THE MAKEWAVES TSUNAMI TESTS AND THEIR RELEVANCE TO TSUNAMI ENGINEERING AND RISK MANAGEMENT

T Rossetto[1], I Chandler[2], K Adams[3], J Cels[1], A Antonini[4], I van Balen[4], M Baiguera[5], E Buldakov[1], D McGovern[3], M del Zoppo[6], W Allsop[7], S Roberts[8], A Raby[8], D Istrati[9], Z Nur Jannah[1], S Lopez Querol[1], H Baskaran[1], J Melo[10], D Wüthrich[4], I Barranco[2], J Harris[2], I Eames[1], M Piggott[11], P Salah[11], S.J Boulton[8]

[1] University College London, London, UK, t.rossetto@ucl.ac.uk

[2] HR Wallingford, Wallingford, UK

[3] London South Bank University, London, UK

[4] TU Delft, Delft, Netherlands

[5] University of Southampton, Southampton, UK

[6] Università degli Studi Federico II, Naples, Italy

[7] William Allsop Consulting

[8] University of Plymouth, Plymouth, UK

[9] National Technical University of Athens, Athens, Greece

[90] University of Porto, Porto, Portugal

[11] Imperial College London, London, UK

Abstract: *MAKEWAVES is an international multi-partner collaborative project bringing together nine academic institutions and two commercial consultancies. The objective of the collaboration is to develop experimental data and associated numerical modelling on tsunami inundation and interaction with boulders, buildings, natural and engineered barriers, towards the development of new internationally accepted guidance for structural codes and standards. Using a pneumatic tsunami simulator (TS) developed jointly by HR Wallingford and UCL the team conducted experiments between November 2022 and April 2023 within a highly instrumented 100m long flume. The TS is capable of simulating realistic trough and crest-led tsunami waves at 1:50, including traces from the The TS is capable of generating very long trough and crest-led waves, and can reproduce at 1:50 scale waves from real life events such as the Mercator trace from the 2004 Indian Ocean event and theand 2011 Tohoku tsunamis. The TS capability has been further extended to include bore-waves. The characteristics of the waves are controlled by adjusting the flow rate and total volume of water drawn in and discharged by the TS. The experimental campaign is was subdivided into discrete research areas, each aimed at furthering knowledge on how different tsunami wave characteristics affect their interaction with manmade and natural structuresenvironments. These include tests aimed at understanding: (1) how roughness representative of coastal forests and mangroves affects tsunami inundation characteristics, (2) how tsunami interact with boulders (3) the effectiveness of offshore breakwaters as tsunami barriers (4) how structural loads and foundation scour are affected by building permeability. This paper presents an overview of the tests conducted and some of the important early observations made that are relevant to future engineering standards and to tsunami disaster management.*

1 Introduction

MAKEWAVES is an international multi-partner collaborative project bringing together nine academic institutions and two commercial consultancies. The collaboration is not funded through a specific project, but developed from an opportunity created by HR Wallingford (HRW) and UCL for the wider academic use of the HRW tsunami simulation facilities and funded through in-kind contributions of the partners.

The objective of the collaboration is to develop experimental data and associated numerical modelling on tsunami inundation and interaction with natural features and engineered elements, towards the development of new knowledge that can contribute to the development of the next generation of tsunami evacuation guidelines and codes of practice for buildings and infrastructure.

