



Western Ring Route – Waterview Connection



Interpretation of Hydrodynamic Design Conditions Report



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1. Introduction

The 'Waterview Connection Project' is the final key project to complete the Western Ring Route (WRR). In 2009 the NZ Transport Agency (NZTA) confirmed that the Waterview Connection Project (Project) would be lodged with the Environmental Protection Authority as a Proposal of National Significance (RoNS). The Project will be the largest roading Project undertaken in New Zealand, and due to its size and complexity has been divided into nine Project Sectors. These Sectors broadly define the different planning and construction requirements of the Project. A diagram of these Sectors is presented in Figure 1.1.

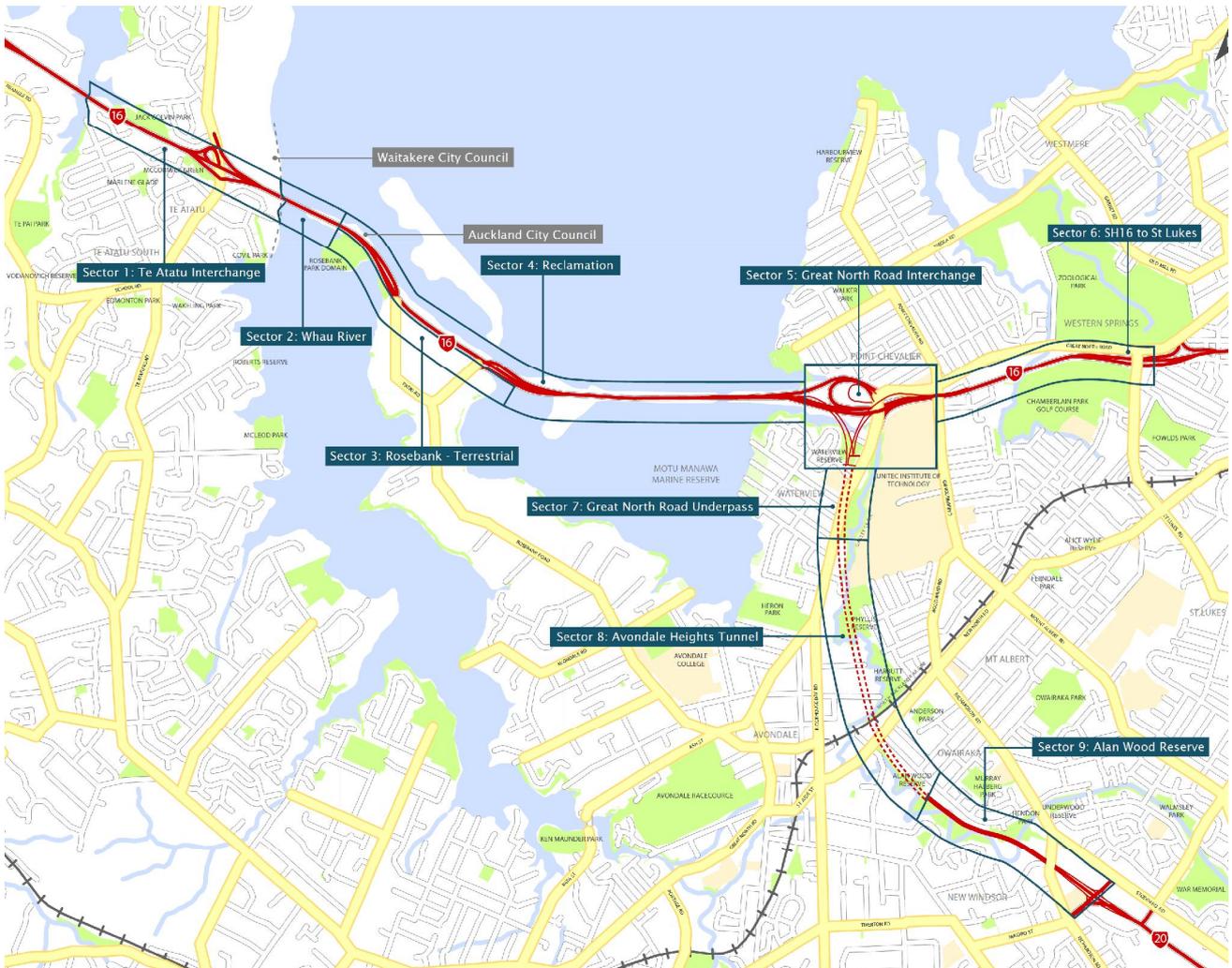


Figure 1.1 - Waterview Connection Project Sector Diagram

The improvements to SH16 provided as part of the Waterview Connection Project are approximately 8km in length, extending from the St Lukes Road Interchange to Henderson Creek, and will primarily consist of widening the existing motorway with additional lanes to accommodate the increased traffic demand from SH20.

The SH16 alignment between the Great North Road and Te Atatu Road Interchanges passes through an estuarine area, crossing parts of the central Waitemata Harbour. From the Great North Road Interchange to the Rosebank Road Interchange, and between the Patiki Road Interchange and Whau River, sections of the carriageway are formed on low man-made embankments and the improvement works will require reclamation of the Coastal Marine Area (CMA).

The section of SH16 between Great North Road and Rosebank Road is commonly referred to as the 'Causeway' (see Figure 1.2). The majority of the reclamation required for the improvements will be along the northern and southern edges of the Causeway. The ground conditions found adjacent to the Causeway are poor due to the underlying very soft Recent Alluvium (marine mud).



