Institution: University of East Anglia

Unit of Assessment: 10 – Mathematical Sciences

Title of case study:

The Violent Forces on Coastal Structures due to Storm Waves

1. Summary of the impact

Mathematical models of violent flows developed by Dr Mark Cooker at UEA have been adopted by industry. The work enhances the capabilities of coastal engineers to design and repair seawalls and coastal structures, and enhances their interpretation of damage inflicted by storm waves. The research has direct industrial application, and is used to contain, interpret and lessen sea-wave damage to structures. Commercial software has proved inadequate in this field, compared with Cooker's mathematical modelling, because computations alone cannot resolve the brief time-scales and short length-scales over which there are large changes in pressure, and sudden excursions of the liquid as splashes. An example of this impact is the design of an observation gantry exposed to storm waves.

2. Underpinning research

This study concerns the work of **Dr Mark Cooker**, appointed 1992. The research was undertaken at UEA from 1993 up to the present.

In wave impact research Cooker has made significant applications of pressure-impulse theory (which he co-developed) to practical situations [1-4]. In particular the idea of pressure-impulse [2,4] is now widely used (for example [5]) by coastal engineers for dynamic forces on seawalls, as it is an efficient way of predicting loads on a structure during breaking-wave impact and therefore has underpinned direct industrial application [6].

The underlying mathematics presented in [2] was started while Cooker was employed at Bristol University, but the paper required substantial further work to satisfy reviewers. This additional theoretical work was carried out by Cooker at UEA, and included a critical point of contention: the occurrence of a singularity in some solutions where the boundary conditions are discontinuous at a right angle in the boundary. This revealed extreme violence in the corner of the fluid domain, and the need for an inner solution to describe the splash-jet root. The resolution of the primary importance of the outer solution was a crucial part of the research, and its subsequent scientific development.

One of the underlying mathematical ideas that Cooker developed in [2], and subsequently for example in [4], involves calculating the pressure-impulse distribution in the water during impact. At each geometric point the pressure-impulse is the time-integral of the large transient pressure over the short duration of an impact. The pressure can rise from ambient value to a peak of several atmospheres and decline again, all within a few milliseconds. The time-integral of the pressure is a mathematically flexible quantity with which to model significant changes in the impacting wave flow. This idea is useful for design, because simplified model equations and easily specified initial data predict the sudden change in fluid velocity, the splash, the total impulse, and the overturning moment on the structure that is hit. The theory [2,4] explains the movement of debris along the seabed *away* from a seawall. The impulses contribute to a wave-excavation of bed material that is then pushed away from the foot of the wall by succeeding impacts. On a seawall, the theory also predicts the forces made by the penetration of wave water into confined spaces, such as cracks. From this the associated impulsive forces on the interior of the structure can be estimated [6].

Experimental results have shown that high pressure coincides with the start of a splash made by a wave impact. At a vertical wall, the forward face of the wave is an accelerating and converging concave surface. From the bottom of the surface, the splash jet emerges and climbs the wall, accelerating as it ascends, ahead of the rest of the advancing wave face. This ultra-violent flow is known as *flip-through*. Flip-through coincides with the conditions for the highest impact pressures.

Cooker's analysis of this important phenomenon, modelled in [3], explains how and where such large and damaging pressures occur.

3. References to the research

(UEA authors in bold)

[1] **Cooker, M.J.** (2009) Theories of wave impact pressures on coastal structures. *Proceedings of the 31st International Conference on Coastal Engineering*, Hamburg 2008. World Scientific for ASCE, 3212-3223
ISBN: 9789814277402

[2] **Cooker, M.J.** and Peregrine, D.H. (1995) Pressure impulse theory for liquid impact problems. *Journal of Fluid Mechanics,* **297**, 193-214
DOI: 10.1017/S0022112095003053

[3] **Cooker, M.J.** (2010) The flip-through of a plane inviscid jet with a free surface. *Journal of Engineering Mathematics,* **67** (1-2), 137-152
DOI:10.1007/s10665-009-9302-2

[4] **Cox, S.J.** and **M.J. Cooker** (1999) The motion of a rigid body impelled by sea-wave impact. *Applied Ocean Research,* **21**, 113-125
DOI: 10.1016/S0141-1187(99)00005-X

[5] Müller, G., Hull, P., Allsop N.W.H., Bruce, T., Cooker, M.J. and Franco, L. (2002) Wave effects on blockwork structures: model tests. *Journal of Hydraulic Research,* **40** (2), 117-124
DOI: 10.1080/00221680209499854

