Extract from Proceedings 1998 IPENZ Conference, Auckland, Volume 3, pp. 113-118.
Winner, Fulton Downer Gold Medal, best technical paper, 1998 IPENZ Conference
Winner, Brian Brown Award, best water-related paper, 1998 IPENZ Conference

The Museum of New Zealand - Flood Protection Lessons

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1. Introduction

The Wellington Regional Council has published a map [1], [2], [3] identifying as tsunami hazard zones about 6 sq km of Wellington, including the entire downtown Wellington business district from the harbour to Lambton Quay. For these areas, where a significant part of the regional population congregates during daytime hours, the "Big One" is likely to be a tsunami, not an earthquake as is generally assumed.

With an intended design life specified of some 500 years or more, the Museum of New Zealand development has from the beginning given far greater emphasis to sustainable design than is usual for building projects. Because the new Museum is located well inside the designated Wellington tsunami hazard zone, the Project Development Board recognised early that at least one major tsunami event was a high probability within a building design life of this order, so that planning for the building to survive such an event was essential.

This paper describes the engineering analysis performed to determine the design tsunami, and the design measures adopted to provide protection against major losses during such an event. Further development of such analysis and design will be needed before the Sustainable City (our Conference Theme) can be established in any coastal area.

2. Historical Tsunamis

According to ancient writings, a great tsunami ended the fabled Atlantis, being so severe that not only was the infrastructure destroyed, but also the capacity for reconstruction. In addition to the apparent loss of critical economic and military mass, the death or loss of status of essential technical specialists may have been a major factor in the collapse of the civilisation. Atlantis can therefore be regarded as the classic "Non-Sustainable City", where an urban state ceased to exist entirely through inadequate tsunami defences.

While accounts of the destruction of Atlantis verge on pre-history, and the exact location of the event is still the subject of much scholarly argument, great historical tsunamis have been observed [4] in two favoured areas: near Crete on 21 July 365 and in the Atlantic Ocean off the Straits of Gibraltar on 1 November 1755. The latter event is generally known as the "Lisbon Earthquake" as much of that city was destroyed by the earthquake and subsequent tsunami. As established by reliable benchmarks, the 1755 tsunami reached levels between 10m and 20m above sea level at Lisbon, and considering the damage done to a relatively modern city including thousands of deaths, could well have been comparable to the wave which overwhelmed Atlantis.

Undoubtedly the favourite of the Hollywood disaster industry was the event on 27 August 1883, when the Krakatau (Krakatoa) volcano exploded in the Sunda Strait separating the

Indonesian islands of Sumatra and Java. Tsunami run-up heights of up to 36m were recorded, and the devastation was almost total in the coasts facing the strait. However, the effects must have dissipated rapidly beyond the strait, as Batavia (now Jakarta) was only 150 km from the explosion centre, yet the tide gauge survived throughout to record fourteen waves in 36 hours.

Japan has an unhappy history of frequent tsunamis, especially on the north-east “Sanriku” coast of the main island of Honshu, where the so-called “Meiji Great Sanriku” tsunami of 1896 claimed over 21,000 lives and had a maximum runup of more than 30m above mean sea level, while a tsunami in 1611 in the same area is rated as even larger [5], and a smaller event in 1933 still claimed over 3,000 lives.

By comparison, New Zealand is less prone to both earthquakes and tsunamis, with the one recent major urban earthquake (Napier 1931) generating only a sudden withdrawal of water from the inner harbour [4]. Presumably the dominance of this single event on the public impression of hazards in New Zealand can be blamed for the lack of weight since given to preparedness for tsunamis in comparison with earthquakes, in contrast with the relatively balanced approach of the Japanese with their far greater awareness of both risks. The Napier earthquake happened to generate a sudden rise in coastal levels which made onshore tsunamis unlikely, but there is no reason to regard this one event as typical.

