15th Australasian Wind Engineering Society Workshop
Sydney, Australia
23-24 February 2012

Cyclone Yasi Storm Surge

George R. Walker

Adjunct Professor, Science & Engineering
James Cook University, Townsville 4811, Australia

Honorary Research Fellow
Aon Benfield Analytics Asia Pacific, Sydney 2000, Australia

Associate, Risk Frontiers
Macquarie University, Sydney 2109, Australia

Abstract

Cyclone Yasi produced one of the largest storm surges to impact Queensland since European settlement. Fortunately it occurred close to low tide but it caused significant damage at Tully Heads. The paper describes the main features of the storm surge, the resulting pattern of damage, and the implications for the structural design of buildings. It is concluded that buildings can be designed in storm surge prone areas which could provide safe havens as an alternative to evacuation, and that design criteria need to be specified for this with the design return period being a critical issue.

Introduction

Cyclone Yasi, with a central pressure of 930 hPa, produced a maximum storm surge of the order of 5.5m. This is of the same order of magnitude as storm surges produced by the two most severe cyclones to cross the Queensland coast during the 20th century – the 1918 Mackay and Innisfail cyclones in January and March respectively (BoM, 2011). Both of these caused a significant number of deaths due to drowning. That there were no deaths from Cyclone Yasi was probably due primarily to the cyclone crossing close to low tide and the almost complete evacuation of residents from the communities most severely impacted. Had Cyclone Yasi crossed the coast a few hours earlier or later it is probable there would have been a significant number of deaths from drowning irrespective of the evacuations.

Historically the worst storm surge in terms of impact to hit the east coast of Queensland was that from Cyclone Mahina in 1899 in Princess Charlotte Bay on Cape York Peninsula, with an estimated highest water level including wave run up reported to be of the order of 14 m above mean sea level and penetration inland of the order of 5 km, and which sank over 100 vessels in a Pearling fleet and drowned over 400 persons. The storm surges from both the 1918 cyclones appear to have peaked around high tide. The Mackay cyclone (933 hPa) produced a storm surge variously reported as between 3.5 m and 5.5 m in height at roughly high tide, which in combination with the flooded Pioneer River inundated much of the town, and in combination with the severe winds destroyed much of it. The Innisfail cyclone (926 hPa) 7 weeks later was an even more powerful cyclone which at Mission Beach produced a storm surge, which in combination with the tide resulted in a depth of water up to about 3.5 m deep sweeping hundreds of meters inland. These three cyclones appear to have not only produced the most severe storm surge damage, but have been the most severe to hit the east coast of Queensland since European settlement.

Since 1918 and prior to Yasi there have been a number of severe cyclones cross the coast with peak storm surge heights between 2m and 3m which could have produced major damage had they crossed near high tide but they didn't. Cyclone Althea produced a storm surge of the order of 2.8m which if it had occurred at high tide would probably have resulted in the loss of several hundred lives because of the lack of recognition of the threat at that time. One consequence of this long period with no significant losses due to storm surge has been a tendency to ignore the threat in relation to buildings, although it is well recognised in terms of warnings when cyclones are threatening. One of the major lessons from Cyclone Yasi should be a much greater recognition of this threat by the community.

Characteristics of Storm Surges

The storm surge accompanying a tropical cyclone is a temporary change in sea-levels produced by the combination of low pressure and strong winds. Well away from the coast the surge is predominantly a mound of water which mirrors the pressure drop, the increase in sea-level being approximately 1 cm for every drop in surface pressure of 1 hPa (Stark, 1980). As this mound of water approaches the coast it is amplified due to frictional effects associated with the shallowing of the water and high wind stresses on the sea surface which push water towards or away from the coast. The storm surge tends to be highest on the edge of the eye where the winds are strongest falling away either side of this. Along the eastern Queensland coastline this would typically result in a profile of storm surge north and south of the eye as shown in Figure 1

