PHILOSOPHICAL
TRANSACTIONS A

royalsocietypublishing.org/journal/rsta

Introduction

**Cite this article:** Raby A, Antonini A, D'Ayala D, Brownjohn JMW. 2019 Environmental loading of heritage structures. *Phil. Trans. R. Soc. A* **377**: 20190276.
http://dx.doi.org/10.1098/rsta.2019.0276

Accepted: 28 June 2019

One contribution of 14 to a theme issue 'Environmental loading of heritage structures'.

**Subject Areas:**
civil engineering

**Author for correspondence:**
Alison Raby
e-mail: alison.raby@plymouth.ac.uk

THE ROYAL SOCIETY
PUBLISHING

# Environmental loading of heritage structures

Alison Raby[1], Alessandro Antonini[2], Dina D'Ayala[3] and James M. W. Brownjohn[4]

[1]School of Engineering, University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK
[2]Department of Hydraulics Engineering, Delft University of Technology, 2628 CN Delft, Netherlands
[3]Civil, Environmental and Geomatic Engineering, UCL, Gower Street, London WC1E 6BT, UK
[4]College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, EX4 4QF, UK

AR, 0000-0002-8959-0080

## 1. Introduction

This theme issue, featuring Environmental loading of heritage structures, provides a snapshot of current civil engineering approaches to assessing ageing structures under a variety of loads. The publication arose from a serendipitous sequence of interactions. Academics at the University of Plymouth were contacted by Trinity House in 2010 to investigate reported vibrations in their rock lighthouses when impacted by storm waves. A pilot study on the nearby Eddystone lighthouse captured structural response data from the catastrophic storms of 2013/2014 and paved the way for a more comprehensive project. The STORMLAMP project brought together expertise across various civil engineering disciplines, hydrodynamics, field-based structural monitoring and structural modelling, at the University of Plymouth, University of Exeter and UCL, respectively. It has investigated rock lighthouses across all three of the General Lighthouse Authorities of UK and Ireland (Trinity House, Irish Lights and the Northern Lighthouse Board). Field modal testing was undertaken at seven rock lighthouses right across this region to support the characterization of extreme impulsive breaking wave loads, and the identified modal properties have subsequently been used to validate structural models. These models have also required the best estimates of likely wave loads in order to predict maximum structural responses, provided by researchers in the team.

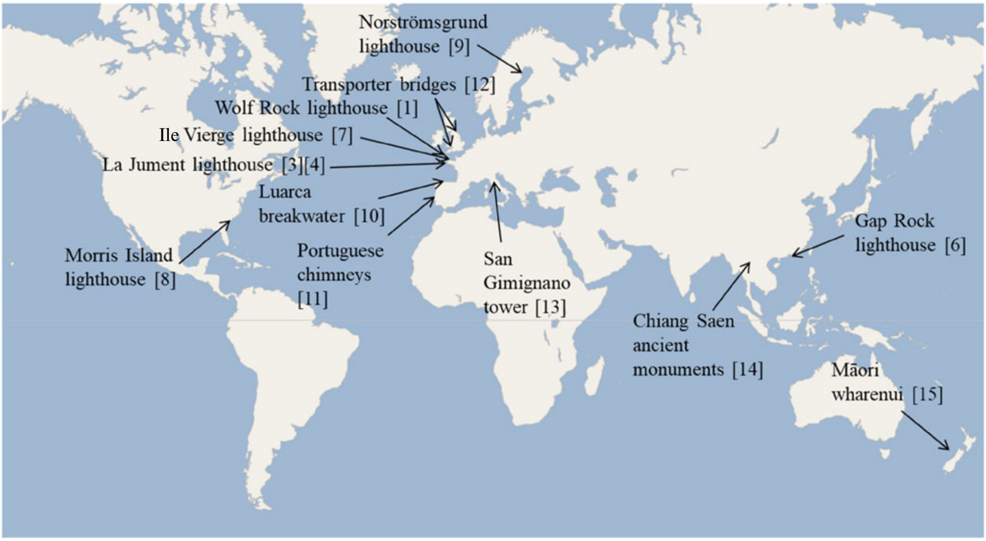

**Figure 1.** Locations of heritage structures described in this Special Issue (adapted from [2]). (Online version in colour.)

