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

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EPICentre: Interdisciplinary Centre for Natural Hazards Resilience

FIFTH INTERNATIONAL ITASCA SYMPOSIUM 2020
VIENNA, AUSTRIA

STORMLAMP

Structural behaviour of rock mounted Lighthouses at the mercy of impulsive waves

PLYMOUTH UNIVERSITY

UCL

UNIVERSITY OF EXETER

General Lighthouse Authorities (GLAs)

Funded by:

EPSRC

Engineering and Physical Sciences Research Council

Why?

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© Peter Halil - https://www.youtube.com/watch?v=BrGCVrKu1k8

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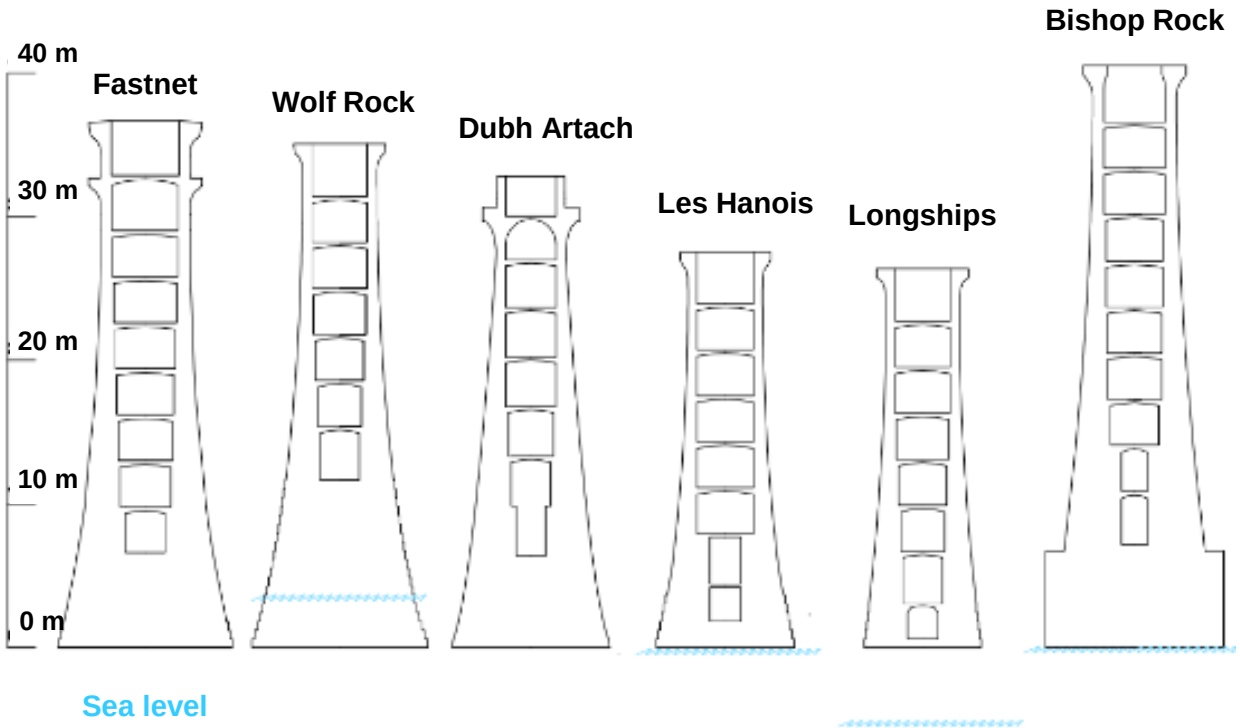
General Lighthouse Authorities (GLAs) – UK & Ireland

- Trinity House *(incorporated in 1514)*
- Northern Lighthouse Board *(incorporated in 1786)*
- Commissioners of Irish Lights *(incorporated in 1786)*

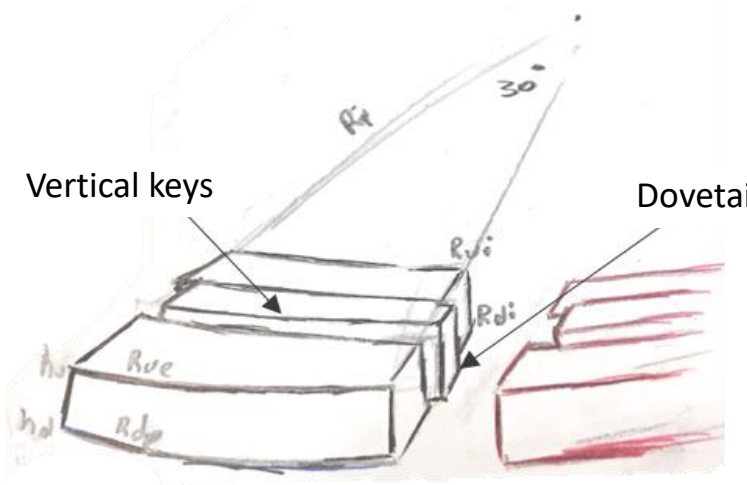
GLAs Question: Are our lighthouses safe against extreme wave impacts?

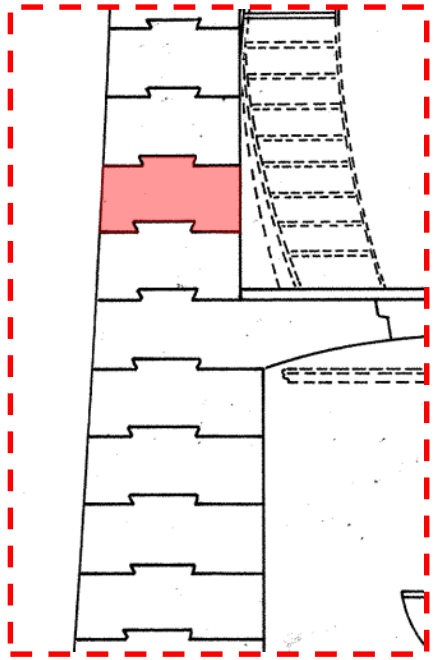


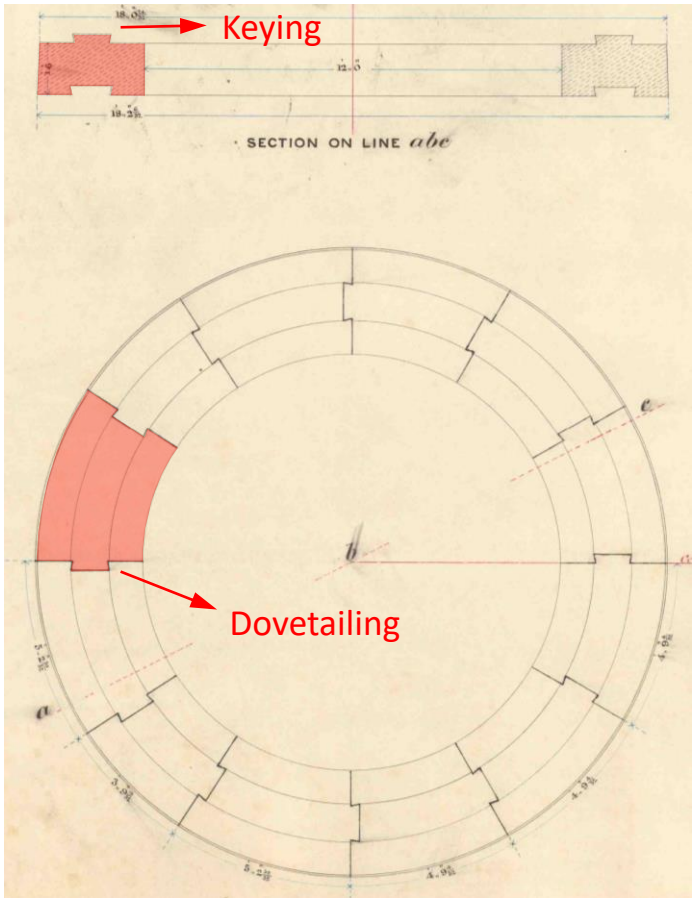
DESCRIPTION

Wolf Rock lighthouse

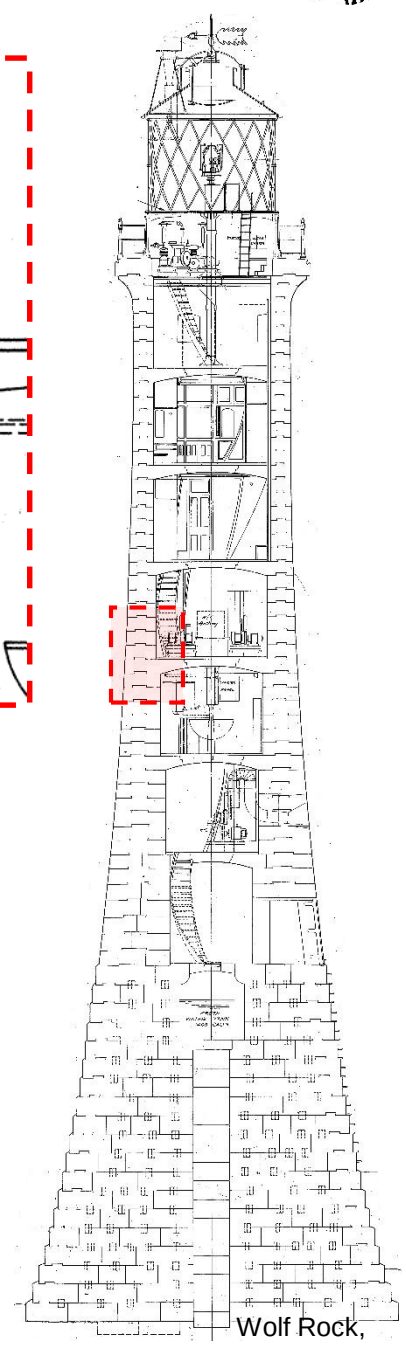
- Construction: 1869
- Height: 35 m
- Typology: Granite interlocked masonry
- Horizontal connections: Dovetailed
- Vertical connections: Keys
- 3570 metric tonnes





