Institution: Manchester Metropolitan University		
Unit of Assessment: B12 Engineering		
Title of case study: Sandscaping and seawalls: wave modelling protects towns and critical national infrastructure from costly floods and damage		
Period when the underpinning research was undertaken: 2000 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Ling Qian	Lecturer to Reader	2000 - present
Zhihua Ma	Research Associate, Lecturer, Senior Lecturer	2009 - 2011; 2012 - present
David Ingram	Lecturer to Reader	1992 - 2006
Derek Causon	Professor	1985 - present
Clive Mingham	Professor	1995 - present
Period when the claimed impact occurred: 1 August 2013 – 31 December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Near-continuous EPSRC research funding over two decades has produced a suite of advanced computational fluid dynamics (CFD) wave models. These tools have informed novel engineering designs for at least 40 major maritime infrastructure projects around the world, including two significant, award-winning UK firsts. Littlehaven's novel 'floodtastic wonderwall' has protected the town's seafront from flooding since 2013 and helped to boost regional tourism. In Norfolk, a "sandscaped" defence now protects 400 homes and secures critical national infrastructure – a gas refinery and the country's only gas pipeline connection to continental Europe – against erosion from a 1-in-10,000 year storm. The economic benefit from these two projects is approximately GBP62,000,000. In China, the models helped to design the world's largest wave flume; experiments here have enabled authorities to plan and assure the safety of the Hong Kong-Zhuhai-Macau bridge over its 120 year lifespan.

2. Underpinning research

Active in the area of free surface hydrodynamics for more than two decades, the Centre for Mathematical Modelling and Flow Analysis (CMMFA) at Manchester Metropolitan University has been at the forefront of research to produce high-resolution models of complex wave dynamics, including the first to integrate the effects of water depth, wind and aeration. These advanced CFD simulations and codes have been applied to challenging wave-structure interaction problems with applications in ocean and coastal engineering. The group has received unbroken funding from EPSRC and the EU, worth more than GBP3,000,000. The body of work is described in over 100 peer-reviewed papers in internationally-focused journals published since 2000.

Supported by complementary numerical and experimental studies at collaborating partner laboratories at Bath, City, Edinburgh, Hull, Imperial, Lancaster, Manchester, Oxford, Plymouth and Queen's Belfast universities, the researchers within CMMFA have led on the construction and validation of computational models of wave propagation and wave-structure interactions. The group was first in the world to apply a novel and robust free surface capturing method for realistic engineering applications. This led to development of the AMAZON code, first described in 2000 **[1]** and since, further extended and validated. Novel and unique aspects of the models include the adoption of a Cartesian cut cell approach for complex geometry and/or moving/floating bodies. The models also use high resolution Riemann solver based methods – traditionally applied for aeronautical engineering problems – for automatically capturing water/air interfaces and potential sharp changes in the solutions **[2-3]**.

The AMAZON suite of novel codes developed by CMMFA include: i) a numerical wave flume based on the shallow water equations (a depth-integrated form of the Navier-Stokes equations) suitable for calculating wave run-up in near-shore regions **[1]**; and, ii) a 3D numerical wave tank (NWT) based on the full multiphase incompressible/compressible viscous Navier-Stokes solution in both air and water regions above and below the free surface which is essential for modelling violent waves hitting structures **[4]**. It is possible to model wave generation, steepening, overturning and breaking over a structure and to generate a full set of flow variables.

More recent research has refined these models and adapted open source CFD codes (e.g. OpenFoam) for extended functionality to include six degrees of freedom of body motions, hydro-elasticity effects and aeration in breaking waves. These refinements permit the high-resolution simulation capabilities at the core of the numerical wave tank concept.