[6] Müller, G., Wölters, G. and **Cooker, M.J.** (2003) Characteristics of pressure pulses propagating through water-filled cracks*. Coastal Engineering*, **49** (1), 83-98
DOI: 10.1016/S0378-3839(03)00048-6

4. Details of the impact

When a sea wave hits a structure such as a seawall, a series of violent fluid flows occur, as vividly illustrated at any harbour during high winds. These impacts may damage the structure and cause hazardous splashes and overtopping. These flows are complex, and demand sophisticated mathematical tools to analyse and predict their movements, forces and outcomes. Better understanding of violent flows leads to improved design, engineering and repair of such coastal structures, and also allows time-dependent safety advice for users of harbour walls to be provided with greater confidence.

Engineers need to interpret the damage made by waves. For example, how do storm waves *withdraw* blocks from a seawall? Violent flows due to breaking-wave impacts can damage a structure by over-straining materials, fragmenting components and undermining foundations. Violent flows are inherently difficult to compute, particularly in domains with complicated shapes of boundary. The International Conference on Coastal Engineering (see [1] above) is a forum of industrial research, at which there is recurring impetus from the designers to the theorists to improve design methods, by developing accurate and efficient mathematical models that predict wave impact forces. The work ultimately has many benefits. For example, wave splashes are hazardous to persons and vehicles on top of a harbour wall, and the harbour master's safety advice may depend on a confident knowledge of the risks from the waves in that setting.

Below we provide three specific examples of the use of Cooker's models of the effects of wave impact in this REF period:

Charles Scott and Partners: In 2006, Cooker began a collaboration with *Charles Scott and Partners*, Glasgow (consulting engineers, providing services in civil engineering) who wanted to understand how and why a gantry had been knocked down by storm-waves in Shetland in November 2005. The gantry was a 5.5 metre high free-standing steel structure with angled struts, designed to allow a person to work safely at an elevated viewpoint, on a beach with high wave exposure. The unexpected failure of the original design presented a safety problem. The company was at a loss to explain the failure, and needed to design a safe replacement. The company had no method to predict the forces on the gantry, so they approached Cooker on the strength of his publications and expertise in predicting wave forces. Drawing on his research, ([2], [4]) Cooker described how and why the gantry was knocked down onto the beach. He showed that the failure was due to the sudden huge loads (and moments about the base) that were exerted on the cylindrical support when struck by waves. The model was crucial to the company's understanding and their subsequent design-work on the new gantry, to obtain the right number of struts and their angles of inclination. Cooker was also able to dispel a false notion that the two front struts of the structure could in some way shelter the two rear struts from wave impact. Using these ideas, a replacement gantry was built to a new design and successfully installed.

The company stated "we would like to take this opportunity to offer our sincere thanks for your invaluable help during the design period" (corroborating source [A]).

Thus, Cooker's theoretical work has provided *Charles Scott and Partners* with a successful predictive method to model, and hence design, all future structures exposed to wave impact.

HR Wallingford Ltd: In the coastal wave-impact context, Cooker was a partner in the EPSRC-funded ViFSNet group (2001-2004). This network identified critical research problems that needed to be addressed post-2004, as judged by professional engineers involved in the design and construction of seawalls and harbours. This led to several collaborations, including with *HR Wallingford Ltd.*, who are a leading centre for (i) coastal-engineering consultancy advice around the world, and (ii) the modelling and computation of waves in the presence of coastal structures (corroborating source [B]). This on-going commercial link ensures that Cooker's research on wave impacts is used by industry.

Atkins UK: In addition, Cooker's expertise on wave impacts is widely sought. For example, his expertise on offshore structures and violent wave-structure interactions, has been applied to estimate the wave impact forces on wave energy extraction devices. He has provided outcomes of his research on wave impacts on several occasions in the past five years to *Atkins*, global engineering and design consultants. The interest by *Atkins* is in the need to account for the potentially damaging and destructive wave forces, as well as the useful energy available for extraction from steep and breaking waves, using devices of novel design (corroborating source [C]).

5. Sources to corroborate the impact

[A] Personal letter of thanks to Cooker from *Charles Scott and Partners*, Glasgow. Held on file at UEA.

[B] Corroboration from *HR Wallingford Ltd.*

[C] Corroboration from *Atkins UK*.