Flood vulnerability

Testing sea level rise effects

Even a small sea level rise can have major impacts, according to a physical model investigation of wave overtopping at Tamaki Drive carried out by Matthew McQueen, Aaron Falconer, Tom Shand and Heide Friedrich.

Tamaki Drive is a key arterial route, running along the coastline of Auckland's Eastern suburbs. The road is, however, exposed to the Hauraki Gulf, with the seawall vulnerable to wave overtopping during storm events. In recent years this has occurred on a number of occasions when strong northeast winds coincide with high tides.

A significant example of this occurred during ex-Tropical Cyclone Ita on 17 April 2014. That morning, strong northeast winds (>30 knots) generated large waves (>1 metre) which, combined with a moderate high tide and a storm surge, resulted in severe wave overtopping (Figure 1).

The overtopping flows caused flooding of the road and adjacent properties. Consequently, there were significant hazards to pedestrians and vehicles, with commitment of resources from emergency management and time delay to commuters as the road was closed. This event put the issue of coastal inundation into the spotlight and also raised questions around whether sea level rise would lead to this becoming a more common occurrence.

In order to accurately forecast such hazardous conditions and assess current and future vulnerability of roading infrastructure, better information on the precise combination of parameters likely to result in significant overtopping is required. While empirical modelling can provide general approximations of overtopping for generic seawall types, physical model testing enables inclusion of site-specific conditions, such as seawall shape and material.

A collaborative research project between the University of Auckland, Tonkin + Taylor, and Auckland Civil Defence was undertaken to better understand the mechanism responsible for overtopping events along Tamaki Drive and test the effect of future sea level rise.

A physical model was constructed in the University of Auckland's Hydraulic Engineering Laboratory, using a 25-metre wave flume, with a scale of 1:10. The model represented a typical cross section based on a site survey of the Tamaki Drive seawall at the western end of Kohimarama. This was the site of the worst observed wave inundation. The model replicated the sloping rock face, vertical seawall that protects the road and the shallow seabed offshore of the wall (Figure 2).

Wave conditions occurring along Tamaki Drive during ex-Tropical Cyclone Ita were determined using Tonkin + Taylor's inner Hauraki Gulf numerical wave model. Waves were found to reach a significant height of 1.4 metres with a mean period of 3.2 seconds and wavelength of 15 metres. The maximum water level was recorded at the Port of Auckland at 2.06 metres above Auckland Vertical Datum 1946 (AVD46, approximately mean sea level), comprising a 1.66 metre AVD-46 high tide and 0.4 metre storm surge.

A mechanical wave paddle position at the end of the flume was calibrated to produce a scaled irregular wave series representative of modelled conditions offshore of the wall. Incident photos and reports from the time validated this modelled wave height as a fair representation, with the choppy irregular waves being driven by the onshore wind channelled between the offshore islands in the Hauraki Gulf. These very steep waves would have been on the verge of breaking as they reached the Tamaki Drive wall.

Each laboratory test lasted 10 minutes, representing 30 minutes in full scale. The irregular waves produced by the paddle in ‘deep water’ conditions travelled over the ‘shallow water’ false floor to impact squarely the scaled seawall model. The interaction with the seawall was recorded using a high speed camera, allowing for qualitative classification of wave overtopping. Overtopping flows were collected in a catch tray behind the model to enable the measurement of overtopping volume.

Tests were completed for five different water level scenarios; the first was at 2.06 metre AVD46, representing the conditions during Cyclone Ita. The second water level tested was 2.13 metre AVD46, corresponding to a one percent Annual Exceedance Probability (AEP) storm level for that part of the Auckland region (Stephens et al., 2013). Additional testing was then undertaken adding 0.2 metres, 0.5 metres and 1.0 metres to this one percent AEP level to test three different future sea level rise (SLR) scenarios. Under the highest SLR scenario, the seawall crest had a freeboard of just 10 centimetres.

Wave overtopping can be classified as both ‘white water’, when an aerated splash from a wave impacting the seawall is carried over the wall, and ‘green water’, when a constant stream of denser water flows over the seawall. Both types were recorded by observers during Cyclone Ita and testing found that both were present across all scenarios. Interestingly, the ratio of ‘white water’ to ‘green water’ overtopping waves was roughly 40:60, and remained constant even as the total number of overtopping incidents increased with the increase in sea level.