Figure 1.2 – Photograph of the Causeway

1.1 Report Purpose and Scope

The NZTA has confirmed the following Project Objectives for the Project:

1. To contribute to the region's critical transport infrastructure and its land use and transport strategies:
 - by connecting SH16 and SH20 and completing the Western Ring Route; and
 - by improving the capacity and resilience of SH16.
2. To improve accessibility for individuals and businesses and support regional economic growth and productivity:
 - by improving access to and between centres of future economic development.
3. To improve resilience and reliability of the State Highway network:
 - by providing an alternative to the existing SH1 corridor through Auckland that links the northern, western and southern parts of Auckland; and
 - by securing the SH16 Causeway against inundation.
4. To support mobility and modal choices within the wider Auckland Region:
 - by providing opportunities for improved public transport, cycling and walking; and
 - by protecting opportunities for future passenger transport development (e.g. rail).
5. To improve the connectivity and efficiency of the transport network:
 - by separating through traffic from local traffic within the wider SH20 corridor.

For the Project to comply with the Project Objectives, SH16 must be widened to improve capacity and provide opportunities for improved public transport, cycling and walking. The elevation of the motorway Causeway between Great North Road and Rosebank Road, and between Patiki Road and Whau River, will also need to be increased to prevent inundation and therefore improve resilience.

Where reclamation is required, the philosophy has been to carefully define the extent needed to accommodate the reclamation, permanent occupation and any necessary temporary works. Therefore all design elements that might affect the overall footprint of the enlarged reclamation have to be fully assessed.

The Coastal Works Report forms the summary of a suite of documents that cover, in detail, the engineering works required within the CMA and justification for their extents. The Coastal Works Report is accompanied by three main supporting documents. A summary diagram showing the relationship between the engineering investigations and analysis that support the Coastal Works Report is presented in Figure 1.3. As shown in Figure 1.3, this report (Interpretation of Hydrodynamic Design Conditions) forms one of the three main supporting documents to the Coastal Works Report. Figure 1.3 also shows the linkages between this report and other technical assessments.