The Manchester Metropolitan codes address many of the limitations of other techniques. Contemporaneous diffraction models and potential flow codes were not suitable for modelling breaking waves whilst previous CFD-modelling, based on the full Navier-Stokes equations, did not include compressible phenomena, such as aeration and cavitation. This is crucially important in quantifying loadings under extreme wave conditions in which structures must survive **[4-5]**. To address the high computational cost associated with the full Navier-Stokes solutions, a zonal CFD approach (domain decomposition) has been implemented within the numerical wave tank, which combines a hierarchy of flow solvers, ranging from fully non-linear potential theory to incompressible and compressible Navier-Stokes flow solvers. The developed numerical wave tank solver has been parallelised to run on high-performance computer clusters including graphics processing units (GPUs) with substantially reduced computational run time **[5]**. In addition, to model potentially large amplitude and arbitrary motion of floating structures under extreme wave conditions, overset grid-based methods and focused wave groups based on the New Wave theory (NWT) have been applied within the NWT **[6]**.

The development of the CMMFA fully-nonlinear multiphase NWT code, with enhanced functionalities and improved computational efficiency, is a key breakthrough in providing a tool to understand better the complex physics involved in violent wave impacts at structures that could lead to structural damage and even loss of life in extreme cases.

3. References to the research

Note: Citations, *Web of Science* (citations and expected citations) – December 2020.

1. Hu K, **Mingham** CG, **Causon** DM, (2000). *Numerical simulation of wave overtopping of coastal structures using the non-linear shallow water equations.* Coastal Engineering 41(4):433-465. DOI: 10.1016/S0378-3839(00)00040-5. *Citations: 164 (expected: 40.56)*
2. **Qian** L, **Causon** DM, **Mingham** CG, **Ingram** DM, (2006). *A Free-Surface Capturing Method for Two Fluid Flows with Moving Bodies.* Proc. R. Soc. A 462(2065):21-42. DOI: 10.1098/rspa.2005.1528. *Citations: 56 (Expected: 20.67).*
3. Hu ZZ, **Causon** DM, **Mingham** CG, **Qian** L, (2011). *Numerical Simulation of Floating Bodies in Extreme Free Surface Waves.* Natural Hazards and Earth Systems Science 11(2):519-527. DOI: 10.5194/nhess-11-519-2011. *Citations: 19 (expected 23).*
4. **Ma** ZH, **Causon** DM, **Qian** L, **Mingham** CG, Gu HB, Martinez-Ferrer PJ, (2014). *A Compressible Multiphase Flow Model for Violent Aerated Wave Impact Problems*. Proc. R. Soc. A 470:20140542. DOI: 10.1098/rspa.2014.0542. *Citations: 13 (expected 13).*
5. Martinez-Ferrer PJ, **Causon** DM, **Qian** L, **Mingham** CG, **Ma** ZH, (2016). *A Multi-region Coupling Scheme for Compressible and Incompressible Flow Solvers for Two-Phase Flow in a Numerical Wave Tank*. Computer and Fluids 125:116-129 DOI: 10.1016/j.compfluid.2015.11.005. *Citations: Scopus 19, WoS 20 (expected: 11.24).*
6. Chen H, **Qian** L, **Ma** Z, Bai W, Li Y, **Causon** D, **Mingham** C, (2019). *Application of an overset mesh based numerical wave tank for modelling realistic free-surface hydrodynamic problems*. Ocean Engineering 176:97-117. DOI: 10.1016/j.oceaneng.2019.02.001. *Citations: 6 (expected: 3.27).*

Funding

The underpinning research has been supported by over 15 EPSRC grants, one European FP7 project and two Joule Centre grants totalling over GBP3,200,000 to Manchester Metropolitan over the last 20 years. A selection of grants related to the underpinning research includes:

- EPSRC GR/M42428/01: Impulsive Wave Over-topping of Seawalls and Related Coastal Structures - Numerical Simulation. 1999-2002. GBP168,385. PI: Causon.
- EPSRC GR/N24162/01: Numerical Prediction of Multi-component Fluid Systems Using a Cartesian Cut Cell Method. 2001-2003. GBP78,190. PI: Causon.
- EPSRC GR/T18622: Free Surface Simulation of Wave Overtopping during Storms. 2005-2007. GBP92,296. PI: Ingram.
- EPSRC EP/D077621/1: Extreme Wave Loading on Offshore Wave Energy Devices Using CFD: a Hierarchical Team Approach. 2007–2010. GBP116,530. PI: Causon.

