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STRUCTURAL HEALTH MONITORING OF HYDRAULIC STEEL STRUCTURES

by

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Keywords: fatigue, hydraulic steel structures, risk-based inspection planning, dynamic Bayesian networks, structural health monitoring

Mots-clés : fatigue, structures hydrauliques en acier, planification des inspections basée sur le risque, réseaux bayésiens dynamiques, surveillance de la santé structurelle

1 INTRODUCTION

Hydraulic steel structures, such as navigation lock gates, play a significant role in keeping navigation traffic continuously moving, and their reliability is essential to the navigation infrastructure. They are usually large steel structures working (partly) underwater and their lifetime is 50-100 years or even more in the future. Currently, in Europe, there are a lot of hydraulic steel structures in operation along inland waterways, as well as all over the world. Many of them were fabricated a couple of decades ago and they are near or having reached their design life (> 50 years).

There are a lot of factors leading to the extensive degradation of hydraulic steel structures including fatigue failure caused by cyclic loading, effects of environmental conditions, increasing load or design requirements overtime. Therefore, it is required to use continuous monitoring system for hydraulic steel structures to provide a regular update of the structural status as a function of time using real-time data. Based on these data, the failure probability of the structure can be updated and optimum maintenance plan can be defined.

This study provides an overview of structural health monitoring and its application in structure monitoring. A specific application using structural health monitoring of the Greenup mitre gate USA) is presented.

2 STRUCTURAL HEALTH MONITORING

Structural health monitoring (SHM) provides the basis for an optimal schedule of inspection and maintenance for hydraulic steel structures. Thus, the health monitoring of structures and its applications is now an attractive issues for hydraulic steel structures.

Structural health monitoring is a modern technology and is considered to be crucial for the future. It is being applied in many fields, for example in bridges, e.g. Collins et al. [1], Ko and Li [2] and Reid [3] for more than 30 years. Successful applications were found in offshore structures, see Kim and Stubbs [4], Mourad et al. [5].

For hydraulic steel structures, Commander et al. [6] performed tests using monitoring strain at over 30 locations on the Emsworth mitre gate to assess the condition of the gate. This research provided additional information to further identify irregular lock gate behaviour. Treece et al. [7] presented SHM use to detect degradation between the quoin and wall boundary on the downstream mitre lock gates at lock N° 27 on the Mississippi River, USA.

Recently, the United States Army Corps of Engineers (USACE) [8] has developed an SHM programme to monitor for changes in behaviour of lock gates and this study utilises SHM data of the Greenup mitre gate. Measured data are collected and extracted every 15 seconds.

Figure 1 shows a strain gauge response at different locations on the Greenup mitre gate in 2014 (over a 12-months duration).

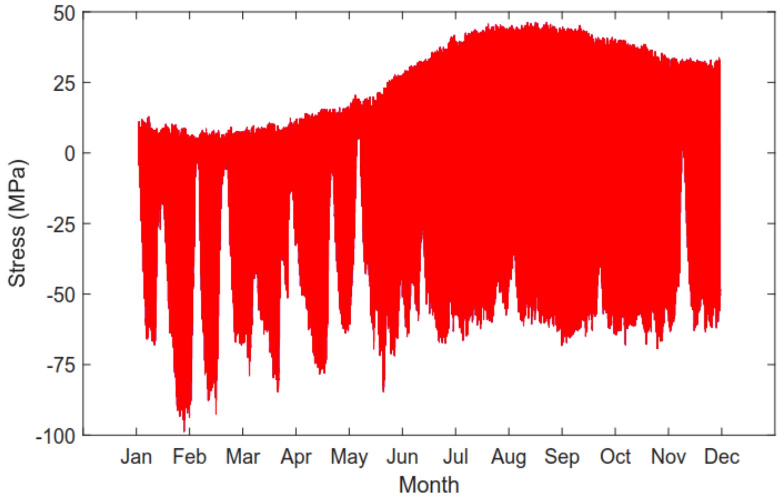

Figure 1: Stress measurements on Greenup mitre gate

3 METHODOLOGY

A fatigue assessment has been performed for the Greenup lock gate, which is an upstream horizontally framed mitre gate. The selection of potential crack locations are limited to the areas exposed to a strong response under fatigue load and its frequency.

This study utilises fatigue crack growth, a model based on fracture mechanics to analyse the crack propagation through the thickness under fatigue loading and evaluates the fatigue life by integrating the crack growth law. The most widely used model is the Paris-Erdogan law [9]. Crack depth at time t can be calculated by Eq. (1).

$$a_t = [a_{t-1}^{1-\frac{m}{2}} + \left(1-\frac{m}{2}\right) C B_{\mathrm{m}}^{m} B_{\mathrm{y}}^{m} Y^{m} B_{\mathrm{s}}^{m} \pi^{m/2} \sum_{j=1}^{k} \left(\Delta\sigma_j^{m_{SN}} n_j\right)]^{2/(2-m)} \tag{1}$$

where a_0 (t =1) is the initial crack size; Y is geometry function; C and m are material parameters; $\Delta\sigma_j$ is stress range and n_j is number of cycles corresponding. B_m, B_s, B_y are, respectively, measurement, load and geometry uncertainties.

A Dynamic Bayesian network (DBN) is a special class of Bayesian network, that represents the temporal evolution of variables over time. DBN allows temporal connections between time slices can be incorporated with condition probabilities among variables to create different time-dependence slices. A DBN framework for stochastic modeling of deterioration process and updating the failure probability is proposed in Straub [10]. In this study, DBN is used to determine degradation modelling for a welded joint. By instantiating the inspection variables I_t in the DBN with the observed events at the times of inspection, the failure probability is updated considering the inspection outcomes, Eq. (2).

$$\mathrm{p}(\mathrm{a_t}, \mathrm{q_t} | \mathrm{I_0}, \ldots, \mathrm{I_t}) \propto \mathrm{p}(\mathrm{a_t}, \mathrm{q_t} | \mathrm{I_0}, \ldots, \mathrm{I_{t-1}}) \mathrm{p}(\mathrm{I_t} | \mathrm{a_t}) \tag{2}$$

The DBN representation including inspection results I_t is shown in Figure 2.

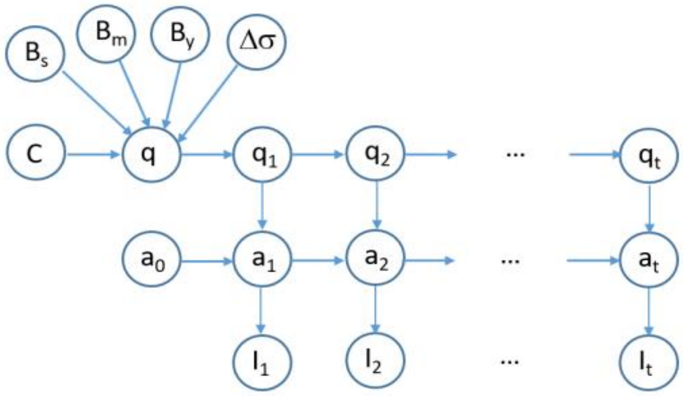

Figure 2: Fatigue crack growth as a DBN

4 RISK-BASED OPTIMAL INSPECTION STRATEGIES USING DYNAMIC BAYESIAN NETWORKS

Risk-based inspection (RBI) is an interesting topic for hydraulic steel structures due to the increase of aging structures where many failures may be detected. The risk-based optimal inspection strategies are identified according to the collected SHM data for the heuristic decision rule *"inspection performed when failure probability threshold is reached"* [11].

The total expected cost during the lifetime E_{tot} may be written as Eq (3).

$$E_{tot} = \sum_{t=1}^{T} C_f P_f(t) \frac{1}{(1+\alpha_r)^t} + \sum_{i=1}^{T_{insp}} \frac{C_r P_r(T_i) + C_{insp}}{(1+\alpha_r)^{T_i}} + C_{SHM} \tag{3}$$

where P_f denotes the annual failure probability in year t and P_r is the probability that a repair is performed in year t after an inspection done in the same year. P_{fc} is the cumulative failure probability. C_f, C_r, C_{insp} and C_{SHM} are failure, repair, inspection and SHM costs.

The different unitary costs are provided in Table 1. The discounting rate α_r is 3 % and the total time period is 100 years.

Unitary cost	Value US$
Inspection cost, C_{insp}	$0.0025C_f$
Repair cost, C_r	$0.04C_f$
Failure cost, C_f	$12{\cdot}10^6$
SHM cost, C_{SHM}	$5{\cdot}10^4$

Table 1: Cost characteristics

Figure 3. shows that the optimal annual failure probability threshold is P_f = $3{\cdot}10^{-4}$ and the expected costs is E_{tot} = $1.21 \cdot 10^5$ (US$).

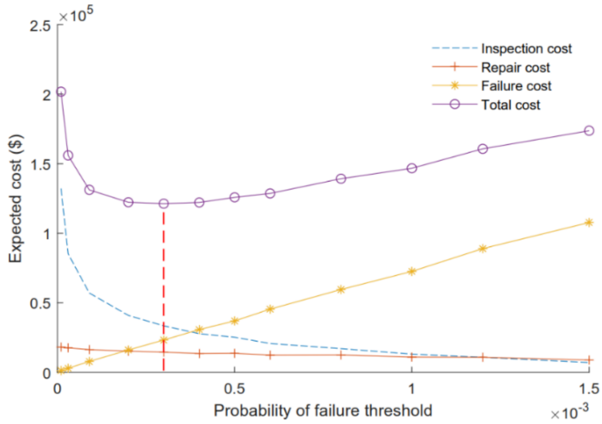

Figure 3: RBI Results – with inspection at failure probability threshold

Figure 4. shows the change of expected cost for three cases ('Do nothing', optimal based on 'periodic inspection' and optimal based on 'failure probability threshold') after 50, 60, 70 and 80 years.

In this study, the benefit of using SHM is analysed and SHM is recommended when the Green up mitre gate is expected having a long-term service (≥ 70 years).

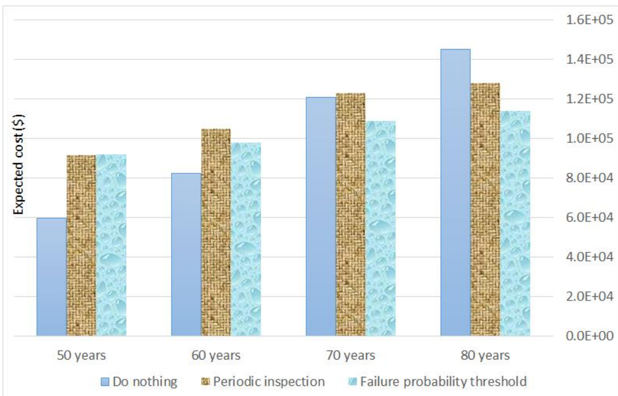

Figure 4: Results for RBI – with inspection at failure probability threshold

5 ACKNOWLEDGEMENTS

The authors acknowledge the financial support by the Wallonie-Bruxelles International (WBI), Belgium. Thanks also to USACE and PIANC WG 199 for the data.

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SUMMARY

Hydraulic steel structures, such as navigation lock gates, play a significant role in keeping navigation traffic continuously moving, and their reliability is essential to the navigation infrastructure. They are usually large steel structures working (partly) underwater and their lifetime is 50-100 years or even more in the future. Currently, in Europe, there are a lot of hydraulic steel structures in operation along inland waterways, as well as all over the world. Many of them were fabricated a couple of decades ago and they are near or having reached their design life (> 50 years).

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This study provides an overview of structural health monitoring and its application in structure monitoring. A specific application using structural health monitoring of the Greenup mitre gate USA) is presented.

RESUME

Les structures hydrauliques en acier, telles que les portes d'écluses de navigation, jouent un rôle important pour maintenir le traffic de navigation en mouvement continu, et leur fiabilité est essentielle pour l'infrastructure de navigation. Il s'agit généralement de grandes structures en acier travaillant (partiellement) sous l'eau et leur durée de vie est de 50 à 100 ans, voire plus à l'avenir. Actuellement, en Europe, il y a beaucoup de structures hydrauliques en acier en service le long des voies navigables, ainsi que dans le monde entier. Beaucoup d'entre elles ont été fabriquées il y a quelques décennies et sont proches de leur durée de vie nominale (> 50 ans) ou l'ont déjà atteinte.

De nombreux facteurs conduisent à la dégradation importante des structures hydrauliques en acier, notamment la rupture par fatigue causée par les charges cycliques, les effets des conditions environnementales, l'augmentation de la charge ou des exigences de conception au fil du temps. Par conséquent, il est nécessaire d'utiliser un système de surveillance continue pour les structures hydrauliques en acier afin de fournir une mise à jour régulière de l'état de la structure en fonction du temps en utilisant des données en temps réel. Sur la base de ces données, la probabilité de défaillance de la structure peut être mise à jour et un plan de maintenance optimal peut être défini.

Cette étude donne un aperçu de la surveillance de la santé structurelle et de son application dans la surveillance des structures. Une application spécificale utilisant la surveillance de la santé structurelle de la mitre Greenup gate (Etats-Unis) est présentée.

ZUSAMMENFASSUNG

Stahlwasserbauwerke wie Schleusentore für die Schifffahrt spielen eine wichtige Rolle bei der Aufrechterhaltung des kontinuierlichen Schiffsverkehrs, und ihre Zuverlässigkeit ist für die Schifffahrtsinfrastruktur von entscheidender Bedeutung. Es handelt sich in der Regel um große Stahlkonstruktionen, die (teilweise) unter Wasser arbeiten, und ihre Lebensdauer beträgt 50-100 Jahre oder sogar noch länger. Gegenwärtig sind in Europa und in der ganzen Welt zahlreiche Stahlwasserbauwerke auf Binnenwasserstraßen in Betrieb. Viele von ihnen wurden vor einigen Jahrzehnten gebaut und stehen kurz vor dem Erreichen ihrer Lebensdauer (> 50 Jahre) oder haben diese bereits erreicht.