The three tsunamis in recent New Zealand history having the largest effects on the coast in general [6] all originated from earthquakes off the west coast of South America, where frequent very large earthquakes are generated by a high rate of strain of the plate boundaries. The relevant earthquakes occurred on 16 August 1868, 10 May 1877 and 22 May 1960, and generated waves of amplitude (i.e. half the peak-to-trough range) of 0.8m, 0.8m and 0.5m respectively in Wellington Harbour. Considerably larger waves were observed elsewhere, particularly in the 1868 tsunami which had a peak-to-trough height of 7.6m in Lyttelton Harbour, and ran up to 6 km inland in the Chatham Islands, drowning an unknown number of people in a Maori village.

Tsunamis pose a continuing threat, with the most recent disaster in the Asia-Pacific region being the Flores Island event in Indonesia on 12 December 1992. This caused runup of up to 20m above sea level, with 2080 deaths following a common pattern of being caused roughly 50% by the earthquake and 50% by the following tsunami.

3. Tsunami Design Guidelines

3.1 Existing Guidelines

There are no New Zealand building code guidelines for tsunami design.

The only hints come from Approved Document E1 “Surface Water” [7] issued by the Building Industry Authority, where Clause E.1.3.2 specifies “Surface water, resulting from a storm having a 2% probability of occurring annually, shall not enter buildings.” “Buildings” are limited to “Housing, Communal Residential and Communal Non-residential buildings” and “Surface water” is defined as “All naturally occurring water, other than sub-surface water, which results from rainfall on the site or water flowing onto the site, including that flowing from a drain, stream, river, lake or sea.” While it is arguable that a tsunami produces “water flowing onto the site” from a “stream, river, lake or sea”, it cannot be seen as “resulting from a storm” of any probability. A proposed revision to change the word “storm” to “event” is under consideration, but generalisation of one word in the code can hardly be said to signal a commitment to defining and enforcing an explicit set of procedures to be followed in designing against tsunami hazards.

The Wellington Regional Council maps tsunami hazard limits in the central city which appear to coincide with a Thorndon Quay/Lambton Quay/Wakefield Street boundary, along a contour of roughly +2.5m NCD (New City Datum), according to Wellington City Council maps [8]. NCD is 0.902 m above harbour Chart Datum, or 0.128 m below the latest [9] Mean Sea Level, so this contour is 2.4m above Mean Sea Level or 1.6m above high spring tides. However, within this contour are areas which are significantly lower, such as the intersection of Grey St and Customhouse Quay which is only 0.7m above high spring tides [8], within the reach of wave amplitudes which have already occurred twice in the last 150 years.

By identifying the area below 2.5m NCD as an “area of tsunami inundation”, the Wellington Regional Council have imposed some requirement on developers to consider tsunamis, and warnings to “obtain professional advice on implications and available countermeasures” should be taken seriously. However, the information provided again falls well short of providing a standard for use in design against tsunami inundation.

3.2 Historically Based Guidelines

Given that tsunami wave amplitudes have reached 0.8m twice in the last 150 years, with a further tsunami reaching 0.5m amplitude, it seems reasonable on historical grounds to assign an amplitude of 0.8m in Lambton Harbour a return period of about 50 years, so that the lower streets in Wellington could expect to be flooded now by such a tsunami occurring at high spring tide. (In fact all three major historical tsunamis appear to have occurred near low tide, so that by the next high tide the largest waves had fortunately passed). If accelerated sea level rise occurs as predicted by the latest climate change scenarios (e.g. [10]), the area at risk even from such a one in 50 year event will expand to most of the designated hazard area within the life of buildings now under construction. This raises the question whether such buildings can even now meet the requirements of Approved Document E1 if they can be entered by surface water from an event with this relatively modest return period.

3.3 Analytically Based Guidelines

Gilmour [6] used energy spectrum records of recent tsunamis to estimate that for a 100-year return period, wave amplitudes of 1.4m might be expected at resonant wave periods of around 30 minutes at the entrance to Wellington Harbour. Using well proven mathematical models, Barnett et al [11] showed that the amplitude of 30 minute waves at the harbour entrance would be doubled in Lambton Harbour by long wave resonance effects. This gives a wave amplitude of 2.8m in Lambton Harbour for the 100 year return period. A comparable effect with tides is confirmed by standard Navy charts [12], which show the tidal ranges in Lambton Harbour are approximately double those outside the harbour entrance at Cape Terawhiti.

