal Levees

Finally, the methodology illustrated in this work is valid for any levee design procedure whatever of the length and shape of the river as well as the complexity of the urban area topography to be protect.

CONCLUSIONS

The most important conclusion is that it is possible to combine different numerical methods in engineering to make a quick design levee in order to improve flood protection. This case can be seen as a proof of concept to find an optimal design in a very limited amount of time. We have seen through this study the ability of the CFD analysis to predict the causes of the erosion in inside faces of levees, as well as its ability to simulate the flood propagation in a complex urban area with an irregular topography, where the flood propagation is gravity flow. The motion of flood water through the urban area has been predicted using an Eulerian - Lagrangian approach in conjunction with a k-ε turbulence model, and an erosion map has been developed using tow erosion models. The modeling was able to successfully predict both the flooded parts of the system and causes of the levee erosion and then results were subsequently used with an optimization approach in the development of a new levee design which has better performance in terms of construction cost, erosion rate, and protection against flooding. Since the Pareto optimality approaches excludes a priori giving any weight to the objectives, the described optimization procedure offers the designer complete freedom to choose the most appropriate solution for a particular application from the Pareto-frontier. The choice of the trade-off solution among the ones located at the Pareto-frontier is depending of some criteria fixed by decision makers, and also the priorities order of objectives in relation to each other. It has been demonstrated that NSGA-II provides robust and acceptable solutions to the levees design optimization problem. This resulted in increased confidence to engineering methods as a tool in the design process, rather than only to investigate problems after they've occurred. Finally, to investigate the usefulness of the NSGA-II method for decision support, the sets of optimal solutions found, should be compared with allocations made by professional land managers, with a range of backgrounds, for a real world application.

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