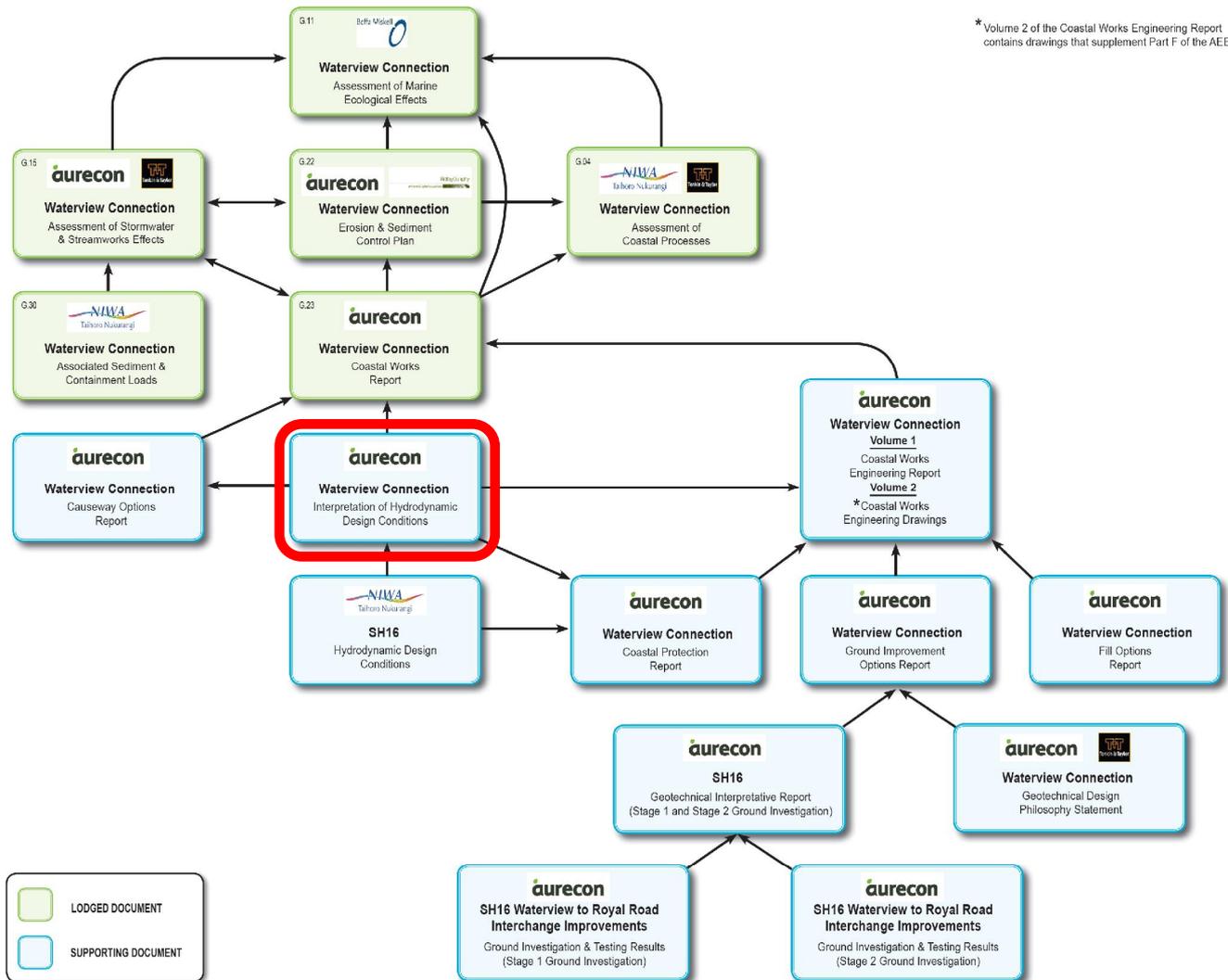


Figure 1.3 – Reports Supporting Causeway Resource Consents

This report defines the design performance requirements the Causeway engineering must achieve taking into consideration the effects of climate change. It also establishes the elevation and coastal protection measures for the motorway embankment to secure future operation of the motorway.

1.2 Report Structure

This report defines the performance requirements for the Causeway. It focuses its attention on Chapter 7 (Causeway overtopping and armour stability) of the Hydrodynamic Design Conditions report^[1]. The factors that will inform the coastal protection design arrangement and crest level required of the Causeway are considered in Chapter 7 of the Hydrodynamic Design Conditions report^[1]. The primary factor which dictates design of the Causeway is wave-induced overtopping onto the carriageway resulting in a safety hazard to traffic, which occurs at lower storm-tide water levels than those that cause actual coastal inundation.

This report is structured as follows:

- **Methods** – outlines the methods and design approach used to establish the Causeway performance requirements. Key outcomes are also summarised;
- **Harbour Water Level** – defines the present day water levels based upon hydrodynamic modelling undertaken by NIWA. Using this information the projected water levels are determined by taking the latest sea-level rise projections;
- **Overtopping** – defines the measures required to protect the safe operation of the motorway up to the 2090–2099 design horizon. The measures were established by using overtopping simulations carried out by NIWA that take into consideration future climatic conditions. It primarily assesses the wave overtopping onto the northern edge of the proposed Causeway using rock armour thickness, revetment gradient, crest width and crest elevations as distinct variables;
- **Conclusions** – provides the conclusions to the overtopping assessment; and
- **Recommendation** – provides recommendations.

2. Methods

The National Institute of Water & Atmospheric Research (NIWA) were engaged by Aurecon to provide coastal analysis as an input into the engineering design and planning process. This report has been written to provide a summary and interpretation of NIWA's analysis, presented in the Hydrodynamic Design Conditions Report ^[1] issued in 2009. This will form the basis for a coastal protection system for the proposed Causeway that is future proofed against wave overtopping to a 2090–2099 design horizon.

The primary factor which dictates the design level of the Causeway is wave overtopping onto the carriageway, caused by the combination of extreme storm-tide water levels and wave conditions, resulting in wave overtopping of “green water” from run-up volumes and wave splash causing a safety hazard to traffic.

The NIWA coastal simulations for wave overtopping discharges are presented as mean overtopping rates and not the peak overtopping rate. The limiting rate for mean wave overtopping for the “unsafe for vehicles at high speed” threshold is 0.02 l/s/m and this has been used as part of the assessment. It is recommended that this threshold is used, as it is considered reasonable to assume vehicles would not be travelling at high speeds in heavy rain and/or high winds likely to accompany coastal storm events.

At the time of writing the Hydrodynamic Design Conditions Report in 2007, NIWA assumed that a rock-armoured revetment type structure (similar to the existing protection) would be used to protect the flanks of the proposed Causeway. Other forms of protection were not considered by NIWA in their overtopping assessment.

NIWA assessed the following variables to understand the most suitable design configuration to be used within the Causeway revetment:

- crest elevation (3m, 3.5m, 4m, 4.25m, 4.5m or 4.75m);
- width of crest (0.75m or 3m);
- double or single layer rock armour; and
- revetment slope (1:1 or 1:2).

Crest elevation excludes any allowance for ground consolidation and settlement following build up of the proposed Causeway.

The wave overtopping performance of the proposed design with a crest elevation of 3.0mRL is:

- sufficient for a storm with an Average Reoccurrence Interval (ARI) 200 year Joint Return Period with a 0.59m increase in sea level by the 2090s; and
- sufficient for a storm with an ARI 70 year Joint Return Period with an increase in sea level of 0.80m by the 2090s.

It was found that in order to satisfy a storm with a 100 year ARI Joint Return Period with an increase in sea level of 0.80m by the decade 2090 to 2099, a 3.06mRL crest elevation would be required. A 3.0mRL crest level is proposed given the uncertainties regarding the future impact of climate change and the practicalities of placing rock boulders to an accuracy of ± 0.01 m. Therefore, a 3.0mRL crest level is considered sufficient to

provide security of the motorway to the 2090–2099 design horizon using the present knowledge regarding increase in sea-levels.

Given the uncertainties regarding the impact of climate change, as stated above, it is necessary that the proposed Causeway has allowance to be modified to respond to any changes to the present sea-level rise projections. The proposed 3m wide crest increases the adaptive capacity, as this could be utilised to increase the Causeway elevation in the future by reducing the crest width to accommodate an increase in crest elevation.

If increasing the elevation of the Causeway is required (above the proposed 3.0mRL crest elevation) it is anticipated that no further ground improvements would be necessary. The founding marine muds below the widened Causeway extensions would have increased in strength over time due to consolidation resulting from these new loads. This could potentially allow greater loads (i.e. additional fill material) to be imposed upon the founding material without creating new instabilities. This would only be possible in the future if the Causeway required further raising but not widening.

