Finite element modelling and limit analysis of Fastnet lighthouse under impulsive ocean waves

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Abstract. Being exposed to strong ocean waves for more than a century, the Fastnet lighthouse is assessed for its structural response to the intense lateral loading. The Finite Element Method (FEM) was implemented for the structural analysis using the commercial software Abaqus. The lighthouse is built with large and meticulously dovetailed granite blocks which make it a very unique structural system. Three different finite element model configurations were tested, modelling the lighthouse as continuous homogeneous (elastic and nonlinear), and as discontinuous with contact interfaces between each course of blocks allowing uplift and sliding. The applicability and efficacy of these approaches is discussed. The impact load of the wave was applied as a time-history sequence, assuming that the wave breaks just in front of the structure surface corresponding to the least favourable scenario. Different intensities and heights were considered for the impact load. Finally, the FEM results are also compared with the results of the limit analysis method which calculates the minimum intensity of lateral static load that is necessary for causing uplift and overturning of rigid bodies. This comparison demonstrates the usefulness of the limit analysis method as a tool for quick preliminary assessment of the lateral load bearing capacity of this particular structural typology. This work is part of the STORMLAMP project (STructural behaviour Of Rock Mounted Lighthouses At the Mercy of imPulsive waves) funded by the UK Engineering and Physical Sciences Research Council, which is gratefully acknowledged.
Keywords: historic lighthouse, limit analysis, finite element method, rocking, wave impact

1 Introduction

Lighthouses on hostile and exposed rocks around the British Isles and Ireland have been resisting the impacts of extreme waves for over a century. However, the history of these landmarks of engineering has not been smooth. Lighthouse engineering has evolved after repeating collapses of under-designed structures and the subsequent upgraded design. The majority of the surviving rock-mounted lighthouses in the area are built based on an ingenious design: a tapered masonry structure with large-scale interconnected blocks, proposed by John Smeaton who designed a lighthouse of Eddystone in the mid-18th century. Prior to this design, three other lighthouses on the same rock had failed. The first presented unrepairable damages in its first winter, the second collapsed after a winter storm in its fourth year, and the third caught fire nearly 50 years after its construction. Though more resilient than their predecessors, plenty of the existing rock-mounted lighthouses have manifested

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uplift and motion after intense wave impacts. The importance of the lighthouse network to the safety of navigation, in combination with the heritage value of these iconic lighthouses, provided the motivation for this structural analysis.

The uplift and rocking behaviour of slender structures was first introduced by Housner [1]. His work evidenced that the structural behaviour of bodies capable of uplifting differs significantly to the one of continuous structures. Later studies verified the complexity of the rocking behaviour [2–4]. However, all of these studies are focused on base excitation and not on lateral wave impacts. Although plenty of research has been devoted on the estimation of wave impacts [5–7], little has been done regarding wave impacted rock lighthouses [8].

In the following sections, the structural analysis of Fastnet lighthouse for various intensities of wave impacts will be presented. Three different Finite Element Method (FEM) modelling approaches will be considered and compared. These approaches include a homogeneous elastic model, a homogeneous non-linear model, and a discontinuous model with contact interfaces between the horizontal courses of stones. Finally, the FEM results will be used for validating the applicability of simplified limit analysis as a tool for preliminary assessment of the lighthouse capacity to resist impulsive waves.

2 Fastnet lighthouse

The Fastnet lighthouse is built on the homonymous rock which is the southernmost point of Ireland (Figure 1a). The current lighthouse, made of granite masonry and finished in 1904, was built to replace an existing and insufficient cast iron lighthouse dating from 1854. The granite body is 36.7 m high and has an 8.3 m high lantern at the top. The diameter of the granite body is 12.10 m at the base and gradually decreases to 6.25 m near the top. The masonry structure consists of 8 vaulted levels, plus the lantern structure on the top. The wall thickness varies between 2.44 m at the entrance level and 0.76 m at the upper level.

The precise geometry of the lighthouse was obtained from archival research on the detailed original drawings (Figure 1b) and photographic material provided by the Irish Lights, a body that serves as the General Lighthouse Authority for Ireland and adjacent seas and islands. Information was also available about the company that provided the granite for the construction [9]. According to a descriptive catalogue of 1911 [10], the material density of this particular granite is 2643 kg/m^3. On-site inspection, experimental dynamic identification and material characterisation validated the archival data [11]. Based on this geometrical and material information, a FEM model calibrated with on-site experimental results, was produced for the Fastnet lighthouse.

