# Keynote Paper: Resilience based design interventions on critical buildings in Sri Lanka

Professor Tiziana Rossetto

*EPICentre, Department of Civil Environmental and Geomatic Engineering, University College London (UCL), London, UK*

## 1. Introduction

Healthcare and education (H&E) services are two of the pillars of development and are central to SDG 3 "Ensure healthy lives and promote wellbeing for all at all ages" and SDG4 "Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all". Functioning H&E services are also critical to community post-disaster recovery and support return to normalcy. In recognition of this, the Sendai Framework for DRR 2015–2030 has as one of its global targets to "substantially reduce disaster damage to critical infrastructure and disruption of basic services, among them health and educational facilities, including through developing their resilience". This shift from risk to resilience effectively sets a challenge to engineers, who should not only consider life-safety in the design and retrofit of buildings for natural hazard effects, but also what can be done to ensure a rapid restoration of buildings' functionality. In fact, in the case of H&E services, implementation of resilient design requires a paradigm shift where hospitals and school buildings are not considered as individual assets, but rather as a part of a network of assets that together provide healthcare and education to communities across geographical scales.

This paper looks to provide examples of where resilience concepts have been/are being used to understand the impact that a future tsunami might have on the healthcare and education system in coastal areas of Sri Lanka. The work presented is part of the research being conducted under the auspices of two research projects funded by Research England called ReSCOOL (2019-ongoing) and HEARTS-SL (2018-2020). These projects comprise international teams of researchers from University College London, Imperial College and Southampton University (UK), University of Moratuwa, University of Peradeniya, South Eastern University (Sri Lanka) and University of Naples Federico II (Italy).

## 2. Approach to the investigation the tsunami resilience of H&E Services in Sri Lanka

From an engineering perspective, schools and hospitals present significantly different levels of complexity for their structural and functional analysis. Schools in Sri Lanka, like in many other countries, are commonly built following a prototype design that has been approved by the Ministry of Education. Schools, therefore, have similar design and construction, and can be represented by one/few archetype building/s. This means that few structural models are required to investigate the structural performance of schools under natural hazards, and hence detailed finite element modelling and numerical analysis can be employed. Following a field survey of 55 schools buildings along the coastlines of the Galle, Batticaloa and Ampara districts in Sri Lanka, three representative building types are being been numerically modelled and analysed under future tsunami scenarios. A non-linear static analysis procedure termed Variable Depth Pushover (VDPO) is adopted for the analysis. This approach simulates the tsunami inundation as a flow with constant Froude Number (Fr) but increasing inundation depth. Accordingly, at each analysis time step, the water depth is increased, and the corresponding hydrodynamic loads are applied to the structural elements up to the inundation height. The adopted approach is capable of simulating the failure of infill walls and vertical loads due to buoyancy on the slab and beams of the structure. This paper presents some key results from the analysis of one archetype school building as well as two variations of this design aimed at improving the schools' performance under tsunami hydrodynamic loads as well as scour effects. The full analysis results can be found in Del Zoppo et al. (2021).

Contrary to the case of schools, Hospitals are composed of several buildings, built a different times and which often have distinctive and different designs, Past studies have investigated the structural response of individual hospital buildings through numerical analysis, however, such an approach is not feasible when a population of hospital structures needs to be investigated. A simple but quantitative approach is required to assess the resilience of healthcare systems to tsunami, which relates not only to hospital building integrity, but also to maintaining hospital functionality. For this purpose, a new tsunami relative risk index (TRRI) was proposed that quantifies the impact of tsunami on critical units, (e.g. Intensive Care Unit, Operating Theatres, etc.) in individual hospitals, as well as the impact on service provision across a network of hospitals. The TRRI consists of three components that represent the structural resistance to hydrodynamic tsunami loads (inclusive of resistance against scour and debris impact), inundation of critical care units, and the likely damage to the key back-up systems that ensure hospital functionality. In its current form TRRI is designed for hospital buildings of reinforced concrete construction, as these are the building types most commonly used worldwide for housing critical units. Following a field survey of 8 hospitals in the Galle district, the TRRI approach was adopted for the relative risk evaluation of the three hospitals along the Galle coastline that contain 85% of all critical units, under three tsunami hazard levels. The results of this evaluation are briefly summarised in this paper, but are presented in full in Baiguera et al. (2020).