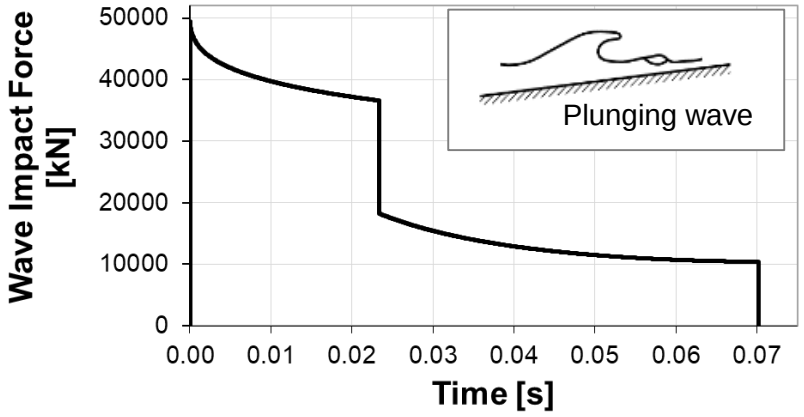


Interlocking prevents sliding but allows uplift



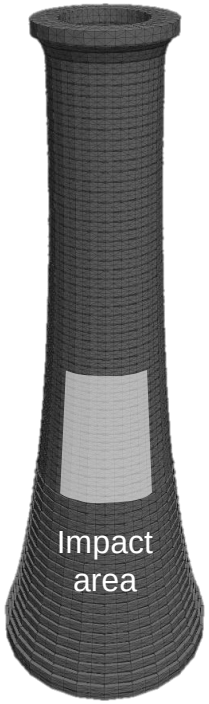
What are the wave forces?

250 years return period wave impact

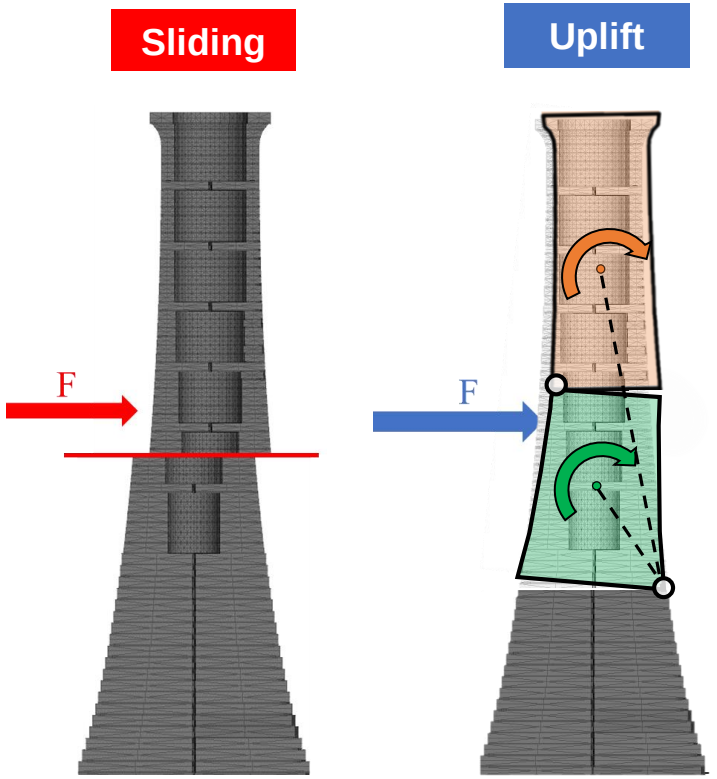


Impact

- Very short duration (0.07s)
- Very high max force (49510 kN)



What is the structural response?

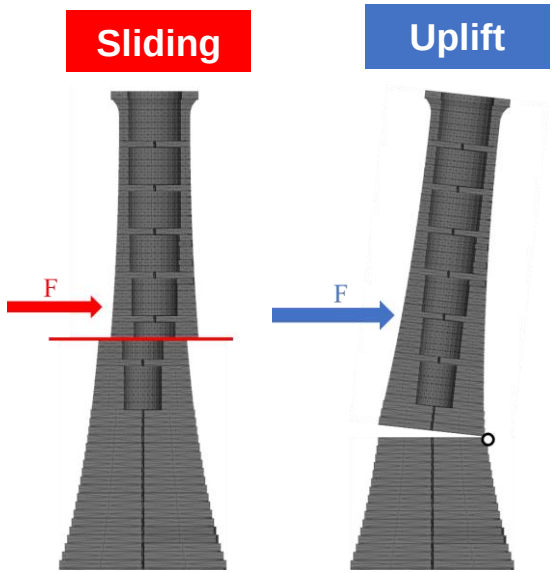


*"A lighthouse-tower might be **destroyed in either of two** ways, either by being moved bodily by the sliding of the base upon its foundation, or by being fractured at some point in its height, and the upper portion being overthrown."*

ICE Proceedings, Vol. 75, 1884

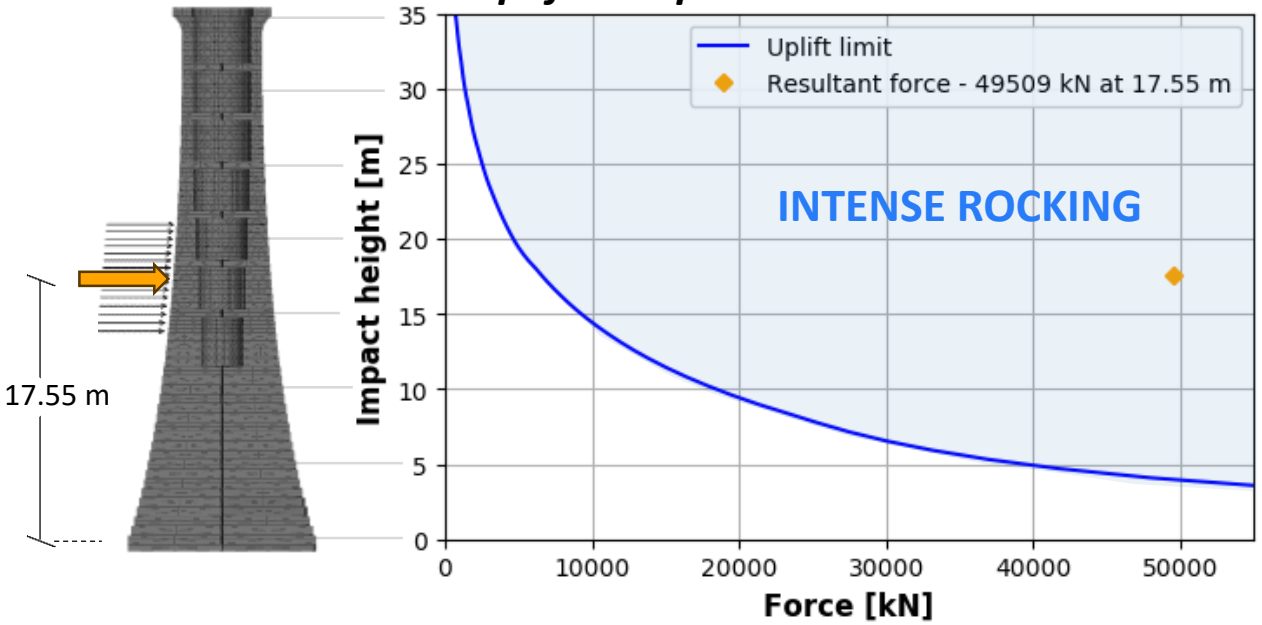
Limit Analysis

- Calculates the critical uplift load
- Calculates the critical sliding load
- Useful tool for preliminary assessment and prioritisation of detailed analysis and interventions



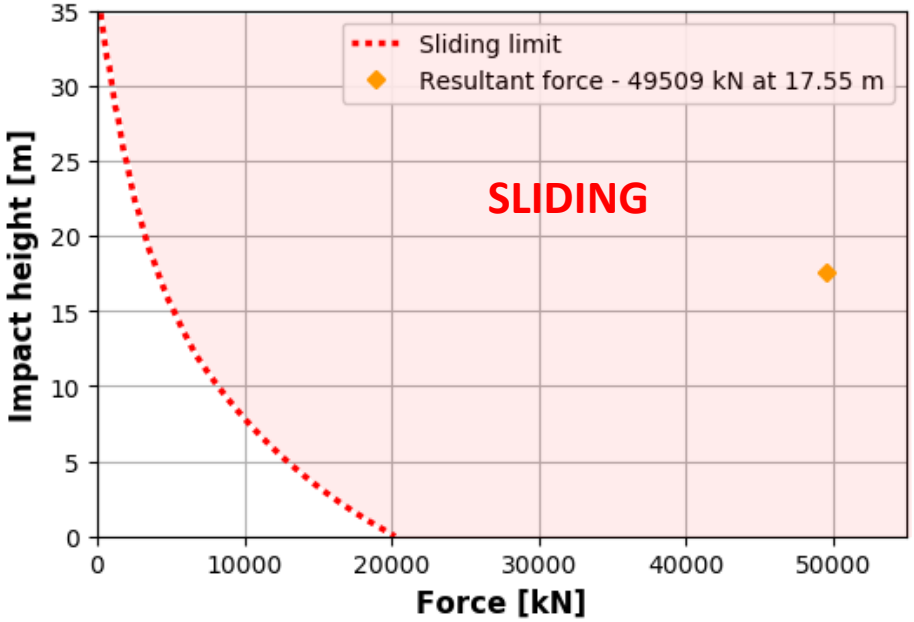
Resultant force >> Uplift limit

Uplift is expected !