Es gibt viele Faktoren, die zu einer weitreichenden Verschlechterung der Stahlwasserbaukonstruktionen führen, wie z.B. Ermüdungsversagen durch zyklische Belastung, Auswirkungen der Umweltbedingungen, zunehmende Belastung oder steigende Konstruktionsanforderungen im Laufe der Zeit. Daher ist es erforderlich, ein kontinuierliches Überwachungssystem für Stahlwasserbauten einzusetzen, um den Zustand der Struktur in Abhängigkeit von der Zeit anhand von Echtzeitdaten regelmäßig zu aktualisieren. Auf der Grundlage dieser Daten kann die Ausfallwahrscheinlichkeit der Struktur aktualisiert und ein optimaler Instandhaltungsplan festgelegt werden.

Diese Studie gibt einen Überblick über die Zustandsüberwachung von Bauwerken und ihre Anwendung in der Bauwerksüberwachung. Es wird eine spezielle Anwendung für die Überwachung des Strukturzustands des Greenup-Gatters (USA) vorgestellt.

RESUMEN

Las estructuras hidráulicas de acero, como las compuertas de las esclusas de navegación, desempeñan un papel importante a la hora de mantener el tráfico de navegación en continuo movimiento, y su fiabilidad es esencial para la infraestructura de navegación. Suelen ser grandes estructuras de acero que funcionan (parcialmente) bajo el agua y su vida útil es de 50 a 100 años o incluso más en el futuro. Actualmente, en Europa hay muchas estructuras hidráulicas de acero en funcionamiento a lo largo de las vías navegables interiores, así como en todo el mundo. Muchas de ellas se fabricaron hace un par de décadas y están cerca o han alcanzado su vida útil (> 50 años).

Hay muchos factores que conducen a la degradación extensiva de las estructuras hidráulicas de acero, incluyendo el fallo por fatiga causado por la carga cíclica, los efectos de las condiciones ambientales, el aumento de la carga o los requisitos de diseño con el paso del tiempo. Por lo tanto, es necesario utilizar un sistema de monitorización continua de las estructuras hidráulicas de acero que proporcione una actualización periódica del estado estructural en función del tiempo utilizando datos en tiempo real. A partir de estos datos, se puede actualizar la probabilidad de fallo de la estructura y definir un plan de mantenimiento óptimo.

Este estudio proporciona una visión general de la monitorización de la salud estructural y su aplicación en la monitorización de estructuras. Se presenta una aplicación específica que utiliza la monitorización de la salud estructural de la puerta de inglete Greenup (Estados Unidos).

ENERGY SAVING IN WATERWAY NETWORKS – FROM PUMP TO HYDRAULIC MANAGEMENT

by

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Keywords: Experimental pump test bench, performance-assessment of large submersible pumps, centrifugal pump modelling, waterways network optimisation, energy saving

Mots-clés : Banc d'essai expérimental de pompes, évaluation des performances des grosses pompes submersibles, modélisation des pompes centrifuges, optimisation des réseaux de voies navigables, économies d'énergie.

1 INTRODUCTION

Pumping is extensively used in waterways, particularly in artificial canals. While Europe promotes energy-saving, the problematic is not straightforward in pumping management. Firstly, the actual efficiency of one pump is not easily estimated in situ. Indeed, pump manufacturers generally provide detailed information on pump efficiency at nominal rotation speed with the nominal characteristics of the motor, which includes the best efficiency point (BEP). However, no or little information are provided concerning off-design pump operation, which is usually the one faced in practice. Secondly, free surface elevation in navigation reaches may fluctuate significantly enough to change the operating point of the pump. Hence, a pump is no more chosen for one specific operating point but for several operating points. The choice of the more suitable pump is then not straightforward. Lastly, energy price fluctuates and energy-consumption may thus be more attractive depending on time. Temporary storing water in reach in-between pumping stations could help optimising pump operation along the day.

The study depicted in this paper is part of a European project entitled 'Greener Waterways Infrastructure' (GreenWIN). This project is one of those listed in the Interreg NWE programme with the ambition to promote key economic and social exchanges, as well as innovation, sustainability, and cohesion. The members of this project are mainly canal operators that aim at improving their infrastructure to reduce the CO_2 footprint of waterways. In this framework, improving pumping process constitutes a key-point. Liege University, a scientific partner of the project, is in charge of the development of a pump test bench, a numerical model for pump operation as well as a hydraulic model for waterway network modelling, as highlighted in Figure 1.

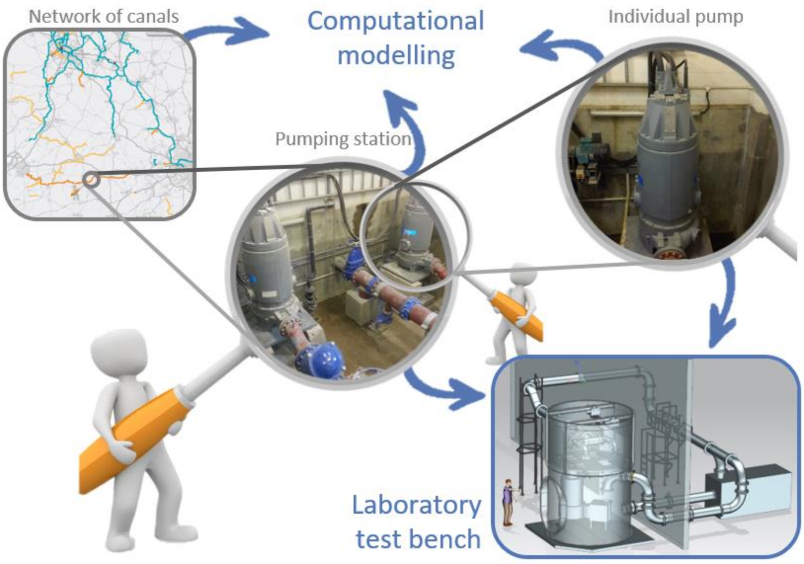

Figure 1: Project articulation emphasises the role of laboratory test bench, pumping station modelling and hydraulic network modelling to optimise energy consumption

2 METHODS

Three complementary avenues are considered through the GreenWin project to achieve more energy-efficient pumping in open-channel networks.

First, detailed characterisation of innovative pumping technologies efficiency for a wide range of realistic discharge and head conditions has been made possible through the design, implementation, and operation of a dedicated large-scale laboratory test-bench. This step helps assessing the effectiveness of enhancing energy-efficiency using 'smarter pumps'.

Second, dynamic modelling of single-site pumping system, involving pumps and variable frequency drives (VFD), enables designing optimal control of individual pumping stations, i.e. 'better use existing pumps'. Calibration and validation of this numerical model benefit from the datasets gained during the laboratory tests, while the computational model enables extrapolating results beyond the range of experimentally tested configurations.

The last step consists in assessing the benefits resulting from temporary water storage in the reaches in-between pumping stations. This couples the optimisation of interconnected pumping stations and requires hydraulic modelling to simulate the dynamic water level variations along the reaches. Different levels of complexity are considered for hydraulic modelling and optimisation. The hydraulic modelling of open-channel networks coupled to the VFD-pump computational model constitutes one key innovation of the research project.

3 RESULTS

3.1 Experimental Pump Test Bench

The novel laboratory test bench is represented in

Figure *2*.a), and is described in detail by Hardy et al. (2021), together with the procedure followed to collect experimental data. It involves a 4.5 m high tank with a storage capacity of 30 m^3, which can accommodate pumps up to 300 kW of power, 0.3 m^3/s discharge and 2 tonnes weight. This test bench for pumps includes a variable speed drive and a complete automatic acquisition system, which enables to characterise the pumping process for nominal and off-design operation as illustrated in

Figure *2*.b).

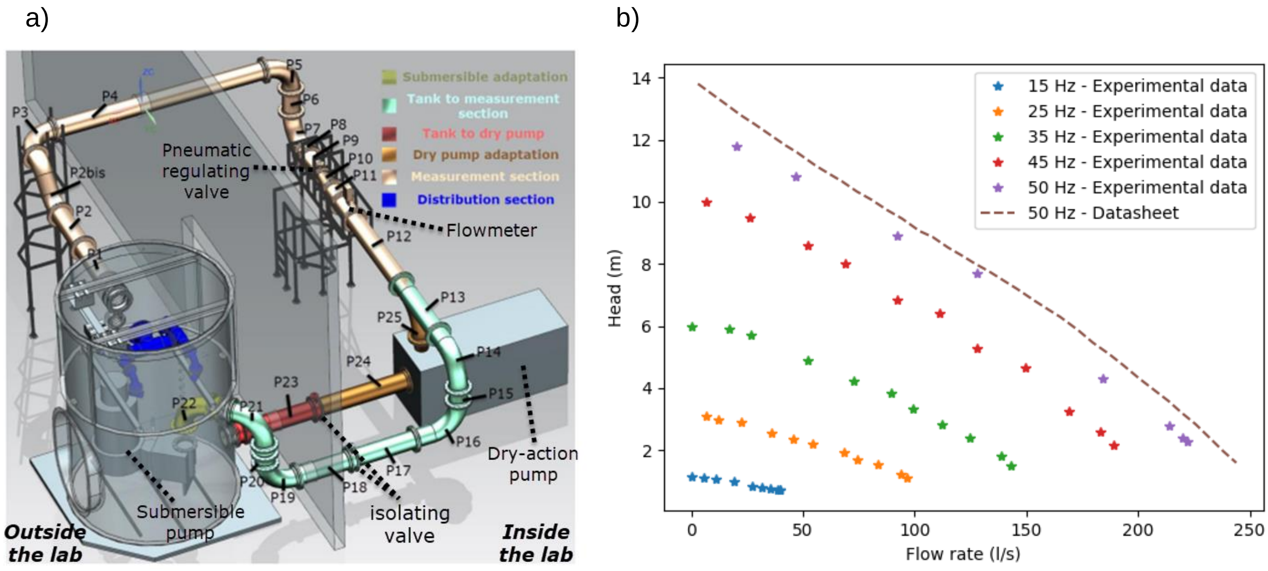

Figure 2: a) Pump test bench CAO; b) Experimental pump curves and comparison to datasheet nominal curve

3.2 Pump Computational Modelling

A numerical model for pump operation, including an asynchronous motor model [Fitzgerald et al., 2003] and also mechanical and hydraulic aspects, has been developed in the framework of the project. It can be calibrated based on a test performed in the test bench. The pump Amarex KRT D 250-400/206UG-S was used as a study case. As seen in Figure 3.a), fairly accurate predictions of pump performance have been obtained for a broad range of operation conditions. The value of this combined experimental and numerical characterisation of the pumps is to provide to the pump operator a full characterisation of the pump performance, well beyond the nominal conditions which are usually reported by the manufacturer. In this instance, an overall efficiency map combining motor efficiency and pump efficiency is shown on Figure 3.b). A software is currently under development allowing pump users to obtain the operating values of their pump for different configurations. The hydraulic efficiency can be taken into account in the overall efficiency by supplying an equivalent head losses coefficient to the whole piping (discharge and suction).

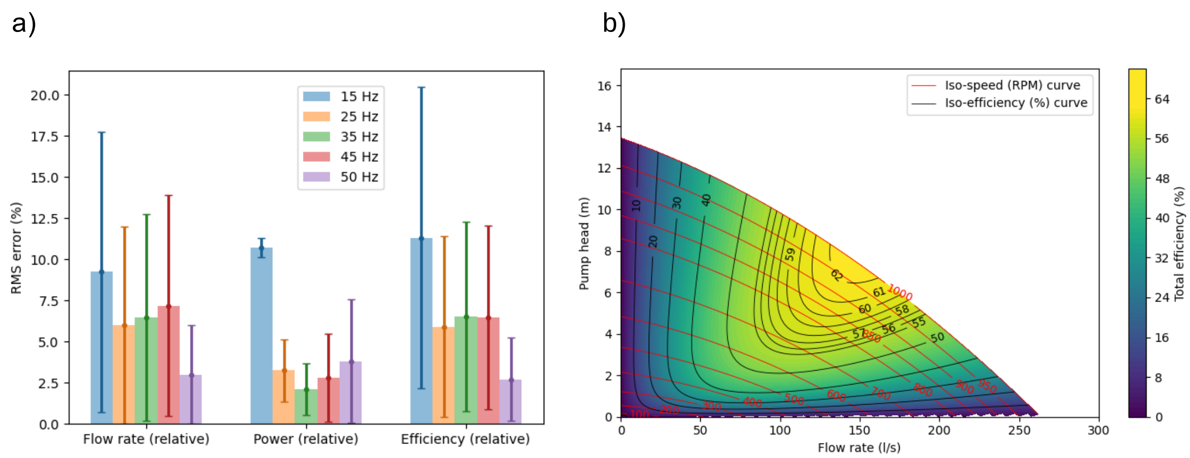

Figure 3: a) Distribution of the RMS relative error and standard deviation for flow rate, power consumption and total efficiency between numerical model and experimental results; b) Mapping of the overall efficiency of the pump for varied flow-rates, heads and rotation speed.

3.3 Waterways Network

The hydraulic numerical model of waterway network is currently under development. Yet, a first analysis of measurements has been performed considering the Kennet & Avon system as a study case using the detailed pump modelling described in the last section. The main water volume exchanges during the year 2017 are summed and described in Figure 4. This Sankey diagram shows a volume of pumped water more than twice the volume of lock exchanges.