Between November 2022 and April 2023, the team conducted experiments at HR Wallingford in a heavily instrumented 100m long flume using a pneumatic tsunami simulator (TS) to physically simulate crest and trough-led tsunami wave forms. The TS was developed jointly by HR Wallingford and UCL, and can reproduce representative tsunami wave forms at 1:50 scale, including wave traces from real life events such as the Mercator trace from the 2004 Indian Ocean event and the 2011 Tohoku tsunami (McGovern et al. 2018). The characteristics of the waves are controlled by adjusting the flow rate and total volume of water drawn in and discharged by the TS, as explained in Rossetto et al. (2011) and Chandler et al. (2021). The experimental campaign was subdivided into discrete research areas, each aimed at furthering knowledge on how different tsunami wave characteristics affect their interaction with manmade and natural structures. These include tests aimed at understanding: (1) how roughness representative of coastal forests and mangroves affects tsunami inundation characteristics, (2) how tsunami interact with boulders (3) the effectiveness of offshore breakwaters in mitigating tsunami impact (4) how foundation scour is affected by building permeability. This paper presents an overview of the tests conducted and some important early observations that are relevant to future engineering standards and to tsunami disaster management.

2 Experimental Set-Up

A schematic of the tsunami simulator and flume set up is shown in Figure 1, and is similar to that adopted in Foster et al. (2017), McGovern et al. (2018) and McGovern et al (2023). The experiments were performed in a flume that is 100m long and 1.8m wide. Tsunami waveforms are produced at a scale of 1:50 (Froude scaling), with periods (T) in the range of 20 – 230 s and wave amplitudes a between 0.03 - 0.14 m. The waves are generated by the pneumatic Tsunami Simulator (TS), which is equipped with a control system to account for the effects of reflections in the wave simulation. The waves travel over flat-bed for 53.3m, after which they propagate over a 1:30 sloping bathymetry for the next 30m, before impinging and inundating a horizontal beach section. The still water level for all the experiments is set at the transition between the slope and flat beach. The horizontal beach section comprises a narrow concrete section followed by a 0.3m deep sediment pit. At the end of the beach section, any overflowing water is captured in a sump.

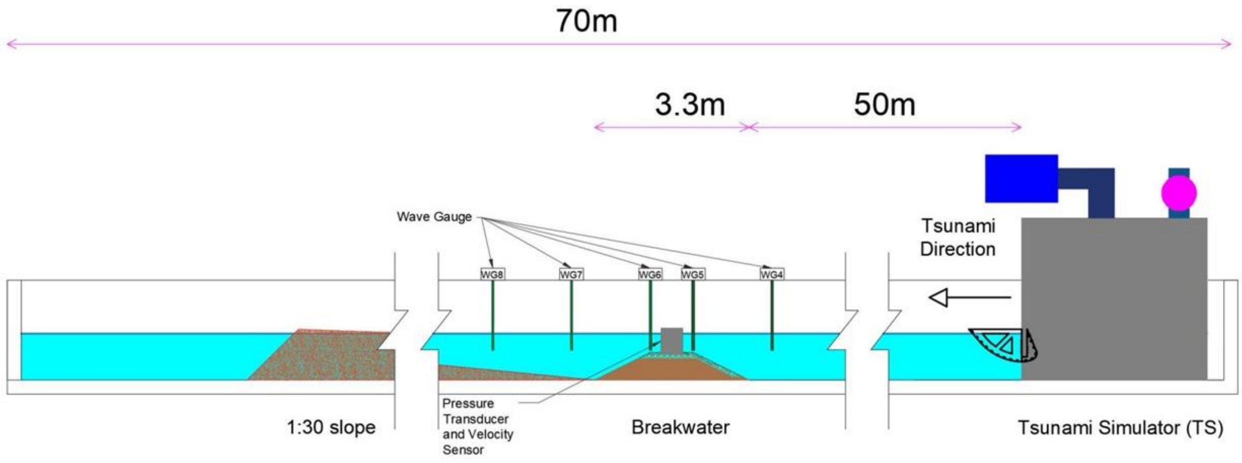

Figure 1. General schematic of the experiment set-up for MAKEWAVES tests.

In the case of the experiments that look at the effect of roughness, interaction with boulders and with the offshore breakwater, the beach and sump sections are covered with a plywood slope to extend the sloping bathymetry such as to allow the full measurement of runup.