Consenting for a Causeway footprint which is sufficiently wide for future-proofing is therefore recommended. Elements of the proposed Causeway profile have been future-proofed to allow greater flexibility should sea-level rise be higher than what can be accommodated with the proposed design. These future modifications, if necessary, should not require any additional reclamation.

3. Harbour Water Level

3.1 Present Day Water Level

Data from the Port of Auckland (PoA) Tide Gauge, in conjunction with hydrodynamic modelling was used to account for change in tide and storm surge characteristic between the PoA and the Causeway location. The modelling process was used to determine the present day extreme storm-tide water levels (Table 3.1) at the Causeway's northern side. The water levels below comprise high tides and storm surge (temporary increase in sea level due to a reduction in atmospheric pressure and influence of wind stress on the sea surface) but do not include wave influence. These estimates are from a best-fit Weibull model but do not include uncertainty bounds, which increase with increasing ARI. These extreme storm-tide levels would only apply for approximately 1–1.5 hours around the high-tide period of the 12.4-hour tide cycle. Refer to Chapters 1–3 of NIWA's Hydrodynamic Design Conditions Report^[1] for a detailed explanation of the modelling and extreme analysis methodology.

Average Recurrence Interval (ARI) (Years)	Present Day Water Level (m AVD-46)
0.1	1.83
0.2	1.89
0.5	1.95
1	1.99
2	2.04
5	2.10
10	2.15
20	2.20
50	2.26
100	2.31
200	2.35
500	2.42

Table 3.1: Extreme Storm-Tide Water Levels relative to Auckland Vertical Datum 1946 (m AVD-46)

3.2 Projected Water Levels

The present day extreme storm-tide levels in Table 3.1 were supplemented with the mean sea-level change projections up to 2090–2099, that were based on values published by the Intergovernmental Panel on Climate Change (IPCC) in their 4th Assessment Report published in 2007.^[2]

The IPCC (2007) projections for sea-level rise were used as the basis for developing the 2008 Ministry for the Environment (MfE) Guidance Manual for Local Government on Coastal Hazards and Climate Change^[3], and therefore the IPCC (2007) projections used in NIWA's 2007 study are compatible with the MfE Guidance Manual.

NIWA incorporated two values for sea-level rise projections in its hydrodynamic assessment. The variables in water level that have been modelled by NIWA are “present-day sea levels”, “present day +0.59m” and “present day +0.80m”. The +0.59m sea-level rise by 2090–2099 is the upper value from various climate–ocean model simulations for the high CO₂ emissions A1F1 scenario in the IPCC (2007) 4th Assessment Report (the A1F1 emissions scenario is a rapid economic growth, fossil fuel intensive scenario).

IPCC (2007) also stated that if Greenland and Antarctica ice sheet contributions to sea-level rise were to grow linearly with global temperature change (over and above the rate observed between 1993–2003), an additional 0.1–0.2 m sea-level rise could be expected at the upper range of projections from climate–ocean modelling. Therefore, a +0.80 m rise by 2090–2099 is at the upper end of the IPCC (2007) projections. This value is also the minimum second-tier sea-level rise (together with a baseline first-tier value to be considered of 0.5 m) that is recommended by the MfE (2008) Guidance Manual. There is a possibility that sea-level rise by 2100 could be even higher, up to or exceeding 1m, if ice-sheet discharges begin to accelerate rapidly.

At this stage, given:

- a) the uncertainties in sea-level rise;
- b) that extreme conditions will only occur around high tide;
- c) the Causeway forms a critical component of the SH16 Motorway and the Auckland motorway network; and
- d) that elements of the Causeway can be future-proofed to allow for future increases in crest height;

the upper sea-level rise projection of +0.8m is a reasonable estimate to use for designing the Causeway upgrade and providing the footprint of the Causeway to be sought in consents.

Table 3.2 represents the projected storm-tide levels, for the northern side of the Causeway, incorporating the sea-level rise components of +0.59m and +0.80m for 2090–2099.

Storm intensities are likely to increase due to climate change and this has been accommodated within the hydrodynamic assessment. NIWA have adopted a conservative wind-intensity increase of 20% for 2090–2099. However, no change in atmospheric pressure of storms was invoked in the study, due to greater uncertainties on likely trends and because waves (and hence winds) are the more critical aspect to design for.

As outlined above, it is recommended that the highest of the two projections used by NIWA (+0.80 m sea-level rise) be used for design purposes.

The NZTA Bridge Manual^[4] requires Ultimate Limit State for floods be designed to 1/2500 Annual Exceedance Probability (AEP) and 1/5000 AEP. These return periods are outside the capabilities of the NIWA study (due to the relatively short historical sea-level records available). However, the extreme storm-tide ARI relationship is quite flat as shown by the 0.06–0.07 m difference in extreme water levels between a 200-year and 500-year ARI event. This flat extreme-event curve is due to physical bounds on tide levels (most of the possible high tide levels occur within the nodal 18.6 year cycle) and physical limits on storm intensities (winds/pressures) in the New Zealand situation where we are not subject to hurricanes or tropical cyclones, and therefore our storm surges are relatively low (< 1m) and limited compared to other countries. Further work would be required to determine what coastal inundation event will be used for Ultimate Limit State design.

