Institution: University of Plymouth		
Unit of Assessment: UoA12		
Title of case study: Provision of tools, techniques and international standards guidance to those responsible for the maintenance of historic rock lighthouses under current and future predicted extreme wave loading		
Period when the underpinning research was undertaken: 01.01.2000 to 31.12.20		
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:**
Professor Alison Raby	Professor of Environmental Fluid Mechanics	1 August 2003 - present
Period when the claimed impact occurred: 01.08.13-31.12.20		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Historic rock lighthouses remain critical to safe navigation around coastlines because GPS is not failsafe. However, these irreplaceable heritage structures are ageing and are potentially under increased loading due to climate change, which is resulting in waves impacting higher up the towers. Raby has led investigations on environmental loading and structural response of lighthouses, and how to model and monitor their behaviour in storms, to ensure long-term survivability. Research has resulted in greater certainty of safety for maintenance teams and a break-through in minimal monitoring. The University of Plymouth (UoP) also used these approaches to investigate the recently-repaired Portreath harbour wall, verifying that the new structure will not fail under the same conditions that caused previous damage. Impact to date takes the form of increased know-how resulting in better-informed working practices for national navigation authorities, with detailed guidelines feeding into international guidelines developed in conjunction with Australian, Asian and South American authorities.

2. Underpinning research (indicative maximum 500 words)

The UoP has been at the forefront of field-based wave loading on structures since the 1980s. During the last 20 years efforts to explain the complex physics of breaking wave impacts were undertaken by Professor Bullock (now Emeritus) who designed an interactive programme of field laboratory and analytical/numerical studies to investigate Breaking Wave IMpacts on steep fronted COastal STructures (BWIMCOST) with the University of Bristol and the Queen's University of Belfast. Field tests were conducted on Admiralty Breakwater (Alderney), the large wave channel in Hannover, Germany and in the School's wave channel [3.1] [G1 & 2]. The resulting 2D analytical/numerical model successfully reproduced all of the main characteristics of observed breaking wave impacts. By including the compressibility effects associated with trapped and entrained air, it was possible to show how pressure waves propagate out from the impact zone and could even become shock waves which pose structural integrity threats. The BWIMCOST laboratory tests then led to the EPSRC-funded OVI project (2005-7), again including Bristol as partners, that considered violent breaking wave impacts and overtopping [3.2] [G3].

In 2010, UoP began working with Trinity House (TH) (the English General Lighthouse Authority), following an introduction through the engineering consultancy AECOM who had conducted structural surveys of the towers. TH had expressed concern about the long-term survivability of their historic rock lighthouses, built on surface-piercing reefs in necessarily exposed situations. As a result, Professor Raby led a pilot project on the Eddystone Lighthouse [G4] with additional financial support from the UK and Irish General Lighthouse Authorities (GLAs) [G5]. The project installed recording equipment: geophones (for measuring vibrations) and video cameras (for providing qualitative information on wave impacts), just in time to capture data from the catastrophic 2013/14 winter storms [3.3]. These data were used to validate a Finite Element (FE) structural model, developed in collaboration with Politecnico di Turino, which was used to estimate factors of safety for potential failure mechanisms of the Eddystone lighthouse [3.4]. The success of this pilot project resulted in Raby leading the EPSRC-funded STORMLAMP project [Grant 6] to consider more exposed rock lighthouses around the British Isles. In addition to the widened scope, STORMLAMP used more in-depth investigations of structural modelling, laboratory modelling and field measurements with the University of Exeter and UCL. Project partners comprised the UK GLAs, AECOM, Atkins, HR Wallingford and the Environment Agency (EA). The latter four partners have interests in how the findings might be applied to more generic coastal structures *e.g.* seawalls and breakwaters. Detailed investigations have been conducted on the Fastnet [3.5] and Wolf Rock lighthouses [3.6] to consider the survivability of those structures into the future, with projected increases in wave loading. On the basis of the STORMLAMP project, Raby led a Special Issue of the Philosophical Transactions of the Royal Society A on *Environmental Loading of Heritage Structures* which drew together key findings from the STORMLAMP paper [3.6] with those from French, US, Norwegian and Hong Kong lighthouse investigations, in addition to including other heritage structure civil engineering projects.