3 Effects of Roughness on tsunami runup

Natural barriers for coastal inundation mitigation have received a growing interest since post-disaster observations made after the 2004 Indian Ocean Tsunami indicated that forests, particularly mangroves, reduced the impact of the tsunami in some locations (Tanaka et al., 2007). As a result, significant international relief and reconstruction efforts focused on extensive forest replantation of coastlines (Satake, 2014).

Several studies have used physical modelling and computational approaches to provide insights into the wave attenuation provided by coastal vegetation. These studies investigated the relationships between incident hydrodynamic conditions, forest configurations and wave height decay (e.g. Mukherjee et al. 2023). However, these studies are few in number, and there are still many gaps in knowledge (Tomiczek et al., 2020). It is essential to improve the understanding as to how wave heights, velocities and runup are influenced by the characteristics of the “obstacles”, (e.g. the forest density), as well as the incident hydrodynamic conditions, (e.g. the wave period).

The first phase of the MAKEWAVES experimental programme therefore focused on conducting experiments to investigate the effects of obstacles (representing coastal forests) on tsunami runup for a variety of incident hydrodynamic conditions. For this, three forest models were built using circular cylinders (wooden dowels), with varying diameter D (5, 8 and 10 mm). The dowels were placed with a regular pattern onto the plywood bathymetry slope extension. The forests of obstacles extended 2m inland, starting at a 0.3m distance from the still water level. The flume was split into two sections, as shown in Figure 2 in order to maximise the number of tests and facilitate comparison of the effects of different obstacles.

Figure 2. General arrangement of the experimental set-up (left) and incident wave (right).

Figure 3 shows the R/a^+ plot for all waves, where R is the run-up height recorded in the experiments and a^+ is the positive wave amplitude. For the latter, the wave height data recorded by the wave gauge located 7.3 m offshore the bathymetry toe was used. The plots show that relative to a smooth slope, the roughness can reduce the relative runup R/a^+ by up to 20% for T < 100 s. Roughness has a greater effect on runup for shorter period waves, and in the case of the 20s waves it is observed that some of the wave is reflected by the front of the obstacles. For T > 100 s, R/a^+ tends to unity, and the roughness causes a less appreciable reduction in runup. For certain combinations of roughness geometry and T, values of relative run-up that are slightly larger than unity are observed.

Within the “forests” as the water is slowed down the inundation height increases as compared to the smooth bed at an equivalent location, and on exiting the forests the inundation front is seen to accelerate again. The slowing down effect of the roughness results in a significant delay in the arrival time of the inundation front to areas behind the roughness. Like for the runup, a greater effect is seen for shorter wave periods.

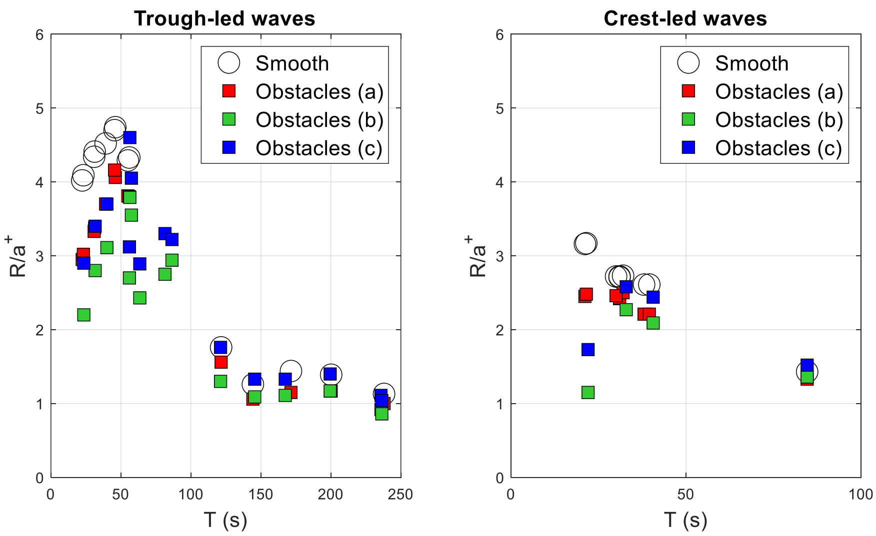

Figure 3. R/a⁺ as a function of T for trough-led waves (left) and crest-led waves (right). Obstacles (a), (b) and (c) refer to dowels of 10, 8 and 5mm, respectively.

