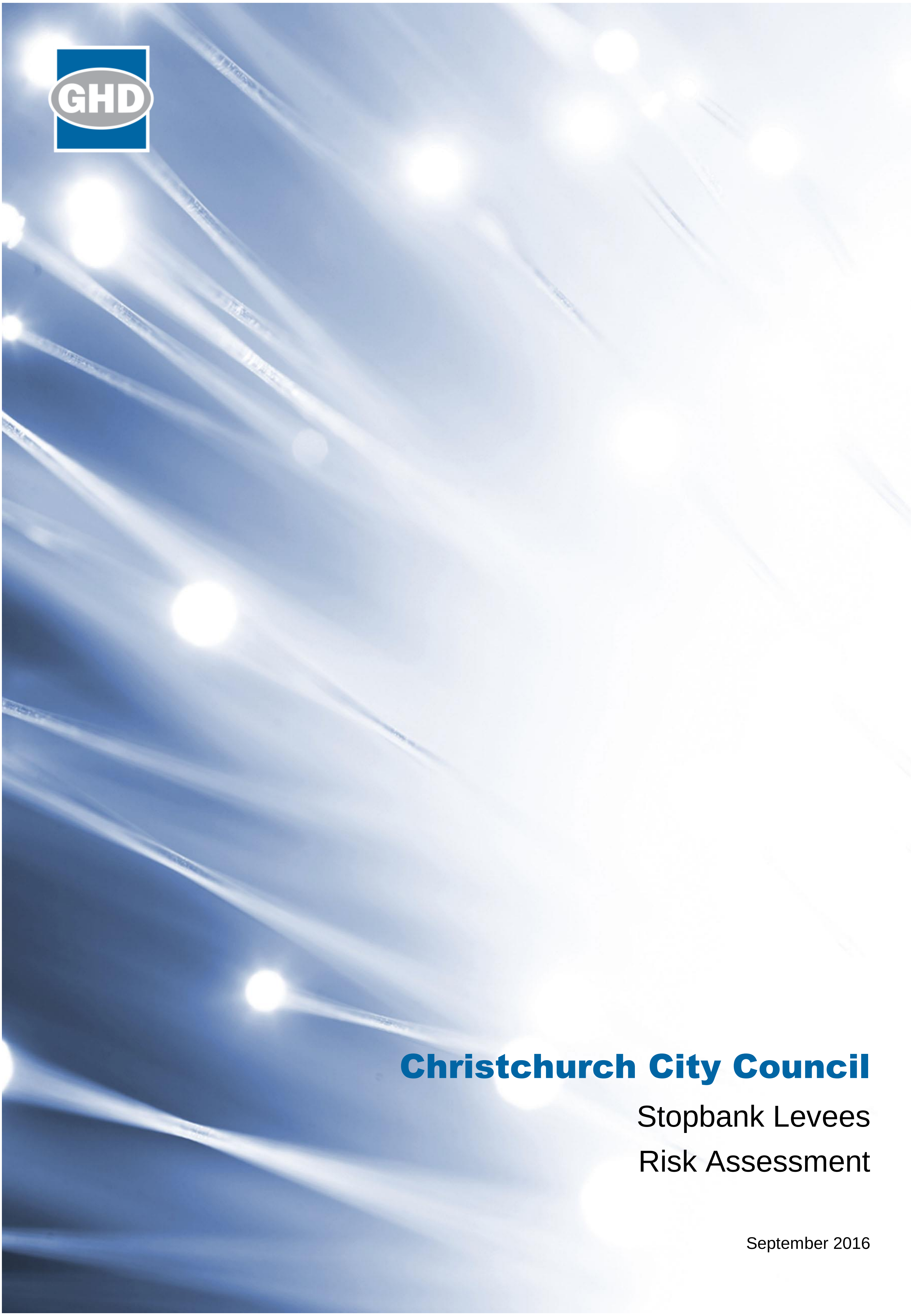


Christchurch City Council

Stopbank Levees

Risk Assessment

September 2016

Executive summary

Background

The Canterbury Earthquake Sequence in September 2010 and February 2011 caused large areas of land to change by differing amounts throughout Christchurch. Land levels fell by more than 300 mm in some areas and rose by similar amounts in others. This exacerbated flooding in several areas of the city, particularly in the tidal reaches of the Avon River. Repairs were completed to the Stopbanks with the objective to restore the river defences to a minimum level of RL 11.2 m for a 10 to 12 year design life prior to impending spring tides.