Furthermore, the analysis of the pumping stations in Figure 5 shows that pumps exhibit around 45 % in efficiency in situ. The general nominal efficiency of pump locates between 60 % and 80 %. The difference between observed and expected efficiency may be explained by operation at higher flow rate than the nominal one. Indeed, the main preoccupation of canal operators is usually to get a high enough flow rate. As a result, pumps are oversized and consequently do not work at their nominal point and lose efficiency. As represented in Figure 3.b), the nominal efficiency can be extended to off-design operating point by adjusting the pump rotation speed. There is still a small decrease in efficiency (a few percent) when decreasing the rotation speed because of electrical motor efficiency, but this is negligible compare to the loss in efficiency of the pump when it doesn't operate at nominal point. Consequently, a 10 % increase of performance may reasonably be achieved for each station if the system operation is optimised.

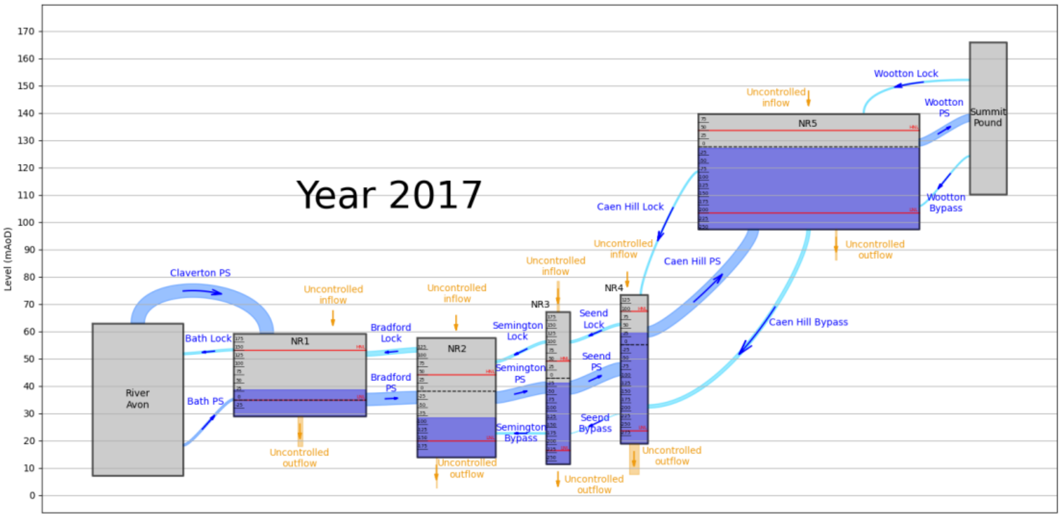

Figure 4: Kennet & Avon canal – Main water exchanges in 2017 (PS: Pumping station; NR: Navigation Reach). The thickness of arrow exchange is directly proportional to the amount of water transferred from one reach to another. Light blue stands for lock exchanges, dark blue for PS exchanges and yellow for water losses (obtained by a mass balance of the reach considering a mean water level constant along the reach) due to evaporation, infiltration and other uncontrolled flows.

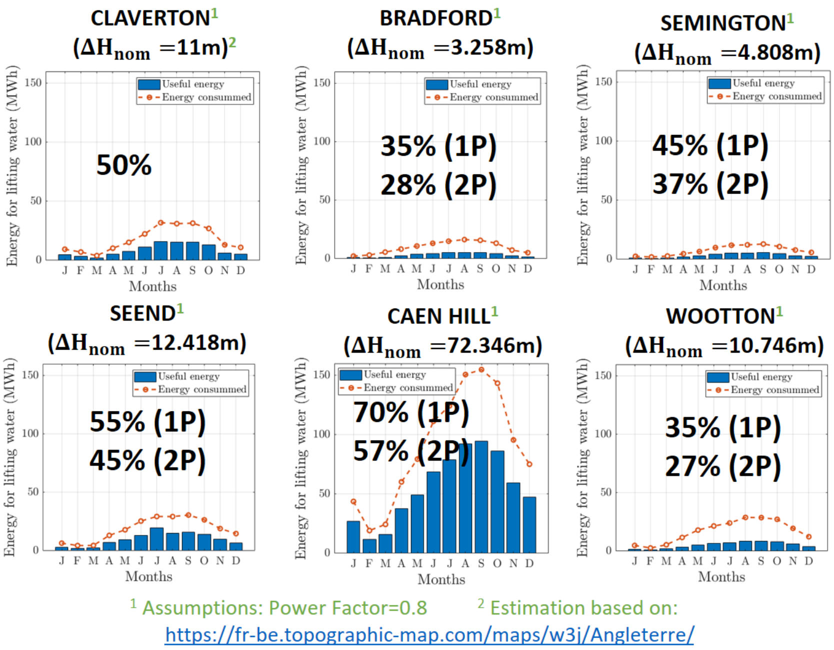

Figure 5: Mean monthly energy consumption of pumping stations in Kennet & Avon from 2010 to 2019. Performance are indicated for each pumping station for both one-pump operation (1P) and two-pump operation (2P).

4 CONCLUSION

The hybrid methodology applied in the framework of the GreenWin project combines laboratory experiments and numerical modelling to gain a better understanding of opportunities for energy-savings in the pumping systems used to operate open-channel navigation networks. It has proven its potential to reduce the energy consumption in waterways through a better pump management. The plus-value of further modelling will be to suggest concrete actions to be applied in the field to get closer of best efficiency-scenarios.

5 ACKNOWLEDGMENTS

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SUMMARY

Worldwide, navigation is made possible in artificial waterways thanks to the support of a considerable number of high capacity pumps. In waterways without natural water supply, pumping is required to maintain the water level within a range suitable for navigation, compensating for water transferred by locks operation and other losses (leakages, infiltration, evaporation). Across Europe, pumping in waterways represents 25-33 % of annual electricity use by WMOs (Waterway-Management-Organisation). However, in terms of energy-efficiency, many of the pumps used in waterways do not operate optimally. Main reasons for this include pump oversizing and the absence of variable speed drive. In this communication, we present an international, interdisciplinary and intersectoral research project based on a novel, large experimental pump test bench, a computational model of the pumping process and a numerical model of waterways exchange. The goal of this hybrid research project is to improve waterways pump management and then to provide energy saving.

RESUME

Dans le monde entier, la navigation est rendue possible dans les voies navigables artificielles grâce à l'appui d'un nombre considérable de pompes de grande capacité. Dans les voies navigables dépourvues d'alimentation naturelle en eau, le pompage est nécessaire pour maintenir le niveau d'eau dans une fourchette adaptée à la navigation, en compensant l'eau transférée par le fonctionnement des écluses et les autres pertes (fuites, infiltration, évaporation). En Europe, le pompage dans les voies navigables représente 25 à 33% de la consommation annuelle d'électricité des WMO (Waterway-Management-Organisation). Cependant, en termes d'efficacité énergétique, de nombreuses pompes utilisées dans les voies navigables ne fonctionnent pas de manière optimale. Les principales raisons en sont le surdimensionnement des pompes et l'absence d'entraînement à vitesse variable. Dans cette communication, nous présentons un projet de recherche international, interdisciplinaire et intersectoriel basé sur un nouveau banc d'essai expérimental de grande taille pour les pompes, un modèle informatique du processus de pompage et un modèle numérique des échanges dans les voies navigables. L'objectif de ce projet de recherche hybride est d'améliorer la gestion des pompes des voies navigables, puis de permettre des économies d'énergie.

ZUSAMMENFASSUNG

Weltweit wird die Schifffahrt auf künstlichen Wasserstraßen durch eine große Anzahl von Hochleistungspumpen ermöglicht. In Wasserstraßen ohne natürliche Wasserversorgung ist das Pumpen erforderlich, um den Wasserstand in einem für die Schifffahrt geeigneten Bereich zu halten und das durch den Schleusenbetrieb übertragene Wasser sowie andere Verluste (Leckagen, Versickerung, Verdunstung) auszugleichen. In ganz Europa entfallen 25-33 % des jährlichen Stromverbrauchs der Wasserstraßenverwaltungen auf das Pumpen von Wasserstraßen. Was die Energieeffizienz betrifft, so arbeiten viele der in Wasserstraßen eingesetzten Pumpen jedoch nicht optimal. Hauptgründe hierfür sind die Überdimensionierung der Pumpen und das Fehlen eines drehzahlvariablen Antriebs. In dieser Mitteilung stellen wir ein internationales, interdisziplinäres und sektorübergreifendes Forschungsprojekt vor, das auf einem neuartigen, großen experimentellen Pumpenprüfstand, einem Berechnungsmodell des Pumpvorgangs und einem numerischen Modell des Wasserstraßenaustauschs basiert. Ziel dieses hybriden Forschungsprojekts ist es, das Management von Wasserstraßenpumpen zu verbessern und anschließend Energieeinsparungen zu erzielen.

RESUMEN

En todo el mundo, la navegación es posible en las vías navegables artificiales gracias al apoyo de un número considerable de bombas de gran capacidad. En las vías navegables sin suministro natural de agua, el bombeo es necesario para mantener el nivel del agua dentro de un rango adecuado para la navegación, compensando el agua transferida por el funcionamiento de las esclusas y otras pérdidas (fugas, infiltración, evaporación). En toda Europa, el bombeo en las vías navegables representa entre el 25 y el 33% del consumo anual de electricidad de las OMA (Organizaciones de Gestión de Vías Navegables). Sin embargo, en términos de eficiencia energética, muchas de las bombas utilizadas en las vías navegables no funcionan de forma óptima. Las principales razones de ello son el sobredimensionamiento de las bombas y la ausencia de accionamientos de velocidad variable. En esta comunicación, presentamos un proyecto de investigación internacional, interdisciplinar e intersectorial, basado en un novedoso banco de pruebas experimental de bombas de gran tamaño, un modelo computacional del proceso de bombeo y un modelo numérico de intercambio de vías navegables. El objetivo de este proyecto de investigación híbrido es mejorar la gestión de las bombas de las vías navegables y, a continuación, proporcionar un ahorro de energía.

ADVANCEMENT OF NUMERICAL WAVE MODELLING FOR COASTAL ENGINEERING APPLICATIONS

by

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Mots-clés : vagues, modélisation numérique, modélisation physique, CFD, génération de vagues

1 INTRODUCTION

Low-lying countries typically have mildly-sloping beaches as part of their coastal defence system. For countries in north-western Europe high-rise buildings are a common sight close to the coastline. They are usually fronted by a low-crested sea dyke with a relatively short promenade, where the long (nourished) beach in front of it acts as a very/extremely shallow foreshore as defined by Hofland et al. (2017). Along the cross section of this hybrid beach-dyke coastal defence system, storm waves are forced to undergo many transformation processes before they finally hit the buildings on top of the dyke. These hydrodynamic processes include: shoaling, sea and swell wave energy transfer to sub- and superharmonics via nonlinear wave-wave interactions, wave dissipation by breaking and bottom friction, reflection against the dyke, wave run-up and overtopping on the dyke, bore impact on a wall or building, and finally reflection back towards the sea interacting with incoming bores on the promenade.

For the design of storm walls or buildings on such coastal dykes, the wave impact force expected for certain design conditions needs to be estimated. Due to the complexity of the processes involved, usually physical modelling is applied, but numerical modelling of these combined processes has become feasible during the last decade. This paper investigates which type of numerical model is practically applicable for this case. Three open-source CFD models are selected, each representing one of the most popular in its category: (1) a Reynolds-Averaged Navier-Stokes (RANS) model (OpenFOAM®, abbr. 'OF'), (2) a weakly compressible Smoothed Particle Hydrodynamics (SPH) model (DualSPHysics, abbrev. 'DSPH'), and (3) a non-hydrostatic NonLinear Shallow Water (NLSW) equations model ('SWASH'). They are validated and compared to large-scale experiments of overtopped wave impacts on coastal dykes with a very shallow foreshore and their model performance is evaluated.

The correct simulation of the waves in the nearshore zone requires the accurate modelling of all the processes involved, such as the generation of the waves, their propagation, transformation and reflection or absorption at the domain boundaries. In this paper, a new wave generation method is also examined for the non-hydrostatic wave model, SWASH, to avoid reflections at the location of the wave generation boundary. The new method is compared and evaluated against other wave generation methods for the practical application of waves diffracting around a breakwater.

2 LARGE-SCALE PHYSICAL MODELLING

The large-scale hydraulic experiments [Streicher et al., 2017] were performed in the Deltares Delta Flume (L x W x H: 291.0 m x 5.0 m x 9.5 m) and the model geometry was built at Froude length scale 1-to-4.3. The moveable sandy foreshore had a transition slope of 1:10 and a slope of 1:35 up to the toe of the dyke (Figure 1). The smooth impermeable concrete dike had a slope of 1:2 and a promenade width of 2.35 m. The promenade had an approximate inclination of 1:100 in order to help drain the water after an overtopping event. At the end of the promenade a 1.6 m high wall was built which covered the entire flume width. Measurements included (but not limited to): 1) free surface elevations along the length of the flume, 2) overtopping flow layer thickness and horizontal velocity U_x on the promenade, 3) overtopping wave impact pressures p and horizontal force F_x on the vertical wall. Both bichromatic and irregular waves were included in the test matrix. The obtained data-set is available open source [Kortenhaus et al., 2019] and is, besides others, used for numerical model validation purposes.