A plot of the wave at various points in Lambton Harbour generated by applying a sinusoidal wave of 1m amplitude (mean level = 1.00m) at the entrance to Wellington Harbour is reproduced from [11] as Figure 1 for ready reference. Note the wave produced is asymmetrical, almost doubling the forcing wave amplitude on the first of the two peaks, while more than doubling the trough amplitude.

Far from providing protection from tsunamis as popularly supposed, Wellington harbour is therefore likely to double their height as it does for tides. This is not surprising, because tsunamis are long "tidelike" waves [13], hence their former name of "tidal" waves.

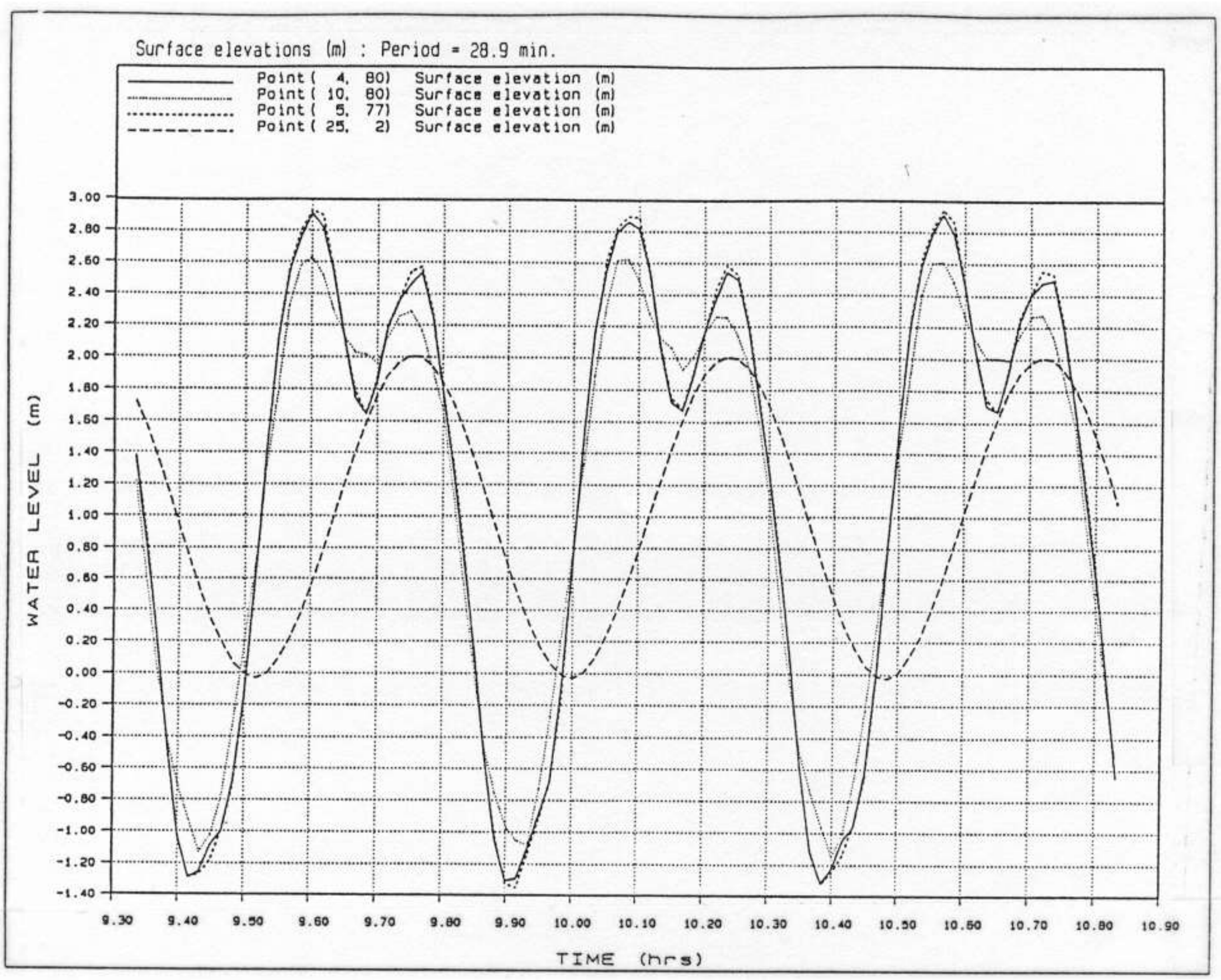

Figure 1: *Wellington Harbour Resonance Simulation for sinusoidal wave input, period = 28.9 minutes, amplitude = 1.0m. Time series plots of surface elevations outside harbour entrance compared to points located in and around Lambton Harbour.*

4. Analagous Hazard Design Approaches

4.1 Analogy with Local Storm Drainage

A return period approach is normally provided, as in Document E1 of the building code. As storms of greater than 50 year return period have obviously been experienced in recent history in many areas, there is an implied tolerance of design failure in limited areas provided the causative storm events can reasonably be associated with long return periods.

4.2 Analogy with River Control

A return period approach is again provided, although there is some informal linkage with the cost of failure. Earlier practice was for “some of the works in moderately developed rural areas being designed against a five year frequency flood and other works protecting intensively developed urban or rural areas, being designed up to a 100 year frequency standard” (Acheson [14]).

In the 1960’s, a 100 year return period flood was practically equivalent to the largest historical flood in European history, but as Doull [15] points out, a 100 year flood has a 26% chance of being equalled or exceeded during a typical flood control scheme life of 30 years, and indeed several floods clearly greater than 100 year return period have occurred in the last 30 years.

Doull was able to create flood depth scenarios using the MIKE 11 UD hydraulic modelling package and the ARC/INFO GIS system, and then use economic analysis based on insurance records and individual property valuations to show a clear justification for using a design return period of at least 1000 years for river control through Palmerston North.