The horizontal and vertical interlocking of the granite blocks through dovetails in the vertical courses and keys in the horizontal courses is shown in Figure 1c. The existence of the dovetailed connections was also verified by examination of photographic documentation produced during the construction of the lighthouse. In this structural typology, apart from uplift, no other high relative movement between blocks is possible without fracture of the dovetailed connections. Sliding, along the horizontal joint between two successive courses of stones, is also blocked by the vertical key connections.

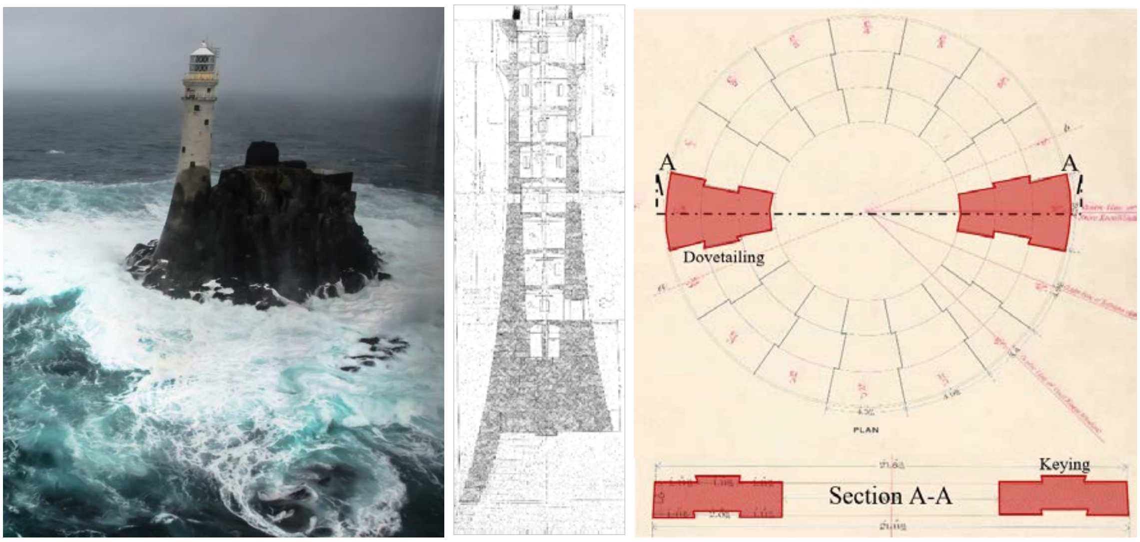


Figure 1. Fastnet lighthouse: (a) aerial photograph, (b) original section drawing and (c) details of dovetailing and keying for a course of stones.

3 Limit analysis

The limit analysis method calculates the magnitude of lateral force that is necessary for triggering a failure mechanism such as overturning or sliding (Figure 2). For overturning, the equilibrium of moments around a rotation hinge is calculated between the stabilisation forces, i.e. self-weight, and the external forces. For sliding, the equilibrium of horizontal forces is calculated by comparing the stabilisation forces, i.e. friction in horizontal joints, and the external forces. Regarding the overturning, three different mechanisms were considered. The first takes into account the whole section of the lighthouse (Figure 2a), the second considers only the front half section (Figure 2b), and the last mechanism considers only a frontal section of 60° (Figure 2c) which coincides with the impact section of the impacting wave [5]. Although the last two mechanisms (180° and 60°) are not realistic since the lighthouse is not fractured and therefore behaves as a continuous body, their calculation can be useful only for estimating the magnitude of external force that can cause a partial uplift. It has to be stated that the activation of an overturning mechanism is reversible. This means that for small duration impacts there can be some uplift and rocking but this does not necessarily mean overturning and collapse [1–3]. Note also that the existence of vertical keys for this lighthouse prevents any large sliding and therefore collapse due to sliding. Nevertheless, finite sliding due to small gaps between the vertical keys of the joints is still possible.