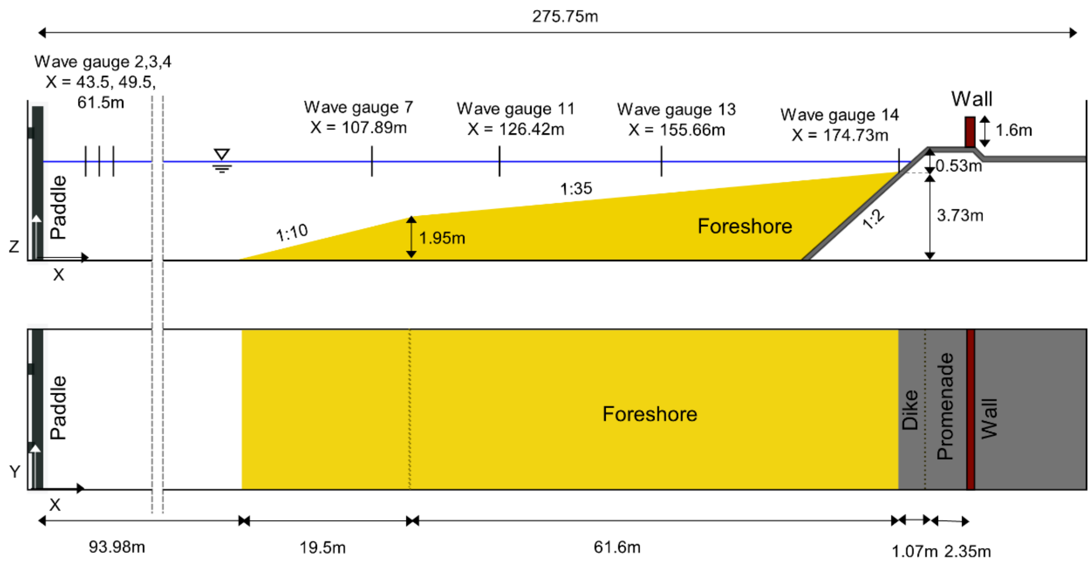

Figure 6: Overview of the geometrical parameters of the wave flume and WALOWA model set-up, with indicated wave gauge locations

Bichromatic wave tests are selected from the experiments for the numerical model validation and comparison, because of their short duration (limits computational cost and a fixed bottom foreshore assumption becomes acceptable).

3 VALIDATION OF OPENFOAM

A RANS multiphase solver for two incompressible and immiscible fluids (water and air), interFoam of OpenFOAM® with olaFlow wave boundary conditions (OF), was applied in 2DV for bichromatic wave transformations over a cross-section of a hybrid beach-dike coastal defence system, consisting of a steep-sloped dyke with a mildly-sloped and very shallow foreshore (Figure 1), and finally wave impact on a vertical wall. OF was validated for the first time in this context [Gruwez et al., 2020a], where – prior to impact – waves undergo many nonlinear transformations and interact with a dyke slope and promenade. A large-scale experiment (EXP) of bichromatic waves and its repetition (REXP) were selected for this validation. The repeated test allowed to assess the accuracy of the measurements, uncertainty due to model effects and variability due to stochastic processes in the experiment.

After a convergence analysis of the most important numerical parameters (i.e. grid resolution and CFL number), and without calibration of the numerical model, a very good qualitative comparison with EXP was achieved by OF (Figure 2), confirmed by a quantitative model performance rating of Very Good compared to the experiment for all relevant design parameters (i.e. η, U_x, p and F_x), which demonstrates

OF's applicability for the design of such hybrid coastal defence systems. Remaining discrepancies were found to be mainly caused by the different wave generation methods applied in OF (static boundary) and EXP (moving wave paddle), which caused an underestimation of the incident wave energy and an overestimation of the wave setup in OF compared to EXP. Consequently, when applying OF for a design of a hybrid coastal defence system, the incident wave energy is recommended to be calibrated, while the wave setup development for a static boundary condition with active wave absorption in OF is actually closer to the field condition compared to EXP (finite water mass).

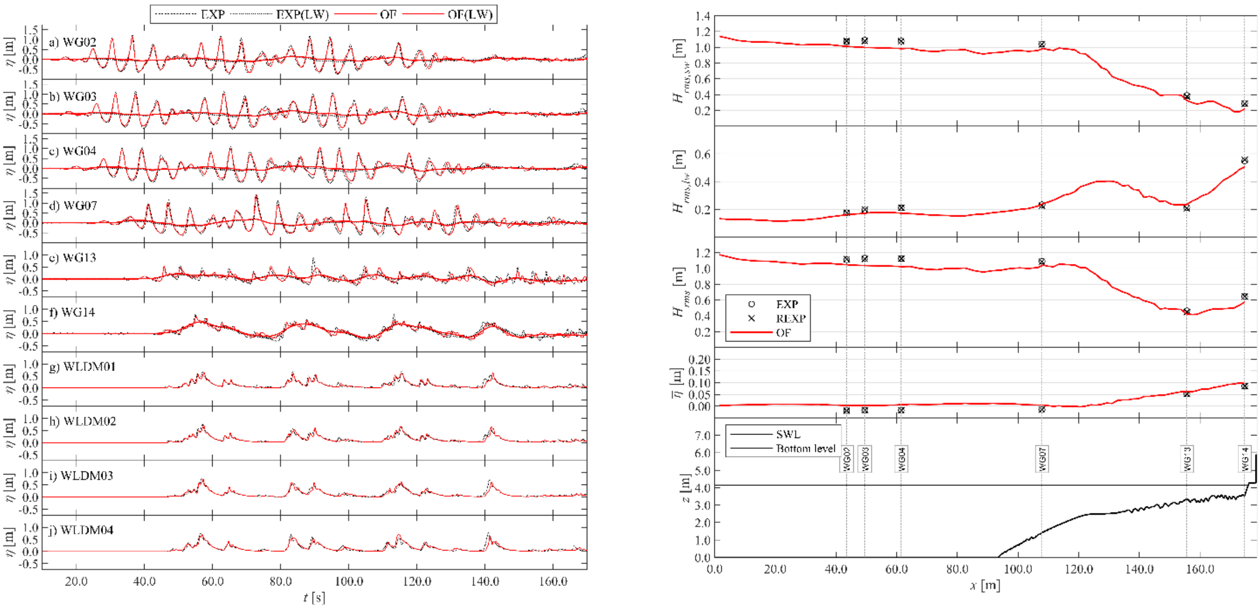

*Figure 7: Left: Comparison of the η time series at all sensor locations, including the long wave η_{LW} in (**a**) – (**f**) (bold lines). The zero-reference is the SWL for (**a**) – (**d**) and the promenade bottom at the sensor location for (**e**) – (**h**). Right: Comparison of H_{rms} between OF and (R)EXP up to the dyke toe. From top to bottom: $H_{rms,sw}$ for the short wave components, $H_{rms,lw}$ for the long wave components, H_{rms} for the total η, the wave setup $\bar{\eta}$ and finally an overview of the sensor locations, SWL and bottom profile.*

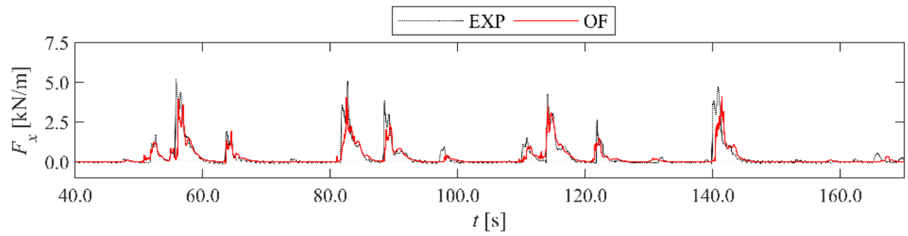

Figure 8: Comparison of F_x time series at the vertical wall between the physical (EXP) and numerical (OF) model.

A detailed comparison of snapshots at key time instants of bore interactions (Figure 4) leading up to the first bore impact on the vertical wall (i.e., t = 56s in Figure 3), revealed that very good pressure profiles along the vertical wall are reproduced by OF when the bore interaction patterns on the promenade are reproduced accurately.

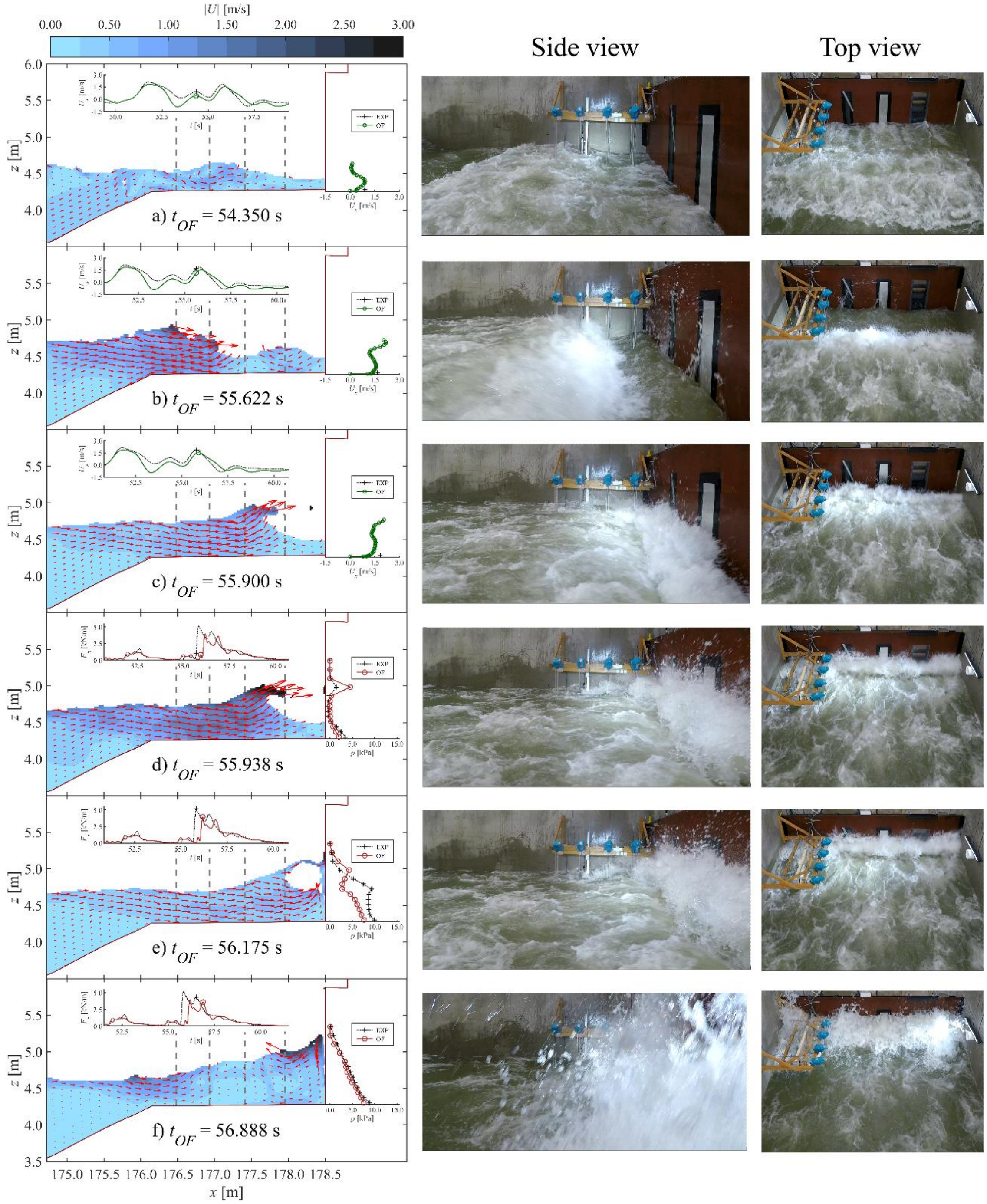

*Figure 9: Snapshots of selected key time instants chronologically over the first main impact (a-f). The OF snapshot (left) is compared to the equivalent EXP snapshot from the side view (centre) and top view (right) cameras. In the OF snapshots, the colours of the water flow indicate the velocity magnitude |U| according to the colour scale shown at the top. The red arrows are the velocity vectors, which are scaled for a clear visualisation. Each OF snapshot has two inset graphs: at the top is a time series plot of U_x (for EXP and $\overline{U_x}$ for OF) (**a-c**) or F_x (**d-f**), in which a circle marker (o) and a plus marker (+) indicate the time instant of the numerical and experimental snapshot respectively. Along the vertical wall U_x (**a-c**) or p (**d-f**) is plotted at respectively the ECM sensor location or each PS location (the vertical axis is z [m]). Along the promenade four vertical grey dashed lines indicate the sensor locations on the promenade, of which the layer thickness gauges are also visible in the experimental snapshots (topped by blue plastic bags). The location of the current velocity meter is at the second vertical grey dashed line from the left. The time instant of the numerical snapshot is provided by t_{OF}.*

4 INTER-MODEL COMPARISON

Next, OF was also compared to two other prominent open source computational fluid dynamics (CFD) numerical models [Gruwez et al., 2020b]: (1) the weakly compressible SPH model DualSPHysics (DSPH) and (2) the non-hydrostatic NLSW equations model SWASH (depth-averaged (K = 1): SW1L, and multi-layered (K = 8): SW8L). The inter-model comparison of those three numerical models to the experiment (EXP) demonstrated that they are all capable of modelling the dominant wave transformation (i.e. propagation, shoaling, wave breaking, energy transfer from the SW components to the bound LW via nonlinear wave-wave interactions) and the wave-structure interaction (i.e. individual wave overtopping, bore interactions, and reflection processes) processes involved leading up to the impacts on the vertical wall, albeit with a varying degree of accuracy. Based on a qualitative time series comparison, all three applied numerical models initially appeared to have a good correspondence of η, U_x, p and F_x to EXP. In the quantitative analysis, none of the numerical models managed to achieve an ideal model performance, but still a rating of Good to Very Good was achieved by all three of them for most parameters and measured locations. The best overall model performance was achieved by OF, but required the highest computational cost. Although DPSH managed the best reproduction of the wave height until the dike toe, accumulation of errors in the wave setup and wave phase in the surf zone and near the dyke toe, caused a lower model performance than OF at the dyke toe and for the processes on the dyke. From this followed that accurate modelling of the wave setup and wave phases at the dyke toe seem to be most important for accurate modelling of the bore interactions on the promenade.