The Special Issue features comprehensive investigations undertaken on the Wolf Rock lighthouse [1], located eight nautical miles from Land's End at the southwest tip of England, and one of the most exposed lighthouses in the British Isles (figure 1).

The Wolf Rock lighthouse was also one of the first rock lighthouses to have a helideck constructed on top of the lantern housing. As part of the STORMLAMP project, a number of interviews were conducted with former lighthouse keepers and helideck designers. There is a surprising lack of published design information on the helidecks, given how innovative they were when first constructed. The helidecks provide access to lighthouses in all but the worst of weather conditions, much more reliably than with boat access. The original designer, Steve Simmons, was able to provide us with highly detailed information about the design. These details were corroborated by Dave Vennings, who went on to revise the design for other rock towers. Simmons' accounts included descriptions of how visitors to the tower would be hauled up the outside of the lighthouse from the boats and bumped along the side of the tower. He estimated that he endured this method of accessing the tower about a hundred times as the young designer at Trinity House. Lighthouse keepers, now well into retirement, were keen to describe to us the experience of being on station during storms. Peter Preston, who now lives on a narrowboat ('a lighthouse on its side'), describes experiencing green water overtopping in 1979, the year of the Fastnet Sailing Race disaster, where 15 crew members died. He described the experience of his ears popping as the waves ran up the side of the tower. But he also remarked on the stability of the tower, saying that a mug of tea might develop only a surface shimmer when the lighthouse experienced a wave impact. Tony Martinez, who had served on Wolf Rock in the early seventies, described the sound of an impacting wave like being in an oil drum and banging it with a hammer. Interestingly, he reckoned that the period of vibration of the tower had increased following the installation of the helideck; however, the structural modelling of the tower and helideck [1] do not support this particular observation.

## 2. Related investigations

In parallel to the research in the British Isles, investigations were also underway in France. The lighthouses around the Brittany coast are among the most photogenic in the world, not just because of their varied architecture, square towers (Ploumanac'h Men Ruz), octagonal (La

Jument), castellated (Les Pierres Noires) and even church-like (Tévennec), but also because they experience some of the most extreme wave climates of any lighthouses in the world. La Jument lighthouse is featured in two different papers: Filipot *et al.* [3] present information on the wave environment and Denarié & Fady [4] focus on the structural response to those waves. This lighthouse is described as 'one of the great manned sentinels of the twentieth century' [5] and is famous for images of what appear to be a wave of mythical proportions wrapping around the tower while the lighthouse keeper stands oblivious in the doorway. Emmanuel Denarié, an academic at École Polytechnique fédérale de Lausanne, had been a frequent visitor to Ushant and knew local guides and fishing folk who had knowledge of the Brittany lighthouses. Under his inspiration, the French equivalent to Trinity House, the CETMEF, which became CEREMA in 2014, conducted Ultra-High Performance Fibre-Reinforced Concrete tests on a marine turret in 2012, and Denarie undertook structural modelling of La Jument and Ar Men lighthouses with MSc students whose work is cited in the paper by Denarié & Fady [4]. The structural modelling that was undertaken on both the British and French towers focused on the structural response of the lighthouses to intense wave impacts. The field monitoring on La Jument determined natural frequencies and damping coefficients of the structure during a dramatic wave impact [4]. The stereo imaging technique that has been described in La Jument [3] is also being implemented on Wolf Rock lighthouse this summer, with expert advice from Alvise Benetazzo one of the paper co-authors. A link to lighthouse investigators further afield was made in 2017 after the STORMLAMP team submitted an aerial photograph of the Fastnet lighthouse (taken from a drone) for an Engineering and Physical Sciences Research Council photography competition. The photograph won second prize in the People and Skills category and appeared in national newspapers. These were picked up in London by the daughter of a Hong Kong academic who had coincidentally started investigating Chinese lighthouses and their British designers. Hence S.W. Poon reports in this Special Issue on early Typhoon damage on the Gap Rock lighthouse [6]. Incidentally, the competition prize money went towards a new drone, the original having expired due to the moist salt-laden air. Further links were made with other lighthouse investigators: Domede & Fady investigating Ile Vierge [7], the tallest lighthouse in Europe; Blyth *et al.* considering the Morris Island lighthouse in the US state of South Carolina where lighthouses are now being used as private assets [8]; and Nord *et al.* looking at the phenomenon of ice loading on Norwegian lighthouses, identifying eigenfrequencies from field data [9].