4 Interaction of tsunami inundation and boulders

Observation of boulders on coastlines and models for their transportation inland by tsunami inundation have been used for estimating the intensity of historical tsunami events (Nott, 2003). The second phase of MAKEWAVES tests was developed to observe how different tsunami wave characteristics influence scaled models of boulders when they are impacted on the 1:30 slope. Two model boulder types were used for the experiments: a cuboid boulder with dimensions 3.4 x 3.3 x 2.7 cm and an irregular boulder (a shape more likely to be found in nature) with approximate dimensions of 7.5 x 3.0 x 2.5 cm. Both boulder models were limestone with a density of 2.75 g/cm³.

Preliminary results indicate that boulder transport distance increases with both increasing wave height and with increasing wave velocity (Figure 4). Unsurprisingly, boulder shape appears to exert some control on the distance moved, with the irregular boulder generally travelling further than the cuboid for the same wave parameters. However, the wave form is also key to understanding boulder transport with differences in transport distance between the three wave types tested.

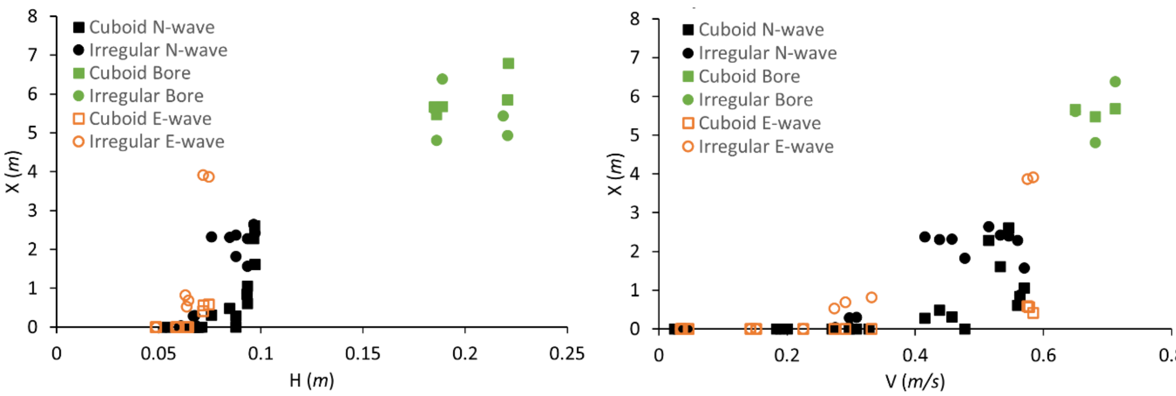

Figure 4. Boulder transport distance (X) plotted against (left) wave height at LWG 5 (H) (right) max flow velocity at the boulder starting position (V).

The behaviour of the boulder models under different wave parameters is still being investigated and dimensional analysis will additionally be utilised to facilitate comparisons between experiments and field data. Relationships between these parameters and dimensionless groups will be investigated to find new methods of hindcasting physical characteristics of waves in the past.

5 Tsunami interaction with offshore breakwater

Breakwaters protect harbours and coastlines from sea and swell waves. Their design relies on well-known and globally accepted design methods. However, scarce guidance exists for the design of tsunami resilient break waters and few breakwaters have been subjected to tsunami. The 2011 Tohoku, Japan, earthquake and tsunami, highlighted that even breakwaters designed to mitigate the effects of tsunami can fail dramatically for larger-than design events Much speculation exists as to the cause of these failures.