This is a reflection of the irregular nature of the wave heights and therefore variations in the relative freeboard for each wave, with a positive freeboard leading to ‘white water’ overtopping, as the wave impacts the wall compared to a negative freeboard where the wave peak is higher than the seawall and therefore flows over it (Figure 3).

While the increase in the number of overtopping waves followed a generally linear trend, discharge volumes at higher sea levels increased in a more exponential manner. To allow for comparability of the results, overtopping flows were converted into average litres per second per linear metre (L/s/m). This is the unit used in the *Coastal Engineering Manual* (USACE, 2006) and *EurOtop Overtopping Manual* (Pullen et al., 2007) which provide guidance on tolerable and intolerable overtopping flows.

For the modelled five-metre wide section (scaled to 0.5 metre), mean overtopping flows were 5.1 L/s/m for Cyclone Ita compared to 7.0 L/s/m for one percent AEP storm tide level. Flows increased to 17.9 L/s/m with 0.2 metres of sea level rise above the one percent AEP level and 46.3 L/s/m with 0.5 metres sea level rise (Figure 4). All results therefore were well above the 0.4 L/s/m value which is considered unsafe for vehicles at any speed and 1.0 L/s/m value above which it is considered very dangerous for pedestrians (USACE, 2006).

For the 0.5 metre sea level rise scenario, discharge is approaching the 50 L/s/m threshold value above which the *Coastal Engineering Manual* suggests that damage to the seawall and the pavement behind is likely.

Overtopping flows during one metre sea level rise would far exceed these critical values and would likely result in significant damage to the current seawall and/or pavement. In our tests we could not accurately record discharge results due to the very high volume of overtopping caused by the very small relative freeboard of the seawall. Additionally, due to the gaps in the crest wall that allow access to a number of stairwells along Tamaki Drive, inundation at higher sea levels will occur regardless of the wave conditions.

As a result of testing, a number of conclusions can be reached:

1. Wave overtopping is potentially hazardous to pedestrians and vehicles at relatively low mean overtopping rates. This is critical for locations such as Tamaki Drive that are both major arterial routes and popular recreational spaces.
2. The volume of overtopping is very sensitive to small changes in the water level. Even 0.2 metres of sea level rise

Figure 1: Overtopping along Tamaki Drive during ex-Tropical Cyclone Ita.

Figure 2: Scale model data collection and development within the University of Auckland wave flume.

Figure 3: Examples of the 'white water' (above) and 'green water' (below) overtopping wave impacts.

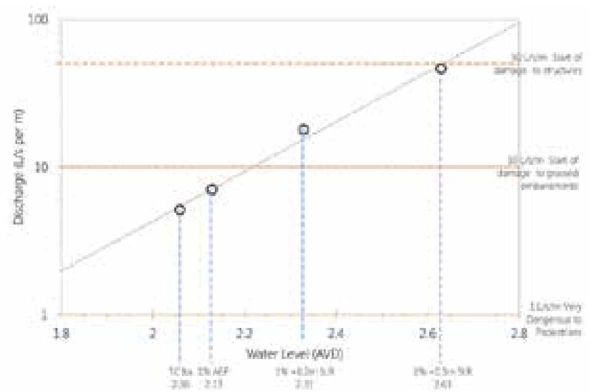

Figure 4: Modelled mean overtopping flows relative to water level and compared to tolerable flows

would lead to at least double the volume of overtopping discharge for similar wave events.

3. Hazardous events would become more frequent under future sea level rise and the magnitude of large events would increase, potentially leading to damage of seawalls and pavement surfaces.
4. Areas not currently susceptible to hazardous wave overtopping could become hazardous with future sea level rise.

For this study physical modelling has improved the understanding of the mechanisms responsible for wave overtopping. Results can be used to calibrate empirical models and allow predictions of overtopping frequency at this and nearby locations, thus enabling asset managers to make informed decisions on future maintenance and upgrade.

The results will allow development of improved early warning systems protecting the public from exposure to hazards and minimising transport network delays. Finally, such research serves to educate the public to the risks of coastal inundation and the potential impacts of future sea level rise. Education and engagement of the public is critical to developing resilient and sustainable communities. **WNZ**

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This study was undertaken by Matthew McQueen and Aaron Falconer as a final year Engineering honours project at the Department of Civil and Environmental Engineering (DCEE), University of Auckland with supervision from Heide Friedrich (DCEE) and Tom Shand, Tonkin + Taylor, Civil and Environmental Engineers.