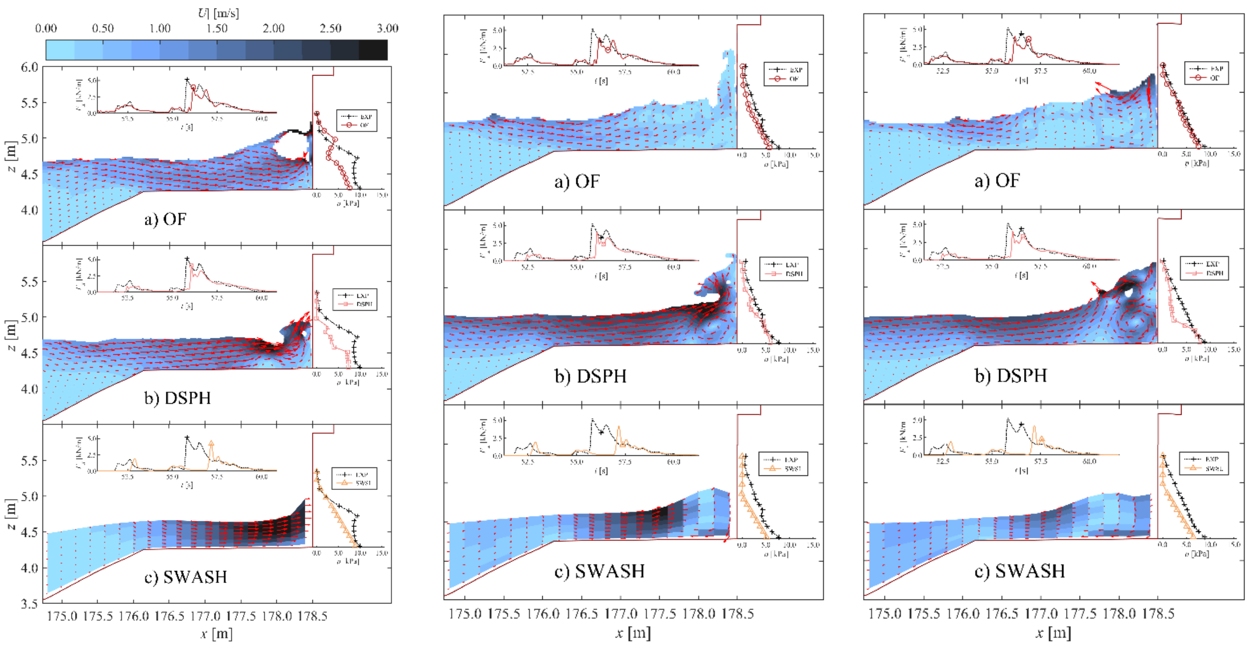

Figure 10: Snapshots of numerical model results on the dyke for three key time instants (red arrows are U vectors).

An analysis and comparison of snapshots of the numerical results on the dike (Figure 5) revealed that these bore interactions are determinative for an accurate reproduction of the impacts on the vertical wall. Even though SWASH is a much more simplified model than both OF and DSPH, it is shown to provide very similar results, even for some of the more complex processes on the dike and impacts on the vertical wall. When the impulse of the force on the structure is of lesser importance, SWASH is still able to predict $F_{x,max}$ relatively accurate for each individual impact, with a significantly reduced computational cost, compared to OF and DSPH. However, SWASH is limited to hydrostatic pressure profiles for the impacts on the vertical wall, which is not always valid during more dynamic impact events (Figure 5c, left).

5 IMPROVED WAVE GENERATION IN SWASH

There are three main methods to generate waves in numerical models. Method 1: weakly reflective wave generation (static boundary), method 2: moving boundary wave generation, and method 3: internal wave generation. In methods 1 and 2, in order to avoid reflections in front of the wave generator, a boundary condition is applied at the same location, according to which the total velocity is a linear superposition of the velocity of the target waves and the velocity of the waves propagating towards the boundary. This condition is making use of the assumption that the waves propagating towards the boundary of the computational domain are shallow water waves with small amplitude and direction perpendicular to the domain boundary and thus, these methods are considered weakly reflective when dispersive and directional waves are examined. To avoid this limitation, a new internal wave generation method has been developed for the non-hydrostatic wave model, SWASH. According to this method, waves are generated internally over an area called the 'source area', while sponge layers (relaxation zones) are used at the domain boundaries to absorb the incoming waves [Vasarmidis et al., 2019].

To verify the added value of the new internal wave generation (method 3) in comparison with the weakly reflective wave generation boundary (method 1), simulations were conducted for irregular short-crested waves diffracting around a breakwater (impermeable vertical wall). In this way, the two different wave generation methods were evaluated against a benchmark experimental test case where oblique dispersive waves propagate back towards the generation area [Vasarmidis et al., 2021]. In Figure 11, a three-dimensional visualisation of the short-crested waves diffracting around the vertical wall is presented using the internal wave generation. The diffraction patterns at the lee side of the wall as well as the increase of the wave amplitude due to the reflection in front of the wall are clearly visible. Figure 12 presents a comparison between the performance of the two wave generation methods for predicting the diffraction coefficients at the lee side of the wall for two cases of irregular waves with narrow (N1) and broad (B2) directional spreading. It can be observed that the error for method 1 is at least double than the one corresponding to the new implemented method 3.

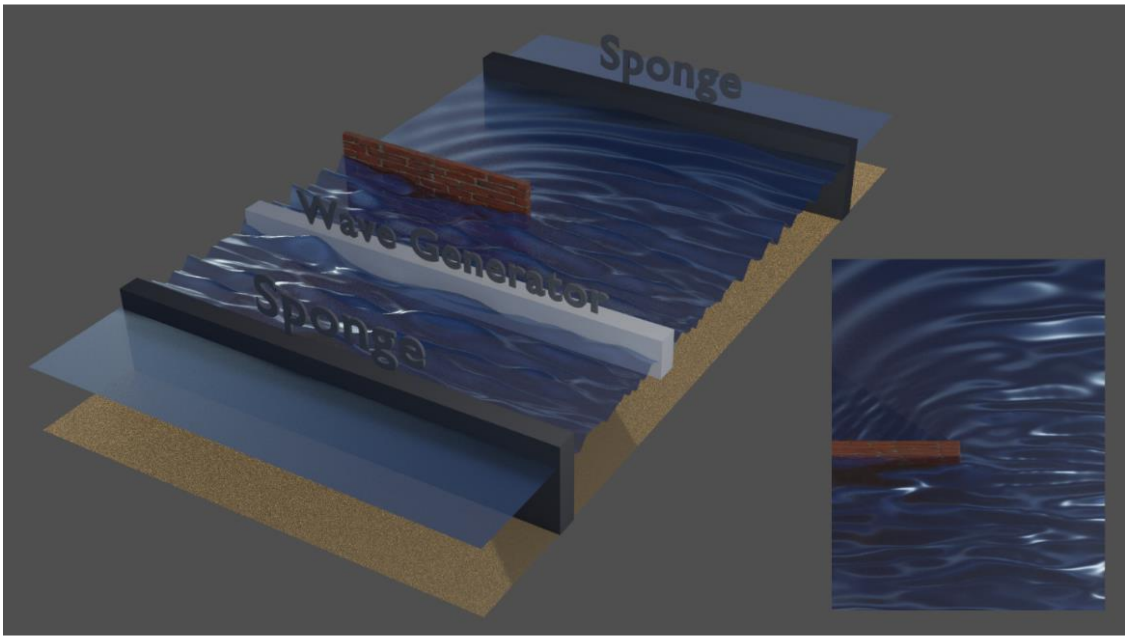

Figure 11: 3-D visualisation of short-crested waves diffracting around a vertical wall as calculated with SWASH using the newly implemented wave generation method 3.

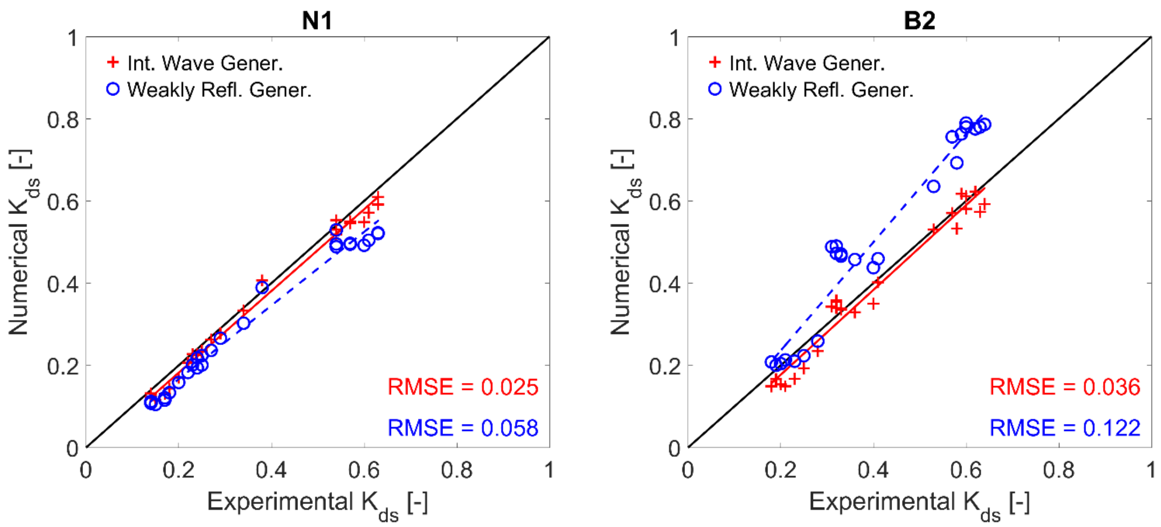

Figure 12: Comparison between the performance of the internal wave generation (method 3, red plus signs) and the weakly reflective generation (method 1, blue circles) for predicting the diffraction coefficients for narrow (N1) and broad (B2) directional spreading

6 CONCLUSIONS

OpenFOAM was successfully validated for the first time for wave transformations over and wave-interactions with a dike on a shallow foreshore, using high-quality large-scale physical modelling data. An inter-model comparison with DualSPHysics and SWASH further showed that OF is most accurate, but requires the longest calculation time. SWASH is by far the fastest model, and can still provide similar results in terms of wave transformations and maximum impact forces, but only for quasi-static impacts and when the force impulse is not important. Finally, it has been proven that the new internal wave generation method increases the capability of SWASH towards the study of wave propagation of highly dispersive short-crested waves in coastal environments with minimal reflection from the boundaries, thereby increasing the accuracy of the generated wave field for practical applications beyond the state-of-the-art. This study has therefore advanced numerical wave modelling in important ways for coastal engineering applications.

7 ACKNOWLEDGEMENTS

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SUMMARY

Over the last decades, numerical wave modelling is increasingly used as an additional tool that is complementary to physical modelling in the design and research of waves interacting with coastal structures. Accurate wave generation and thorough validation of these numerical wave models are crucial first steps in that process. Three prominent open source computational fluid dynamics (CFD) numerical models – OpenFOAM®, DualSPHysics and SWASH – are compared and successfully validated to large-scale physical model experiments in the Deltares Delta Flume (the WALOWA project) of waves interacting with a dike on a shallow foreshore (the typical geometry of e.g. the Belgian coastal defence system against flooding). In addition, a new wave generation method is implemented in SWASH to increase the accuracy of the generated wave field for practical applications beyond the state-of-the-art.

RESUME

Au cours des dernières décennies, la modélisation numérique des vagues est de plus en plus utilisée comme un outil complémentaire à la modélisation physique dans la conception et la recherche des vagues interagissant avec les structures côtières. La génération précise de vagues et la validation approfondie de ces modèles numériques de vagues sont les premières étapes cruciales de ce processus. Trois modèles numériques de dynamique des fluides numériques (CFD) à source ouverte – OpenFOAM®, DualSPHysics et SWASH – sont comparés et validés avec succès par rapport à des expériences de modèles physiques à grande échelle dans le Delta Flume de Deltares (le projet WALOWA) de vagues interagissant avec une digue sur un estran peu profond (la géométrie typique, par exemple, du système de défense côtière belge contre les inondations). En outre, une nouvelle méthode de génération de vagues est mise en œuvre dans SWASH afin d'augmenter la précision du champ de vagues généré pour des applications pratiques au-delà de l'état de l'art.

ZUSAMMENFASSUNG

In den letzten Jahrzehnten wird die numerische Wellenmodellierung zunehmend als zusätzliches Instrument eingesetzt, das die physikalische Modellierung bei der Planung und Erforschung der Wechselwirkung von Wellen mit Küstenstrukturen ergänzt. Die genaue Erzeugung von Wellen und die gründliche Validierung dieser numerischen Wellenmodelle sind entscheidende erste Schritte in diesem Prozess. Drei bekannte numerische Open-Source-CFD-Modelle (Computational Fluid Dynamics) – OpenFOAM®, DualSPHysics und SWASH – werden mit groß angelegten physikalischen Modellexperimenten im Deltares Delta Flume (WALOWA-Projekt) verglichen und erfolgreich validiert, bei denen Wellen mit einem Deich auf einem flachen Vorland interagieren (die typische Geometrie z. B. des belgischen Küstenschutzsystems gegen Überschwemmungen). Darüber hinaus wird in SWASH eine neue Wellenerzeugungsmethode implementiert, um die Genauigkeit des erzeugten Wellenfeldes für praktische Anwendungen über den Stand der Technik hinaus zu erhöhen.