Phase 3 of the MAKEWAVES experiments, therefore, focused on trying to understand the interaction of tsunami waves with different characteristics and an idealised breakwater. The breakwater model was inspired by the Kamaishi breakwater’s trunk cross-section (Arikawa et al., 2012). The 1:50 scale experimental set-up considered a composite vertical wall breakwater composed of wood caisson 560 mm high and 460 mm wide installed on top of a rubble mound foundation for the entire width of the wave flume (Figure 5). Three different grading and concrete toe protection blocks were used to reproduce the foundation. The water depth at the toe of the structure was equal to 1000 mm, the rubble mound foundation extended from the bottom to 460 mm below the still water level, the caisson has a freeboard of 60 mm and is installed 40 mm below the top surface of the foundation. Twelve pressure sensors were installed along the 4 sides of the caisson, wave gauges were placed in front of, above and behind the caisson, while a Nortek Vectrino was positioned close to the rear side toe of the caisson to capture the hydrodynamic load due to the overflow.

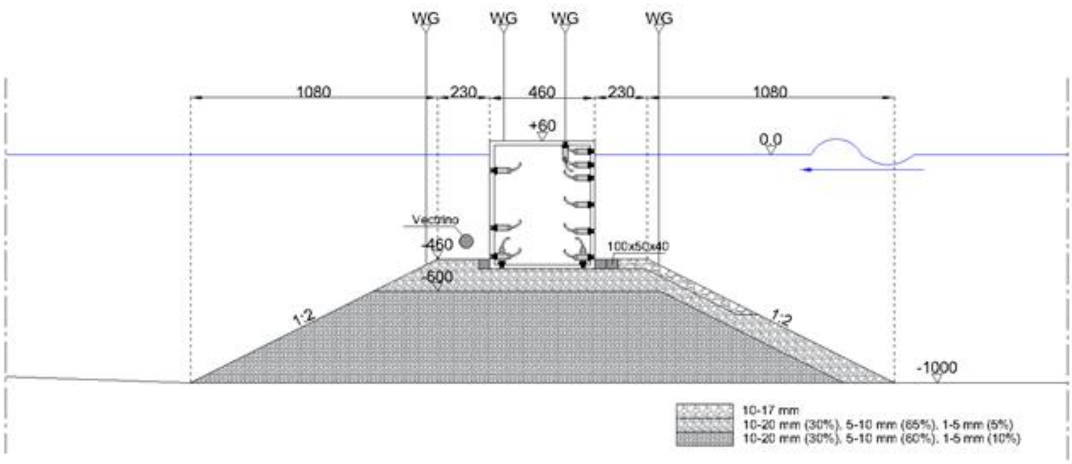

Figure 4. Drawing of the breakwater configuration and location of instrumentation used in the MAKEWAVES breakwater experiments.

Preliminary results highlight the effectiveness of the breakwater in minimising wave transmission, with significant energy being reflected back offshore by the breakwater. Pressure on the offshore side of the caisson appears to resemble the hydrostatic distribution after the first impact, however, slightly larger values have been preliminarily observed. Larger peak pressure values are recorded on the rear side at the bottom of the caisson, and occur at the moment of the overflow impact with the still water level.

An interesting observation was made during the experiments, i.e. that transmission is not only caused by the expected overtopping, but that there is also significant transmission through the porous foundation. This was particularly evident in the case of trough-led waves with small crests (that did not cause overtopping). In these cases, a trough led waves was seen to develop on the landward side of the breakwater and propagate to the slope. This observation is explainable by permeability (perhaps Darcy or Forchheimer laws), as when the trough arrives at the breakwater it sets up a head difference between the offshore and landward side of the structure. Due to the long wavelength of the simulated tsunami waves, seepage flows occur through the rubble mound, lowering the landward water level and setting up a trough-led wave. The seepage then reverses in direction when the crest part of the wave reaches the breakwater.