This result of formal analysis appears to match intuitive community judgements, as experience of floods greater than a 100 year return period (for example in Gisborne during Cyclone Bola in March 1988) results in willingness to pay for higher standards. The extra cost of protection against a 1000 year flood is not perceived as forbiddingly high in comparison with the reduction in hazard, and in practice any failure of flood control schemes under super-design conditions leads to a call for higher standards of protection.

Attitudes to flood protection should be transferable to tsunami protection in an enlightened community by reference to, say, Japanese experience with the use of quite ordinary stopbanks [5] for successful tsunami protection since the 1960 Chilean tsunami. Sadly, however, direct and tragic local experience of major tsunami flooding may be required before the connection is made.

4.3 Analogy with Earthquakes

A return period approach as discussed above is not explicitly followed for earthquake design, at least as understood by the author, who disclaims specialist expertise in this area. Park [16] summarised the approach of “seismic codes in Japan, New Zealand and other countries” as “structures are made capable of yielding in a ductile manner during a major earthquake and brittle collapses are avoided.” How a “major earthquake” is defined implies indirect return period considerations, but it is difficult to believe such terminology would apply to an event with a return period less than a few hundred years. For the purposes of this paper it will therefore be taken that earthquake designers are required to consider events with a return period of at least several hundred years.

It is also clear from [16] that seismic codes are not fixed, but are continually re-evaluated from experience with major events when they occur.

4.4 Discussion

For river control schemes and earthquake design, community expectations appear to support return periods of several hundred years for design purposes, whereas a lower return period of the order of fifty years appears to be tolerated for local drainage design. The following factors appear to have an influence:

(a) Local flooding usually affects buildings by relatively slow moving flows, which pond up around the foundations. These cause considerable nuisance if they rise above floor levels, but are not perceived as life threatening. In contrast, river control or earthquake design failures may occur too rapidly for individual reactions to be effective in avoiding casualties.

(b) Local flooding is progressive, so that a 100 year event is only marginally worse than a 50 year event, for example flooding say 2% of buildings instead of 1%. In contrast, river floods or earthquakes will have minimal effects below a certain trigger level, but a large and uncontrolled effect above that level. The additional costs of raising that trigger level tend to be small compared with the damage associated with failure.