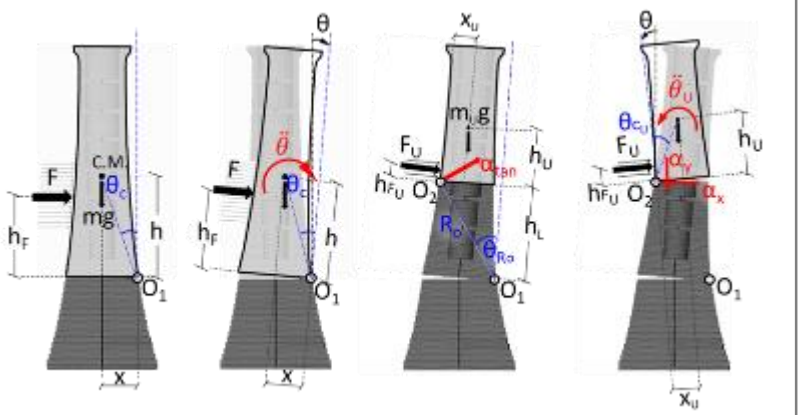
Resultant force >> Sliding limit

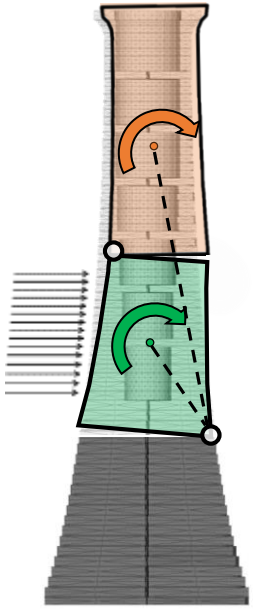
But... the interlocking prevents any sliding !



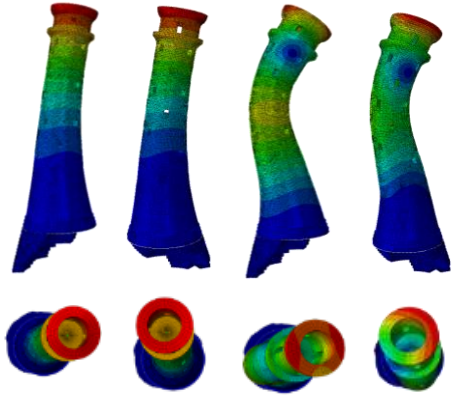
What structural analysis tool?

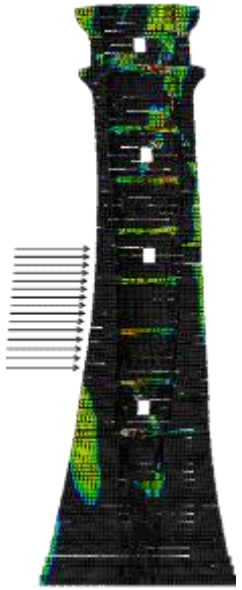
Rocking Analytical Formulations



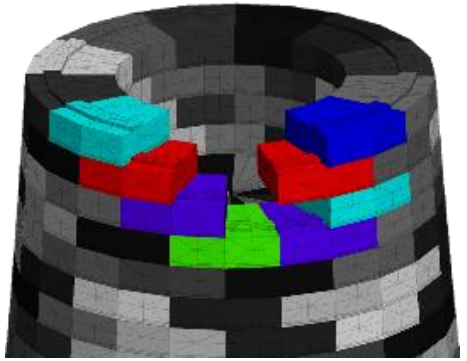


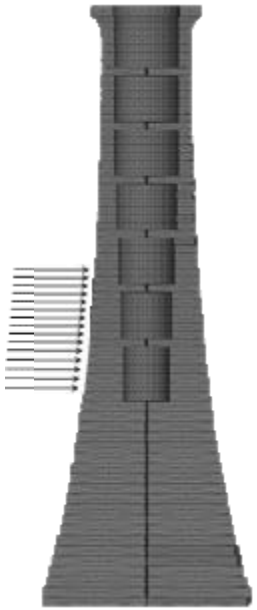
Finite Element Method (FEM)





Distinct Element Method (DEM)





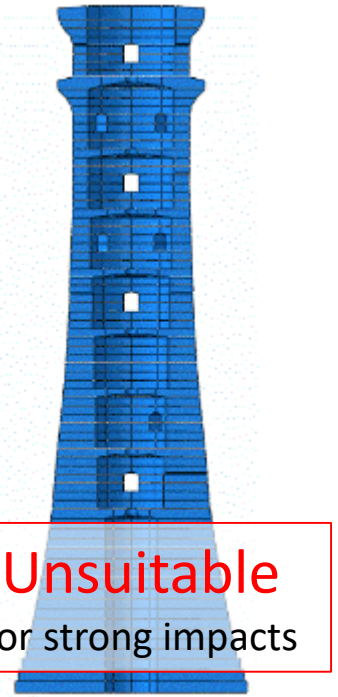
FEM Software: Abaqus 6.14 (Dassault Systèmes)

- The discontinuous structure has a highly nonlinear behaviour.
- Different FEM modelling approaches were tested.

MODEL #1 | **MODEL #2**

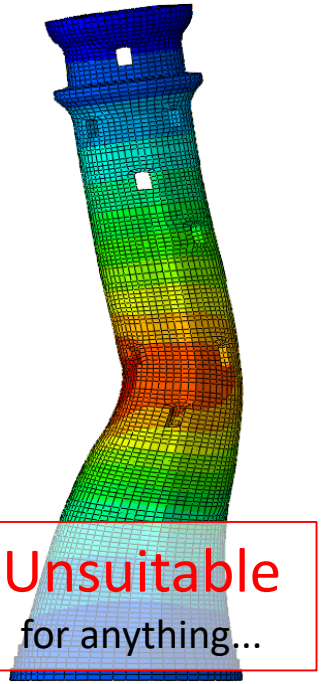
Homogeneous continuous material

Linear | **Non-linear**



Unsuitable
for strong impacts

- Too stiff (-)
- Very small deformations (-)
- Very high stresses (-)

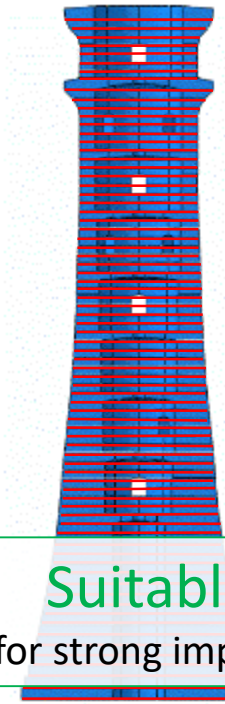


Unsuitable
for anything...

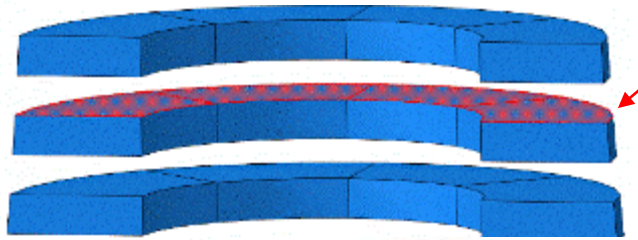
- Very unrealistic for structures with oriented discontinuities (dovetailed structures) (-)

MODEL #3

Discontinuous structure

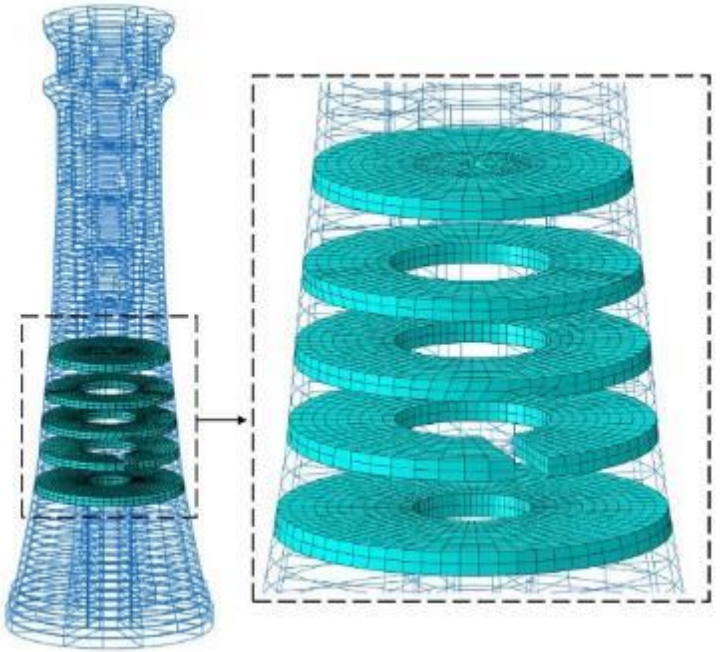


Suitable
for strong impacts



Contact interfaces

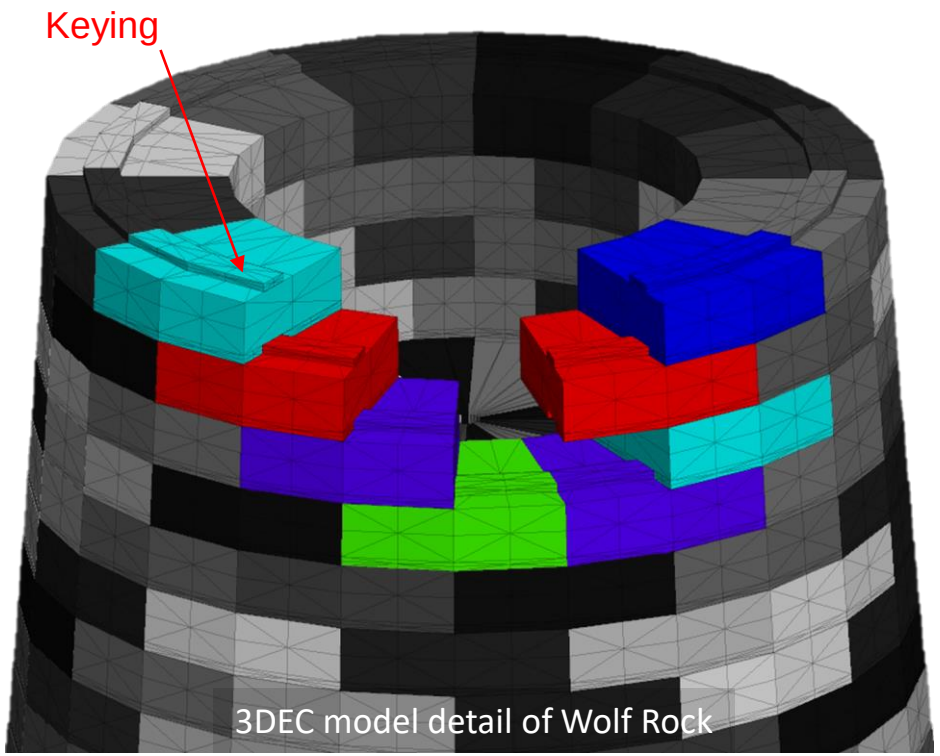
- Hard contact
- No sliding
- No tensile strength