More generic heritage coastal structures have been included in this special issue, as it features the historic Luarca breakwater in Spain [10]. Away from the coastal zone, and experiencing significant wind loading, two unusual heritage structures are investigated: masonry chimneys in Portugal [11] and steel transporter bridges in the UK [12]. Finally considering heritage structures under seismic loading, this issue also includes masonry chimneys in Portugal [11]; masonry towers in Italy [13]; temples in Northern Thailand [14]; and Maori buildings in New Zealand [15].

## 3. Environmental loading

When these heritage structures were designed and built, far less was understood about the nature of environmental loading and structural response. Civil Engineering standards were generally not developed until the end of the nineteenth century; for wave loading in particular, the seminal research on interactions with walls did not take place until well into the twentieth century when wave loading on walls was investigated by Hiroi in 1919 [16] and waves on cylinders by a team led by Morison in 1950 [17]. Domede & Fady [7] provide a historical review of wind loading that was used in the design of the Ile Vierge lighthouse, developed by the British lighthouse engineer John Smeaton, making a comparison to modern Eurocodes. They discover that the lighthouse was over-designed, with a safety factor of approximately 10. Carter *et al.* [12] considered the unusual steel transporter bridges located in Newport, Wales, and Middleborough, northeast England, built more than 100 years ago. They reveal that the survival of the steel transporter bridges is due in part to the fact that wind loading on each structural element was applied with no consideration of the sheltering of neighbouring elements.

Considering a statistical description of loads, extreme environmental design conditions have been historically defined by means of classical stationary extreme values analysis theory. Unfortunately, we are facing a period of accelerating climate change which might result in most previously identified design parameters being obsolete. Hence, the development of advanced techniques for non-stationary extreme analysis investigation is a priority in order to properly consider climate change effects within design parameters. Moreover, as field measurements are usually rare, the scarcity of data arises as an additional difficulty, implying a great amount of uncertainty on the estimation of the design parameters. In this light, Bayesian inference can be successfully used to deal with this unavoidable uncertainty of the results, incorporating different sources of prior information/knowledge providing a rigorous methodology for quantifying the involved uncertainties in the problem. The versatility of the Bayesian method is reflected in the applications present in this issue: Bartoli *et al.* [13] use a Bayesian model updating framework with probabilistic structural analyses leading to fragility curves for seismic loading and Raby *et al.* [1] use a Bayesian method with informative prior distributions to consider how the wave climate may change 50 years into the future at the Wolf Rock and show the potential implications on the lighthouse. Finally, a time-dependent contemporary probabilistic design approach is applied to the Luarca breakwater in Spain by Lara *et al.* [10], showing how the structure serviceability and stability have been evolving over time in a context of uncertainty.