- EPSRC EP/J012793/1: FROTH: Fundamentals and Reliability of Offshore Structure Hydrodynamics. 2012–2015. GBP241,712. PI: Qian.
- EPSRC EP/K037889/1: Virtual Wave Structure Interaction (WSI) Simulation Environment. 2013-2017. GBP323,344. PI: Qian.
- EPSRC EP/N008839/1: A Zonal CFD Approach for Fully Nonlinear Simulation of Two Vessels in Launch and Recovery Operations. 2015-2019. GBP317,832. PI: Qian
- EPSRC EP/M022382/1: A CCP on Wave/Structure Interaction: CCP-WSI. 2015-2020. Total award: GBP483,159. Total to Manchester Metropolitan: GBP30,343. Co-I: Qian

Additional indicators of quality

- The group is one of the founding members of the CCP-WSI consortium and UK Fluid Network. It was the only academic group in the UK to be simultaneously active in both SUPERGEN WIND and SUPERGEN MARINE.
- Collaborative research involving more than ten academic collaborators and 20 industrial partners, including some international firms.
- Zonal CFD project (EP/N008839/1) shortlisted for Engineer's Collaborate to Innovate award (2017).

4. Details of the impact

In the IPCC *Special Report on the Ocean and Cryosphere in a Changing Climate* (2019) scientists concluded that extreme coastal flooding, previously expected only once every 100 years, could become annual events by 2050. Further analysis for the UK has shown that large swathes of Norfolk and the East Coast are at significant risk, especially when rising sea levels combine with rough seas and high tides. Urgent innovation in the engineering of coastal defences is vital to protect coastal communities most at risk – or at least buy time before large-scale evacuation is inevitable.

Changing commercial coastal engineering design practice and cost savings

A former Manchester Metropolitan PhD student promoted the use of the AMAZON shallow water code (see reference [1]) in Dutch engineering firm Royal HaskoningDHV (RHDHV) **[A]**. According to the company's Technical Director, Maritime and Aviation, RHDHV has now used AMAZON in approximately 40 coastal defence and infrastructure projects (20 since 2013), including some flagship and award-winning innovations that are now protecting UK communities and critical national infrastructure against flooding and erosion due to rising sea levels and storm surges caused by climate change. The code enables complex modelling that is not possible or is too expensive using current gold standard CFD or physical flume experiments. Use of AMAZON saves approximately GBP50,000 for physical modelling and GBP15,000 for off-the-shelf CFD per project (up to GBP1,300,000 total savings across 20 projects since 2013) **[A]**.

An award winning, UK first: the Bacton Sandscaping project

The firm used AMAZON simulations to inform the design of a UK first: the GBP20,000,000 Bacton Sandscaping project in North Norfolk **[A]**. After a 1-in-100 year storm surge in December 2013, the land between the Bacton gas terminal and the sea was severely eroded, leaving just 15 metres between it and the sea **[B]**. The terminal is considered to be the UK's most important energy hub; it processes one-third of the country's natural gas supplies and is the terminus of the UK's only gas supply lines from continental Europe. As such, it is designated to be a critical national infrastructure. The increasing risk of storm surges and rising sea levels were a threat to hundreds of homes in the nearby villages of Bacton and Walcott being lost to the sea **[B]**.

RHDHV proposed a 'sand engine' to replenish the beach and roll it back to how it looked 30 years ago. AMAZON simulations determined the required beach recharge crest level to ensure that the designed beach profile would withstand erosion by maritime storms **[A]**. Construction was completed in August 2019, after 1,800,000m^3 sand (half the volume of Wembley Stadium) had been pumped and 'sandscaped' along a 6km stretch of the coast. At its highest level, the new beach and dune stands 7m above previous levels and extends as much as 250m out to sea **[B]**. It is specified to protect against a 1-in-10,000 year storm. The significance of the project was highlighted by the RHDHV project manager who told the BBC *"The problem is so big and so unsolvable that it needs something radical like this"* **[C]**.