(c) If an upgrade in local drainage standards is perceived to be necessary, this may be undertaken piecemeal by progressive improvements of the existing drainage network within annual budgets. An effective solution is often simply to raise those houses found to be most under threat. In contrast, retrofitting structures to an upgraded earthquake design standard is very expensive compared with designing them to a conservative standard from new. Progressive upgrades of river control works may also not be possible if a new stopbank alignment is required, so that previous works have to be abandoned or even removed.

(d) Local flooding typically affects only a minority in the community, and those with little influence tend to be over-represented in flood prone housing. On the other hand, the hazard from earthquakes or river control failures affects the majority of the community, and such failures also tend to attract dramatic media coverage, so it is easier to justify mobilising community resources on a large scale.

Clearly, in terms of these factors, the tsunami hazard can be classed with river control and earthquake hazards rather than local drainage hazards, justifying tsunami design for a return period of at least several hundred years. This coincides with the design brief for the Museum, as the Sustainable City also ought to have a life expectancy such that the occurrence of a tsunami with a return period of a few hundred years is highly probable.

4.5 Development of Criteria

The adoption of a return period of several hundred years raises the difficulty of predicting the characteristics of such an event from the limited experience of the last 150 years. In river control and earthquake problems, this is not seen as a barrier to developing design standards, but for tsunami work the problem cannot be treated statistically as a stationary process (that is, a process the probability distribution of which is time-independent), because of the continuing rise in sea level. A rise of 0.128m since the “New City Datum” was established means that, for example, the 1868 tsunami would now rise some 13 cm higher than historically observed. This may not seem much, but in view of the trigger level effect described above, a change of this magnitude at critical points would make the difference between minimal damage and significant damage. The accelerated rate of rise now anticipated through human-induced global warming aggravates this problem (also calling into question assumptions that storms can be treated statistically as a stationary process for river control design).

Two approaches seem appropriate to this problem:

A. In deep water, the effect of sea level rise on the transmission of waves can be neglected. Therefore, the statistics of tsunamis arriving at the entrance to harbours and bays can be treated as stationary, and the time dependence taken into account by routing these arriving waves into shallow water (and overland where peak levels exceed ground levels) using well proven mathematical modelling.

B. Examine records of major tsunami events to evaluate the performance of predictive models - this is comparable with the approach taken in [16] to re-evaluate the performance of existing codes in the light of experience with the Hanshin earthquake. For Wellington, the obvious case in addition to the three Chilean tsunamis is the tsunami following the 1855 earthquake, of which there are several eye-witness accounts (e.g. in [17]).

5. Museum Design

The above considerations were brought to bear in relation to the proposed Lambton Harbour site on the design of the Museum against tsunami hazards.

The results are presented in [11] but can be summarised as follows:

(a) Gilmour's estimate for 30 minute waves of 1.4m external amplitude was used for design. On historical evidence Gilmour's assessment may seem conservative for a 100 year return period, but certainly not in the context of a return period of several hundred years.
(b) This amplitude converted to 2.8m peak height above mean level at the Museum site through the effect of harbour resonance (see Figure 1).
(c) A mean harbour level of 1.5m above chart datum (or 0.6m NCD) was assumed, corresponding [9] to Mean High Water Springs. (Coincidence of the design tsunami with extreme spring high tides would seem unduly pessimistic.)
(d) A rise in general sea levels of 0.5m was allowed for "greenhouse" effects. This would apply near the beginning of the proposed design life if pessimistic forecasts are accepted, or near the end of the proposed design life if optimistic forecasts are accepted.
(e) The total of 2.8m wave amplitude plus 0.6m for high tide plus 0.5m for sea level rise was rounded up by 0.1m to a design tsunami level of 4.0m above New City Datum. Note this design tsunami would inundate the boundary of the tsunami hazard zone marked on the Wellington Regional Council map [1] to a depth of some 1.5m. Since the 2.8m wave amplitude applies only to Lambton Harbour, the 4.0m design level should not be used outside the downtown Wellington area.
(f) An additional problem was identified by examining the records of the 1855 tsunami (and also other tsunamis), which showed clear evidence of a single wave running high up the beach directly following the main earthquake shock. This wave reached higher than any subsequent waves but was of very brief duration, limiting its damage potential. On physical analysis this was determined [11] likely to be an "immediate wave" caused by the collapse shorewards of the mound of water thrust upward by the sudden seaward movement of a breastwork or beach through the lateral ground displacement caused by the earthquake.
(g) The height reached by an immediate wave striking the vertical wall of a building depends on the intermediate quay height, the distance of the wall from the harbour edge, the duration