It should be noted that NIWA’s study does not include an assessment for tsunami events.

Average Recurrence Interval (ARI) (Years)	Storm-tide Water Level		
	Present day (m)	SL + 0.59m water level (m)	SL + 0.80m water level (m)
0.1	1.83	2.42	2.63
0.2	1.89	2.48	2.69
0.5	1.95	2.54	2.75
1	1.99	2.58	2.79
2	2.04	2.63	2.84
5	2.10	2.69	2.90
10	2.15	2.74	2.95
20	2.20	2.80	3.00
50	2.26	2.86	3.06
100	2.31	2.91	3.11
200	2.35	2.97	3.17
500	2.42	3.03	3.24

Table 3.2: Extreme Storm-Tide Water Levels relative to Auckland Vertical Datum 1946 including two sea-level rise projections to 2090-2099

4. Overtopping

4.1 Northern Revetment

NIWA's simulation of the existing northern sidewave climate suggests: "the wave climate is generally benign with more than 60% of the time exhibiting waves smaller than 50mm in height, but significant wave heights can reach 0.60m during high adverse winds".^[1]

NIWA has simulated the wave climate for 2100 taking into account the two sea-level rise scenarios (+0.59m and +0.80m) and adopted a wind intensity increase of 20%. From Figure 5.5 of NIWA's Hydrodynamic Design Conditions report, it is suggested in 2100 the northern sidewave climate is still relatively benign but significant wave heights during adverse winds would rise from 0.60m (present day) to 0.70m (2100).

NIWA simulated a range of joint-probability water level and wave conditions for both present day and future climate-change projections, and applied these against a range of Causeway configurations and coastal protection measures. For each configuration, the assessment provided (for different average joint return periods) the potential mean wave overtopping volumes and the probability that there will be at least one wave overtopping event in a sequence of waves (defined in the NIWA study as 1000 waves or approximately a 1 hour period). The design variables that make up the range of Causeway configurations that were assessed included:

- double or single layer rock armour;
- revetment slope (either 1:1 or 1:2);
- width of revetment crest (either 0.75m or 3m); and
- crest elevation (3m, 3.5m, 4m, 4.25m, 4.5m and 4.75m).

At the time of writing the Hydrodynamic Design Conditions Report, NIWA assumed that a rock-armoured revetment type structure (similar to the existing protection) would be used to protect the flanks of the Causeway. Other forms of protection were not considered by NIWA as part of its overtopping assessment.

Figure 4.1 is a sketch showing an indicative rock armour revetment slope.

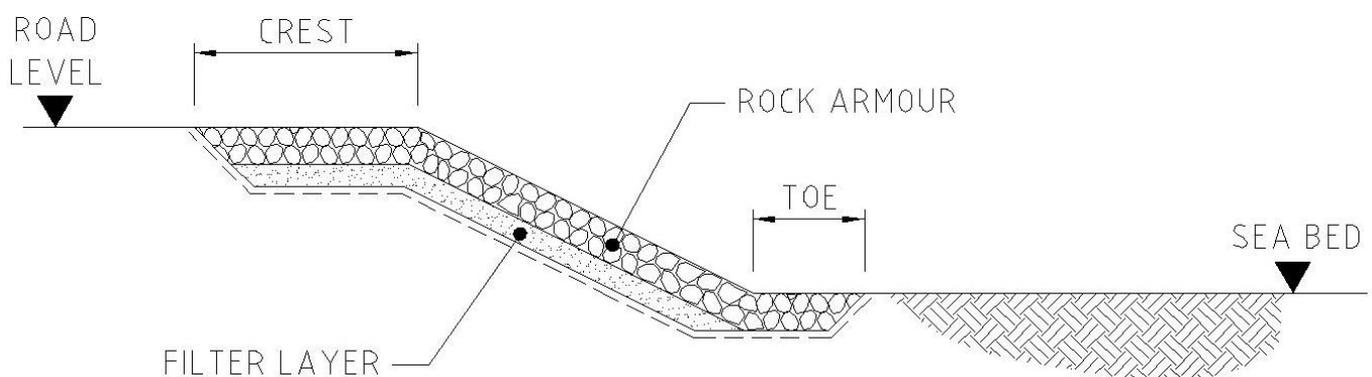


Figure 4.1 – An indicative rock armour revetment slope

4.1.1 Rock Armour Layers

Rock armour coastal protection consists typically of two layers of primary armour. The thicker the primary layer the better the wave energy absorption and wave run-up reduction. It also provides better protection against wash out of underlying filter layers, a more consistent protection (i.e. less risk of "large holes" due to variation in rock sizes), and additional protection when some damage has occurred in a storm event. A one layer primary armour system would require larger diameter primary armour and additional underlying filter layers. A one layer armour has therefore been discarded as a design variable and two layers of primary armour is proposed.

4.1.2 Revetment Slope

The decision to use a 1:2 revetment slope in the design is based on standard coastal engineering design principles. Within the industry, typical rock armour coastal protection structures are designed for slopes up to 1:1.5 maximum, but preferably at flatter slopes. Steeper slopes increase construction and maintenance effort and the risk of slope instability, and also generally require larger sized armour. It is also noted that current ground conditions at the Causeway are poor (estuarine muds), which would further increase the risk of instability. A 1:1 slope has therefore been discarded as a design variable and thus a 1:2 revetment slope is proposed. Further analysis and design optimisation regarding the revetment slope is recommended during detailed design, which would include physical modelling.