According to the Christchurch City Council (CCC) RFP for the Temporary Stopbank Management and Interim Stopbank Strengthening, the Stopbanks were considered to be near the end of their design life and the Christchurch City Council (CCC) needed to understand the risks associated with the ongoing reliance on the temporary stopbanks for flood protection.

GHD was engaged to investigate the risks, benefits and costs associated with the ongoing reliance on the Avon River temporary stopbanks, for flood protection in the tidal reaches of the Avon River. In order to achieve this, a risk assessment approach was used as follows.

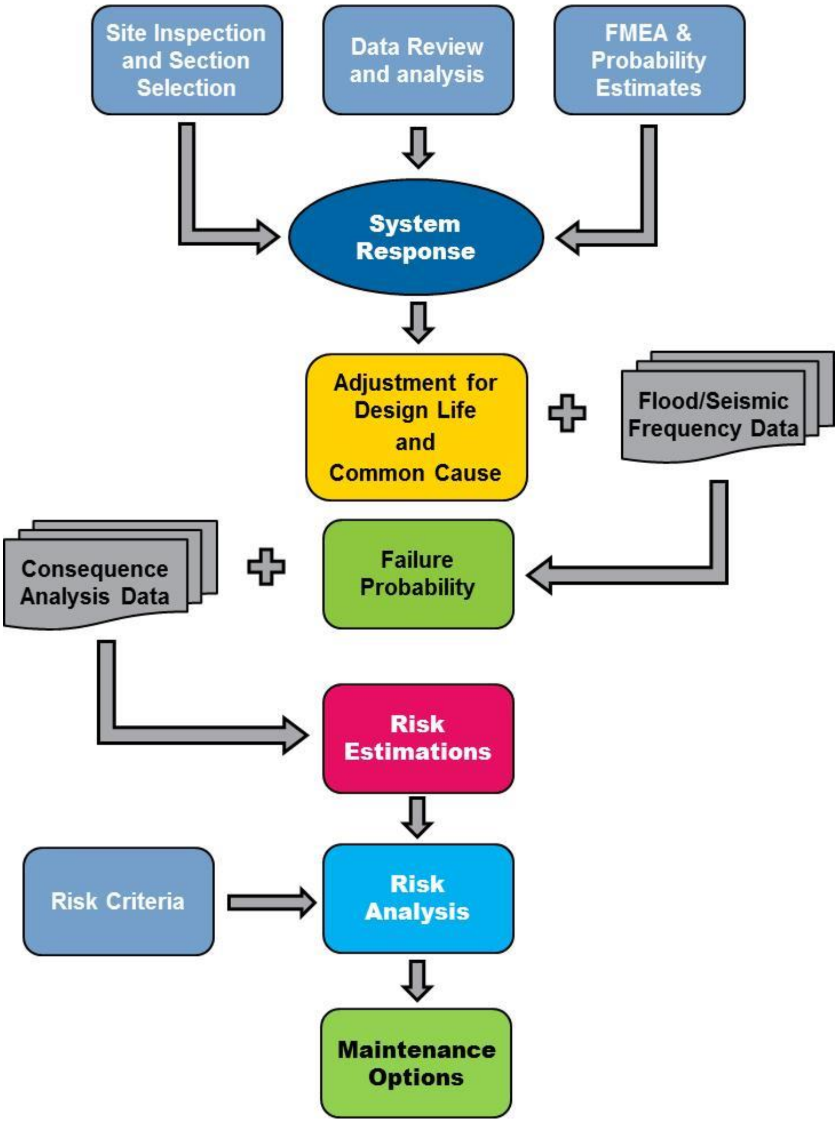
This report is subject to, and must be read in conjunction with, the limitations set out in 1.4 and the assumptions and qualifications contained throughout the Report.

Risk Assessment Methodology

The risk assessment was competed using the following process.