A drawback of the limit analysis is that the magnitude of activation force that is necessary for triggering the overturning mechanism depends on the selection of the hinge. Therefore, many hinge positions have to be tried in order to find the mechanism with the lowest activation force. Similarly, for the sliding mechanism, different joint levels have to be considered. To perform these calculations, an iterative procedure was written in Python 3.6 programming language. The self-weight of each course of stones is calculated based on the detailed geometrical data obtained during the archival research. All possible positions of horizontal activation forces were considered. Subsequently, all possible hinge or sliding levels were regarded for each external force scenario. The results for each height position of external force and the necessary magnitude for activation of the respective failure mechanism are presented in Figure 3. This graph illustrates the importance of the impact height to the structural stability. The combination of bigger diameter and greater weight near the bottom makes the lighthouse able to resist significantly bigger forces if the impact area is near the bottom. Moreover, the huge importance of the vertical keying to the stability of the lighthouse is revealed. Excluding the non-realistic 180° and 60° mechanisms, the dotted line shows that without vertical keying, the lighthouse would fail in sliding rather than in overturning. Particularly for impact heights lower than 5 m, the ratio of the capacity against overturning to the capacity against sliding is much higher than 2.0. Note also that although an overturning mechanism can be reversible (i.e. exceeding of the threshold does not necessarily mean damage), the sliding mechanism is not reversible.

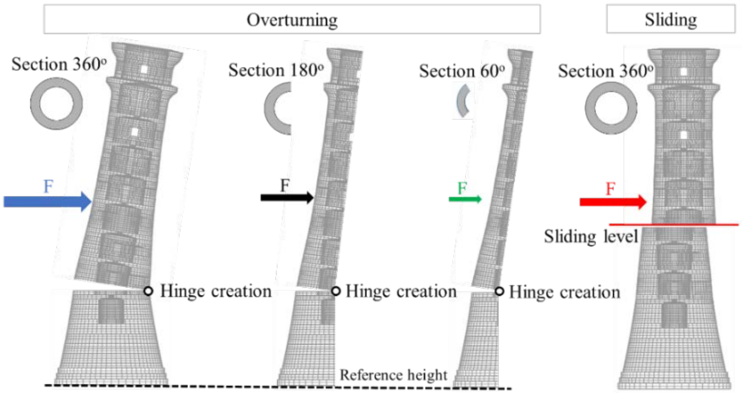


Figure 2. Failure mechanism for limit analysis: (a) overturning for 360° section, (b) overturning for 180° section, (c) overturning for 60° section, (d) sliding for 360° section

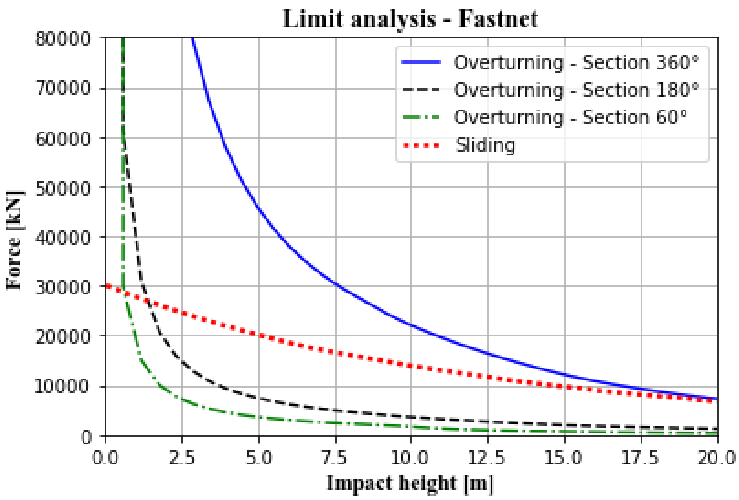


Figure 3. Limit analysis curves for overturning (continuous, dashed and dash-dot lines) and sliding (dotted line)

4 Numerical analysis

4.1 Wave impact

Force time-histories of impulsive wave can be calculated based on the theory of Wienke & Oumeraci [5] which is also used for ISO 21650 ‘Actions from wave and currents on coastal structures’ [12]. Methods for defining the wave time-history for a specific rock mounted lighthouse are provided from a pilot study on the Eddystone lighthouse [8]. The reader can refer to this for more details about the analytical formulations which include a knowledge of the site bathymetry. For the purposes of this present investigation a generic load curve, based simplistically on the Eddystone location was used. Also, in order to perform a parametric analysis on the effect of the wave intensity on the structural response, various scaled force time-histories were tested. This overly simplistic approach is only appropriate as the scope of this work is not to perform a structural assessment of Fastnet lighthouse but to investigate the difference between the modelling approaches. More rigorous site-specific definitions of the wave load are being undertaken in on-going work.