## 3. Preliminary results of school resilience investigation

The structural performance of two archetype Sri Lankan schools subjected to tsunami-induced loads (drag and uplift forces and buoyancy), was investigated. The first archetype school consisted in a two-storey RC frame with brick infills of typical construction. The second school is a modified version of the first school design that was proposed in Sri Lanka after the 2004 Indian Ocean Tsunami to provide more redundancy against scour (termed SSE school design, see Fig.1). As compared to the archetype school, the SSE design contains an additional column in its end bays and much stronger infill walls that are supposed not to break-away in the case of tsunami inundation. Although the additional column is beneficial to help provided added support to the end bays against tsunami scour, and the in-plane behaviour of the stronger exterior infill walls increases the flexural capacity and lateral stiffness of the SSE structure, however, it also shown that the inclusion of non-breakaway infill walls in the SSE school building design consistently leads to premature structural failure mechanisms, associated with the concentration of drag forces on seaward columns only. Overall, this leads to the SSE building performing worse than the prototype building (see Fig.2) and this comparison shows the benefit of designing the exterior infill walls to fail under sustained tsunami loading so that the tsunami forces on the structural elements are reduced. An alternative design is therefore proposed, that maintains the additional column as per the SSE design but includes break-away infills and this is shown to provide better performance under tsunami lateral loads (see Fig 2).

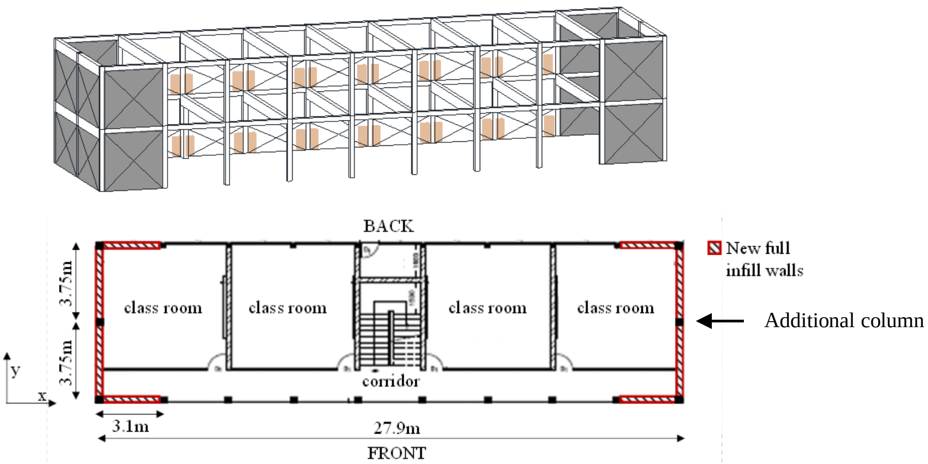


**Fig.1**: Illustration of the elevation (above) and type plan (below) of SSE School design, adapted from Del Zoppo et al. (2021)

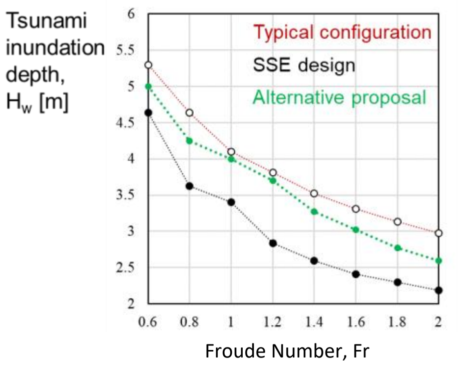


**Fig.2**: Example result of the tsunami resistance of the archetype school, SSE school and alternative SEE school design, in terms of tsunami inundation depth, for different values of Froude Number, adapted from Del Zoppo et al. (2021).

Despite the proposed enhancements, the structural assessment shows that the typical school design has an overall poor resistance to tsunami, and that it would not be adequate for the vertical evacuation of children. For example, for a typical tsunami inundation Froude Number of 1, Fig. 2 shows that the archetype school would fail when the inundation reached around 4m. Fig 3. Shows a map of the inundation depths expected at the schools surveyed in the Ampara District, from a recurrence of the 2004 Indian Ocean Tsunami. It is clear that most of these coastal schools would collapse or be heavily damaged under such an event. The situation would not be as bleak however if lower tsunami velocities were experienced (e.g. at a Froude Number of 0.6).