- Complete a site inspection of the Stopbank to familiarise the team members with the stopbank section types and general layout
- Identify typical sections for analysis in the risk assessment
- Review the available data for the stopbank remedial works and carry out additional geotechnical investigation and testing to confirm material parameters for the foundations where required
- Define the levees sections and their appurtenant structures
- Assess the possible failure modes for each section considered in the risk assessment
- Screen the hazards to determine the applicable loading conditions to be considered in the risk assessment
- Quantify the seismic, flood and tidal loading conditions
- Develop event trees for each failure mode
- Determine the probability of each event in the event trees using the piping toolbox and various other available tools from which to assess the probability of stopbank failure for each section
- Make adjustments for the failure probabilities to account for the common cause failure resulting from the seismic, flood or tidal event
- Estimate the population at risk and potential life loss (PLL) in the event of a breach for each section with consideration of flooding or tidal events
- Calculate the risk of failure as the product of the annual probability of failure and the PLL for the current temporary stopbank levees for 1, 5, 10 and 20 year design lives under the flood, tide and seismic loading

- Evaluate the risk based on current ANCOLD risk guidelines
- Make recommendations for ongoing maintenance options.



Conclusions

The risk analysis has been completed for the Avon Stopbanks with consideration of the following hazards:

- Seismic events with tidal levels varying from the annual tidal level to the 200 year ARI event.
- Tidal events alone varying from the annual tidal level to the 200 year ARI event
- Flood events alone with floods varying from the annual event to the 200 year ARI event.

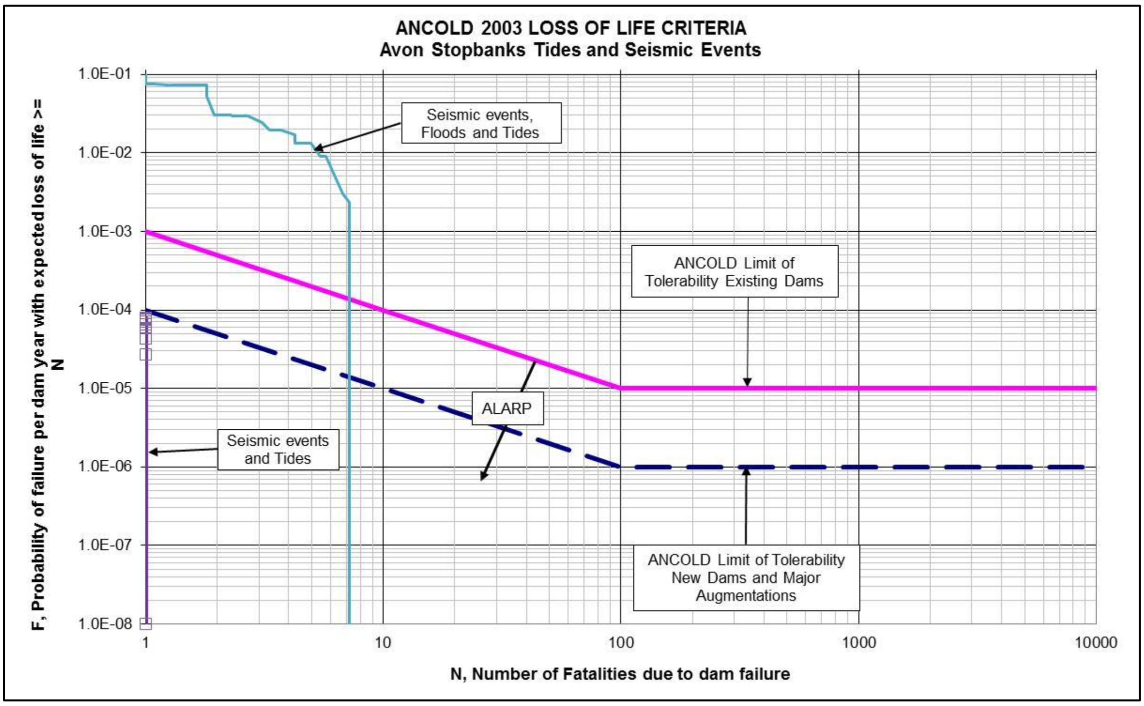
The Societal Risk for the Stopbanks is well in excess of the ANCOLD Tolerable limit for the seismic, floods and tidal events and is within the ALARP region for the Seismic and Tidal events, as shown below.