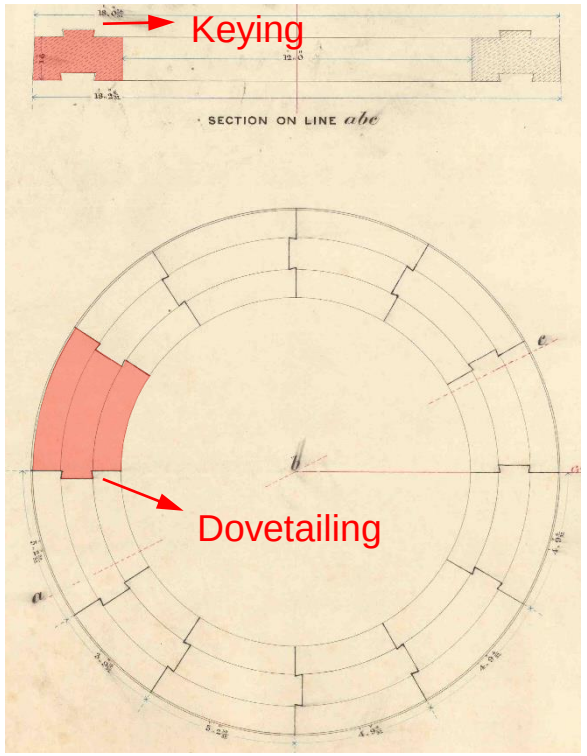
- Opening of horizontal joints (+)
- Rocking behaviour (+)
- Vertical keys modelled indirectly (-)
- Extreme computational cost (-)

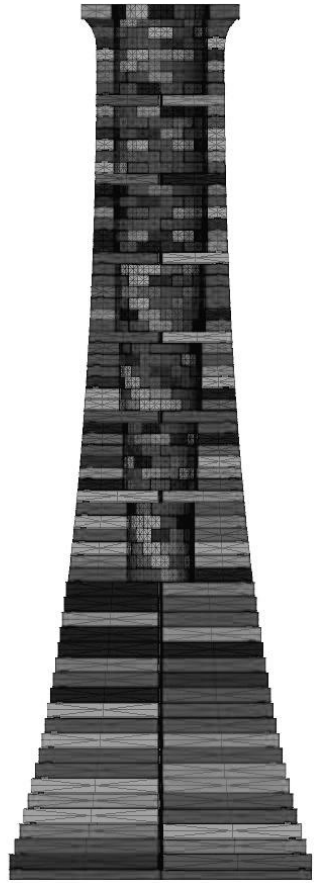
DEM Software: 3DEC 5.0 (Itasca Inc.)

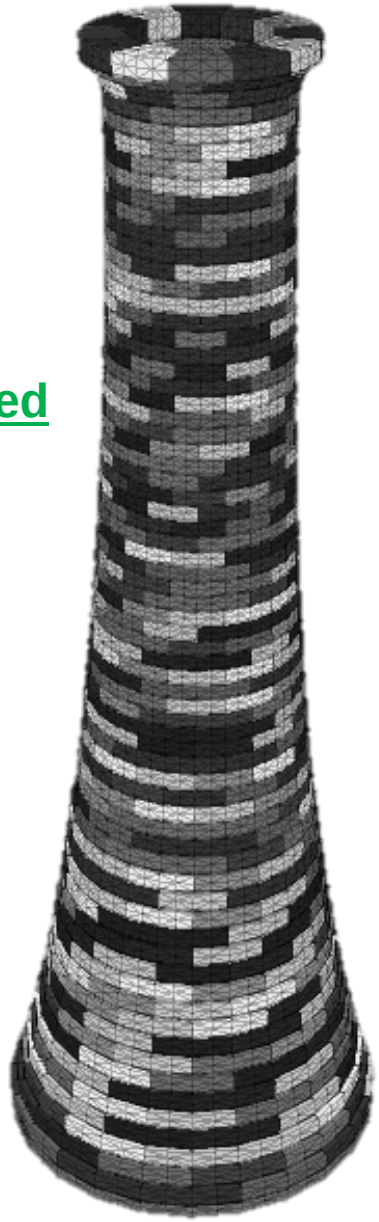
- Allows detachment and separation of blocks → Essential for this non-continuous structure
- Detailed geometry based the **archive drawings** → **Python script** was developed
- The courses created as rings with '**drum**' and '**tunnel**' commands
- Only the **vertical keys** were modelled (no dovetails) → **Sliding is prevented**; **Uplift is allowed**
- The model was simplified to **12 blocks** per course



3DEC model detail of Wolf Rock







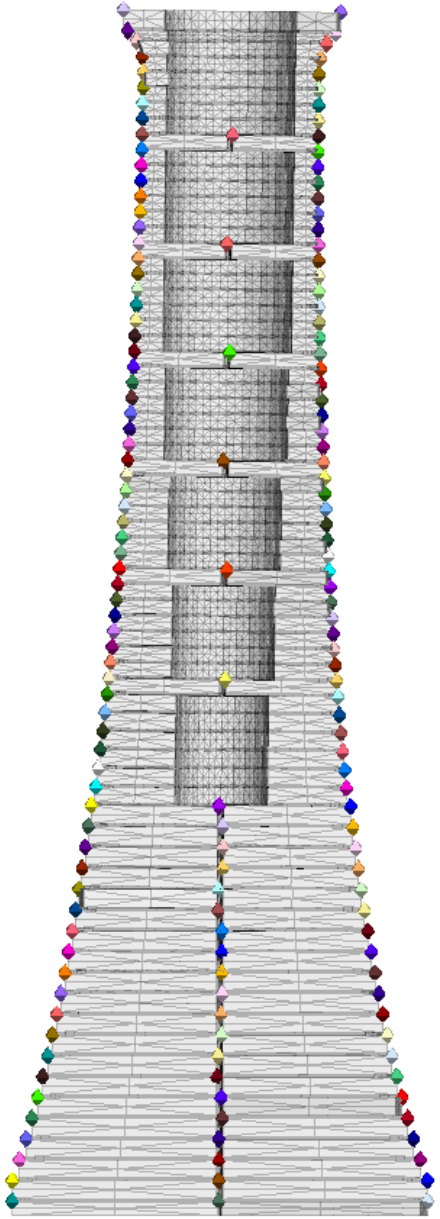
DEM

Model properties

- **Joint normal stiffness** =7.31·10^{10} Pa/m → equivalent compressive Young's modulus of 37 GPa (accounted as 69 in-row springs).
- **Joint shear stiffness** = 5.48·10^{10} Pa/m.
- Friction angle = 30°
- **Mass proportional Rayleigh damping 0.75% at 4.67 Hz** → based on field modal tests (Brownjohn et al. 2017).

Outputs

- Horizontal & vertical displacements
- Horizontal & vertical velocities
- 385 histories