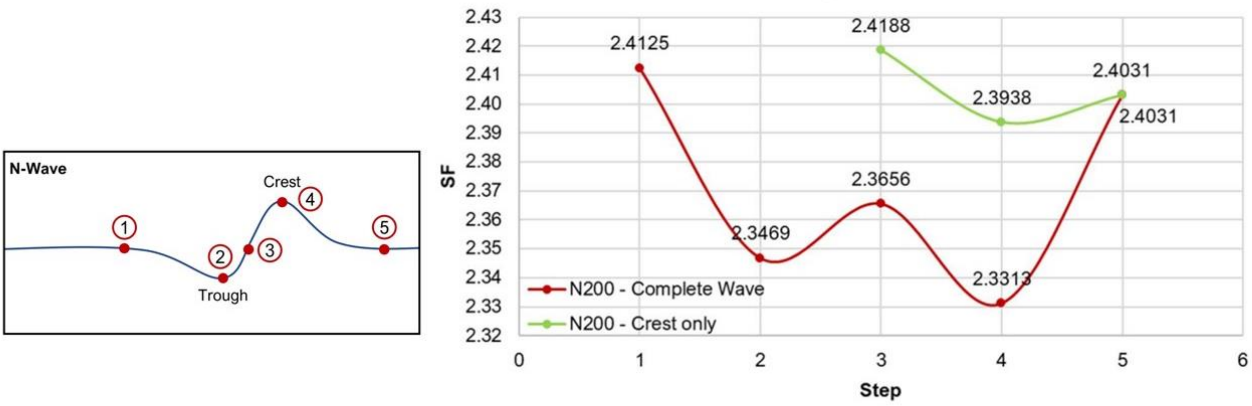

Figure 5. Example graph of the safety factor (SF) calculated in MIDAS GTS NX for the modelled rubble mound breakwater and N200 tsunami (right). In the graph, SF is calculated at a series of steps that correspond to arrival at the breakwater of key parts of the trough led wave (left).

Past studies of tsunami-breakwater interaction have mainly focused on tsunami with crest-only waves, neglecting trough-led waves and related seepage forces. However, these experiments show that the trough should not be ignored, and could affect breakwater stability. To explore this phenomenon further, a 3D model of the rubble mound was set up in the geotechnical software MIDAS GTS NX (https://www.midasgeotech.com), and the model validated against the MAKEWAVES tests. The analysis encompassed seepage-stress coupling and the rubble mound safety factor against failure was computed for the range of waves tested in the experiments. The analysis was able to capture both local failure (in the rubble mound at the base of the rear side of the caisson) and global failure (rotation failure) mechanisms. It is found that the safety factor decreases with bigger wave amplitudes and longer wave periods. The lowest safety factors calculated were in the range of 2-2.5, and were obtained for the longest trough-led waves used. An example of the calculation output is shown in Figure 6 for a trough-led wave with wave period 200s (N200). Although the calculated safety factors under the range of waves analysed is high enough to prevent rubble mound failure, it is consistently observed that the safety factors calculated considering both the trough and crest components of tsunami wave traces is significantly lower than when the calculation is conducted considering only the crest (see Figure 6).

This initial analysis highlights the critical importance of accounting for both trough-led and crest-led waves in the study of breakwater behaviour and stability.

6 Tsunami forces and scour around permeable structures

Foundation scour was widely observed around buildings and infrastructure following past tsunami events, and was one of the primary mechanisms driving infrastructure failure (Rossetto et al. 2004 and Chock et al., 2013). A greater understanding of this mechanism is needed to improve mitigation strategies. McGovern et al. (2019) demonstrated that the duration of the tsunami inundation, which is related to the wave period of the tsunami wave, significantly influences the scour development. The fourth phase of MAKEWAVES investigated the effects of structural permeability on tsunami induced scour development.

Impermeable structure Semi-permeable structure Fully permeable structure

Figure 7. Pictures of the MAKEWAVES experiments of scour development for three building permeabilities.