The Societal Risk plot is based on the ANCOLD 2003 Risk Guidelines and subsequent 2015 review of the guidelines currently in progress. The plot represents the probability that the loss of life is greater than or equal to N. The tolerability criteria were based on internationally acceptable tolerable limit, as presented in the 1994 ANCOLD Guidelines on Risk Assessment.

The truncation of the tolerable risk limit at 1E-5 for existing dams was based on the understanding of ANCOLD at that time of the lowest risks that could be realistically assured in light of:

- Present knowledge and dam technology.
- Methods available to estimate the risks

The Tolerable risk for new dams or major augmentations was set at an order of magnitude lower risk on the basis that current practice would result in a lower risk level.

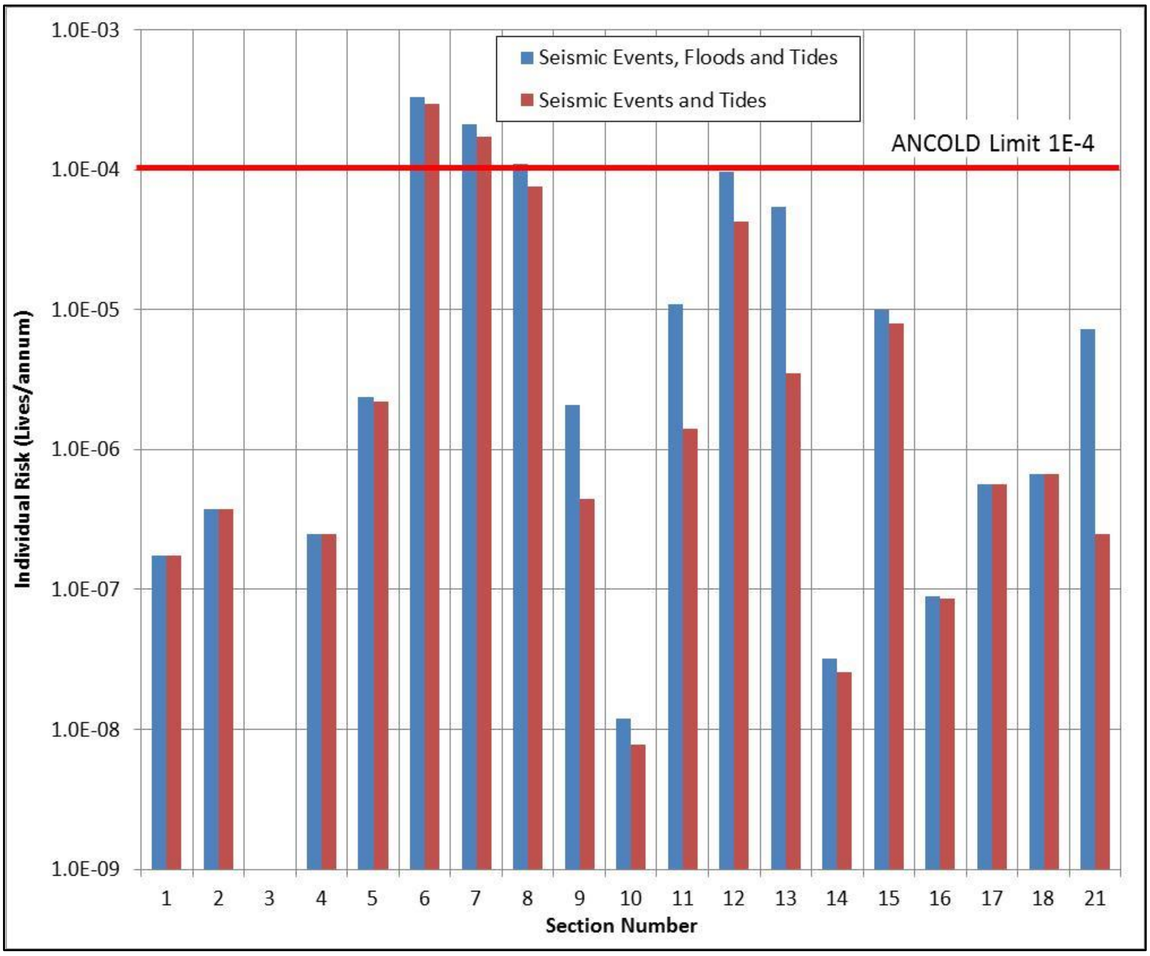


Avon Stopbanks Societal Risk for Seismic events with Tides and Tides and Floods (Based on ANCOLD 2003 Risk Guidelines)