Control points

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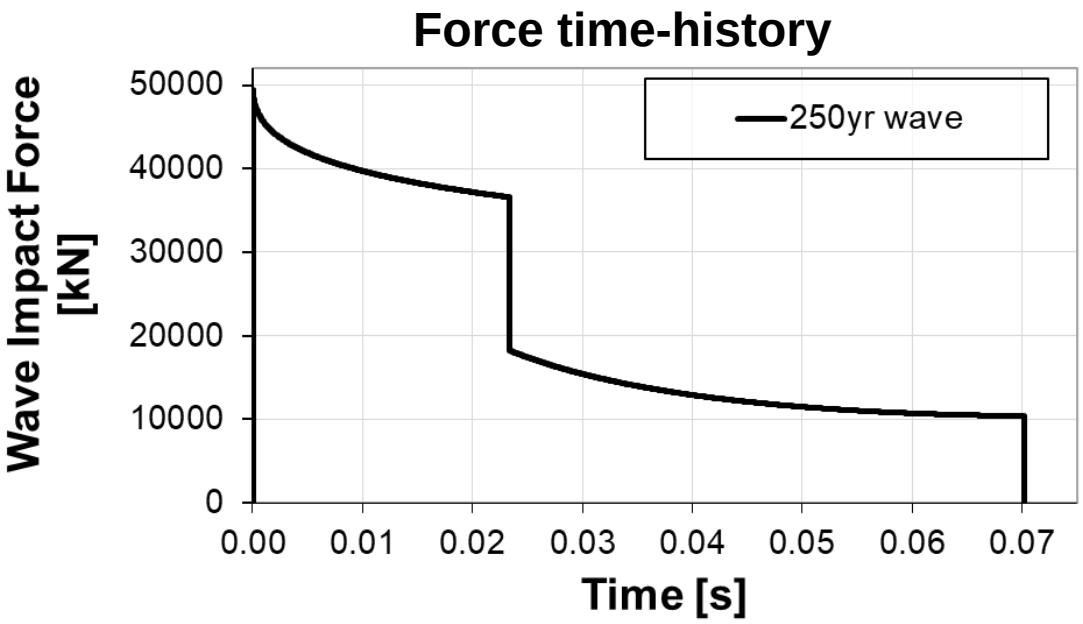
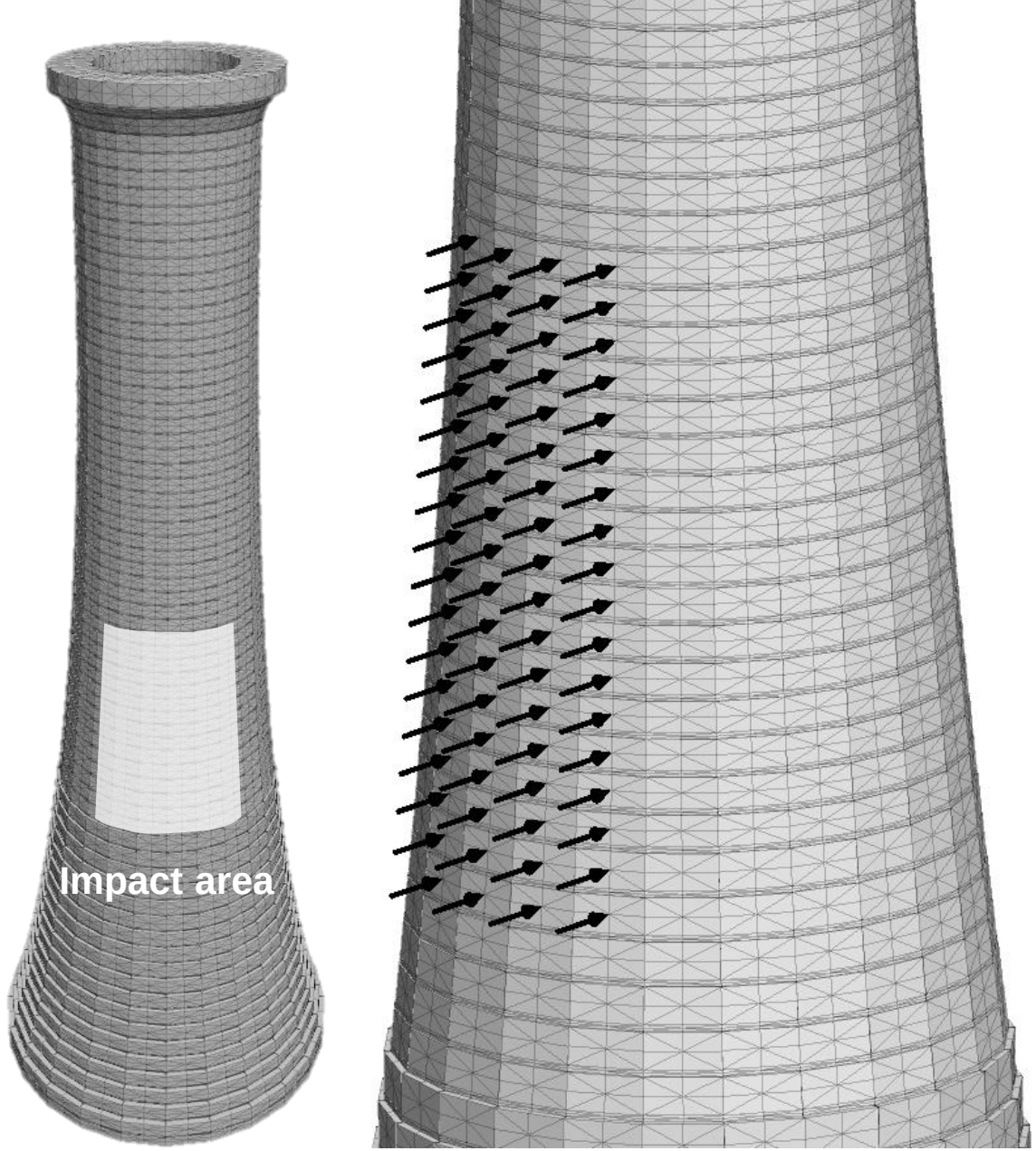
DEM

Wave impact load

- Applied as **force time-history**
- Distributed **uniformly** in 68 points
- Frontal section of **60°**
- Resultant Force at **17.55 m** from the base

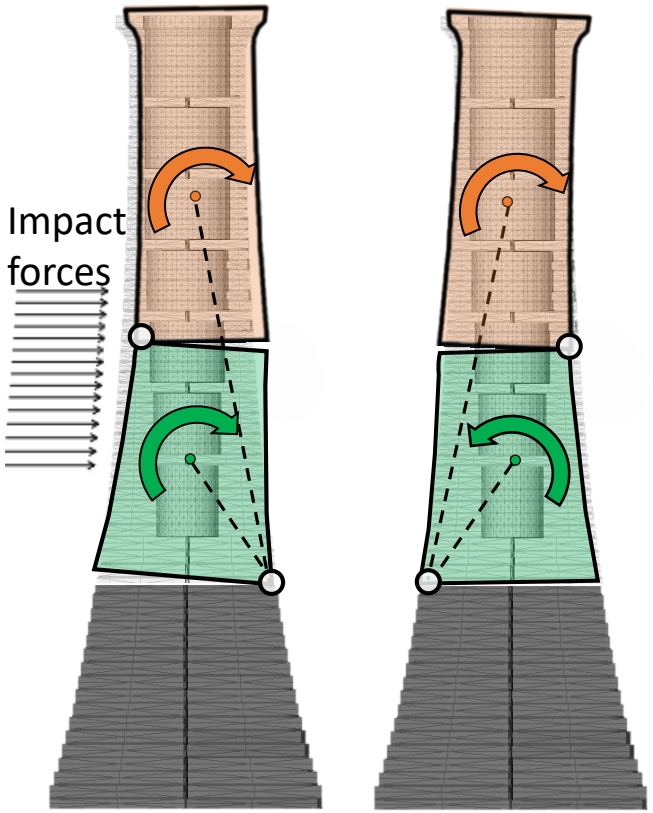


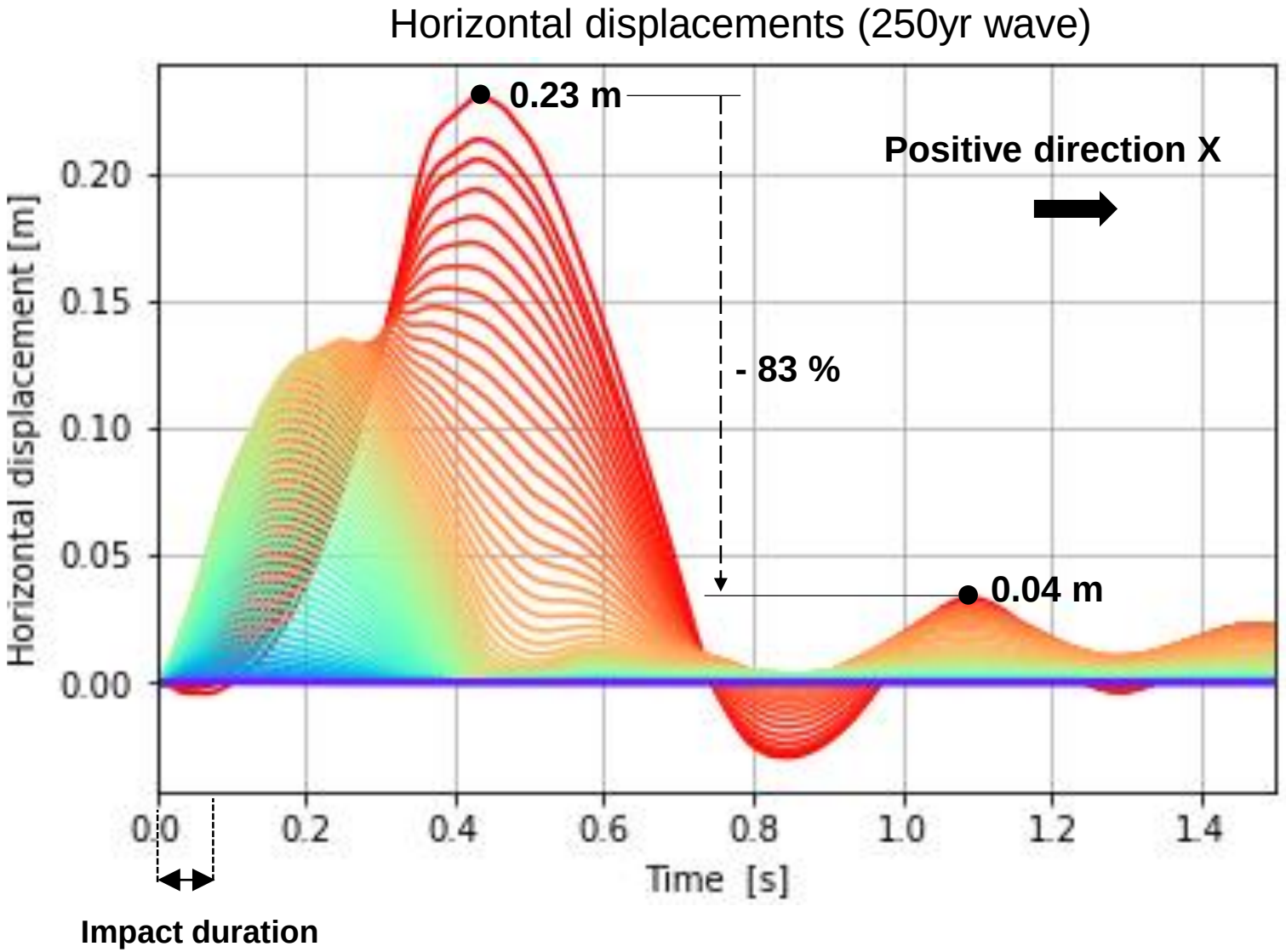


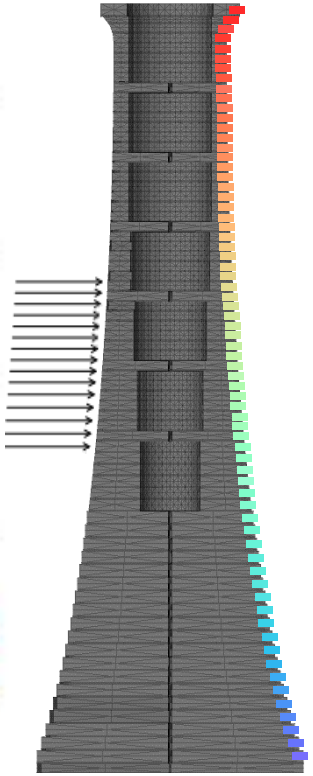
Force vectors (3DEC)