The total duration of the impact is equal to 0.204 s, and the maximum impact force, at t = 0, chosen to be 7573 kN. The force was applied between the height of 13.0 m and 17.1 m on a frontal section of 60° with uniform distribution. Thus, the load is applied on 9 courses and the force resultant is at a height of 15.1 m. The time-history of the total force that the impulsive wave applies on the structure is presented in Figure 4.

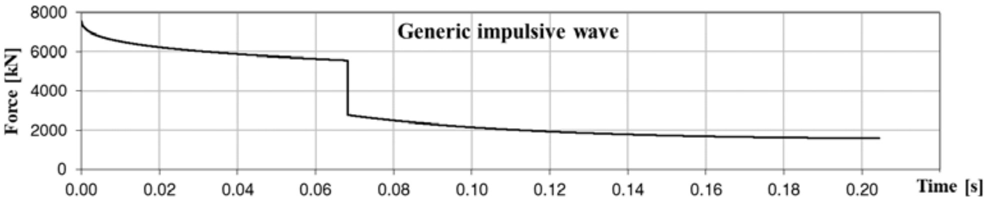


Figure 4. Time-history of the impulsive wave total force applied on the structure

4.2 FE models description

Three Finite Element (FE) models of Fastnet lighthouse were created with the commercial software Abaqus 6.14 [13]. These models are: a homogeneous elastic model (#1), a homogeneous non-linear model (#2), and a discontinuous model with horizontal contact interfaces between the courses (#3). The exact geometry of the masonry body and the openings was reproduced. Also, non-structural masses were added on the top stone course of the structure for simulating the mass of the lantern with the lighting apparatus and the circular cast-iron pedestal support. The weight of the rotating device itself is estimated around 6 tonnes [9]. The total mass of each model is around 3805 tonnes.

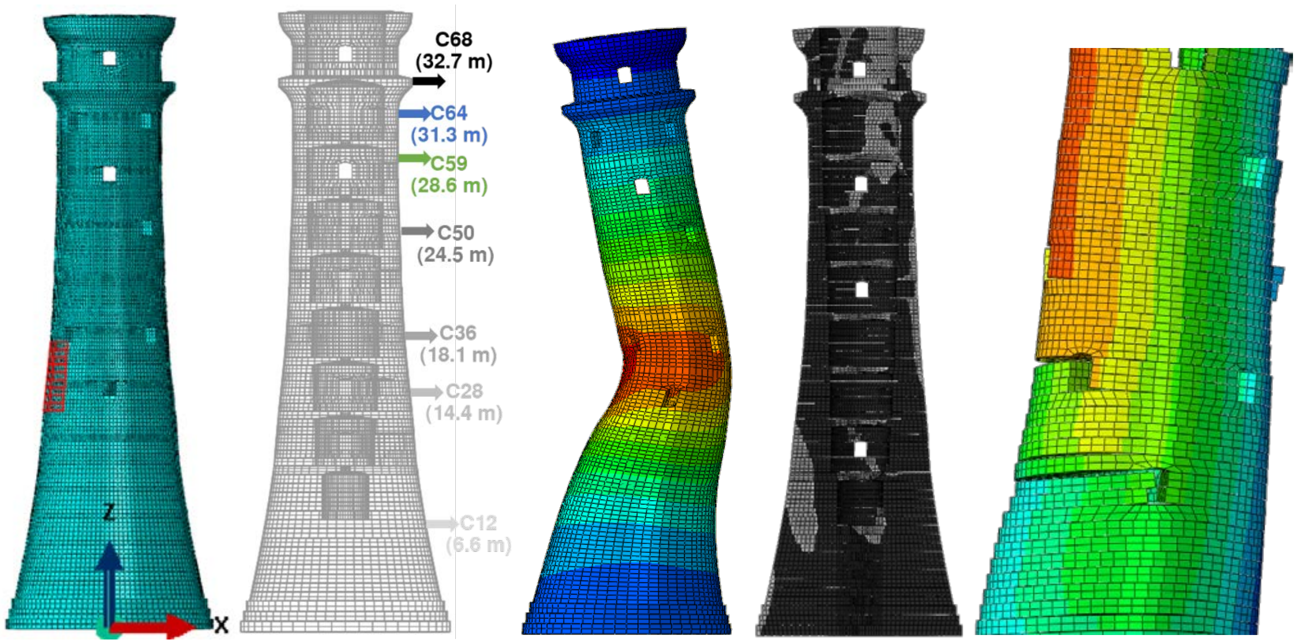
A calibrated FE model of Fastnet lighthouse based on on-site dynamic identification result, had been produced in previous work [11]. With the exception of the substructure that is not included in the models presented herein, the geometry of the models remains the same. The same values of the Young's modulus of elasticity E and material density that were used for the calibrated model are used in this paper. A structured and swept mesh with 8-node reduced integration linear brick elements C3D8R was used for the FE models. However, for avoiding excessive computational costs, a coarser mesh was adopted for the Nonlinear (#2) and Interface (#3) models in comparison to the elastic model (#1). A very high friction coefficient was taken for model #3 in an attempt to eliminate sliding, which in the real structure is prevented by the vertical keys. The numerical material properties and characteristics of the three different modelling approaches are presented in Table 1.