The results clearly show that the individual risk for the Avon Stopbanks is above the tolerable limit of 1.0E-4 lives/annum as shown on following figure and summarised on the table below.

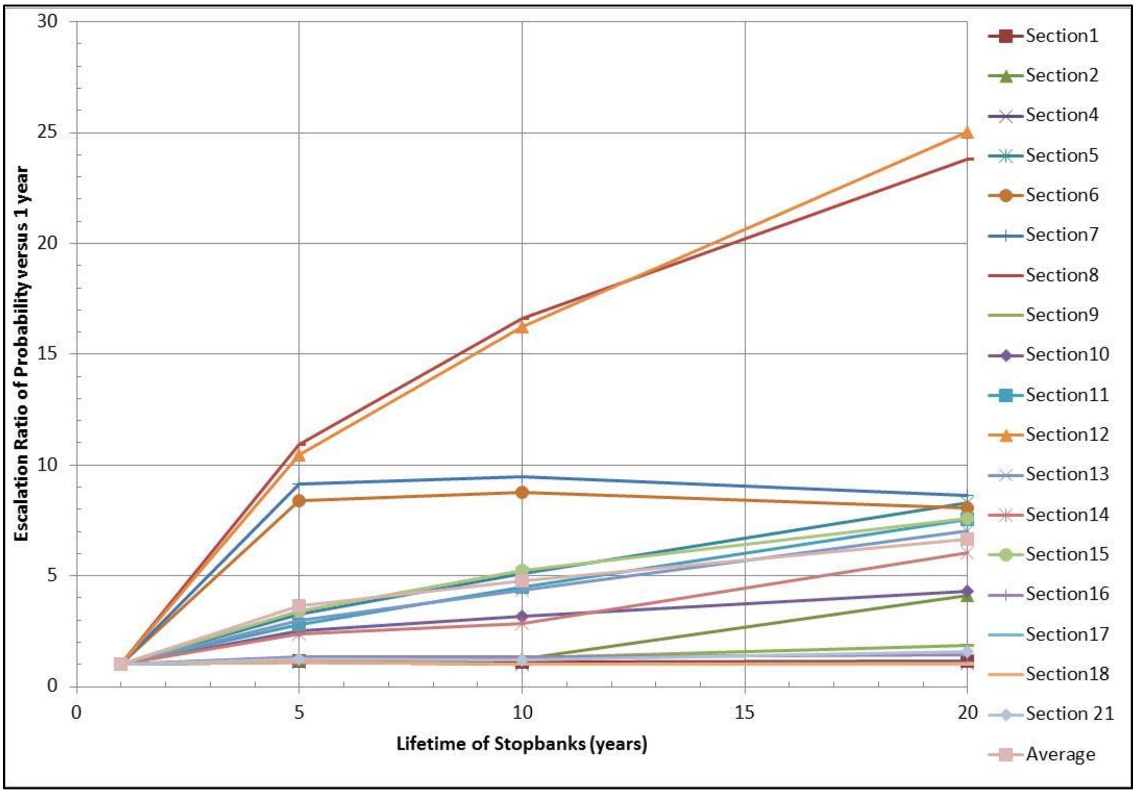
Avon Stopbanks Individual Risks above or close to the ANCOLD limit of Tolerability

Section	Tides and Seismic events	Tides, Floods and Seismic Events
Section 6	2.95 E-4	3.28E-4
Section 7	1.73E-4	2.13E-4
Section 8	7.57E-5	1.10E-4
Section 12	4.26E-5	9.70E-5



Avon Stopbanks Individual Risk

The results show a significant escalation in potential failure of the stopbank sections within the next five years, as shown on the figure below of between 8 to 11 for Sections 6, 7, 8 and 12 where sandbags have been used for tidal protection. Section 2, which also has sand bags, has a lower increase of about 1.2 owing to the use of the more substantial sandbags combined with earthfill at this section. The overall increase in failure potential is 3.66 times the annual failure probability within the next 5 years of operation.