Figure 7 shows the 400mm by 200mm 1:50 scale structure with three permeabilities: impermeable, fully permeable with 55 by 50mm perforations (representing a bare frame structure), and semi-permeable with 40mm by 50mm perforations. The full scour timeseries around the building were recorded using eight ‘scour gauges’ (standard resistance wave gauges calibrated to detect changes in burial depth) located around the structure. Tests results of the impermeable structure validate the observations of McGovern et al. (2019). Namely, that as the flow velocity slows down, the sides of the scour pit lose stability and slump, backfilling the scour pits by as much as 30% of the maximum scour depth. This raises concerns over the scour depth guidance provided by existing codes, which are commonly based on post-event observations.

Preliminary results from the permeable and semi-permeable structures indicate lower maximum scour depths around the leading building edges. Interestingly, scour formed at the back of the structures (onshore side) as the flow passed, and accelerated, through the openings. Although the maximum scour depth at the edges of the structures decreased, there was however greater scour development at the central front portion of the structures.

These studies highlight two important benefits to maximizing the opening ratios at the lower levels of a structure. The first is that greater opening ratios significantly reduce the drag forces exerted on the front of the structures. The second benefit is an overall reduction in maximum scour depth around the front edges of a structure. Permeable lower building levels, with sufficiently strong columns, could act as a key guiding principle in the design of tsunami resistant foundations and super-structures.

7 Conclusions

The experiments conducted in the MAKEWAVES project present a number of observations that are relevant to tsunami hazard evaluation, engineering and disaster miitigation:

- The extent of tsunami-induced boulder transportation is not only based on the flow velocity and height, but also on boulder shape and tsunami wave shape characteristics. These observations may result in modifications to models for estimating historical tsunami intensities from data on boulder movement.
- Natural barriers (e.g. coastal forests and mangroves) are more effective in reducing the runup of smaller tsunami or storm-type waves than of tsunami with very long wavelengths. However, in all cases, they delay the arrival time of tsunami inundation flows and could potentially contribute to increasing available evacuation tim. This observation may be of particular importance for coastal areas near tsunami sources.
- The experiments confirm that breakwaters can be effective in reducing tsunami transmission. However, where breakwaters have permeability (like the case of rubble mound breakwaters), seepage induced by both trough and crest-led tsunami, of appropriate wavelength, should be considered in their stability assessment.
- Scour models developed from post-tsunami observations may under-predict the maximum scour depth observed during a tsunami.
- Building permeability can significantly change the pattern of scour around a structure and may result in a reduced scour concentration around the fromt (seaward-facing) corners of buildings.

These observations are preliminary, and the experimental data needs to be further elaborated and supporting numerical analyses conducted to further confirm, quantify and gerenarlise these observations into usable relationships and guidance.

8 Acknowledgements

The experiments presented in this paper are part of the Multidisciplinary Advancement of Knowledge on Extreme Waves (MAKEWAVES) project. MAKEWAVES has largely funded by the in-kind contributions of the partner universities and institutions, with HR Wallingford making available the flume facility and providing technical support, UCL contributing monitoring equipment and Southampton University and TU Delft contributing to consumables. Some grant funding was obtained from the AKT 269 Innovate UK awarded to London South Bank University, and from a Royal Society Exchanges Grant awarded to UCL and TU Delft.

9 References

Arikawa, T., Sato, M., Shimosako, K., Hasegawa, I., Yeom, G.S. and Tomita, T., (2012). Failure mechanism of Kamaishi breakwaters due to the Great East Japan earthquake tsunami. Coastal engineering proceedings, 1(33), p.16.

Bressan, L., Guerrero, M., Antonini, A., Petruzzelli, V., Archetti, R., Lamberti, A., Tinti, S. (2018) A laboratory experiment on the incipient motion of boulders by high-energy coastal flows. Earth Surf. Process. Landforms, 43: 2935–2947.