Table 1: Numerical material properties and FE model features

	Elastic model (#1)	Nonlinear model (#2)	Interface model (#3)
Typology	Homogeneous	Homogeneous	Discontinuous
Number of user defined elements	152331	67842	76017
Modulus of elasticity (*E*)	30 GPa	30 GPa	30 GPa
Material density (*d*)	2643 kg/m^3	2643 kg/m^3	2643 kg/m^3
Compressive strength (f_c)	-	146 MPa	-
Tensile strength (f_t)	-	0.1 MPa	-
Interface type	-	-	Friction only
Friction coefficient (μ)	-	-	10

4.3 FEM results

The FE models were tested for various impact intensities by scaling thegeneric wave time-history. The results are compared qualitatively and also quantitatively for the response measures recorded on the control points distributed along the height of the model (Figure 5b). Rayleigh damping with 1% damping at 5 Hz (a = 0.31416, β = 0.000318) was used for all analyses. After sensitivity analysis, a maximum time-step of 0.002 s was adopted for the time-history analyses.



Force application area (a) | Control points (b) | Model #2 scale factor = x4 (c) | Model #3 Vertical stresses (d) | Model #3 scale factor = x50 (e)

Figure 5. FE model of Fastnet lighthouse: (a) red lines indicating area of application of impulsive forces; (b) control points: (c) homogeneous nonlinear model deformed shape (scaled exaggerated); (d) vertical stresses for interface model; (e) joint opening for interface model (scaled exaggerated)

Regarding the model #2 with the nonlinear homogeneous material, its performance was found to be very poor. This model exhibited intense and unrealistic permanent deformations up to 0.6 m in horizontal direction for the generic wave (Figure 5c). Although this approach is widely used for structural analysis of masonry under loading conditions such as earthquake, it is not applicable in this particular structure under impulsive wave loading conditions. Adopting a homogeneous tensile approach is not appropriate for this typology of interlocked masonry whose only weak point is the opening of horizontal joints.

Model #3, with discontinuous material properties and interface contacts that allow detachment, had the best performance. The initial opening of the horizontal joints was found to take place in similar regions with the ones yielded by the limit analysis method. Figure 5d shows the partial elimination of compressive forces (grey areas), which means opening of horizontal joints. The joint opening is shown in Figure 5e (scaled x50 times for visual clarity). The structural response of model #3 for the impact of the generic wave is presented in Figure 6. This graph shows the horizontal displacement of all control points for a duration of 3.3 s, which includes the impact time (initial 0.204 s) and a damped post-impact free-vibration. It is worth noticing the intense phase difference of the upper versus the lower control points for the beginning of the motion. The higher frequencies (dominating in the lower courses) though are gradually damped out and all areas of the lighthouse pass to an in-phase vibration (Figure 6).