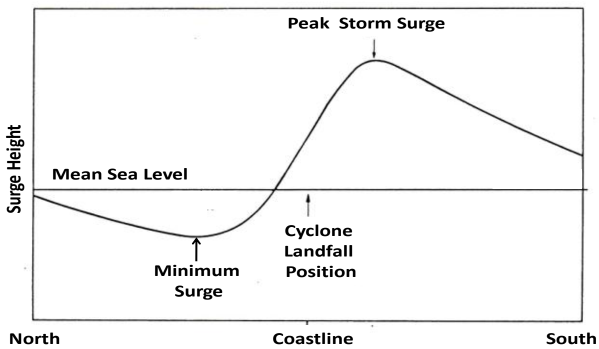

Figure 1. Schematic of variation in height of storm surges along the east coast of Queensland

The actual storm surge height at the shoreline depends on the characteristics of the tropical cyclone such as central pressure, size, track and history over the ocean, forward speed, and wind field, as well as the bathymetry of the ocean adjacent to the coast, the shape of the coast, and islands and reefs over which the cyclone passes. As a result for a given central pressure at landfall the peak storm surge can vary greatly, and the variation along a coastline can also vary greatly from the smooth curve shown in Figure 1. However mathematical modelling of storm surge development taking these factors into account is a relatively well established technique, and has become the basis of most forecasting of storm surge heights.

Time wise a storm surge resembles a tide rising and falling over a period of hours not minutes, with the peak roughly corresponding to when the centre of the tropical cyclone crosses the coast. In this respect it is quite different from a tsunami with which it is often compared, and more like major riverine flooding with steadily rising water accompanied by a reasonably strong current but not the extremely strong currents associated with a tsunami. What makes it different from riverine flooding is the accompanying wave action which produces additional forces on structures adjacent to the shoreline.

The level of impact of the storm surge on coastal buildings and other structures depends on the combination of storm surge height, the normal astronomical tide levels on which it is superimposed, and the associated wave action, which increases the actual water level at the coastline due to wave set up. This combination is depicted schematically in Figure 2.

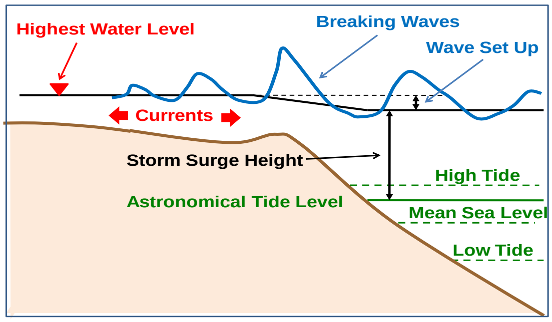

Figure 2. Schematic of Combination of Storm Surge, Tide and Waves at Coastline

In regions where the tidal range is small such as the Gulf coast of the southern US the timing of the crossing of the tropical cyclone is not very critical, but in regions like the east coast of Queensland where the tidal range is of the order of metres the timing of the landfall of the centre of the cyclone can make a big difference. Major storm surge losses occur in this region when tropical cyclones with relative large storm surges landfall at close to high tide, which fortunately is relatively rare.

Yasi Storm Surge

Figure 3 shows the measured storm surge heights in Yasi at different locations along the east coast of Queensland relative to Clump Point which approximately corresponds to where the centre of the eye is believed to have crossed the coast. Also shown is the actual maximum sea level relative to Highest Astronomical Tide (HAT) which gives a better indication of the actual sea level at any locality, and the potential maximum sea level relative to HAT if the storm surge had coincided with the maximum adjacent high tide, which in this case was the following high tide around 8 hours later.

The maximum storm surge height was of the order of 5.4m at Cardwell. Fortunately this occurred at about 1am at about quarter tide, as shown in Figure 4, which greatly reduced its potential impact with the maximum water level being about 2.2m above HAT. Had the maximum storm surge been about 8 hours later the maximum water level would have been about 4.7m above HAT.

