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DEM analysis of the Wolf Rock interlocked masonry lighthouse under extreme wave impacts

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1 INTRODUCTION

The granite lighthouses of the UK and Ireland, situated on exposed and hostile reefs, are of utmost importance to the safety of navigation. Built with a slender tapered shape and with an ingenious system of interlocked large-size masonry blocks, the lighthouses have been resisting the impacts of extreme waves since the early 19^{th} century. This interlocked masonry system does not constrain the uplift between consecutive courses of stones, but prevents relative sliding thanks to the presence of vertical keys and horizontal dovetails. Therefore, the structural response to intense ocean wave impacts manifests a highly nonlinear behavior. Continuous Finite Element Method (FEM) was found incapable of reproducing the structural behavior whereas discontinuous FEM models with interface elements provided better results but at the expense of extreme computational cost (Pappas et al. 2019). The Distinct Element Method (DEM) has been proved the most efficient approach for modelling such a nonlinear complex structural response (Pappas et al. 2018, Psycharis et al. 2003). *3DEC* (Itasca 2013a) was used for the analysis of a 250-year return period wave calculated for the rock mounted lighthouse of Wolf Rock, located around 13 km south-west of the coastline of Cornwall, UK. The UK and Irish General Lighthouse Authorities need to know the structural condition of their assets and whether Wolf Rock and other lighthouses of the same typology will remain in the mid and long-term future. The work presented herein was developed in the STORMLAMP project, funded by the UK Engineering and Physical Sciences Research Council.

2 STRUCTURAL DESCRIPTION AND METHODOLOGY

Completed in 1869, Wolf Rock is 35.1 m high and has a 6.1 m high lantern at the top (Fig. 1a). The original drawings suggest that the diameter of the granite body is 12.2 m at the base and gradually decreases to 5.2 m near the top. The masonry structure consists of 6 vaulted levels, plus the lantern structure on the top. The wall thickness varies between 2.4 m at the entrance level and 0.7 m at the upper level. According to the drawings, the vertical keys are around 76 mm high. Wolf Rock has a variable number of sector stone blocks per ring, ranging from 16 blocks for the lower rings to 9 blocks for the upper ones. The masonry tower is estimated to have a total mass of around 3570 tonnes. Nowadays completely automated, the lighthouse also bears a steel helideck installed in the early 1970s on the top of the masonry structure for facilitating the relief of lighthouse keepers (Nicholson 1983).

A DEM model was created with *3DEC* based on the detailed geometry of Wolf Rock lighthouse extracted from archive drawings. A python script was developed for enabling the automatic creation of the *3DEC* model. The courses of stones are initially created as rings with the consecutive execution of 'drum' and then 'tunnel' commands of *3DEC*. Subsequently, volumes on the upper and lower part of each course were removed in order to create the vertical keying. Although the real structure is built with a varying number of blocks per course, the model was simplified to 12 blocks per course. This decision was dictated by the necessity to simplify the circular edges of the structure to straight sectors in *3DEC*, hence needing to calculate the exact coordinates of each segment for the creation of the vertical keys. Details of the *3DEC* model of Wolf Rock are shown in Figure 1.