RESUMEN

En las últimas décadas, la modelización numérica de las olas se utiliza cada vez más como herramienta adicional y complementaria a la modelización física en el diseño y la investigación de las olas que interactúan con las estructuras costeras. La generación precisa de olas y la validación exhaustiva de estos modelos numéricos de olas son los primeros pasos cruciales en ese proceso. Tres destacados modelos numéricos de dinámica de fluidos computacional (CFD) de código abierto – OpenFOAM®, DualSPHysics y SWASH – se comparan y validan con éxito con experimentos de modelos físicos a gran escala en el Deltares Delta Flume (el proyecto WALOWA) de olas que interactúan con un dique en una costa poco profunda (la geometría típica de, por ejemplo, el sistema de defensa costera belga contra las inundaciones). Además, se implementa un nuevo método de generación de olas en SWASH para aumentar la precisión del campo de olas generado para aplicaciones prácticas más allá del estado del arte.

ROYERS LOCK

by

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Keywords: (Royers) lock complex, renovation, construction pit, BIM-model, Port of Antwerp

Mots-clés : Complexe d'écluses (Royers), rénovation, fosse de construction, modèle BIM, Port d'Anvers

1 INTRODUCTION

The Royers Lock is one of the oldest locks in the Port of Antwerp, dating from 1907. It is the southernmost of five locks on the right bank of the port. Due to its excellent location, it almost directly links the Albert Canal – which is the most important inland waterway in Belgium in terms of traffic – with the tidal Scheldt river.

Built in 1907 and put into operation in 1908, the lock is 182.5 m long, 22 m wide and 13.41 m deep. Originally intended for maritime shipping, the lock was until recently mainly used for inland navigation. As a consequence of the economies of scale in maritime shipping, the lock became too small for most maritime vessels. But even for inland navigation, the lock has become rather small. For example, a convoy of four push-barges can't pass through the lock.

Being in operation for almost 115 years, the lock was outdated and required a lot of maintenance in order to be kept operational. The Royers Lock will now be renovated and upgraded, to be better adapted to the size and needs of current day inland navigation. The new dimensions will be 235 m long (inside the lock doors), 36 m wide and 13.41 m deep. The design of the new lock will also take into account climate resilience, as the new lock will be part of the Scheldt river basin flood defence system.

Figure 1: Existing situation vs. artist impression of the new lock complex (© ZJA architect of the Royers lock)

A movable bascule bridge will be built on both sides to allow vehicles and cyclists to pass easily over the lock. The design is based on the Kieldrecht lock and consists of two single rolling gates. The lock gates are moved by winches that are located behind the gate chambers in the machine buildings and that operate the gates by means of cables. The winches are powered by motors. The bridges are moved by hydraulic cylinders that are installed in the bridge basements.

To realise this, a dry construction pit is needed.

2 CHALLENGES FOR THE DESIGN OF THE CONSTRUCTION PIT

Research in several archives showed that the Royers lock has a comprehensive history between 1700 and today. First, there was the old river Vosseschijn on the location of the Royers lock. Later on, the Lefebvre dock was build. Afterwards the construction of the precursor of the Royers lock was started, which was situated closer to the river Scheldt than the current lock. However, flooding of the construction pits forced an early stop of the execution works. Finally, the existing lock was constructed around 1900. It was built with large steel caissons, filled with concrete that were sunk to the right level. These steel caissons are located at the three gate recesses and at the quay walls in the entrance canal.

This short summary of the history of the project location clarifies why the soil is quite disturbed and contains a lot of underground structures. An additional challenge for the design of the construction pit is the presence of (heritage) buildings in the neighbourhood. Some of these historical buildings have to be preserved in their present condition.

3 DESIGN ALTERNATIVES

The base design option was to create a dry construction pit to be able to demolish the existing lock and build the new lock without big influence on the existing ground water levels. Therefore a water retaining wall behind the existing lock walls in combination with two cofferdams (one at the river side and one at the dock side) was needed.

3.1 Design With Vertical Diaphragm Walls

The first design of the construction pit consists of vertical diaphragm walls. These walls have a retaining height varying between 14.8 m and 21.5 m (ground level at +7.00 mTAW, excavation level between –14.50 mTAW and -7.80 mTAW). The bottom of the walls is situated in the Boomse clay layer, so that the construction pit can be drained. Because of the large retaining height ground anchors and/or struts are needed at two levels. To limit execution risks, ground anchors are only provided above the ground water level (approximately 2 m below ground level). When using struts the large dimensions of the construction pit are an important restriction: at some locations it is not possible to have struts between two opposite walls because of the buckling length. In that case the only option is to realise the lock floor in several stages so that the middle part of the floor can be used as a reaction massive for the struts.

Taking into account the restrictions mentioned above, two solutions are found for the diaphragm walls. One possible solution consists of a diaphragm wall with thickness 1.5 m, ground anchors above the ground water level and struts to the middle part of the new realised lock floor. Another solution is increasing the passive resistance of the walls by grouting below the excavation level (approximately 7 m depth x 12 m width). In that case only the ground anchors are necessary and the struts can be left out.

In both solutions the verifications in ultimate limit state (geotechnical stability, structural calculation of the wall) are fulfilled, but the horizontal deformations of the wall are quite large. The horizontal and vertical deformations of the nearby ground level are also significant. As a result important damage can be expected for the (historical) buildings and the pumping station located close to the construction pit.

3.2 Design With Slopes

As an alternative the construction pit can be designed without vertical retaining walls but with slopes. Because of the disturbed underground a gentle slope of 10/4 must be used. For the watertightness a cement bentonite wall is needed at the borders of the construction pit. This cement bentonite wall has a thickness of 80 cm, a bottom level in the Boomse clay layer, and is only water retaining (not earth retaining).

3.3 Final Design

Both designs of the construction pit (with diaphragm walls or with slopes) have their advantages and disadvantages.

The design with slopes takes more open space, which is an important disadvantage in an urban environment like Antwerp. For that reason the implantation of the roads on site is already taken into account in the global layout of the construction pit. In the design with slopes some historical buildings are situated within the construction pit and can't be retained, which is another disadvantage.

The main disadvantage of the solution with diaphragm walls, in this case, is the higher cost price comparing with the slopes. Especially the cost of anchors, struts and/or grouting has a significant contribution in the total cost. Another disadvantage of the solution with diaphragm walls is the 'difficult' execution compared with a construction pit with slopes. As a result, more problems can be expected during execution.

Taking into account the arguments mentioned above, the design with slopes is chosen.

4 LOCK MASTER RESIDENCE

The lock master residence is a historical classified building, situated within the construction pit, in the area of the slopes. To preserve this building, a diaphragm wall will be constructed around it. In this way the lock master residence can stay as a 'tower' in the construction pit. The ground level between the building and the diaphragm wall is equal to the initial ground level, while the ground level outside the diaphragm wall equals the excavation level of the construction pit. On top of the diaphragm walls a concrete capping beam with anchors is provided. The anchors have a horizontal alignment and connect two opposite sides of the diaphragm walls to each other. In addition, the lock master residence is stabilised by jetgrouting to prevent vertical settlements.

5 INTEGRATED APPROACH IN ONE BIM-MODEL

Part of the design study was the creation of a fully integrated 3-D BIM model: the lock, as well as the bridges, electromechanical equipment and surrounding infrastructure were modeled. Very important was the evaluation of the design in various positions and conditions, as these are moving parts. All sub-models of steel, concrete, earthworks, mechanics and infrastructure were brought together into one coherent, coherent and qualitative design.

Applying a BIM model within infrastructure projects has numerous benefits:

- a better quality and more transparent cooperation between all parties
- the interfaces of the various disciplines are attuned to each other
- a clash-free design means less failure costs and a faster throughput time overall
- the extracts are one on one correct and reliable

Finally, this BIM model of the Royers lock can also be used as a basis for visualisations, a VR environment and digital safety walks. For a brief video how this is implemented for the Royers lock, click here: https://www.youtube.com/watch?v=sdWNks5rtjE.

Figure 2: example output of the BIM model (© SBE nv)

6 ROYERS LOCK AS A PART OF OOSTERWEEL

In 2015, the Flemish Government took a major decision on the most emblematic project from the Masterplan 2020, the closure of the Antwerp ring road (also called ‘Oosterweelverbinding’). A new crossing under the Scheldt river will be constructed, aimed at solving the huge road congestion problems in the Antwerp region. An important interchange (‘Oosterweelknoop’) of this road project and a tunnel (‘Kanaaltunnel’) are in the direct vicinity of the Royers Lock site.

Figure 3: Location of the Royers Lock and location of the interchange and tunnel (dotted line) (© Lantis)

As indicated in the figure above, the construction sites of the interchange and tunnel on the one hand and the lock on the other hand interfere with each other. The upper lock head and the tunnel tube will be linked. That is why it was decided to jointly tender the construction of the interchange ‘Oosterweelknoop’ and the renovation and upgrading of the Royers Lock. Having one contractor for both infrastructure projects should ensure that construction works on one project don’t affect or harm the other project or its construction site.

This decision is reflected in the practical arrangements for this project. The infrastructure manager for the ring road project, Lantis (official name: BAM NV van publiek recht), was assigned as the tendering authority for a tender consisting of two lots: 1) the interchange ‘Oosterweelknoop’ (on behalf of Lantis) and 2) the renovation and upgrading of Royers Lock (on behalf of Port of Antwerp). The main construction contract in relation to the renovation and upgrading of the Royers Lock was thus tendered by Lantis, with Port of Antwerp and the Flemish Department of Mobility and Public Works being involved in the evaluation process.

The preparatory works for the ‘Oosterweelknoop’ interchange have started in the summer of 2021.

Between May 2022 and August 2023, a cofferdam will be constructed near the location of the upper lock head of the new Royers Lock. This will have an impact on the lock project, as without this cofferdam the works on the building pit for Royers Lock can’t be finished. Apart from that, both projects run more or less in parallel, without too much interference. The constructions works on the ‘Oosterweelknoop’ interchange will run from 2023 until 2030, while construction works on this project of the Royers lock run from October 2021 until December 2027.

For the lot on the Royers Lock, Port of Antwerp is the client in the ongoing execution phase, being the owner of the construction site and future operator of the lock. The renovation of the Royers Lock is one of the top priorities in Port of Antwerp’s 10 year investment plan. In accordance with the modalities of the cooperation agreement signed on 21 April 2021, Port of Antwerp and the Flemish Government (Department of Mobility and Public Works) agreed that the latter would ensure inter alia technical management, safety coordination and site control during the construction of the project.

7 ROYERS PROJECT ON SITE – PLANNING

Due to an incident in February 2021, the lock was permanently taken out of service, causing hindrance for inland navigation. Waiting times for inland navigation seeking to enter the port of Antwerp or the Albert Canal also increased due to the closure of the Royers Lock.

Construction works on the new lock have started on 11 October 2021 and are expected to be finished by the end of 2027. The works can be divided in four main categories:

1. Preparatory works, related to the clearing of the construction site and permanent operation of the construction site during execution. This includes inter alia:
    a. Demolishing the existing lock, adjacent infrastructure and service buildings, removal of building rubble from the construction site. 75 % of all the building rubble will be transported by inland barge.
    b. Removing or rerouting cables and pipes on the construction site.
    c. Driving sheets piles with a total surface of 24,800 m² around the construction site.
    d. Permanently lowering the ground water level at the construction site at -15m TAW (TAW is the Belgian reference level), whereas the ground level on site is +7m TAW.

2. Ground works, related to the excavation and later filling of the construction pit. This also includes the construction of water-retaining cofferdams around the construction pit. It is estimated that more than 400,000 m³ of soil will have to be excavated for the construction pit and afterwards 435,000 m³ of soil will be needed to fill the construction site again. According to the latest planning most of the ground works will take place within the framework of this application. 75 % of all the transports related to the soil excavation or filling will happen by inland barge.

3. Concrete works. New waterborne infrastructure will be built, the main components being:
    a. the lock chamber, including culverts
    b. door chambers
    c. bridge cellars
    d. the mobile flood defence system

    The total amount of concrete needed in the global project is estimated at 152,250 m³, most of which will be processed within the framework of this application. 14,000 tonnes of reinforcing steel will be needed for the concrete works as well. Please note that sustainable concrete will be used for this task, resulting is much lower greenhouse gas emissions during the production of the concrete. The self-closing mobile flood defence system is an innovative solution in order to ensure climate resilience of the new infrastructure. It respects the flood protection norms of the Scheldt river basin. Flood protection at +9.25m TAW will be ensured, whereas the ground level on site is +7 m TAW.

4. Lock doors: the construction and installation of two new lock doors. The lock doors will be constructed elsewhere in Flanders. 1,800 tonnes of steel will be used for the construction of the two new lock doors. As the lock doors are floating constructions, they will be transported to the construction site over water.

By the end of December 2026, the major construction works on the waterborne infrastructure should be finished: door chambers, bridge cellars, lock chamber, lock doors and the mobile flood defence system. Works on the mechanics, electronics and hydraulics, as well as on the ancillary infrastructure continue after the end of this project. The new lock complex (the global project) will be in operation by the end of 2027, eliminating a capacity bottleneck for inland navigation.

SUMMARY

The Royers Lock is one of the oldest locks in the Port of Antwerp, dating from 1907. It is the southernmost of five locks on the right bank of the port. Due to its excellent location, it almost directly links the Albert Canal – which is the most important inland waterway in Belgium in terms of traffic – with the tidal Scheldt river.

Built in 1907 and put into operation in 1908, the lock is 182.5 m long, 22 m wide and 13.41 m deep. Originally intended for maritime shipping, the lock was until recently mainly used for inland navigation. As a consequence of the economies of scale in maritime shipping, the lock became too small for most maritime vessels. But even for inland navigation, the lock has become rather small. For example, a convoy of four push-barges can't pass through the lock.