3. References to the research (indicative maximum of six references)

3.1 **Bullock**, G.N., Obhrai, C., Peregrine, D.H., Bredmose, H. (2007). Violent breaking wave impacts. Part 1: Results from large-scale regular wave tests on vertical and sloping walls. *Coastal Engineering* 54 (8): 602-617.

3.2 Bredmose, H., **Hunt-Raby, A.C.**, Jayaratne, R., & **Bullock, G.** (2010). The ideal flip-through: Experimental and Numerical investigation. *Journal of Engineering Mathematics* 67(1-2): 115-136.

3.3 **Raby**, A., **Bullock**, G.N., Banfi, D., Rafiq, Y. Cali, F. (2015). Wave loading on rock lighthouses. *Maritime Engineering* 169(1): 15-28 (10.1680/jmaen.15.00002). Winner of the Institution of Civil Engineers Halcrow Prize in 2017.

3.4 Trinh Q., **Raby** A. C., Corrado M., Chiaia, B., Rafiq Y., Cali F. (2016) Modelling the Eddystone Lighthouse response to wave loading. *Engineering Structures* 125: 566-578 (10.1016/j.engstruct.2016.06.027).

3.5 Antonini A., **Raby** A.C., Brownjohn J., Pappas A. & D'Ayala D. (2019) Survivability assessment of Fastnet lighthouse. *Coastal Engineering* 150: 18-38 doi.org/10.1016/j.coastaleng.2019.03.007.

3.6 **Raby**, A.C., Antonini, A., Pappas, A., Dassanayake, D.T., Brownjohn, J.M.W., D’Ayala, D. (2019) Wolf Rock lighthouse: past developments and future survivability under wave loading. *Philosophical Transactions of the Royal Society A* doi.org/10.1098/rsta.2019.0027

Grants

G1 Breaking Wave Impacts On Steep Fronted Coastal Structures,01.08.01 – 31.10.04 £289k

G2 Breaking Wave Impacts On Steep Fronted Coastal Structures: Supplementary Studies, 1.8.04 – 31.10.05 £108k

G3 Fundamentals of overtopping from individual violent water wave impacts 1.10.06 – 30.09.08 £176k

G4 Wave loading on rock lighthouses 1.10.12 – 30.09.15 £58k

G5 Wave loading on rock lighthouses 2013 – 2015 £60k

G6 STORMLAMP - STructural behaviour Of Rock Mounted Lighthouses At the Mercy of imPulsive waves 8.7.16 – 29.11.21

Value of the grant: £453k to Plymouth University (there are linked grants at UCL (structural modelling) and University of Exeter (field testing) but Alison Raby is contributing to all work packages, is leading the hydrodynamic modelling and is overall PI of the c. £1m total grant).

4. Details of the impact (indicative maximum 750 words)

The importance of rock lighthouses for safe marine navigation grows with world trade. The most recent World Bank data show this growth as Twenty-foot Equivalent (container) Unit (TEU) traffic rising from 560 million in 2010 to over 790 million in 2018 (https://data.worldbank.org/indicator/IS.SHP.GOOD.TU), much of it accommodated by an increased merchant fleet. As an island trading nation experiencing some of the world's strongest storms, the UK is particularly vulnerable to maritime navigation failure; the loss of one strategic lighthouse will have incalculable effects on safety and trade. The GLA maintenance programmes for rock lighthouses have previously been limited to visual inspections, repairs of obvious damage and weatherproofing. UoP research has provided a more systematic approach to long-term survivability, which was beyond the capability of the GLAs.