and magnitude of the lateral ground displacement, and the height of the breastwork acting as wave generator. Figure 2 shows the wave height produced by computational modelling for the design case based on 1855 earthquake parameters of a full depth breastwork moving 4.9m laterally in 1 second, with a quay level of 3.5m (chart datum) and width of 16m. The maximum wave height reached was 6.3m (chart datum). For a building within 6m of the harbour edge, the maximum immediate wave height came to 8m (chart datum) or 7.1m (NCD).

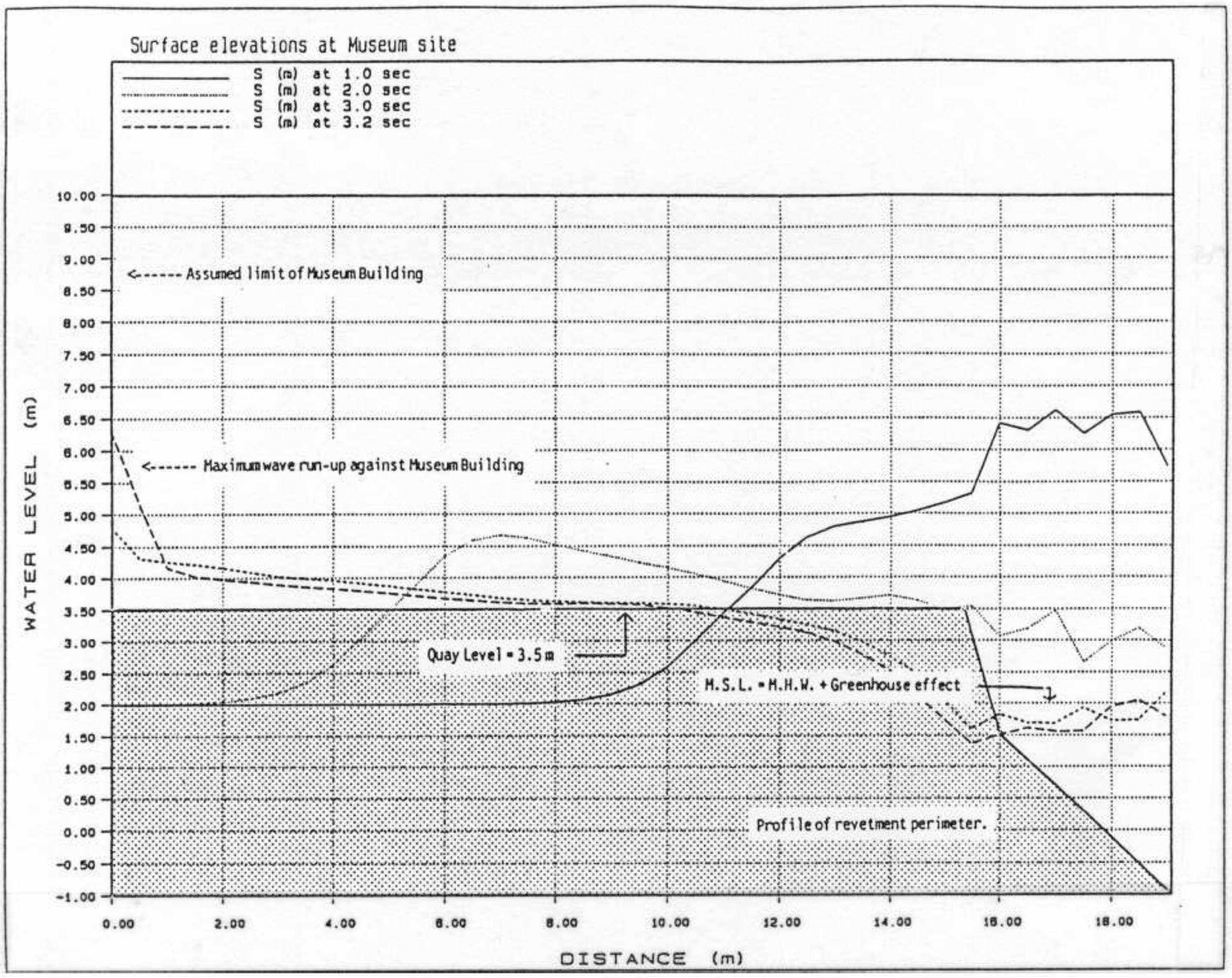

Figure 2. *Cross-section through Museum site of water surface elevations at 1.0, 2.0, 3.0 and 3.2 seconds. Limit of Museum Building assumed to be 16m from harbour edge revetment.*
As a result of this analysis, the Museum was designed [18] with entry floor level of 3.8m NCD and main floor level of 8.1m NCD. It was decided that the entry floor level would mainly consist of car parking space which could be cleared in the event of warning of a major remote tsunami, so dropping just below the recommended design level of 4.0m NCD was justified, while the main floor was set 1m clear of the most pessimistic estimate of the immediate wave height.

Since this entry floor level was still 1.3m above the adjacent Cable St, a considerable mound was constructed to raise the whole building site by the required amount. This can readily be seen by visitors to the site as indicated by the recent photograph in Figure 3.