Chandler, I., Allsop, W., Robinson, D. and Rossetto, T., (2021). Evolution of pneumatic Tsunami Simulators–from concept to proven experimental technique. Frontiers in Built Environment, 7, p.674659.

Chock, G., Carden, L., Robertson, I., Olsen, M. and Yu, G., (2013). Tohoku tsunami-induced building failure analysis with implications for US tsunami and seismic design codes. Earthquake spectra, 29(1_suppl), pp.99-126.

Foster, A.S.J., Rossetto, T. and Allsop, W., (2017). An experimentally validated approach for evaluating tsunami inundation forces on rectangular buildings. Coastal Engineering, 128, pp.44-57.

Imura, K., & Tanaka, N. (2012). Numerical simulation estimating effects of tree density distribution in coastal forest on tsunami mitigation. Ocean Engineering, 54, 223–232. https://doi.org/10.1016/j.oceaneng.2012.07.025

McGovern, D. J., Robinson, T., Chandler, I. D., Allsop, W., & Rossetto, T. (2018). Pneumatic long-wave generation of tsunami-length waveforms and their runup. Coastal Engineering, 138, 80–97. https://doi.org/10.1016/j.coastaleng.2018.04.006.

McGovern, D.J., Todd, D., Rossetto, T., Whitehouse, R.J.S., Monaghan, J. and Gomes, E., (2019). Experimental observations of tsunami induced scour at onshore structures. Coastal Engineering, 152, p.103505.

McGovern, D. J., Allsop, W., Rossetto, T and Chandler, I (2023). Large-Scale experiments on tsunami inundation and overtopping forces at vertical sea walls. Coastal Engineering. 179, p. 104222. https://doi.org/10.1016/j.coastaleng.2022.104222Mukherjee, A., Cajas, J. C., Houzeaux, G., Lehmkuhl, O., Suckale, J., & Marras, S. (2023). Forest density is more effective than tree rigidity at reducing the onshore energy flux of tsunamis. Coastal Engineering, 182, 104286. https://doi.org/10.1016/j.coastaleng.2023.104286

Nandasena NA, Scicchitano G, Scardino G, Milella M, Piscitelli A, Mastronuzzi G. (2022) Boulder displacements along rocky coasts: A new deterministic and theoretical approach to improve incipient motion formulas. Geomorphology. 2022 Jun 15;407:108217.

Nott, J. (2003). Waves, coastal boulder deposits and the importance of the pre-transport setting. Earth and Planetary Science Letters, 210(1-2), 269-276.

Rossetto, T., Peiris, N., Pomonis, A., Wilkinson, S.M., Del Re, D., Koo, R. and Gallocher, S., (2007). The Indian Ocean tsunami of december 26, 2004: observations in Sri Lanka and Thailand. Natural Hazards, 42, pp.105-124.

Rossetto, T., Allsop, W., Charvet, I., & Robinson, D. I. (2011). Physical modelling of tsunami using a new pneumatic wave generator. Coastal Engineering, 58(6), 517–527. https://doi.org/10.1016/j.coastaleng.2011.01.012

Satake, K., 2014. Advances in earthquake and tsunami sciences and disaster risk reduction since the 2004 Indian ocean tsunami. Geoscience Letters, 1(1), pp.1-13.

Tanaka, N., Sasaki, Y., Mowjood, M.I.M., Jinadasa, K.B.S.N. and Homchuen, S., (2007). Coastal vegetation structures and their functions in tsunami protection: experience of the recent Indian Ocean tsunami. Landscape and ecological engineering, 3, pp.33-45.

Tomiczek, T., Wargula, A., Lomónaco, P., Goodwin, S., Cox, D., Kennedy, A., & Lynett, P. (2020). Physical model investigation of mid-scale mangrove effects on flow hydrodynamics and pressures and loads in the built environment. Coastal Engineering, 162, 103791. https://doi.org/10.1016/j.coastaleng.2020.103791