DEM

Horizontal displacements



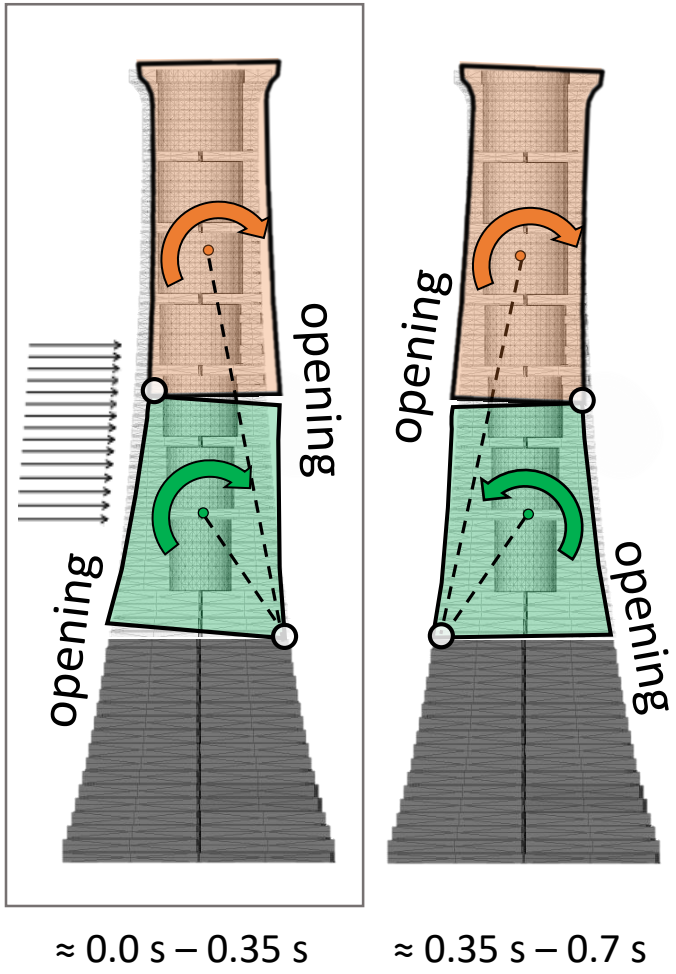




control points
right

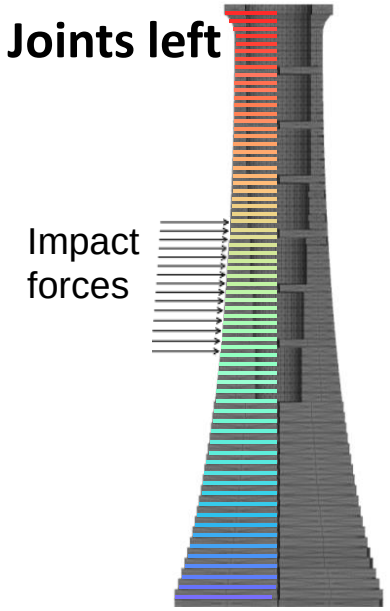
DEM

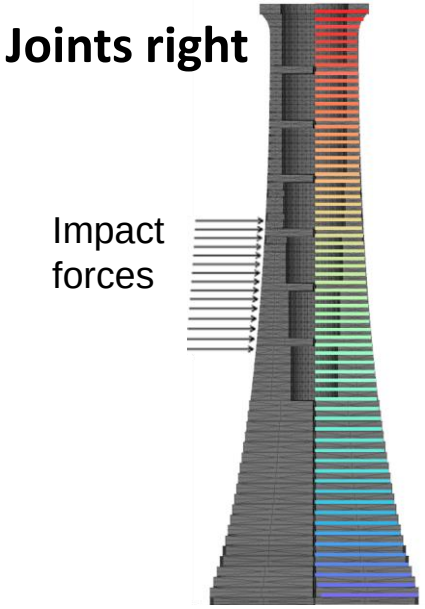
Joint opening

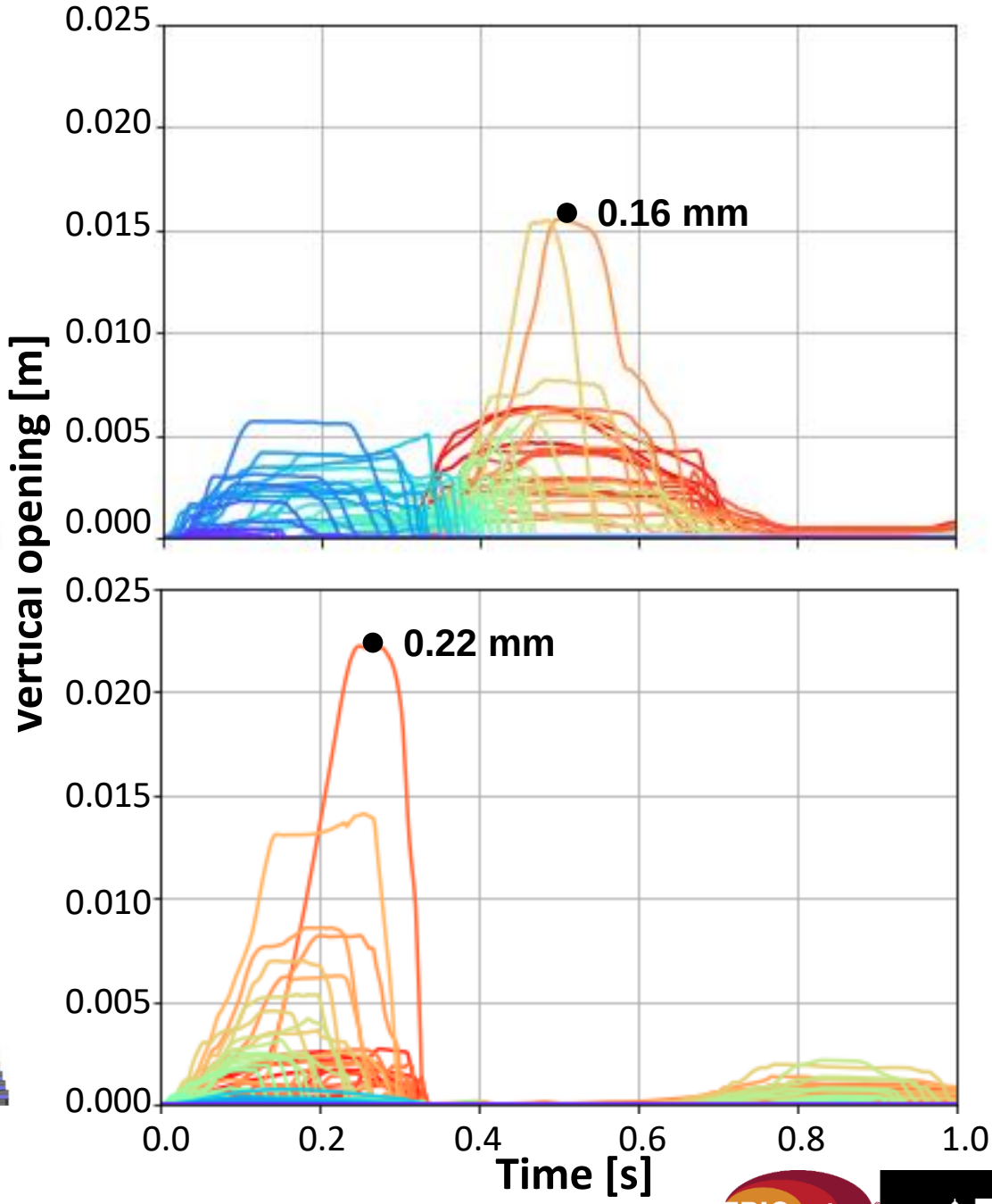


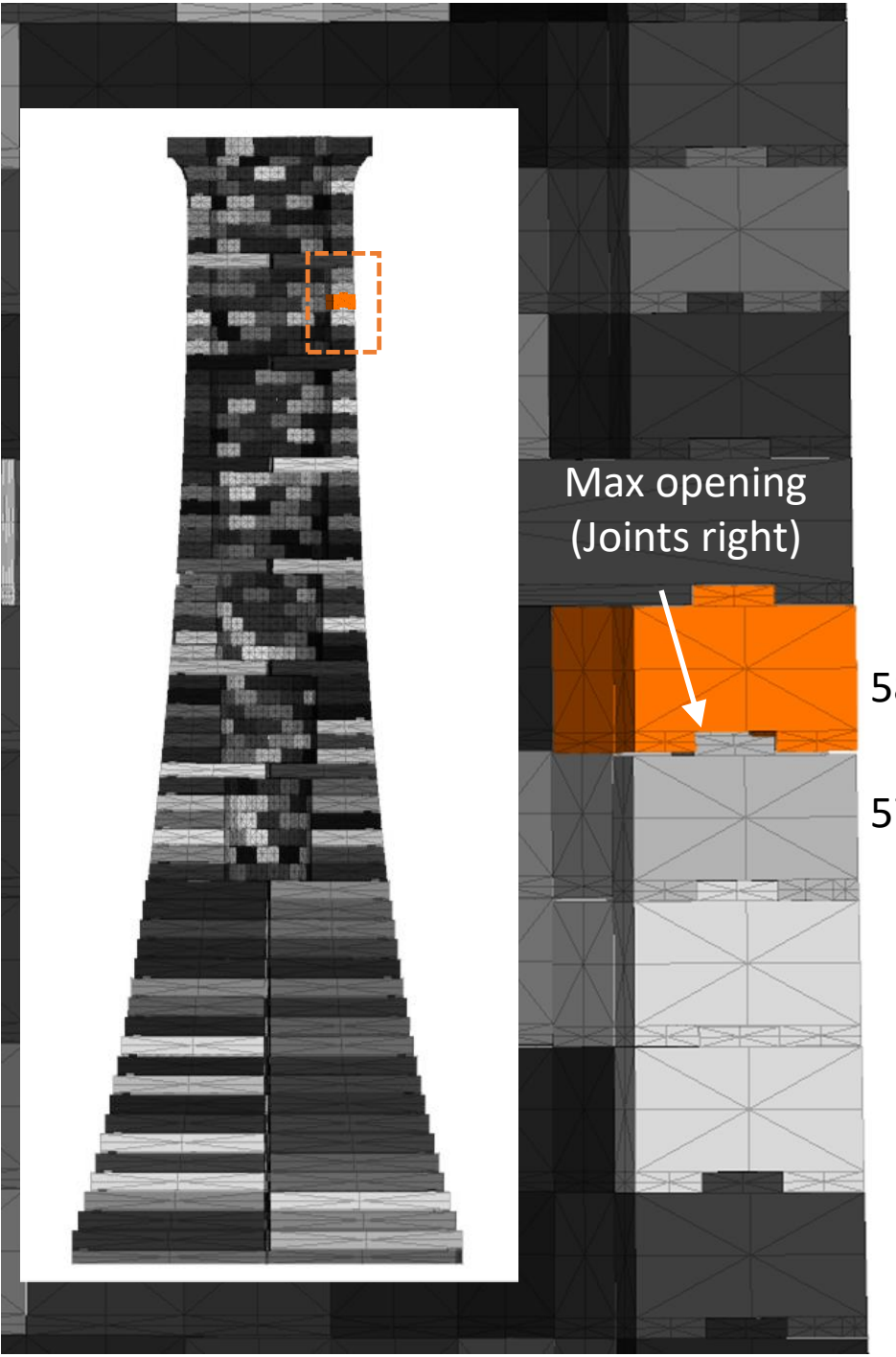
≈ 0.0 s – 0.35 s