The completed work now provides 400 homes (2,000 residents) and the gas terminal with 15-20 years protection against erosion and flooding. Following high, stormy seas in the autumn of 2019, a council spokesperson said that the sandscaping had protected homes in the area, stating, *"Had the beach nourishment scheme not been undertaken, it is likely that high tides* *would have overtopped the sea wall, and homes and businesses along the stretch from Walcott to Bacton would have been under a very real flood risk"* **[B]**. One property developer has already submitted a planning application for new-build homes, stating that the sandscaping work had pushed back the 100-year erosion line by 25 years **[D]**.

The project delivers calculated total economic benefits of approximately GBP33,000,000 for the two villages and nearby roads at risk **[E]**. The project's significance to UK energy security is evident in remarks from one energy analyst that *"any disruption at the Bacton terminal would have huge ramifications. On the wholesale market, price increase would be astronomical. The energy security of the UK would be threatened"* **[B]**.

Since completion, the project has won or received commendations in five regional and national awards, including the Institute of Environmental Management and Assessment (IEMA) Sustainability Impact Awards 2020, New Civil Engineer 100 Awards 2019 and Flood and Coast Awards 2020 **[A]**. This cross-sectoral recognition is an indicator of the significance of the project and its innovation for UK coastal engineering and climate resilience management.

The Bacton project has been so significant and successful that RHDHV is now working with the Environment Agency, Crown Estates and local authorities, and is using AMAZON as part of investigations on the potential for sandscaping to protect 20 additional sites in the UK, including the Mount's Bay Marine Conservation Zone in Cornwall **[A,F]**.

Flood protection for Littlehaven: attracting tourists and keeping business open

AMAZON was also used during the design of the new Littlehaven promenade and sea wall to study wave overtopping and flood risk to the town during high seas and storms. Damage to the sea wall was causing frequent flooding along the front, leading to closure and loss of income for local amenities. Proposed seawall designs could not be represented in EurOtop, the industry 'standard' overtopping calculation tool by the Environment Agency, and it was too costly to use full CFD or physical modelling. The AMAZON shallow water solver was, again, the suitable and affordable solution **[A]**.

Also known as the 'Flood-tastic Wonderwall', the GBP5,000,000 project replaced a more traditional 'vertical' flood wall with a softer, more aesthetically appealing coastal defence system. The AMAZON simulations helped with the innovative design, and modelled the impact of retreating the seawall by 50m to make more use of natural beach **[G]**.The project won four national awards in 2014 and 2015, including one from the Royal Institution of Chartered Surveyors and the 'Design for a Medium Scale Development' and 'Climate Change Adaptation' categories in the Landscape Institute Awards 2015 **[G]**.

The significance of the wall to Littlehaven was confirmed during the December 2013 North Sea storm surge, two months before the project was actually completed, when sea levels rose a record-breaking 4m (a 1-in-450 year event). Waves reached only halfway up the new wall with some breaking water and spray in the top half **[G,H]**. Responses to FOI requests confirm that no flooding has occurred since completion of the wall in 2014, including during the October 2019 storms and high tides. The benefits appraisal of the project calculates the net present value benefit of approximately GBP29,000,000 (compared with "do nothing") **[H]**.

A key legacy of the project will be to reinvigorate and grow the town's attraction as a seaside resort. Tourism contributes GBP331,000,000 to the local economy and supports over 3,000 jobs in South Tyneside *"so any activity to ensure its position as a popular destination, such as the Littlehaven Promenade project, is very important"* (South Tyneside Council) **[H]**. The promenade has become a visitor attraction and is now accessible all year round, extending the tourist season and the duration of visits to the town (with a benefit to local businesses). Visitor numbers to the borough have risen from 5,511,000 visitors in 2012 to approximately 6,592,000 visitors in 2018 (latest figures) **[H]**.

Design of the world's largest wave flume

The Tianjin Research Institute for Water Transport Engineering, China, used the AMAZON code to study the piston wave-making power during design of the world's largest wave flume facility; calculations were not possible using published literature. The flume was constructed between 2010 and 2014 at a cost of RMB180,000,000 (01-2014). It is the world's most powerful wave flume and can reproduce 16m high waves and 10m high tsunamis at various scales.