## 4. Structural modelling

Regarding the structural response to environmental loading, several of the contributions to this special issue undertake structural modelling with finite-element modelling (FEM) or discrete-element modelling (DEM). Raby *et al.* [1] describe a combined FEM and DEM approach to investigate the structural response of the Wolf Rock helideck finding that it could present localized damage due to the vibration of the tower caused by extreme wave impacts. Validating a model is not without logistical challenges, as described by Raby *et al.* [1] and Denarié & Fady [4], but the rewards include the possibility of conducting inverse analysis to determine the actual load, for a given monitored response. FEM was also undertaken by Carter *et al.* [12] to determine likely failure modes on the transporter bridges and by Guedes *et al.* [11] to assess the wind and earthquake loading effect on brick masonry industrial chimneys.

## 5. Future of heritage structures

The structures have experienced adaptation through their lifetimes: the helideck at Wolf Rock [1] associated with the automation of lighthouses, and some structures may require interventions in the future (reinforcement of masonry chimneys [11] and Māori wharenui [15]) to be safe. Blyth *et al.* [8] highlight the absence of a standardized process for comprehensive damage analysis and seek to produce this for the Morris Island Lighthouse in Charleston, South Carolina under investigation. The need to monitor heritage structures for both cultural and operational reasons is described by both Blyth *et al.* [8] and Raby *et al.* [1]. The Wolf Rock helideck is critically important to the continuing use of the lighthouse. Where structures have been retained for cultural purposes retrofitting may be required to ensure their safety [11]. However, Crum *et al.* [15] sound a word of caution about substantial engineered retrofit which might place a heritage building at further risk.

Many of these heritage structures still serve their original purpose, with most of the featured lighthouses continuing to be used as navigational aids. The Luarca harbour breakwater still protects the port after which it is named, despite several failures over the years that have required repairs [10]. The presence of the breakwater has played a crucial role in the development of the community that it protects. The cultural buildings in Thailand [14] and New Zealand [15] remain precious to their users; the International Council on Monuments and Sites (ICOMOS) has identified the strong relationship between heritage and development, and the inherent value of heritage conservation to the cultural, social and economic development of communities [18]. Crum *et al*. [15] describe the need to accommodate pragmatic solutions as people and structures transition.

However, some of the structures are now defunct. The Portuguese chimneys are the only reminder of past industrial activity [11] and the transporter bridges relatively quickly became redundant as tall-masted ships which led to such an extreme bridge design were replaced by steam-driven vessels [12]. Regarding the future of rock lighthouses: in the UK and Ireland, the General Lighthouse Authorities are committed to their use into the future, hence the funding of the STORMLAMP project. However, Filipot *et al*. [3] hedge their bets and suggest that even if the La Jument lighthouse may be too expensive to keep as an aid to navigation in the future, it may serve as an outdoor laboratory to study extreme waves.

Reflecting on the papers presented in this Special Issue we hope that the reader is able to appreciate how these heritage structures can 'serve as a record of societal and cultural progression in the fields of engineering' [8].

Data accessibility. This article has no additional data.

Competing interests. I declare I have no competing interests.

Funding. This research has been undertaken as part of the STORMLAMP project, funded by the EPSRC (EP/N022947/1, EP/N022955/1 and EP/N023285/1) and the UK and Irish General Lighthouse Authorities (GLAs).

Acknowledgements. We are grateful to Peter Dobson at Trinity House for helping us establish communication with knowledgeable retired staff and to Mark Lewis, Education Officer at the Association of Lighthouse Keepers, who also made useful introductions to retired lighthouse keepers; they are thanked for their valuable contributions.