Therefore, from an overtopping aspect, the crest elevation and width of the Causeway remain the unknowns and require further investigation.

4.1.3 Crest Width

NIWA's assessment compares mean overtopping discharges of both "green water" (from run-up of waves) and wave splash for limiting structural values with those for vehicle safety.

It is a key requirement for the motorway Causeway to remain operational during large storm-tide events, but it was considered reasonable to assume vehicles would not be travelling at high speeds due to heavy rain and/or high winds. For the Causeway protection measures to perform to this safety level, an overtopping water discharge below 0.02 l/s/m must be achieved, i.e. within the "unsafe for vehicles at high speed" threshold.^[5] It is suggested that this threshold is to be used as the limiting overtopping rate for design purposes.

It is recommended that the Joint Return Period, where the limiting level of overtopping rate (0.02 l/s/m) should not be exceeded, is the 100 year ARI in 2100 for the +0.59m sea level rise, and the 50 year ARI in 2100 for the +0.80m sea level rise.

It should be noted that NIWA's overtopping assessment was carried out for the 2100 scenario only and assumes no wave overtopping protection from roadside safety barriers, Bio-filters or other street furniture. Also, the overtopping analysis conservatively assumes that vehicles are travelling immediately adjacent to the edge of the proposed crest. In reality the calculated overtopping discharge may be reduced due to a distance

between the edge of the crest and the live traffic lanes. However, for future proofing and to allow more flexible use of the Causeway it is considered prudent not to reduce the calculated overtopping discharge.

Using a 1:2 revetment slope, double layer of rock armour and the maximum value of 0.02 l/s/m for overtopping, Figure 4.2 was generated from the left-hand panels of the plots in Appendix 2 of NIWA’s Hydrodynamic Design Conditions Report. Six of these plots have been reproduced, with annotations, and included in Appendix A of this report. Note: linear interpolation was used to determine the joint return periods for the various crest levels and crest widths.

Figure 4.2 shows the joint probability (for combined wave and water levels) of exceeding the 0.02 l/s/m overtopping rate against minimum crest height for two crest widths (0.75m or 3.0m) and two sea level rise scenarios (0.59m or 0.80m).

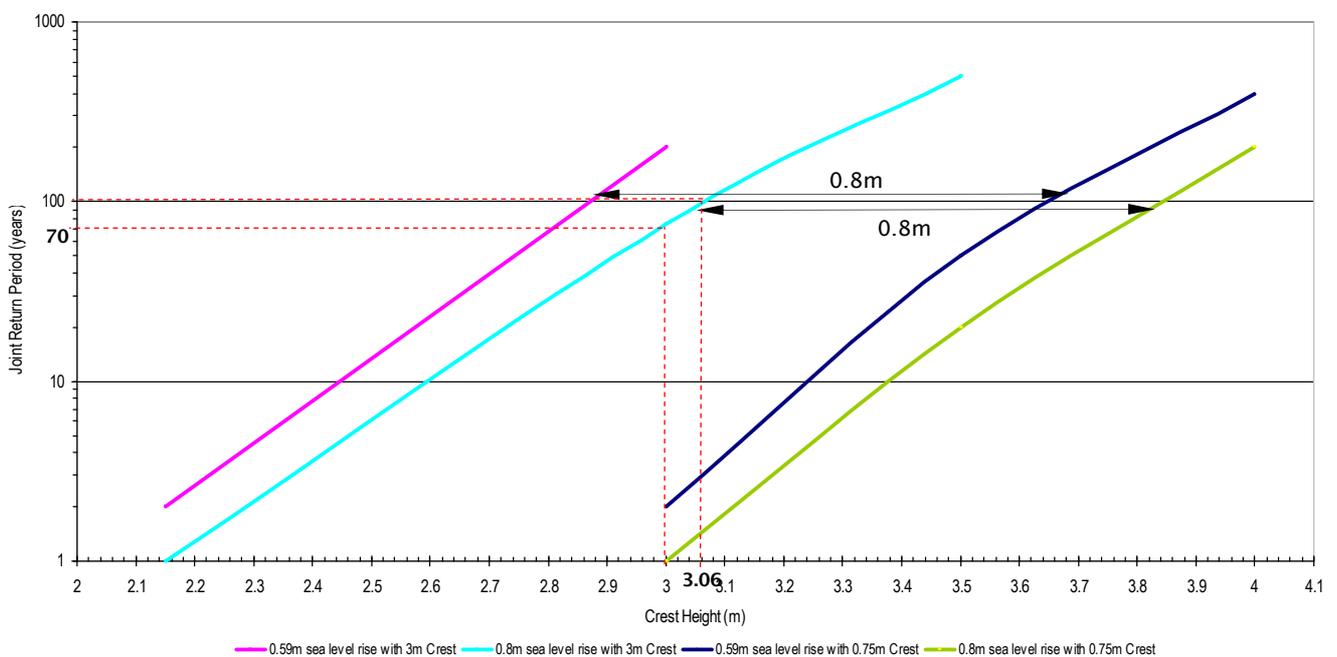


Figure 4.2 – Joint Return Period against Crest Height for the upper limit of mean wave overtopping discharge (unsafe for vehicles at high speed)

As it can be seen the two different crest widths have a greater influence in wave overtopping than the two different sea-level rise scenarios. To achieve the same joint return period exposure, a crest width of 0.75m would need to be constructed approximately 0.80m higher than a crest width of 3m. This extra 0.80m of fill would need to be placed across the entire carriageway, and therefore the volume of extra fill required would be substantial. This would demand further ground improvements to the weak underlying ground to support the additional bulk fill, resulting in greater costs and construction time. To achieve the same design performance, the Causeway footprint would be approximately 2m wider with a crest width of 0.75m compared with a crest width of 3m.