Being in operation for almost 115 years, the lock was outdated and required a lot of maintenance in order to be kept operational. The Royers Lock will now be renovated and upgraded, to be better adapted to the size and needs of current day inland navigation. The new dimensions will be 235 m long (inside the lock doors), 36 m wide and 13.41 m deep. The design of the new lock will also take into account climate resilience, as the new lock will be part of the Scheldt river basin flood defence system.

A movable bascule bridge will be built on both sides to allow vehicles and cyclists to pass easily over the lock. The design is based on the Kieldrecht lock and consists of two single rolling gates. The lock gates are moved by winches that are located behind the gate chambers in the machine buildings and that operate the gates by means of cables. The winches are powered by motors. The bridges are moved by hydraulic cylinders that are installed in the bridge basements.

To realise this, a dry construction pit is needed.

RESUME

L'écluse Royers est l'une des plus anciennes écluses du port d'Anvers, datant de 1907. Elle est la plus méridionale des cinq écluses situées sur la rive droite du port. Grâce à son excellent emplacement, elle relie presque directement le canal Albert – qui est la plus importante voie navigable intérieure de Belgique en termes de trafic – à l'Escaut à marée.

Construite en 1907 et mise en service en 1908, l'écluse mesure 182,5 m de long, 22 m de large et 13,41 m de profondeur. Destinée à l'origine à la navigation maritime, l'écluse était jusqu'à récemment principalement utilisée pour la navigation intérieure. En raison des économies d'échelle réalisées dans la navigation maritime, l'écluse est devenue trop petite pour la plupart des navires maritimes. Mais même pour la navigation intérieure, l'écluse est devenue plutôt petite. Par exemple, un convoi de quatre péniches ne peut pas passer par l'écluse.

En service depuis près de 115 ans, l'écluse était obsolète et nécessitait beaucoup d'entretien pour rester opérationnelle. L'écluse de Royers va maintenant être rénovée et modernisée, afin d'être mieux adaptée à la taille et aux besoins de la navigation intérieure actuelle. Les nouvelles dimensions seront de 235 m de long (à l'intérieur des portes de l'écluse), 36 m de large et 13,41 m de profondeur. La conception de la nouvelle écluse tiendra également compte de la résilience climatique, puisque la nouvelle écluse fera partie du système de défense contre les inondations du bassin de l'Escaut.

Un pont basculant mobile sera construit des deux côtés pour permettre aux véhicules et aux cyclistes de passer facilement au-dessus de l'écluse. La conception est basée sur l'écluse de Kieldrecht et consiste en deux portes roulantes simples. Les portes de l'écluse sont actionnées par des treuils qui se trouvent derrière les chambres des portes dans les bâtiments des machines et qui actionnent les portes au moyen de câbles. Les treuils sont actionnés par des moteurs. Les ponts sont déplacés par des cylindres hydrauliques installés dans les sous-sols des ponts.

Pour réaliser cela, une fosse de construction sèche est nécessaire.

ZUSAMMENFASSUNG

Die Royers-Schleuse ist eine der ältesten Schleusen im Hafen von Antwerpen und stammt aus dem Jahr 1907. Sie ist die südlichste von fünf Schleusen am rechten Ufer des Hafens. Aufgrund ihrer hervorragenden Lage verbindet sie den Albert-Kanal – die wichtigste Binnenwasserstraße Belgiens – fast direkt mit der gezeitenabhängigen Schelde.

Die 1907 erbaute und 1908 in Betrieb genommene Schleuse ist 182,5 m lang, 22 m breit und 13,41 m tief. Ursprünglich für die Seeschifffahrt gedacht, wurde die Schleuse bis vor kurzem hauptsächlich für die Binnenschifffahrt genutzt. Als Folge der Größenvorteile in der Seeschifffahrt wurde die Schleuse für die meisten Seeschiffe zu klein. Aber auch für die Binnenschifffahrt ist die Schleuse eher klein geworden. So kann beispielsweise ein Konvoi von vier Schubleichtern die Schleuse nicht passieren.

Da die Schleuse seit fast 115 Jahren in Betrieb ist, war sie veraltet und erforderte einen hohen Wartungsaufwand, um betriebsbereit zu bleiben. Die Royers-Schleuse soll nun renoviert und modernisiert werden, um sie besser an die Größe und die Bedürfnisse der heutigen Binnenschifffahrt anzupassen. Die neuen Abmessungen werden 235 m Länge (innerhalb der Schleusentüren), 36 m Breite und 13,41 m Tiefe betragen. Bei der Konstruktion der neuen Schleuse wird auch die Klimaresistenz berücksichtigt, da die neue Schleuse Teil des Hochwasserschutzsystems des Scheldebeckens sein wird.

Auf beiden Seiten wird eine bewegliche Klappbrücke gebaut, damit Fahrzeuge und Radfahrer die Schleuse problemlos passieren können. Die Konstruktion basiert auf der Schleuse von Kieldrecht und besteht aus zwei einzelnen Rolltoren. Die Schleusentore werden von Winden bewegt, die sich hinter den Torkammern in den Maschinenhallen befinden und die Tore mit Hilfe von Seilen betätigen. Die Winden werden durch Motoren angetrieben. Die Brücken werden mit Hydraulikzylindern bewegt, die in den Brückenkellern installiert sind.

Hierfür ist eine Trockenbaugrube erforderlich.

RESUMEN

La esclusa de Royers es una de las más antiguas del puerto de Amberes, ya que data de 1907. Es la más meridional de las cinco esclusas de la orilla derecha del puerto. Gracias a su excelente ubicación, enlaza casi directamente el Canal de Alberto – que es la vía fluvial más importante de Bélgica en términos de tráfico – con el río Escalda, que tiene una gran cantidad de mareas.

Construida en 1907 y puesta en funcionamiento en 1908, la esclusa tiene 182,5 m de longitud, 22 m de ancho y 13,41 m de profundidad. Originalmente destinada a la navegación marítima, la esclusa se utilizaba hasta hace poco principalmente para la navegación interior. Como consecuencia de las economías de escala en la navegación marítima, la esclusa se quedó pequeña para la mayoría de los buques marítimos. Pero incluso para la navegación interior, la esclusa se ha quedado pequeña. Por ejemplo, un convoy de cuatro barcazas no puede pasar por la esclusa.

Al estar en funcionamiento durante casi 115 años, la esclusa estaba anticuada y requería mucho mantenimiento para mantenerse operativa. Ahora, la esclusa de Royers será renovada y modernizada para que se adapte mejor a las dimensiones y necesidades de la navegación interior actual. Las nuevas dimensiones serán de 235 m de largo (dentro de las puertas de la esclusa), 36 m de ancho y 13,41 m de profundidad. El diseño de la nueva esclusa también tendrá en cuenta la resistencia al clima, ya que la nueva esclusa formará parte del sistema de defensa contra inundaciones de la cuenca del Escalda.

Se construirá un puente basculante móvil a ambos lados para que los vehículos y los ciclistas puedan pasar fácilmente por la esclusa. El diseño se basa en la esclusa de Kieldrecht y consta de dos compuertas rodantes simples. Las compuertas de la esclusa se mueven mediante cabrestantes que

están situados detrás de las cámaras de las compuertas en los edificios de máquinas y que accionan las compuertas mediante cables. Los cabrestantes son accionados por motores. Los puentes se mueven mediante cilindros hidráulicos instalados en los sótanos de los puentes.

Para ello se necesita un foso de construcción en seco.

LIFE4FISH PROJECT: DOWNSTREAM MIGRATING FISH PROTECTION AT HYDROPOWER PLANTS ON THE RIVER MEUSE IN WALLONIA

by

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Mots-clés : Migration des poissons, Dévalaison; Hydroélectricité; Modélisation; Comportement des poissons

1 INTRODUCTION

River damming is a key element in navigable rivers equipment. It also creates adequate conditions for hydropower production. However, the construction of dams and weirs leads to river fragmentation, which can affect the natural flow dynamics in certain segments of the river and has a severe impact on river ecology with potentially detrimental effects on fish populations [Vörösmarty et al., 2010 ; Liermann et al., 2012]. In particular, such structures hinder fish migration to and from spawning grounds and subsequently threaten the aquatic biodiversity. First science-based efforts to facilitate upstream migration of fish through or around hydraulic structures were noted in the beginning of the 20th century [Katopodis and Williams, 2012], while downstream passage was considered more recently. However, fish passage efficiency for both upstream and downstream migration is still not enough [Ovidio et al., 2017 & 2021] and additional actions are required.

In this context, the EU funded Life4Fish project (www.life4fish.be) aims at restoring downstream connectivity at six hydropower plants (HPP) along 83 km of the Meuse River in Wallonia by testing and implementing passage solutions for European eels (Anguilla anguilla) and Atlantic salmon smolts (Salmo salar), while minimizing renewable energy production loss.

The project is carried out by an interdisciplinary and intersectoral team gathering people from research and industry, with biology or engineering background, and extends over 5 years (Figure 1). It started with an initial field survey aiming at characterising the initial situation (reference situation) in terms of fish passage at the HPPs but also fish presence and health status in the Meuse River and its main tributaries. Indeed, HPPs may not only have a direct impact in terms of mortalities, injury and migration delay but also an indirect one in terms of physiological or immune changes that can compromise Atlantic salmon smolts and European adult's eel ability to escape successfully to the ocean [Ben Ammar et al., 2020-2021]. Therefore, it is important to assess the health status to estimate the efficiency of turbines and passage solutions on fish ability to migrate.

Then, varied solutions to improve downstream passage have been developed and designed at two pilot sites. These solutions include temporary shut off of the HPP coupled to a migration prediction model, implementation of a safe downstream passage route (through mobile dam flap gate or a dedicated passage) possibly coupled to a repulsive barrier, and implementation of eco-sustainable turbines. The solutions have been implemented for testing at the 2 pilot sites and a second field survey has been conducted to assess their efficiency for both eels and smolts migration. Then, the most effective solutions have been implemented for each of the 6 HPPs along 83 km of the Meuse River. The efficiency of the global solution will be assessed on next year by a third field survey.

In this paper, we present the varied solutions that have been tested to improve downstream passage in the framework of the project.

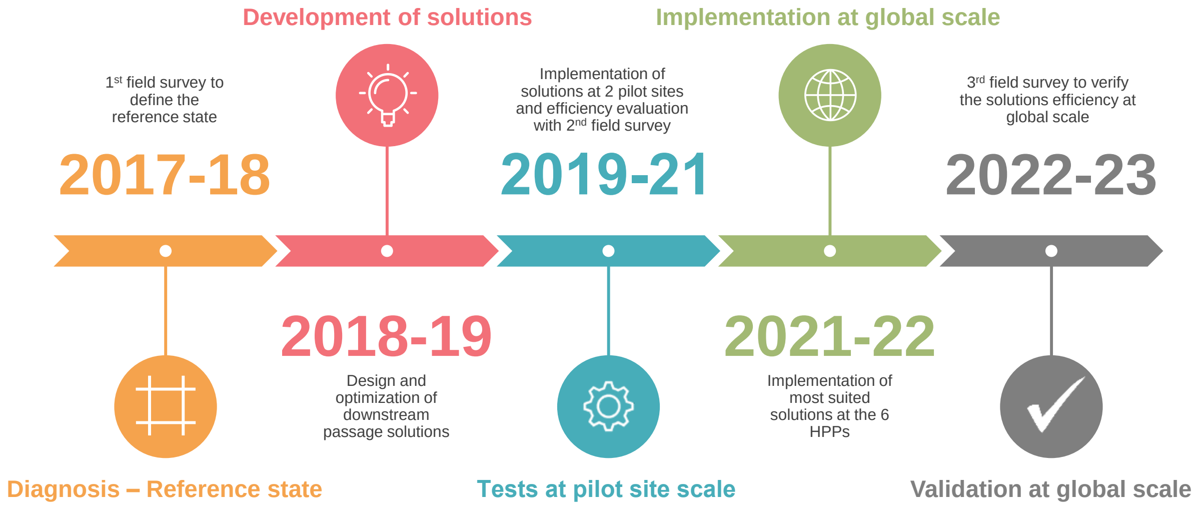

Figure 1: Timeline of the Life4Fish project

2 MIGRATION PREDICTION MODEL

If fish migration can be predicted timely and accurately, decisive mitigation measures such as HPP temporary shutdown and sluice gate opening can be implemented with high efficiency and with a limited impact on energy production.

Logistical models for salmon smolts and eels migration prediction have been developed in the framework of the Life4Fish project [Teichert et al., 2020a-b-c]. They are based on hydrological data such as river discharge, water temperature and photoperiod. The model for eels predicts the migration peaks during a fixed period (September to February). The model for salmon smolts provides a phenological indicator such as onset, end and duration of migration with high accuracy (Figure 2).

3 DOWNSTREAM PASSAGE ROUTE AND REPULSIVE BARRIERS

To prevent fish passage through the turbines during downstream migration, it is mandatory to offer an alternative safe route. Such a route can be created either using existing elements, for instance flap gates at mobile dams, or by creating a dedicated structure. Location of the fish passage is extremely important since fish will have to find it prior to going through the turbines, which means that the passage must be located on the path followed by the fish when they swim to the turbines. Also, the passage has to be attractive, i.e. has to induce flow conditions prone to encourage migrating fish to swim through it.