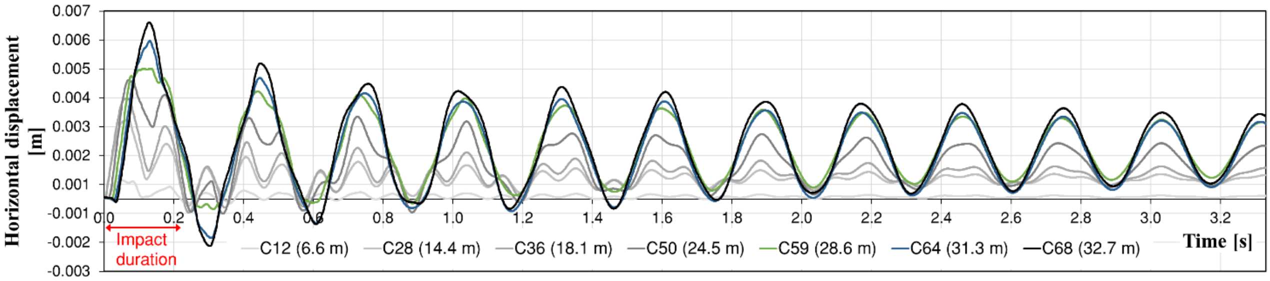


Figure 6. Structural response of model #3 for the generic wave with impact area between 13.0 m and 17.1 m: horizontal displacements recorded at the control points

The relation of the structural response to the applied force is shown in Figure 7 where the maximum impact force is normalised for the limit analysis threshold (overturning mechanism of the whole section, shown also as continuous line in Figure 3). It is worth emphasising the rapid increase of the displacement levels of model #3 especially after the limit analysis threshold for normalised force greater than 1.0.

Finally, the structural analysis of model #1, which has linear homogeneous material properties, did not yield satisfactory results. Figure 7 presents the comparison between models #1 and #3. It is shown clearly that the linear model is not capable of even giving the same order of magnitude of structural response, especially for forces that exceed the limit analysis threshold.

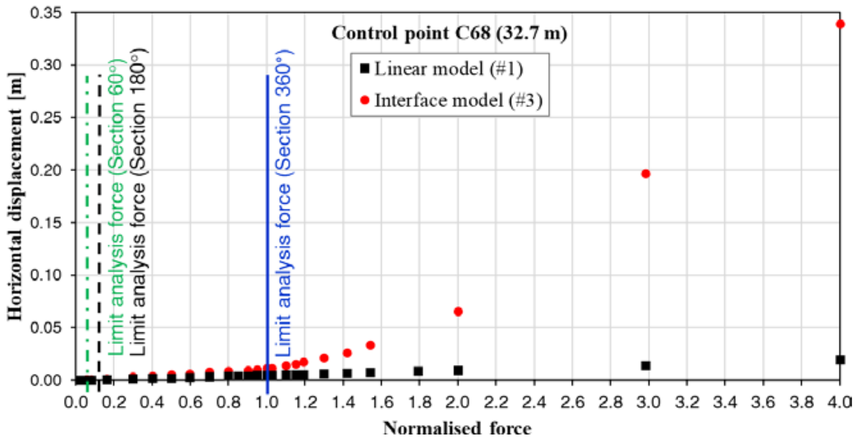


Figure 7. Horizontal displacement at control point C68 at 32.7m for the FE models #1 and #3 together with threshold levels of forces calculated based on the limit analysis method

5 Conclusions

The performance of FE models #1 and #2 with continuous homogeneous material properties (elastic and non-linear respectively) against the approach #3 of a discontinuous structure with horizontal contact interfaces was studied. It was found that for the Fastnet Rock lighthouse that the models #1 and #2 do not yield satisfactory results. The elastic model underestimates the level of motion, especially for strong impacts, and the nonlinear model manifests unrealistic deformations. The discontinuous FE model which allows uplift and detachment of the horizontal joints was the most reliable approach. It was found that the structural response (i.e. horizontal displacement at control points) of the lighthouse impacted by dynamic wave forces is not proportional with the magnitude of these forces. The horizontal displacement near the top of the lighthouse increases drammatically for forces that exceed the threshold calculated by the limit analysis. Therefore, the iterative procedure that was created for generating the limit analysis curves was found to be a reliable approach. This tool can be used for quick structural assessment of similar structures under wave loading. Moreover, it can be used in future research for performing parametric analyses and investigating which are the structural properties with the highest influence in the stability of lighthouses severely exposed to impulsive waves.

6 Acknowledgments

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