A narrow (0.75m) crest has therefore been discounted, with a 3m wide crest being preferred for the northern revetment. The wider crest also provides a buffer for future-proofing the height of the Causeway, with a narrower crest if sea-level rise by 2100 was higher than accommodated in the design outlined.

In summary, it is recommended that the northern revetment should consist of:

- 3m wide crests;
- a double layer of primary rock armour; and
- a revetment slope of 1:2.

4.1.4 Crest Elevation

NIWA states that defining the Causeway elevation will depend on the wave overtopping performance both in terms of mean discharge rate for a particular joint return period, and the peak wave overtopping probability. In this respect the Wave Overtopping of Seawalls: Design and Assessment Manual (HR Wallingford, 1999)^[5] suggests where vehicles are at risk, the probability of a peak overtopping event during a sequence of waves should be less than 1% (i.e. 0.01 as shown in the right-hand panels of each plot in Appendix 2 of NIWA's Hydrodynamic Design Conditions Report).

Owing to the sheltered harbour environment with limited wind fetch, the wave heights and wave periods are relatively small. The energy contained in these waves and the volume of overtopping expected from individual waves is relatively low. For this reason, more emphasis is placed on assessing the mean wave overtopping rate rather than reducing the probability of a single wave (in a series of 1000 waves) from overtopping the crest.

Based on the preferred revetment slope of 1:2, a 3m wide northern crest and double rock armour layer (Figure 4.2) can be used to determine the required crest elevation for wave overtopping purposes. As it can be seen (Figure 4.2), in order to satisfy a storm with a 100 year Joint Return Period with an increase in sea level of 0.80m by the decade 2090 to 2099, a 3.06mRL crest elevation is required.

A 3.0mRL crest level is proposed, given the uncertainties regarding the future impact of climate change and the practicalities of placing rock boulders to an accuracy of ± 0.01 m. The allowance of a 3m wide crest will cater for future increases in Causeway elevation, if required, to respond to any change in sea-level rise projections. Refer to Appendix B for a drawing showing the existing, proposed and a potential future Causeway typical cross section.

The future wave overtopping performance of the proposed Causeway with a crest elevation of 3.0mRL (Figure 4.2) is noted as:

- sufficient for a storm with an ARI 200 year Joint Return Period with a 0.59m increase in sea level by the 2090s, and
- sufficient for a storm with an ARI 70 year Joint Return Period with an increase in sea level of 0.80m by the 2090s.

Therefore a 3.0mRL crest level is considered sufficient to provide security of the motorway to the 2090–2099 design horizon using the present knowledge of sea-level rises.

4.2 Southern Revetment

The data within Chapter 7 of the NIWA report applies to the northern side of the Causeway only. Due to the minimal wave conditions and negligible wave overtopping anticipated on the sheltered southern side of the Causeway, the design requirements can be considerably reduced compared to the northern side.

In addition, NIWA considered the potential increase in water level on the 'inland' side of the Causeway (Waterview Estuary) caused by 100 year ARI rainstorm discharge (ARC TP108)^[6] from the Oakley catchment to the semi-enclosed Waterview Inlet Estuary behind the Causeway, with a sea-level rise of +0.8m for the 2090s (making the conservative assumption that no discharge of estuary and stream waters occur under the Causeway Bridges during a 2 hour high-tide period). Initial results based upon this conservative approach indicated an increase in water level of between 0.04m to 0.08m from the catchment run-off discharge, which was not considered significant to warrant further modelling.

However, NIWA recommended an additional 0.1m of freeboard could be added to the extreme storm-tide levels (Table 3.2) to allow for rainstorm runoff backwater effects and minor wave chop on the southern side of the Causeway.

5. Conclusions

Sea levels will increase and storm intensities are likely to increase with climate change and this has been accommodated within the hydrodynamic assessment carried out by NIWA in 2007. For changes in storms, NIWA adopted an increase in wind intensity of 20% from present-day levels to those in 2100. No change in atmospheric pressure due to climate change was invoked in the study.

As the Causeway forms a critical component of SH16 and the wider Auckland motorway network, it is recommended using +0.80m sea-level rise by 2100 rather than the alternative +0.59m rise for design purposes. The +0.80m rise is at the upper end of the projections presented in the 2007 IPCC Fourth Assessment Report, although the IPCC did state that a best estimate or an upper bound for sea-level rise could not be provided due to uncertainties surrounding the response of ice-sheets to increased warming.

At this stage, given:

- a) the uncertainties in sea-level rise;
- b) that extreme conditions will only occur around high tide;
- c) the Causeway forms a critical component of the SH16 Motorway and the Auckland motorway network; and
- d) that elements of the Causeway can be future-proofed to allow for future increases in crest height;

the upper sea-level rise projection of +0.80m is considered to be a reasonable estimate to use for designing the Causeway upgrade and providing the footprint of the Causeway to be sought for in consents.