Since opening, the flume has produced over 1,000 hours of experimental data in 18 live projects, including experimental studies of scouring around the piles of the Hong Kong-Zhuhai-Macao Bridge, the world's longest sea-crossing structure. During construction of the bridge, concerns about scour around supporting piles emerged as the effect was not as previously predicted. Thanks to the piston, large-scale experiments helped to minimise scale effects; findings improved the prediction of scour processes and hence, evidence-based safety measures to protect the supporting piles throughout the bridge's 120-year design life **[I]**.

Supporting uptake of advanced CFD and wave modelling in industry

Under its 'Software as an Infrastructure' initiative, in 2015, EPSRC awarded a consortium, including Manchester Metropolitan, with funding to develop a national numerical wave tank community to drive forward adoption of advanced numerical modelling, CFD coding and high-resolution simulation methodologies, such as those pioneered at Manchester Metropolitan. The Collaborative Computational Project in Wave Structure Interaction (CCP-WSI) consortium (see Section 3) has built critical mass and delivered a return on EPSRC's sustained research investment through upskilling and transfer to industry. Knowledge, skills and expertise have been shared through activities including cross-sectoral road-mapping, training and hackathons **[J]**. Since its launch, the community has grown to 169 members (from academia and industry) collectively producing 510 commits to the code repository **[J]**. Collaboration across the community completed development of wsiFoam, an open source numerical modelling tool based on OPENFOAM, first developed by Manchester Metropolitan (see EP/K037889/1, Section 3) **[J]**. The significance of CCP-WSI's academia-industry support and training ecosystem is evidenced by its successful expansion and the award in 2020 by EPSRC of an additional GBP312,512 funding for a second 5-year period (2020-2025) *"to build on impacts"* (Grant ref: EP/T026782/1) **[J]**. The expanded consortium includes partners from across Europe, Australia, Japan, India, Hong Kong and China. Nine industrial partners include multinationals like Airbus Group, large engineering consultancies, and several offshore energy firms. The initiative is now tasked *"to accelerate development of Fully Coupled Wave Structure Interaction (FCWSI) modelling suitable for dealing with the latest challenges in offshore and coastal engineering"* **[J]**.

5. Sources to corroborate the impact

A. Technical Director, Maritime and Aviation, HaskoningDHV *provides testimonial evidence about the use of, and cost savings from, the AMAZON codes in Royal HaskoningDHV, with specific details about the Littlehaven and Bacton Sandscaping projects and awards.*

B. Four news stories *provide evidence of the national significance of the Bacton gas terminal, the threat to homes in Bacton and Walcott, and further details of the sandscaping operation.*

C. BBC video (https://www.bbc.co.uk/news/av/science-environment-49024354) *includes comment from RHDHV spokesperson on the project's significance.*

D. Eastern Daily Press article *gives evidence of planning application, with comments from property developer that the sandscaping would help slow down erosion rates.*

E. Bacton sandscaping outline business case *provides measures of economic and other benefits compared with "do nothing" scenarios.*

F. New Civil Engineer article *describes RHDHV collaboration to explore sandscaping across 20 UK sites including in Cornwall.*

G. Royal HaskoningDHV case study on the Littlehaven seawall *provides evidence of flood protection and subsequent design awards.* Landscape Institute Awards 2015 website *lists Littlehaven promenade as winner of two awards.*

H. South Tyneside Council and Environment Agency responses to FOI requests *describe unbreached flood protection 2014-2020, local business benefits, a net present value benefit of GBP29,316,724, growth in visitors numbers (including out-of-season) and longer visit duration due to the new seawall (and the expectation it will be open year round).*

I. Testimonial from Director, Centre of Ocean Engineering, Tianjin Research Institute, China *provides data on the specifications of, and impacts from, use of the experimental flume.*

J. Selection of webpages from the CCP-WSI website and UKRI Gateway to Research funding pages *provide evidence of CCP-WSI's reach and outcomes including: consortium partners and CCP-WSI membership figures; training activities; code development; development of the wsiFoam tool with Manchester Met leadership, successful consortium expansion and follow-on funding to develop Fully Coupled Wave Structure Interaction (FCWSI) modelling.*