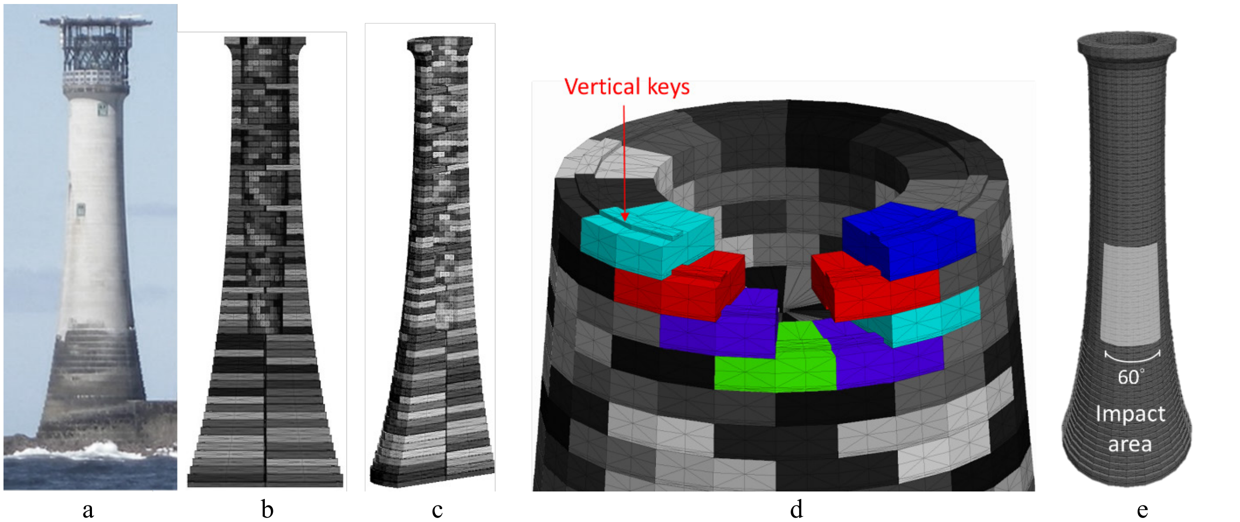


Figure 1. (a) Wolf Rock lighthouse, (b,c) *3DEC* model sections, (d) *3DEC* model detail of interlocking (e) impact area of 250-year return period wave.

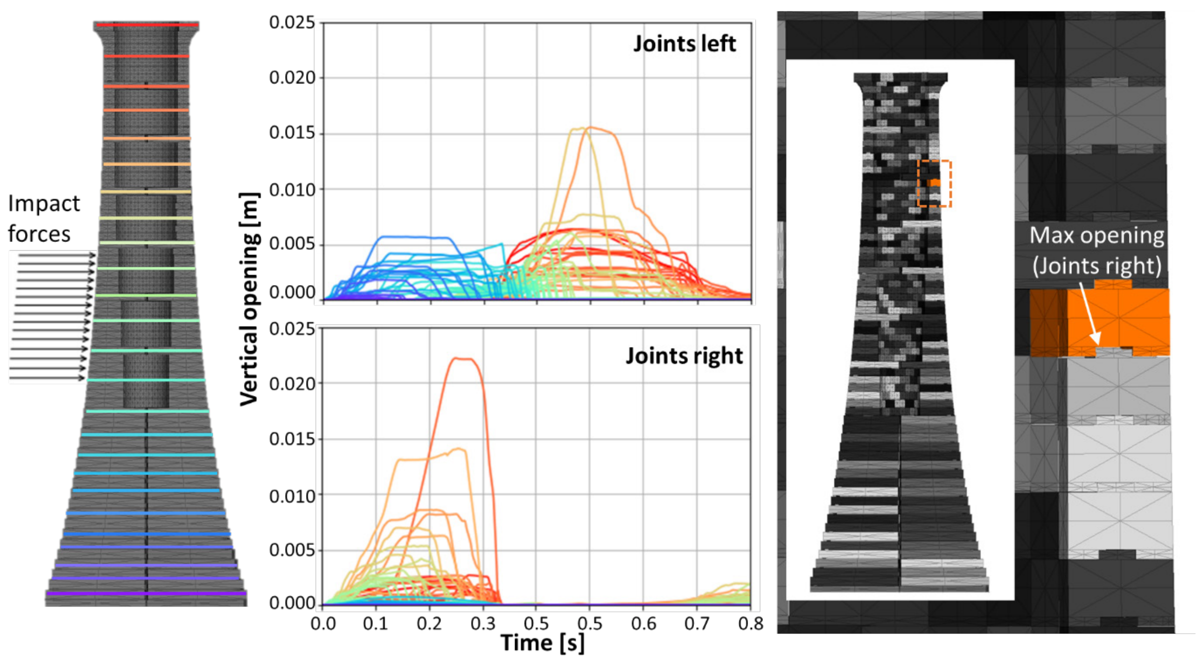
The purpose of this work was to assess the structural performance of the lighthouse for extreme wave impacts. The characteristics of the extreme wave impact were determined based on complex statistical modelling of environmental extremes near Wolf Rock (Raby et al. 2019). The Wienke method (Wienke & Oumeraci 2005) was used to describe impulsive wave load. According to this model and the statistical analysis, the 250-year return period wave has a total impact duration of 0.070 s and maximum horizontal impact force, at t=0, equal at 49510 kN. Note that the impact duration is significantly shorter than the first pair of modal periods, i.e. between 0.21 and 0.15 s. Wienke's method also proposes spatially uniform load distribution at a frontal area between ±30° with respect to the wave direction. The calculated wave impacts the Wolf Rock lighthouse in the area between the 23rd and 40th course, at an average height of 17.55 m from the bottom of the structure (Fig. 1e).