Guidelines on storm waves for international navigation authorities

The UoP STORMLAMP project has resulted in the development of guidance documents for the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) which includes authorities in the US China, Russia, Brazil, India, South Africa, and Australia. The national members of the IALA are legally responsible for aids to navigation (AtoNs), *e.g*. lighthouses and buoys. Raby's findings on environmental loading of heritage structures [*5.1*] led to an invitation to contribute to the IALA Engineering Committee Working Group 2 (Technical Knowledge and Sustainability). This committee prepares and reviews guidance on technical matters and monitors specific developments of issues relating to navigation aids, working in cooperation with International Organization for Standardization (ISO). Following the October 2020 meeting, approaches developed in the STORMLAMP project are cited in the draft IALA Guideline: *Extreme Environmental Conditions* that identifies appropriate standards for AtoN equipment. Although available for day-to-day use already, as per standard IALA working practices this draft guideline will be formally adopted, after the consultation period, as a full guideline focusing particularly on wave loading and structural response, using the STORMLAMP project as its base; the next committee session will start in 2022. Other key contributors will include the Australian organisation AMS Group, the Korea Institute of Aids to Navigation, and Armada de Chile Directemar. These guidelines ensure that mariners have aids to navigation which meet their needs, both now and in the future, thus, contributing to a reduction of marine accidents and increased safety of life and property at sea [5.2]. The report of the 12th session of the IALA ATON Engineering and sustainability committee 30/9-16/10 2020 noted that *"Alison Raby made a significant contribution on wave impact on rock lighthouses"* and in his testimonial IALA's Deputy Secretary-General & Dean comments that: "The outcome of the study has now been incorporated into a revised Guideline titled *"AtoN equipment and structures exposed to extreme environmental conditions"… the Guideline describes the approaches developed in the STORMLAMP project and the project outcomes. [This]… will be part of the many guidelines available internationally for reference by AtoN maintainers and Authorities."* And goes on to say *"The unique and ground breaking research of Professor Raby and her team has increased our understanding of the behaviour of lighthouses in the stress of the sea, our understanding of their long term viability and enabled the organisation to revise guidelines which will inform practice in the sector. This is a specialised field and we are grateful for the knowledge gained and shared by this study which will be used by International AtoN authorities and maintainers in order to keep their AtoN estate in good and safe order for the future."*

Guidelines on rock lighthouse monitoring and modelling
The STORMLAMP findings have also been incorporated into a Guidance Note for the UK & Irish GLAs: *Wave Loading on Rock Lighthouses - STORMLAMP project techniques and findings* [5.3]. This includes more comprehensive information than is included in the current IALA

guidelines. It was developed iteratively with the GLAs to ensure an appropriate form for utilisation by their engineers. In his comments to the final workshop of the STORMLAMP project Trinity House's Director of Operations stated [5.4]: *"…it [STORMLAMP] has proven to be of great value. As a result there is now far greater understanding of the behavior of our structures especially in the sort of extreme wave loading conditions which may be more prevalent in the future with the impact of climate change."*

Ensuring safe operating conditions for maintenance teams
Our research has informed procedures for monitoring lighthouse behaviour and periodic onsite surveys for the Trinity House rock lighthouses [5.5]. These lighthouses are no longer manned but remain an important part of safe navigation with automated lights and remote monitoring. This modern approach to usage of legacy structures has introduced several new challenges. STORMLAMP data has been used to assure maintenance teams of safe operating conditions and helps inform planning for safe maintenance schedules. In addition, STORMLAMP modelling work has provided crucial details for how to undertake more focused inspections of the existing helidecks; how to retrofit and redesign helidecks which are now at the end of their design life and how to design the next generation of helideck structures. We have also provided a break-through in minimal monitoring of inaccessible structures. Systems have been developed for low cost, low-power (hence low-carbon), long-lived instrumentation for structural vibrations and to potentially provide video evidence of damage to helideck structures, solar photovoltaic panels, and lantern glazing following storms. This will reduce helicopter visual checks with associated economic (£3,000 / hour for helicopter flights) and CO_2 savings (~0.2 tonnes per 20 minute flight with required 1 hour positioning[1]). In his testimonial, the Northern Lighthouse Board's Asset Manager stated: *"…provision of equations to enable us to conduct limit state analysis of all our rock stations. This tool effectively allows us to do an overall structural stability calculation for all of our assets, potentially savings thousands of pounds in consultancy surveys and services. Having this information allows us to operate safely into the future, with our team's confidence in the lighthouse conditions and mariners assured of an everlasting navigational beacon"* [5.6].