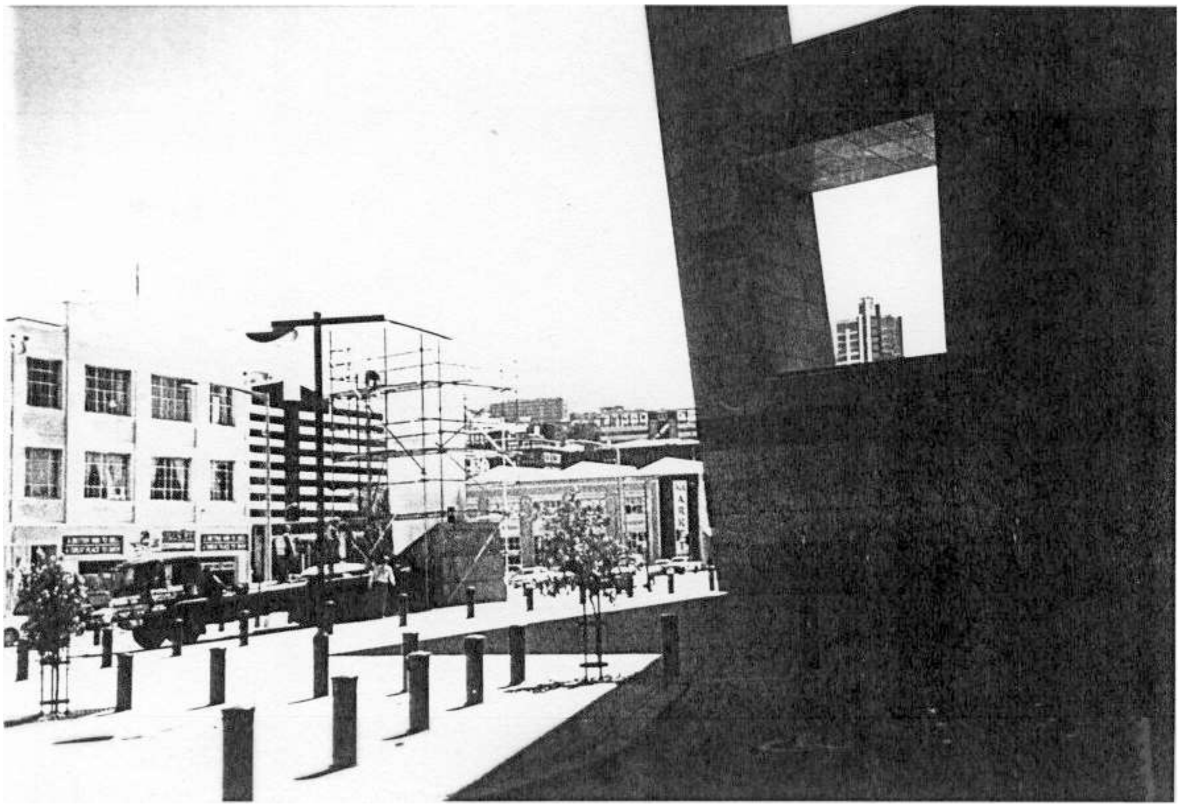

Figure 3. *Photograph of Museum Forecourt looking west along Cable Street. Note slope from site ground level down to Cable St indicated by angle of truck on left of picture.*

Note that areas adjacent to Cable St are even lower lying, so that the Museum entry floor level is almost 2m above most of Wakefield St and 2.2m above the intersection of Grey St and Customhouse Quay. In the event of the design tsunami, these streets will be flooded by fast flowing harbour waters to these depths while the Museum will be only marginally flooded at the entry level, with paved surfaces preventing damage from scouring.

Protection against the design tsunami could be provided for the entire inner city by the construction of a floodbank around Lambton Harbour to a design height of 4m NCD. This would also largely protect against an immediate wave provided the bank was hardened enough to withstand overtopping for a few seconds. Such a bank would be comparable in scale to the existing river floodbanks protecting Lower Hutt against a comparable hazard. Without this, Wellington must continue to be a less Sustainable City than Lower Hutt.

6. Conclusions

1. The Museum of New Zealand is being designed for a life expectancy of some 500 years, comparable with that of the Sustainable City (the conference theme).
2. The new Museum is located well inside the tsunami hazard zone designated by the Wellington Regional Council, so there is a high probability of at least one major tsunami event during the required design life.
3. A number of historical examples illustrate the severe impact of major tsunamis on cities. Atlantis is the classic “Non-Sustainable City”, where an urban state ceased to exist entirely through inadequate tsunami defences.

4. Planning for the building to survive a major tsunami is therefore essential. However there are no New Zealand guidelines for the design of tsunami defences.
5. Historical records from Wellington Harbour suggest a wave amplitude of 0.8m can be assigned a return period of about one in fifty years.