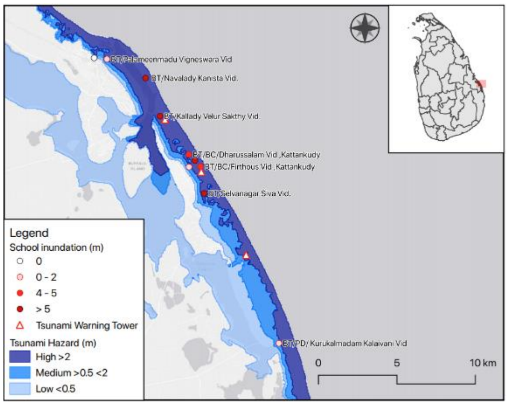


**Fig.3**: Tsunami inundation heights expected at the location of surveyed schools in the Ampara District if there were a recurrence of the 2004 Indian Ocean Tsunami. Map care of Jonas Cels (UCL) and inundation simulations conducted by Shuaib Rasheed and Prof. Matthew Piggott (Imperial College).

As previously stated, the resilience of the education system is not solely one of school physical strength. As we have seen in the recent COVID-19 pandemic, education can continue without the physical presence of schools, even though this is far from ideal. Disaster preparedness can mitigate the immediate impact of a tsunami on teachers and children, and planning for possible post-disaster disruptions may help to mitigate the adverse effects of disasters on education provision. Hence, in May 2021 interviews were conducted with a select number of school principals and officials of the regional and national offices of the Ministry of Education. Initial analysis of the interview has highlighted that tsunami are still today perceived to be a very high risk, and that there is a strong reliance on tsunami warning systems for triggering evacuation. The evacuation planning is largely left to school principal with no guidance provided, and no specific training in what to do in a disaster is provided to school teachers. Hence, beyond structural analysis of schools, we aim to use maps of school damage under different tsunami events, (similar to that in Fig. 3), and the interview results to provide the focus for workshops to be organised with officials from the Ministry of Education and other stakeholders in 2022. These workshops will look to discuss elements of disaster preparedness in schools, the mitigation of post-disaster disruption to education (e.g. by partnering at-risk schools with those further inland), and explore potential school physical strengthening options.

## 4. Preliminary results of hospital services resilience investigation

A preliminary assessment of the resilience of critical healthcare services to tsunami was conducted by evaluating the TRRI for three hazard levels and 13 buildings within three hospitals along the south coast of Sri Lanka (see Fig. 4). These 13 buildings, all 2-4 storey reinforced concrete moment resisting frames, house 85% of the Intensive Care Units (ICU), Operating Theaters (OT), Labor Rooms (LR), Maternity Wards (MW), and Pediatric Wards (PW) across the three hospitals. The remaining 15% of such critical units are housed in six one-storey load-bearing unreinforced masonry (URM) structures, which are deemed to be highly vulnerable to tsunami and would not be expected to be operational following tsunami inundation.

The results of the analysis of TRRI for the three hospitals and Hazard Levels shows a high vulnerability of back-up systems and critical units under low levels of tsunami inundation. For example, under Hazard level 1, despite it being likely that only one building in DGH Matara would be structurally compromised, this hospital would lose all of its critical unit functionality. This is due to the direct inundation of 5 of its critical units and the failure of its back-up systems rendering the remaining 4 units not functional. Across the network of three hospitals, this would result in a reduction of 40–45% in the number of ICU and MW units, and of 50% in the number of LR and

OT units. Loss of critical unit functionality at DGH Matara would put particular stress on BH Tangalle, which is the closest hospital to it. In this study it is demonstrated that, re-positioning critical units and back-up systems to higher floors within all three hospitals would improve the functional resilience of the hospitals significantly under low- to moderate tsunami hazard levels. It is also shown that the combined repositioning of back-up systems and critical units is a much more effective intervention than the repositioning of only one of these.

Building failure plays an increasing role in the critical unit operationality for "moderate to high" tsunami hazard levels. In particular, scour of foundations can precipitate building failure. It is observed that the TRRI is able to identify the most critical buildings, and can be used as a preliminary prioritization tool for further engineering investigation and towards a strengthening intervention. The full analysis is presented in Baiguera et al. (2020).