Reassurance on structural safety
As climate change causes rises in sea level, the impact of wave loading on the Fastnet lighthouse was causing concern about its survivability in an increasingly hostile environment. Our research reassured the Commissioners of Irish Lights that Fastnet is in no danger from rising sea levels for at least the next 50 years. This reassurance enabled savings, both in terms of cost (helicopter and staff) and CO_2 output (numerical indicators given in the above example) accrued from reductions in detailed assessments or far more costly intervention if the structure was thought to be at risk. This insight could not have been delivered by a commercial engineering consultancy company due to the comprehensive nature of the investigation and the use of sophisticated analysis methods. In his testimonial the Operations and Property Manager, of the Commissioners of Irish Lights [5.7] stated: *"The overall assessment from the STORMLAMP project is that the stability of the Fastnet lighthouse, in its current condition, gives no cause for concern with the sheer mass of the lighthouse and its interconnected masonry construction capable of withstanding the worst of the Atlantic storms and the predicted increases in sea levels and wave impacts arising from climate change effects. We are also very pleased to be associated with results that will be disseminated via the International Association of Lighthouse Authorities (IALA) and be used as guidance for other light authorities facing similar challenges. We have a role in global aids to navigation best practice and are pleased that this work has demonstrated for the first time anywhere in the world how modern science can help us mange heritage structures."*

Our baseline data from the modal testing of Dubh Artach, one of the Northern Lighthouse Board (NLB)'s rock lighthouses situated off the west coast of Scotland, is of great value to that authority. Source 5.7 states: *"…particular aspects that will inform our operations now and into the future… [the] concept of a simple, low-cost monitoring system for our lighthouses that will enable us to remotely monitor their structural behaviour, and compare with baseline data to see if the structural response changes, indicating damage not discernible to the naked eye allowing appropriate early intervention".* Future sea level rise associated with climate change could cause breakage to the interlocking blocks in the tower. The NLB will be able to compare the baseline data with data obtained from simple (user friendly) equipment for long-term monitoring of the lighthouse during winter months. Any change will indicate that damage has occurred; this may not have been apparent otherwise [5.8].

STORMLAMP also resulted in assurance and economic savings for the EA [5.9]. The EA has £5.2 Billion to spend on Flood and Coastal Erosion defences for the period 2021 - 2027; much of this will involve repair and rehabilitation of existing masonry structures subject to chronic and acute wave loading. Through their engagement with the project they have gained insight into the modelling response of masonry structures to wave loading, specifically, the Portreath harbour wall which underwent repair work following storm damage in 2018. Finite Element modelling as part of our project verified that the new structure will not fail under the same wave loading that caused the recent damage: *"…the techniques considered and applied and the learning and guidance provided will undoubtedly help us better understand the management of maritime masonry assets and plan for the maintenance and their management going forward."* The Environment Agency's National Coastal Manager.

5. Sources to corroborate the impact (indicative maximum of 10 references)

5.1 Lead authorship of a Special Issue of the Philosophical Transactions of the Royal Society A on Environmental Loading of Heritage Structures published in August 2019. https://royalsocietypublishing.org/toc/rsta/2019/377/2155
5.2 Testimonial letter from IALA Engineering Committee Chair, Simon Millyard
5.3 Guidance Note for the UK & Irish GLAs (led by Raby)
5.4 STORMLAMP end of project workshop (YouTube link)
5.5 Testimonial letter from Peter Dobson, Trinity House
5.6 Testimonial letter from Eoghan Lehane, Commissioners of Irish Lights
5.7 Testimonial letter from Andrew Stevenson, Northern Lighthouse Board
5.8 Testimonial from Nick Ely, Environment Agency
5.9 The journal articles relating to the projects:
Trinity House Flash Journal Summer 2016 Issue 25 article page 8 & 9: *Wave Loading on Rock Lighthouses* https://www.trinityhouse.co.uk/about-us/media-centre/flash-journal

Trinity House Flash Journal Spring 2020 Issue 32 article page 14 & 15: *Are the rock lighthouses finally giving up their secrets?* https://www.trinityhouse.co.uk/about-us/media-centre/flash-journal

The Royal Society Mathematical Physical and Engineering Journal Volume 377, Issue 2155 https://royalsocietypublishing.org/toc/rsta/2019/377/2155

IALA Bulletin 2018