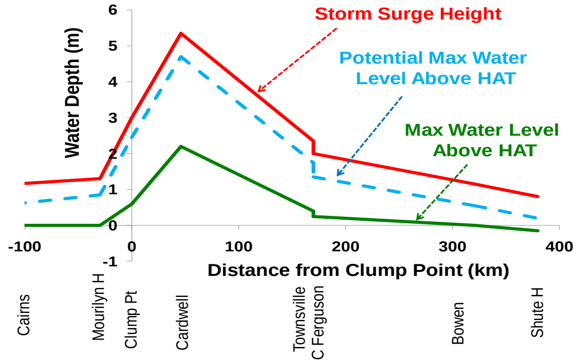

Figure 3. Storm surge profile along coast

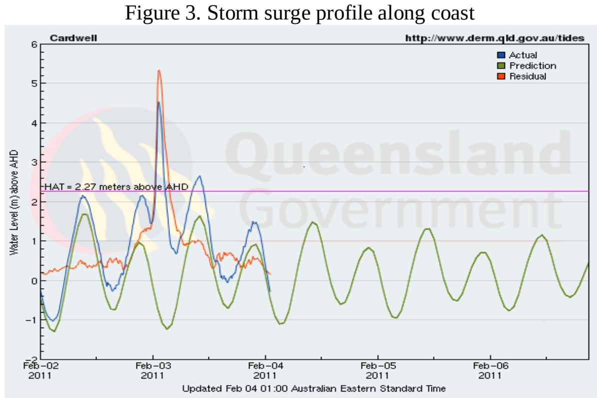

Figure 4. Cardwell tide gauge data (DERM, 2011)

Comparison with Figure 1 shows no evidence of the expected negative surge north of the track. This may be due to the dominance of the 'inverted barometer effect' from a relatively low central pressure and off-shore wind speeds less than typical due to the topography of the area. The jump in levels between Townsville and Cape Ferguson probably demonstrates the effect of different local features, with Townsville facing north within Cleveland Bay with Cape Cleveland to the east and Magnetic Island to the north, and Cape Ferguson being on the southern side of the Cape Cleveland peninsula and facing south.

The storm surge of 2.35m at Townsville approximately 180km from Clump Point was only about half a meter lower than that recorded in Cyclone Althea which crossed the coast about 50km north of Townsville. The storm surge was still greater than a metre at Bowen over 300 km south of Clump Point. Furthermore the peak storm surge in Townsville persisted for about 2 hours, perhaps due to the influence of Magnetic Island, and then persisted at a relatively high level for well over 12 hours with a secondary peak of the order of 1.2m corresponding to the following high tide resulting in a maximum water level of 0.4m above HAT, considerably greater than experienced during the major passage of the cyclone several hours earlier.

Pattern of Structural Damage

Contrary to what might have been expected from Figure 3 the maximum structural damage from the storm surge occurred at Tully Heads where the storm surge would probably have been between 3 and 4 metres, with highest water levels probably of the order of a metre or so above HAT unless there were local features which amplified it. This storm surge height and highest water level above HAT were considerably below the corresponding values for Cardwell. Furthermore the corresponding values at South Mission Beach and Mission Beach would probably not have been much less than at Tully Heads. Yet at Tully Heads almost all the houses alongside the road parallel and closest to the beach suffered major damage from storm surge while at Mission Beach and at Cardwell there appeared to be very little structural damage from storm surge.

The reason for this difference appeared to be the height of the ground floor level relative to HAT. Figures 5 and 6 contrast the coastal situation at Tully Heads and at Port Hinchinbrook in the Cardwell area. At Tully Heads the back lawn shown is hardly above beach level, the rocks scattered about the lawn apparently coming from a destroyed seawall which was intended to protect the property. At Port Hinchinbrook the houses are on top of a bank significantly above beach level, and this is the same in Cardwell itself. As a consequence at Tully Heads water surged through properties up to a depth of over a metre on the seaward side of the street and up to 0.8 m on the landward side of the street, cleaning out the ground floor of 2 storey houses as shown in Figure 7. Single storey houses were also cleaned out if not totally washed away as shown in Figure 8. In the Mission Beach and Cardwell areas maximum levels of inundation reported were of the order of 200 mm with minimal structural damage and only moderate damage to contents in general as shown in Figure 9.