6. Mathematical modelling shows some tsunami amplitudes at the harbour entrance will be doubled in Lambton Harbour. The well documented doubling of Cook Strait tidal amplitudes inside Wellington Harbour supports this conclusion.
7. Analogies can be drawn with design practice for local storm drainage, river control, and earthquakes. The tsunami case appears closest to river control and earthquake design, for which the return period considered is several hundred years.
8. Community attitudes to hazards seem heavily conditioned by local experience, so that direct and tragic experience of major tsunami flooding may be required before precautions are taken comparable with those successfully applied in Japan.
9. The problem of predicting a major tsunami event from limited local experience is proposed to be overcome by adjusting for sea level rise only within harbours, and by examining records of major events for consistency with predictive models.
10. A design level of 4.0m NCD is derived for the downtown Wellington area around Lambton Harbour. This would inundate the boundary of the Regional Council tsunami hazard zone to a depth of some 1.5m.
11. The possibility in an 1855 type earthquake of an immediate wave of limited damage potential briefly striking the building to a height of 7.1m was also raised.
12. The Museum site was therefore raised well above surrounding streets to provide an entry floor level of 3.8m NCD, mainly for parking, with the main floor level at 8.1m NCD, well clear of possible attack from an immediate wave.
13. Protection against the design tsunami could be provided for the entire inner city by the construction of a floodbank comparable to that protecting Lower Hutt against a hazard of similar probability.
14. Apart from the Museum, Wellington continues to be a less Sustainable City than Lower Hutt until this is done.

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Acknowledgements

The author wishes to thank the Museum of New Zealand Project Director, Mr T.G. Shadwell, for permission to publish design material, and JASMAX for providing the final design floor levels.