3 RESULTS AND DISCUSSION

The normal stiffness of the joints was calibrated based on the results of field modal tests (Brownjohn et al. 2017). Although all blocks are rigid, the structure is deformable due to the finite stiffness of the contact interfaces. The joint was given normal stiffness equal to $7.31 \cdot 10^{10}$ Pa/m. Accounted as 69 in-row spring elements, this stiffness value gives an equivalent compressive modulus of elasticity of the whole structure equal to 37 GPa. The joint shear stiffness was taken equal to $5.48 \cdot 10^{10}$ Pa/m. The Coulomb friction law was implemented for the joints between blocks with zero cohesion and friction angle of 30°.

Mass-only Rayleigh damping was applied for matching the field modal tests which revealed a damping ratio around 0.75% at 4.67 Hz which is the fundamental frequency of the lighthouse (Brownjohn et al. 2017). The stiffness damping term was set to zero due to the extreme computational cost that it causes due to the reduction of the critical time-step which is necessary for numerical stability (Itasca 2013b). Sensitivity analysis revealed that the internal forces, e.g. impacts between blocks and on the bed joints and vertical keys, cause a damped response during rocking motion even with zero or very modest Rayleigh damping levels. Therefore, although in this *3DEC* analysis the damping level was very low and the stiffness damping term was omitted (Rayleigh coefficients: a=0.22, b=0), the structural response of the lighthouse quickly dies out after a small number of rocking oscillations.

During intense impacts the structure is expected to perform rocking oscillation with opening of bed joints both on the left (impact side) and right (side opposite to impact). This is shown by the left and right side joint opening graphs in Figure 2a. The primary focus of the analysis was to identify the areas of joint opening and the maximum level of joint opening. Recent research revealed that the vertical key interlocking system, without which the lighthouse would fail even for medium intensity wave impacts, is crucial for the resilience of the structure (Pappas et al. 2018). Therefore, opening of bed joints at levels near or greater than the height of the vertical keys could be interpreted as a critical condition. The analysis revealed that for Wolf Rock the maximum bed joint opening takes place between 57th and 58th course, on the side opposite to the impact Figure 2b. The maximum value of this opening becomes equal to 27 mm at 0.26 s. Although this is a significant amount of uplift, it remains lower than the available key height of 76 mm hence not permitting sliding failure. Note that unlike joint uplift which is reversible, sliding would have detrimental effects causing permanent deformation or failure of the structure. On the impact side, the maximum vertical separation between successive courses of stones due to wave impact is equal to 5.7 mm and is recorded between the 10th and 11th course.



a b

Figure 2. (a) Uplift of bed joints on the left and right side, (b) maximum joint uplift of 27 mm at 0.26 s on the side opposite to the impact.

In terms of absolute displacements, the analysis yielded maxima of horizontal and vertical displacement on the top course around 68 mm and 22 mm respectively. The obtained displacement time-histories on the top were used in a separate nonlinear FEM analysis for assessing the effect of intense rocking of the granite tower to the structural performance of the steel helideck that is mounted on the top of Wolf Rock lighthouse (Raby et al. 2019).

4 CONCLUSIONS

The detailed *3DEC* model of Wolf Rock lighthouse, with 69 courses of interlocked stones and 12 blocks per course, was suitable for analyzing the highly nonlinear behavior of rocking, with multiple joint openings, of the structure due to extreme wave impacts. The 250-year return period wave, calculated based on existing environmental records and bathymetry data near Wolf Rock, is expected to trigger intense rocking causing uplift of joints both on the impact side and opposite side. However, the amplitude of joint opening is expected to be lower than the available height of vertical interlocking keys and therefore sliding is prevented. Moreover, the DEM time-history analysis revealed that the model manifests a damped behavior, largely attributed to the internal impacts and friction between the blocks, irrespective to the level of mass-only Rayleigh damping that was assigned to the model.

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