Figure 5. Back Lawn at Tully Heads

Figure 6. Back Lawn at Port Hinchinbrook

Figure 7. 2 Storey house on seaward side of road at Tully Heads. (Same property as Figure 6)

On the positive side at Tully Heads, the upper floor and roof of most 2 storey homes suffered little or no structural damage with loss of some guttering the main loss, and one house appeared to have escaped the destruction altogether as shown in Figure 10. Significantly this latter house was on stumps which allowed the surge to go under the house without putting significant forces on it.

Figure 8. Single storey houses at Tully Heads - one washed away

Figure 9. Marks on chair leg and cane settee show depth of storm surge inundation at Port Hinchinbrook

Figure 10. Undamaged house at Tully Heads close to sea
(Photo G.N. Boughton)

The pattern of damage highlighted a number of factors.

- The level of the ground floor of a building relative to the Highest Astronomical Tide (HAT) level is important
- Buildings can survive in storm surge locations if the ground floor is above the maximum water level experienced and the substructure is designed to allow the water to flow largely unimpeded beneath – although possible scour needs to be taken into account
- 800 mm inundation by storm surge is destructive but 200 mm is not, indicating that if the cyclone had crossed about 8 hours later on high tide there would probably have been mass destruction at Tully Heads, and major destruction along the coastal strip from Bingil Bay to South Mission Beach, and in the Cardwell – Port Hinchinbrook area.
- If well designed for wind, as most of the houses were at Tully Heads, floor levels above inundation level can be safe havens.
- A large storm surge coinciding with ordinary high tide has the potential to cause a catastrophic disaster where large communities have been constructed in low lying coastal areas.

Design Implications

Currently the Building Code of Australia does not provide criteria for the design of buildings at risk from storm surge. It is assumed that this is a land zoning issue to be controlled by local flood risk by-laws with life safety being ensured by evacuation. Both these approaches have their limitations. Flood risk zoning tends to be based on excluding construction on land with an annual risk of inundation more than 1 percent, which would allow construction in many areas at risk from a major storm surge, since at any location the risk of a major storm surge is low in the first place, and the risk of it occurring at high tide reduces the risk still further. Evacuation may be practical in small isolated communities but may not be in large communities at risk – eg those located on low lying coastal areas in the vicinity of Cairns, Townsville and Mackay – especially in relation to major events like Yasi. Furthermore evacuation may limit loss of life but it does not limit the economic cost of disasters which in recent years has become just as important (Walker et al, 2011). No lives were lost in the 2011 Brisbane River flood but the economic cost made it a major disaster. A similar level of storm surge damage in Cairns, Townsville or Mackay would not be considered acceptable by the community.

The performance of buildings in Yasi did demonstrate that there is potential for mitigating storm surge damage by appropriate building design irrespective of location. It is the height of the lower floor above the astronomical highest tide level in addition to minimising the resistance to flowing water under it that is important. Buildings well designed in this respect, as well as for wind, can be safe havens minimising the risks associated with large scale evacuations.

These factors were recognised in the United States many years ago and structural design criteria established to deal with them. Construction is permitted in areas at risk from storm surge but the ground floor must be at a specified level above HAT and the substructure under the floor must be designed to allow the surge to flow through it relatively unimpeded and to take possible scour into account. The detailed guidelines for construction in coastal high hazard areas are published by the Federal Emergency Management Agency (FEMA, 2011). In this document the design criteria differentiates between the area at significant risk from wave action in addition to the surge flow, known as the V-Zone, and areas behind the V-Zone which is at risk from the surge flow only, which is known as the A-Zone. There appears to be a strong argument for adopting a similar approach in storm surge risk areas in Australia.