≈ 0.35 s – 0.7 s

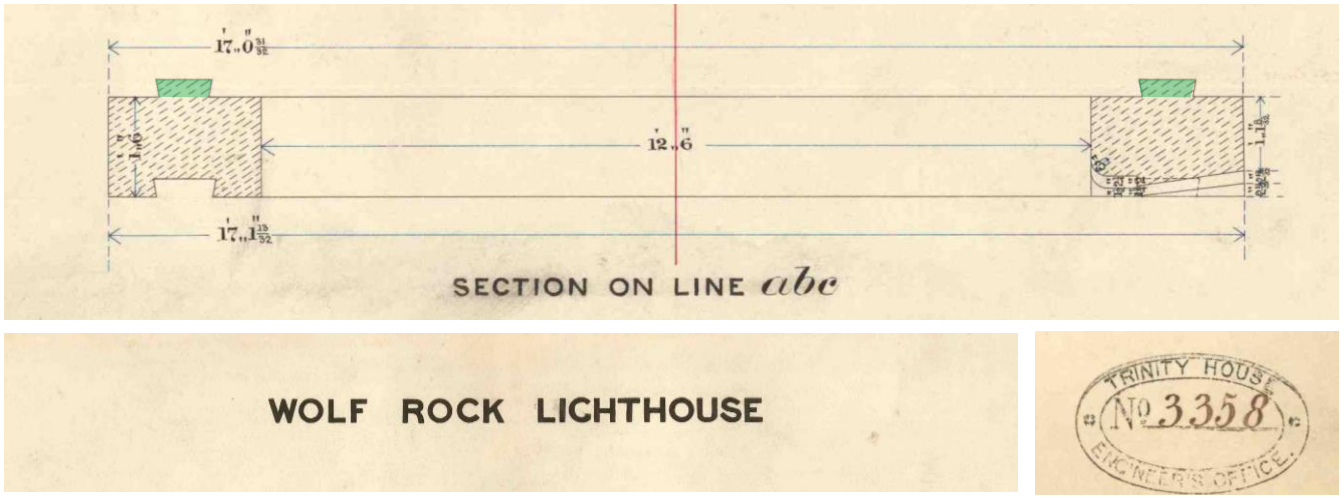








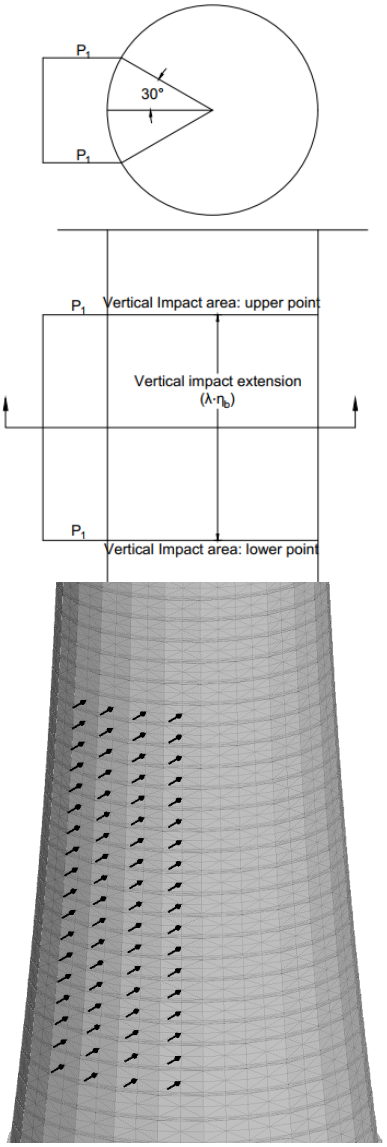
Max joint opening: 22 mm < Vertical key (76 mm)



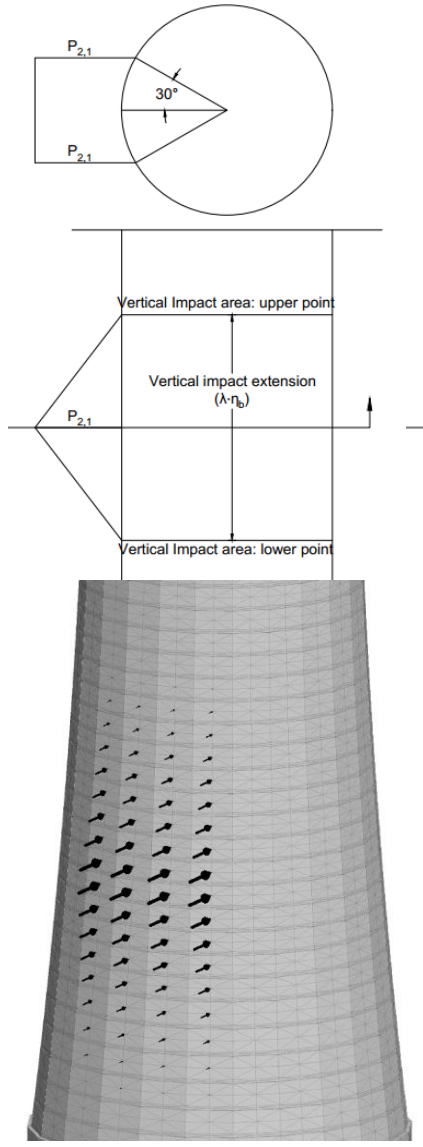
Sliding failure is prevented

How does the wave force spatial distribution influence the lighthouse response?