## References

1. Raby AC, Antonini A, Pappas A, Dassanayake DT, Brownjohn JMW, D'Ayala D. 2019 Wolf Rock lighthouse: past developments and future survivability under wave loading. *Phil. Trans. R. Soc. A* **377**, 20190027. (doi:10.1098/rsta.2019.0027)
2. World map. 2019 https://upload.wikimedia.org/wikipedia/commons/thumb/4/44/World_map_blank_shorelines_semiwikimapia.svg/1280px-World_map_blank_shorelines_semiwikimapia.svg.png (Accessed 18 June 2019)
3. Filipot J-F *et al.* 2019 La Jument lighthouse: a real-scale laboratory for the study of giant waves and their loading on marine structures. *Phil. Trans. R. Soc. A* **377**, 20190008. (doi:10.1098/rsta.2019.0008)
4. Denarié E, Fady N. 2019 Structural response of French offshore heritage lighthouses. *Phil. Trans. R. Soc. A* **377**, 20190011. (doi:10.1098/rsta.2019.0011)
5. Guichard J. 2002 *North Atlantic lighthouses*. Paris, France: Flammarion.
6. Deng KY, Poon SW. 2019 The Gap Rock Lighthouse: construction and typhoon damage. *Phil. Trans. R. Soc. A* **377**, 20190013. (doi:10.1098/rsta.2019.0013)
7. Domede N, Pena L, Fady N. 2019 Historical review of lighthouse design under wind load: the Ile Vierge lighthouse. *Phil. Trans. R. Soc. A* **377**, 20190167. (doi:10.1098/rsta.2019.0167)
8. Blyth A, Napolitano R, Glisic B. 2019 Documentation, structural health monitoring and numerical modelling for damage assessment of the Morris Island Lighthouse. *Phil. Trans. R. Soc. A* **377**, 20190002. (doi:10.1098/rsta.2019.0002)
9. Nord TS, Petersen ØW, Hendrikse H. 2019 Stochastic subspace identification of modal parameters during ice–structure interaction. *Phil. Trans. R. Soc. A* **377**, 20190030. (doi:10.1098/rsta.2019.0030)
10. Lara JL, Lucio D, Tomas A, Paolo BD, Losada IJ. 2019 High-resolution time-dependent probabilistic assessment of the hydraulic performance for historic coastal structures: application to Luarca Breakwater. *Phil. Trans. R. Soc. A* **377**, 20190016. (doi:10.1098/rsta.2019.0016)
11. Guedes JM, Lopes V, Quelhas B, Costa A, Ilharco T, Coelho F. 2019 Brick masonry industrial chimneys: assessment, evaluation and intervention. *Phil. Trans. R. Soc. A* **377**, 20190012. (doi:10.1098/rsta.2019.0012)

12. Carter AJ, Taylor PH, Santo H, Blakeborough A. 2019 Wind loads on open truss structures: applications of blockage to historic transporter bridges. *Phil. Trans. R. Soc. A* **377**, 20190017. (doi:10.1098/rsta.2019.0017)
13. Bartoli G, Betti M, Marra AM, Monchetti S. 2019 A Bayesian model updating framework for robust seismic fragility analysis of non-isolated historic masonry towers. *Phil. Trans. R. Soc. A* **377**, 20190024. (doi:10.1098/rsta.2019.0024)
14. Ornthammarath T. 2019 Seismic damage to ancient monuments in Chiang Saen (Northern Thailand): implication for historical earthquakes in Golden Triangle area. *Phil. Trans. R. Soc. A* **377**, 20180255. (doi:10.1098/rsta.2018.0255)
15. Crum A, Brown D, Fa'aui T, Vallis N, Ingham JM. 2019 Seismic retrofitting of Māori wharenui in Aotearoa New Zealand. *Phil. Trans. R. Soc. A* **377**, 20190003. (doi:10.1098/rsta.2019.0003)
16. Hiroi I. 1919 On a method of estimating the force of waves, pp. 19. In *Memoirs of engineering facility*. Tokyo, Japan: Imperial University of Tokyo.
17. Morison JR, O'Brien MP, Johnson JW, Schaaf SA. 1950 The force exerted by surface waves on piles. *J. Petrol. Trans.* **189**, 149–154, (doi:10.2118/950149-G)
18. ICOMOS. 2011 The Paris Declaration on heritage as a driver of development, XVII Assemblée générale. (https://www.icomos.org/Paris2011/GA2011_Declaration_de_Paris_EN_20120109.pdf)