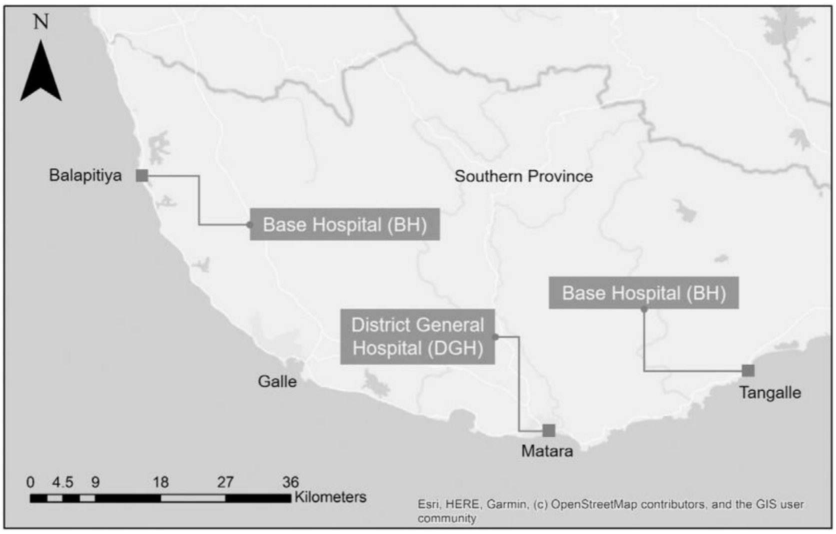


**Fig.2**: The three hospitals investigated. It is noted that under Tsunami Hazard levels 1, 2 and 3, respectively, each hospital is assumed to have the following tsunami inundation depths: BH Balapitiya – 0m, 0m, 1.37m; DGH Matara – 0.57m, 2.08m, 3.58m; BH Tangalle – 0m, 0.29m, 1.79m.

One of the weaknesses of the developed TRRI is that it adopts an extremely simple approach to link critical unit functionality to all back-up systems. Furthermore, it assumes that if the structure is damaged and the critical unit is not directly inundated, that the unit maintains functionality, which may not be the case. To improve the TRRI further information is required to better understand how a hospital functions and is managed post-disaster. To this purpose, we are currently looking to undertake a series of interviews with hospital directors and doctors in several hospitals in Sri Lanka.

## 5. Conclusions

This paper presents some of the findings of two collaborative research projects that are looking to better understand the resilience of the Healthcare and Education services in Sri Lanka, The investigations shift from looking at the physical vulnerability of the school and hospital structures, to their functionality and how that may be compromised by tsunami inundation even when the structures do not collapse. This involves a multi-disciplinary approach and the use of several research methods, namely: field surveys, numerical analysis, risk index evaluation and interviews. The latter are particularly needed to better understand how these complex systems work, and their dependency on the physical infrastructure that supports them. Through this approach we aim to foster stakeholder discussions and make recommendations on resilience interventions that not only improve the performance of individual structures under tsunami, but can also reduce the impact of tsunami on healthcare and education service loss across the hospital and school network.


## Acknowledgements

The research presented in this paper has been funded by Research England via the UK Global Challenges Research Fund under the auspices of two research projects "Resilience Of Schools To Extreme Coastal FlOOding

Loads" (ReSCOOL), and "Hospital Engineering Assessment for Resilience to Tsunami and Storm surge—Sri Lanka" (HEARTS-SL), awards 177813. The research derives from a collaboration between the following people and institutions: Prof. Tiziana Rossetto, Prof. Ian Eames, Prof. Angela Little, Juan Palomino, Dr Susana Lopez-Queroll Dr Ioanna Ioannou, Dr David Robinson, Jonas Cels, Maria Kontoe (University College London), Dr Marco Baiguera (University of Southampton), Prof. Priyan Dias, Dr Chandana Siriwardana, Dr Chinthaka Malikarachchi, Hashan Hasalanka (University of Moratuwa), Dr Kushan Wijesundara (University of Peradeniya), Dr Marta Del Zoppo, Prof. Marco Di Ludovico, Prof. Andrea Prota (University of Naples Federico II), Dr Julian Thamboo (South Eastern University), Prof. Matthew Piggott, Shuaib Rasheed (Imperial College).

## References

Baiguera, M., Rossetto, T., Palomino, J., Dias, P., Lopez-Querol, S., Siriwardana, C., Hasalanka, H., Ioannou, I., Robinson, D. (2021). A New Relative Risk Index for Hospitals Exposed to Tsunami. *Frontiers in Earth Science*, 9, 93.

Del Zoppo M., Wijesundara K., Rossetto T., Dias P., Baiguera M., Di Ludovico M., Thamboo J., Prota A. (2021). Influence of exterior infills on the performance of RC frames under tsunami loads: case study of school buildings in Sri Lanka. *Engineering Structures*. 234, 111920.