A significant weakness of the approach in the US is that the specified minimum level of the lowest floor corresponds to an annual risk of inundation of 1%. Because of the very low tidal range along most of the south eastern US coastline, the normal tide level at the time of maximum storm surge does not have as significant an effect on the maximum water levels as it does in Australia. However it is still inadequate for extreme hurricanes.

There is a major difference between wind damage and storm surge damage. In general wind design criteria needs to be exceeded by a significant degree before there is a high risk of destruction over a large area. This is not so for storm surge damage. The difference between high tide and low tide can be the difference between no damage and catastrophic damage over a considerable area. For this reason there needs to be much more caution in the specification of the lowest floor design level. There would seem to be a strong argument for adopting at least the same level of risk as adopted for wind design – ie for the water level arising from combined storm surge, tide and wave set up which has an average frequency of exceedance of less than once on 500 years – as a minimum requirement. From the point of view of individual building safety this may be adequate. However it may not be adequate if the building is a multistorey building to be used as a safe haven for a considerable number of people, or is part of a large community equally at risk from the storm surge and thus posing the potential for a major disaster. With their focus on individual building safety only and no regard given to community impact in the event of design criteria being exceeded, current structural codes do not address this latter issue, a weakness which the author believes needs addressing (Walker et al. 2011). It is particularly important in respect of storm surge because of the greater sensitivity to design criteria being exceeded. The recently promulgated Queensland Coastal Plan (DERM 2012) is based on the traditional approach to flooding incorporating an annual risk of 1% of inundation of houses in storm surge prone localities, a criterion which in the opinion of the author seriously underestimates potential magnitude of storm surge disasters from housing damage and will do little to mitigate the magnitude of disasters arising from extreme storm surges such as Yasi. Housing at this level of risk from storm surge is only insurable at very high premiums unless subsidised by the ret of the population.

Conclusions

Cyclone Yasi produced one of the largest storm surges experienced in modern times on the Queensland coast. Had the eye crossed the coast at high tide instead of low tide the consequences could have been catastrophic. The intense damage it caused in the small community of Tully Heads should be regarded as a warning from which lessons can be learnt. Buildings can be built in areas at risk from storm surge which will be safe both structurally and as a haven for their occupants, but design criteria is needed to achieve this. In this respect much can be learned from the US, but a much lower risk needs to be incorporated if the risk of a major disaster from storm surge is to be mitigated.

Acknowledgements

This paper is based on a report prepared by the author for the investigation of Cyclone Yasi undertaken by the James Cook University's Cyclone Testing Station for the Australian Building Codes Board. The author's involvement in this study was part sponsored by Aon Benfield Australia. The opinions expressed in the paper are those of the author and not necessarily those of the above organisations.

References

Boughton G N, Henderson D J, Ginger J D, Holmes J D, Walker G R, Leitch C J, Somerville L R, Frye U, Jayasinghe N C, Kim P Y (2011) Tropical Cyclone Yasi Structural Damage to Buildings. Technical Report 57, Cyclone Testing Station, James Cook University, Townsville. www.jcu.edu.au/cts

BoM, (2011) Queensland 1918, a devastating couple. Bureau of Meteorology, Melbourne, www.bom.gov.au

DERM (2011) Coastal Impacts Unit, Department of Environment & Resource Management, Queensland Government.

DERM (2012) Queensland Coastal Plan, Department of Environment & Resource Management, Queensland Government. www.derm.qld.gov.au

FEMA (2011) Coastal Construction Manual, 4th Edition, FEMA P-55, Federal Emergency Management Agency, Washington. www.fema.gov

Stark K P (1980) Management solutions for storm surge. In: Oliver J (ed) Response to Disaster, James Cook University, Townsville.

Walker G, Grundy P, Musulin R (2011) Disaster risk reduction and wind engineering, Proc. 13th International Conference on Wind Engineering, Amsterdam.