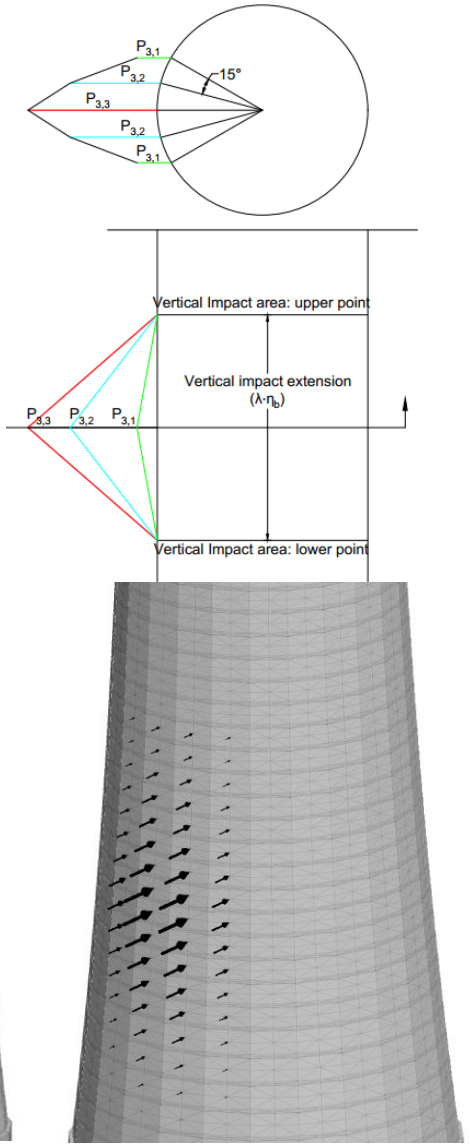
DISTRIBUTION #1



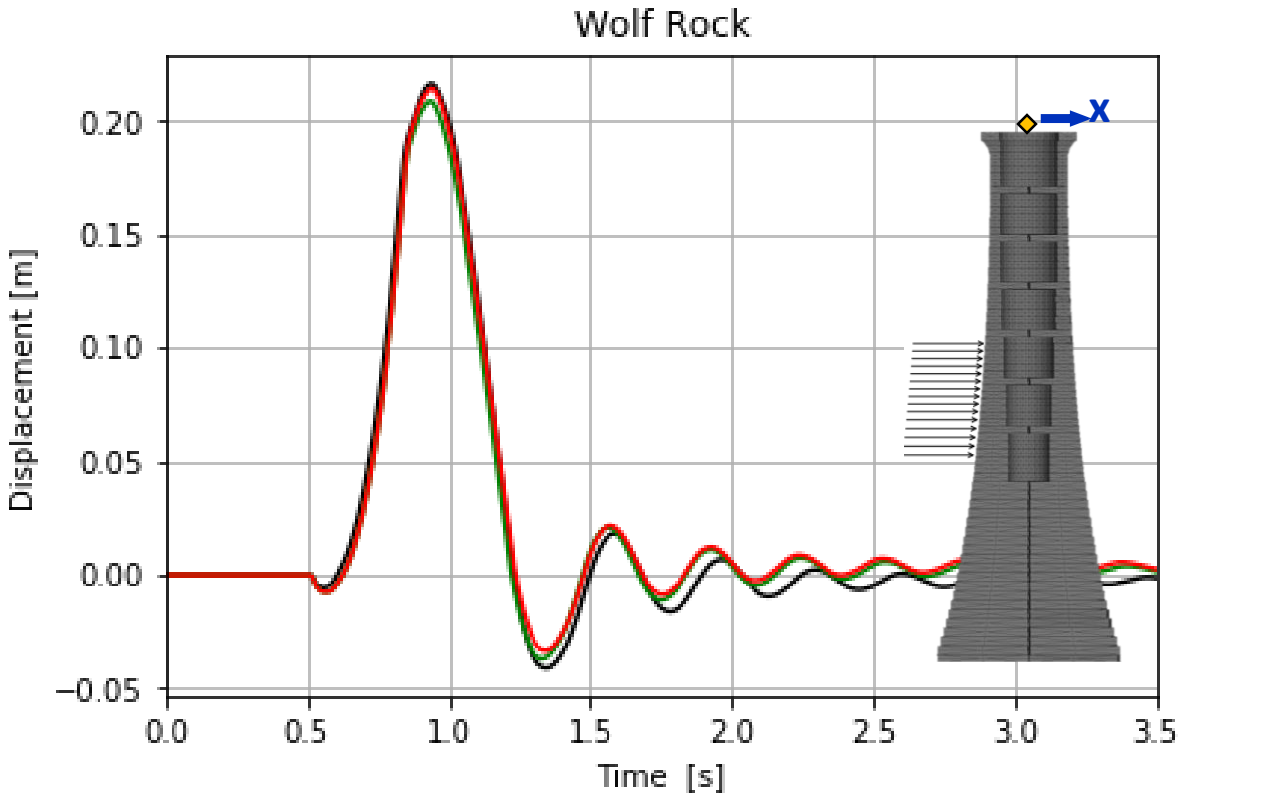
DISTRIBUTION #2



DISTRIBUTION #3

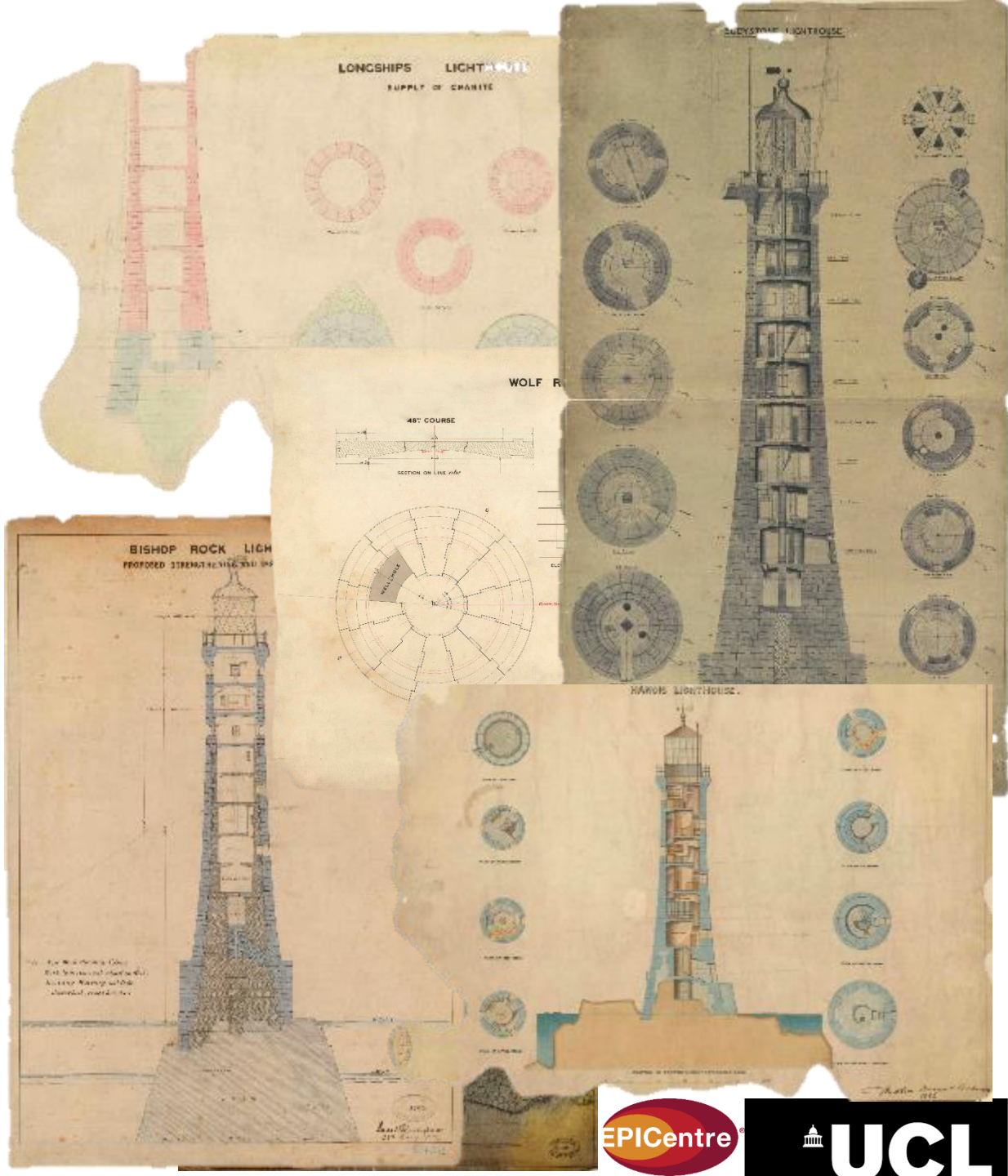


Horizontal displacement on top



CONCLUSIONS

- Detailed structural analysis needs discontinuous model, i.e. FEM with interface contacts or DEM
- The wave force time-history type influences the structural response far more than the pressure distribution
- The lighthouses have survived till now to a great extent thanks to the vertical keys
- Wolf Rock will vibrate intensely for the calculated 250 years return period wave, but it will not fail.



Acknowledgments to:

- The Engineering and Physical Sciences Research Council (EPSRC) for the financial support of the STORMLAMP project EP/N022947/1, EP/N023285/1
- The Trinity House for the provision of detailed drawings and for physical access to the Wolf Rock lighthouse

STORMLAMP project

More resources at: https://stormlamp.org.uk/

(Some) Publications

- Brownjohn, J., Raby, A., Bassitt, J., Hudson, E., & Antonini, A. (2017). Modal testing of offshore rock lighthouses around the British Isles. *Procedia Engineering*, *199*, 3326–3331. http://doi.org/10.1016/j.proeng.2017.09.440
- Pappas, A., D'Ayala, D., Antonini, A., Brownjohn, J., & Raby, A. (2017). Numerical modelling of Fastnet lighthouse based on experimental dynamic identification. In *International Conference on Advances in Construction Materials and Systems ICACMS-2017*. Chennai.
- Antonini, A., Raby, A., Brownjohn, J., Pappas, A., & D'Ayala, D. (2018). Survivability assessment of Fastnet lighthouse. *In 36th International Conference on Coastal Engineering ICCE-2018.* Baltimore
- Antonini, A., Raby, A., Caputo, P., Brownjohn, J., Pappas, A., & D'Ayala, D. (2018). An integrated approach for marine structures survivability assessment: the Fastnet lighthouse within the STORMLAMP project. *XXXVI Convegno Nazionale di Idraulica e Costruzioni Idrauliche Ancona, 12-14 September 2018*
- Brownjohn, J., Au S., Wang X., Zhu Z., Raby, A., & Antonini, A. (2018). Bayesian operational modal analysis of offshore rock lighthouses for Structural Health Monitoring. *The 9th European Workshop on Structural Health Monitoring, 10-23 July 2018*. United Kingdom
- Pappas, A., D'Ayala, D., Antonini, A., & Raby, A. (2018). Rock mounted iconic lighthouses under extreme wave impacts: Limit Analysis and Discrete Element Method. *The 9th International Conference on Computational Methods (ICCM2018) – Rome, Italy.*
- Pappas, A., D'Ayala, D., Antonini, A., & Raby, A. (2018). Finite element modelling and limit analysis of Fastnet lighthouse under impulsive ocean waves. *The International Conference on Structural Analysis of Historical Constructions (SAHC 2018) – Cusco, Peru.*
- Brownjohn, J., Raby, A., Bassitt, J.,Antonini, A., Hudson, E., & Dobson, P. (2018). Experimental modal analysis of British rock lighthouses. *Marine Structures*, 62, 1–22. https://doi.org/10.1016/j.marstruc.2018.07.001
- Antonini, A., Raby, A., Brownjohn, J. M. W., Pappas, A., & D'Ayala, D. (2019). Survivability assessment of Fastnet lighthouse. *Coastal Engineering*. https://doi.org/10.1016/j.coastaleng.2019.03.007
- Raby, A., Antonini, A., Pappas, A., Dassanayake, D., Brownjohn, J., D'Ayala, D., (2019). Wolf Rock lighthouse: past developments and future survivability under wave loading. Philosophical Transactions of the Royal Society A: Mathematical Physical and Engineering Sciences, 377(2155), http://dx.doi.org/10.1098/rsta.2019.0027
- Raby, A., Antonini, A., Brownjohn, J., D'Ayala, D., (2019). Environmental loading of heritage structures. Philosophical Transactions of the Royal Society A: Mathematical Physical and Engineering Sciences, 377(2155), https://doi.org/10.1098/rsta.2019.0276
- Dassanayake, D.T., Raby, A. and Antonini, A. (2019), Physical Modelling of the Effect of Shoal Geometry on Wave Loading and Runup on a Cylinder, In: Proceedings of ASCE Coastal Structures Conference, Hannover, Germany.
- Dassanayake, D.T., Raby, A. and Antonini, A. (2019), Efficacy of Analysis Techniques In Assessing Broken Wave Loading On A Cylinder Upon A Shoal, In: Proceedings of the 38th International Conference on Ocean, Offshore and Arctic Engineering – OMAE 2019, Glasgow, Scotland, UK.

EPICentre UCL

Questions ?

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Funded by:
EPSRC
Engineering and Physical Sciences Research Council