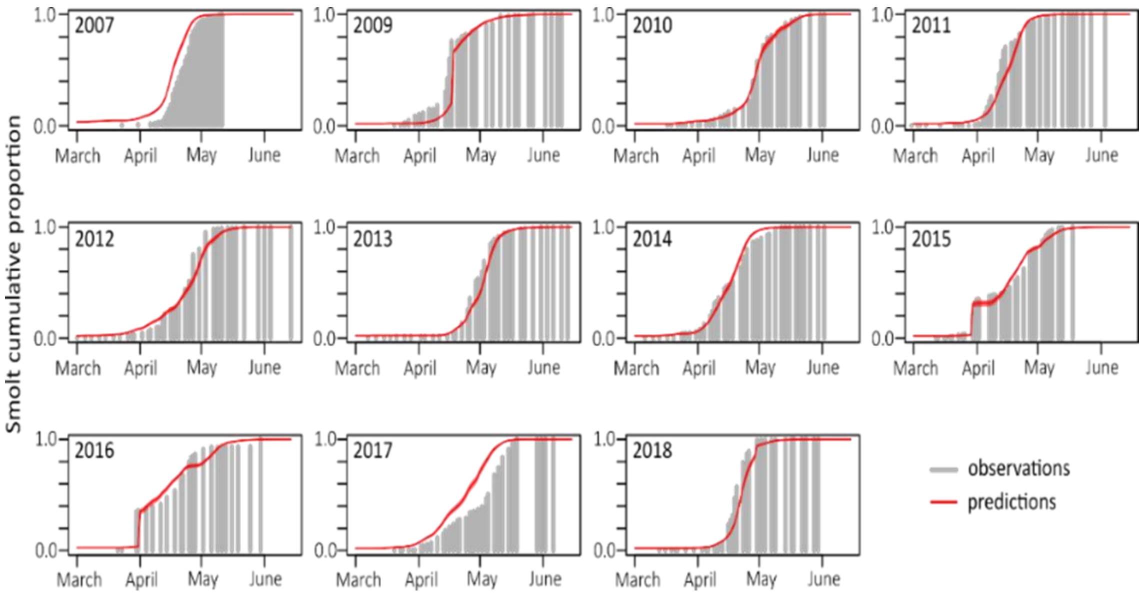

Figure 2: Example of logistical model results for salmon smolt migration on the Ourthe River [Teichert et al., 2020a]

In the framework of the Life4Fish project, downstream passage solutions identification, design and optimisation has been done by means of experimental and numerical models considering fish location data from field survey and hydraulic data from numerical modeling (Figure 3). Fish presence density maps gained from onsite survey showed where fish were searching for a passage to continue their way downstream when they were blocked upstream of the powerplant. This is a key information to locate properly a fish passage. Hydraulic numerical modeling of the area upstream of the powerplant provided detailed flow conditions. These are key data to understand why fish were concentrated at some places and to pre-design a passage structure able to influence flow conditions where fish were located. Then, the pre-designed fish passage has been implemented on a physical scale model and tested for varied flow conditions considering the river and powerplant operating configurations in order to assess its efficiency in creating attraction current and to optimise its design. Finally, the passage solution has been implemented on site. In addition to fish passage implementation, repulsive barriers (electrical or bubble curtain) have been installed to assess their efficiency in guiding fish to the passage and in preventing them to swim through the turbines.

Depending on the sites configuration, it has been found that suited passage for salmon smolts can be provided by using a flap gate at the mobile or required building of a peculiar structure.

This analysis has been complemented with specific experimental tests in a laboratory flume considering real salmon smolts in order to analyze the influence of some fish passage parameters (trash rack geometry and location) on the fish behavior [Erpicum et al., 2022].

New in situ survey with eels and salmon smolts proved the effectiveness of the implemented solutions to improve fish passage at both pilot sites.

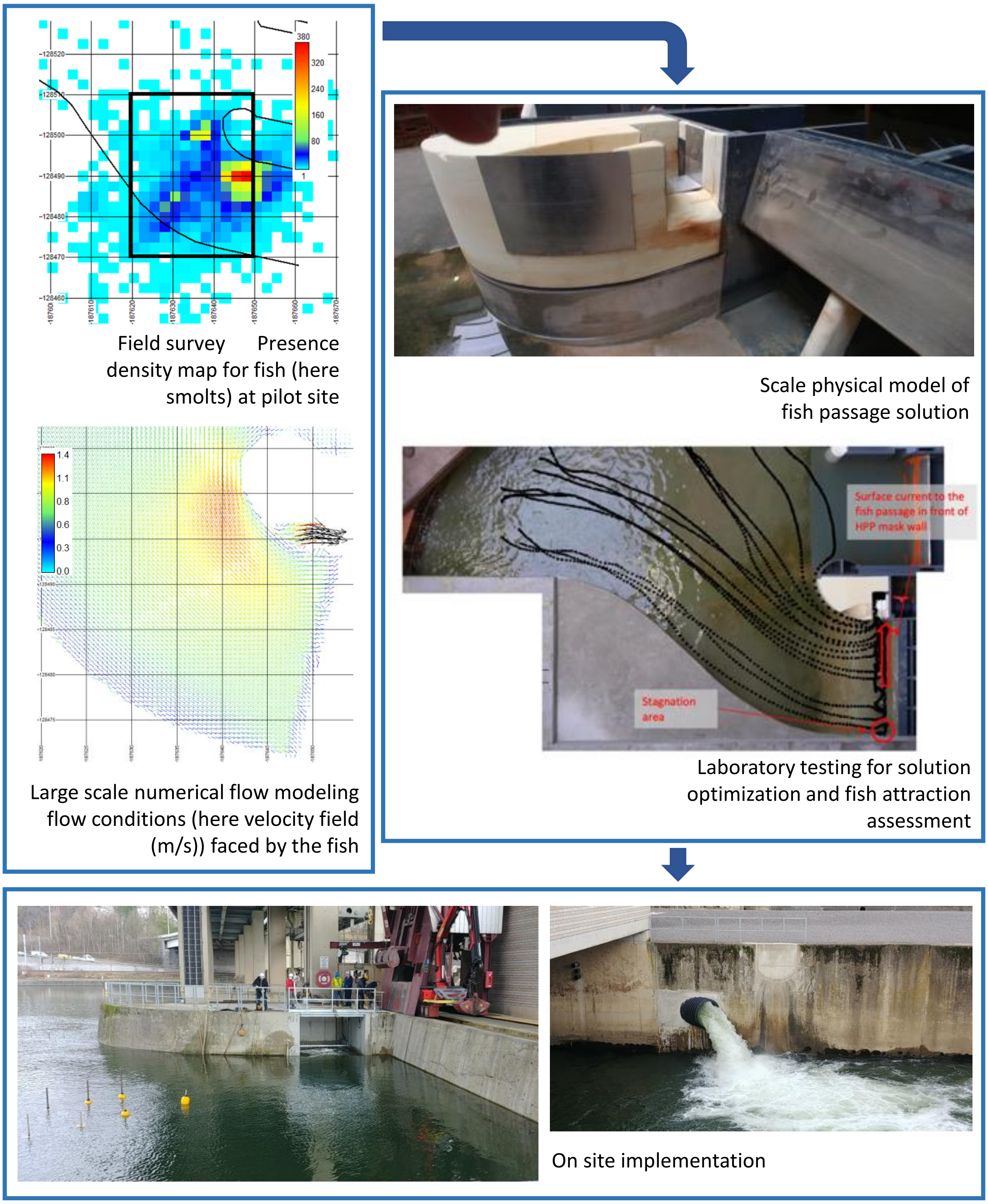

Figure 3: Procedure for downstream passage design by means of field survey, and experimental and numerical hydraulic modeling

For eels, a repulsive barrier working with low voltage electrical field has been deployed across the HPP forebay to virtually close the entrance of the power station. For river flow conditions where the HPP subtracts more than 50 % of the river discharge, the barrier reduced by 52 % the entrainment rate of eels towards the turbine and favored an escapement through the mobile dam. For higher hydrological conditions, most of the eels already migrated through the mobile dam, with less need of guidance away from the turbines.

For salmon smolts, the operation of the new downstream passage enabled to safely transfer 55 % of the fish, while the observed attractiveness of the inlet was 68 %. The operation of this fish passage improved by a factor more than 3 the escapement rate of smolts on the pilot site. With 100 % survival rate and based on physiological and immune parameters measured, the passage through the bypass seems to not impact health status and vulnerability of salmon smolts. An electrical barrier installed in order to guide smolts to the entrance of the fish bypass was not effective, since apparent too high voltage associated with too high water velocities induced electrical narcosis and favored the passage of smolts through turbines. The in-situ tests showed thus that careful tuning of electrical barrier characteristics is extremely important to avoid counterproductive effect on fish movements. In addition, bubbles barrier implementation was seen to be difficult and its satisfactory operation challenging.

The 50 cm or 90 cm opening of the dam flap gate close to the HPP intake also succeeded to safely transfer 49 % to 65 % of the smolts. At another site, a 90 cm opening of the dam flap gate on the opposite bank of the HPP intake only attracted 41 % of the smolts. Also, if a flap gate of the mobile dam can be used as downstream passage, this eases the management of floating debris that is challenging with dedicated fish passage structure. Depending on the dam configuration, this may also be a cheaper solution than building a new dedicated structure, even if flow rate and then energy production lost are generally more important when using a flap gate.

4 ECO-SUSTAINABLE TURBINES

The turbines of Monsin HPP were more than 70 years old and required a full refurbishment. Even if the retrofit of the turbines was not part of the Life4Fish project funding, such an operation may represent a huge opportunity to improve HPP impact on fish passage. Indeed, recent developments in turbine design proved to be effective in decreasing drastically the impact on fish swimming through the machine.

However, due the high level of complexity of hydraulic turbine design, it is difficult to obtain contractually a commitment from the manufacturer regarding fish impact. Consequently, it has been decided to set up a specific protocol summarising all known technologies related to the design of turbines with proven very low impact on fish passage, i.e. eco-sustainable turbines. As a result, a dedicated list of specifications has been produced with key relevant criteria enabling to select the best turbine features and best supplier. These specifications concern the rotating speed, the numbers of blades, the width of the blades, the minimum gap between all moving and rotating parts (2 mm is required).

Figure 4: New eco-sustainable turbine at Monsin HPP

After the new turbines (Figure 4) commissioning, dedicated validation tests have been done. The results overpassed expectations since the impact of the new turbines on the two reference species has been drastically reduced compared to the one of classical Kaplan turbines. Indeed, direct impact on smolts has been found to be below 2 % impact and for eels below 7 %. Considering these very encouraging results, it is foreseen to follow the same process for refurbishment of turbines at other HPPs. Several health parameters were also studied, including mid-term mortality, stress and immune biomarkers. They will allow to evaluate the short- and medium-term impact of the turbine on the survival, the physiological and health status of both species and assess whether the ability of fish to escape successfully to the ocean is compromised or not.

5 DISCUSSION AND CONCLUSION

The design and implementation of effective fish passage solutions at dams and hydropower plants is a complex problem that requires an interdisciplinary approach, with inputs from biology and hydraulic experts [Williams et al., 2012 ; Sylva et al., 2018 ; Renardy et al., 2021]. Varied solutions may be proposed but no one is perfect nor implementable at every location. However, when the problem is considered holistically, it is usually possible to set up efficient solutions that remain also effective regarding green energy production.

The Life4Fish project is a successful example of such a global multidisciplinary approach. The experience gained by the project partners is now available and can be deployed to any hydraulic site featuring limited fish passage capacities.

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SUMMARY

The EU funded Life4Fish project aims at restoring downstream connectivity at six hydropower plants along the Meuse River in Wallonia by testing and implementing passage solutions for European eels and Atlantic salmon smolts, while minimising renewable energy production loss. The project is carried out by an interdisciplinary and intersectoral team gathering people from research and industry, with biology or engineering background, and extends over five years. This paper presents the varied solutions that have been tested to improve downstream passage in the framework of the project.

RESUME

Le projet Life4Fish, financé par l'UE, vise à restaurer la connectivité en dévalaison de six centrales hydroélectriques le long de la Meuse, en Wallonie, en testant et en mettant en œuvre des solutions de passage pour les anguilles européennes et les smolts de saumon de l'Atlantique, tout en minimisant les pertes de production d'énergie renouvelable. Le projet est mené par une équipe interdisciplinaire et intersectorielle réunissant des personnes issues de la recherche et de l'industrie, ayant une formation en biologie ou en ingénierie, et s'étend sur cinq ans. Cet article présente les diverses solutions qui ont été testées pour améliorer le passagevers l' aval dans le cadre du projet.

ZUSAMMENFASSUNG

Das von der EU geförderte Projekt Life4Fish zielt darauf ab, die stromabwärts gerichteten Verbindungen an sechs Wasserkraftwerken entlang der Maas in Wallonien wiederherzustellen, indem Lösungen für die Durchgängigkeit für europäische Aale und atlantische Lachssmolts getestet und umgesetzt werden. Das Projekt wird von einem interdisziplinären und sektorübergreifenden Team aus Forschern und Industrie mit biologischem oder technischem Hintergrund durchgeführt und erstreckt sich über fünf Jahre. In diesem Beitrag werden die verschiedenen Lösungen vorgestellt, die im Rahmen des Projekts zur Verbesserung der Durchgängigkeit flussabwärts getestet wurden.

RESUMEN

El proyecto Life4Fish, financiado por la UE, tiene como objetivo restablecer la conectividad aguas abajo en seis centrales hidroeléctricas del río Mosa, en Valonia, probando y aplicando soluciones de paso para las anguilas europeas y los esguines de salmón atlántico, al tiempo que se minimiza la pérdida de producción de energía renovable. El proyecto lo lleva a cabo un equipo interdisciplinar e intersectorial que reúne a personas de la investigación y la industria, con formación en biología o ingeniería, y se extiende durante cinco años. Este documento presenta las diversas soluciones que se han probado para mejorar el paso aguas abajo en el marco del proyecto.