The assessment concluded that the northern revetment will consist of:

- a double layer of primary rock armour;
- a rock armour revetment slope of 1:2;
- 3m wide rock armour crest; and
- a crest elevation of 3.0mRL.

It is noted that the 3.0mRL crest elevation excludes any allowance for ground consolidation and settlement following build up of the Causeway.

The wave overtopping performance of the proposed design with a crest elevation of 3.0mRL is:

- sufficient for a storm with an ARI 200 year Joint Return Period with a 0.59m increase in sea level by the 2090s, and
- sufficient for a storm with an ARI 70 year Joint Return Period with an increase in sea level of 0.80m by the 2090s.

It was found that in order to satisfy a storm with a 100 year ARI Joint Return Period with an increase in sea level of 0.80m by the decade 2090 to 2099, a 3.06mRL crest elevation would be required. A 3.0mRL crest level is proposed given the uncertainties regarding the future impact of climate change and the practicalities of placing rock boulders to an accuracy of $\pm 0.01\text{m}$. Therefore, a 3.0mRL crest level is considered sufficient to provide security of the motorway to the 2090–2099 design horizon using the present knowledge regarding increase in sea-levels.

Given the uncertainties regarding the impact of climate change, as stated above, it is necessary that the Causeway has allowance to be modified to respond to any changes to the present sea-level rise projections. The 3m wide crest increases the adaptive capacity, as this could be utilised to increase the Causeway elevation in the future by potentially steepening the slope gradient to 1:1.5 or reducing the crest width to accommodate an increase in crest elevation (refer to Appendix B).

If increasing the elevation of the Causeway is required (above the proposed 3.0mRL crest elevation) it is anticipated that no further ground improvements would be necessary. The founding marine muds below the widened Causeway extensions would have increased in strength over time due to consolidation resulting from these new loads. This could potentially allow greater loads (i.e. additional fill material) to be imposed upon the founding material without creating new instabilities. This would only be possible in the future if the Causeway required further raising and not widening.

Consenting for a Causeway footprint which is sufficiently wide for future-proofing is therefore recommended. Elements of the proposed Causeway profile have been future-proofed to allow greater flexibility should sea-level rise be higher than what can be accommodated with the proposed design. These future modifications, if necessary, should not require any additional reclamation.

6. Recommendations

Following the NIWA Hydrodynamic Design Conditions assessment it is recommended that:

- the northern siderevetment of the SH16 Causeway consists of:
 1. a double layer of primary rock armour;
 2. a rock armour revetment slope of 1:2;
 3. 3m wide rock armour crest; and
 4. a 3.0mRL crest elevation;
- the Joint Return Period where the limiting level of overtopping rate (0.02 l/s/m) should not be exceeded is the 100 year ARI in 2100 for the +0.59m sea-level rise and the 50 year ARI in 2100 for the +0.80m sea-level rise;
- due to the minimal wave conditions and negligible overtopping anticipated on the sheltered southern side of the Causeway the design requirements can be reduced compared to the northern side. Therefore, it is recommended that an additional 0.1m of freeboard is added to the design storm-tide level to more than cover for 1/100 AEP rainstorm runoff backwater effects and minor wave chop;
- a physical model should be developed for detailed design purposes to provide more accurate design parameters for the recommended revetment and crest configuration. The hydrodynamic modelling and analysis carried out by NIWA as summarised in the Hydrodynamic Design Conditions Report^[1] is based upon empirical equations, theoretical modelling and computer simulations. A physical model provides the ability of obtaining more accurate hydrodynamic data and will assist analysis and design optimisation of the Causeway;
- further work is undertaken to determine what flood event will be used for Ultimate Limit State design for bridge structures. The NZTA Bridge Manual requires Ultimate Limit State for floods be designed to 1/2500 AEP and 1/5000 AEP. These return periods are outside the capabilities of the NIWA study (due to the relatively short sea-level records available); and
- NIWA's study does not include an assessment for tsunami events. Further work is to be undertaken to determine Ultimate Limit State design for a tsunami event.

7. References

[1] **NIWA (2009)**, "North Western Motorway (SH16) Upgrade: Waterview to Royal Road. Hydrodynamic Conditions." NIWA Client Report HAM2007-075 prepared for Connell Wagner Ltd., June 2007 and updated October 2009.

[2] **IPCC (2007)**, "Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change" [Solomon, S. Qin; M. Manning; Z. Chen; M. Marquis; K.B. Averyt; M. Tignor and H.L. Miller (eds)]. Cambridge University Press, Cambridge. United Kingdom and New York, NY, USA.

[3] **Ministry for the Environment (2008)**, "Coastal Hazards and Climate Change. A Guidance Manual for Local Government in New Zealand". 2nd edition. Revised by Ramsay, D., & Bell, R. (NIWA), Report ME892 published by the Ministry for the Environment, URL: <http://www.mfe.govt.nz/publications/climate/#local>

[4] **Transit New Zealand (2005)**, "Transit New Zealand Bridge Manual", Second Edition 2005.

[5] **HR Wallingford (1999)**, "Wave Overtopping of Seawalls: Design and Assessment Manual." Environmental Agency R&D Technical Report W178.

[6] **Auckland Regional Council (1999)**, "Guidelines for Stormwater Runoff Modelling in the Auckland Region", ARC Technical Publication No. 108 (ARC TP108), 1999.

APPENDIX A: Summary Plots of Overtopping Performance [NIWA]

APPENDIX B: Proposed and Potential Future Causeway Cross Sections