Avon Stopbanks Escalation factors for probability of failure during lifetime

The failure potential and resulting risk for tidal and seismic events is dominated by the seismic deformation resulting in overtopping failure contributing 97.2% of the total risk for the annual events.

The trees within the embankments do not contribute significantly to the failure probabilities or risk.

There are a number of areas where the Stopbank levels are below the design level of RL 11.2 m which exacerbates the overtopping failure resulting from tides or tides and flood events.

Recommendations

Based on the results of the risk analysis, the following are recommended.

- Reinstate the stopbank levels to the design level of RL 11.2 m
- Replace or upgrade the sandbag sections 6, 7, 8 and 12 with a conventional gravel section.

Consideration should be given to the overall risk posed by the Stopbanks with seismic, tidal and flood events, which has a higher risk than the seismic and tide events alone. Raising the Stopbanks has the adverse effect of confining the flow, which will require additional raising of the stopbanks beyond the flood levels analysed to date. The raising of the Stopbanks will require the following works to be completed:

- Use "glass wall" stopbank levels which do not permit any overtopping to occur for the design level to be considered.

- Complete additional hydrological and hydraulic analyses to determine the flood levels along the Stopbank
- Complete a cost analysis for raising and potentially re-aligning the Stopbanks to provide the optimal solution for the Stopbanks based on a cost benefit analysis

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1. Introduction

1.1 Background

The Canterbury Earthquake Sequence in September 2010 and February 2011 caused large areas of land to change by differing amounts throughout Christchurch. Land levels fell by more than 300 mm in some areas and rose by similar amounts in others. This exacerbated flooding in several areas of the city, particularly in the tidal reaches of the Avon River.

Fulton Hogan Limited was engaged by the Department of Civil Defence with the objective to restore the river defences initially to a minimum level of RL 10.8 m and then to RL 11.2 m (Christchurch City Council Drainage Mean Level of Sea MLOS Datum) for a 10 to 12 year design life prior to impeding spring tides. Construction continued between March and June 2011 with the aim of utilising a variety of stopbank forms. Construction advice and supervision was provided to Fulton Hogan Limited by GHD.

A “standard design’ was developed utilising a cut off drain, 1 in 4 slopes and an approximate crest width of 1 m. A “dirty’ pit run was developed to construct the temporary stopbanks. The dirty pit run was developed by blending 3 different materials, one of which had significant fines content. Limited space meant the standard design could not be used in all areas along the lower Avon Stop banks. Sand bags were utilised in small areas where there was virtually no room. Some areas had room for an aggregate stop bank but there was not enough space for heavy machinery to construct it. Therefore these banks do not have cut off drains, engineered foundations and they have not been compacted using compaction equipment.

Following the original construction minimal maintenance has been undertaken to date by Fulton Hogan. Maintenance has comprised of periodic crest level surveys and subsequent topping up of areas less than RL 11.2 m.

The temporary stopbank are now near the end of their design life. The Christchurch City Council (CCC) needs to understand the risks associated with the ongoing reliance on the temporary stopbanks for flood protection. The CCC requested proposals for an investigation into risks, benefits and costs associated with the ongoing reliance on the Avon River temporary stopbanks, for flood protection in the tidal reaches of the Avon River.

Extending the life of the temporary stopbanks will allow further consideration of Residential Red Zone options and delay the large capital outlay required for new stopbanks.

1.2 Project Requirements

The project is required to evaluate the risk profile of the temporary stopbanks along the length of the Avon River and develop a strategy for their operation over the short to medium term.

The following main elements have been considered in the project

1. Review of the current/baseline maintenance methodology and cost. Compare this to the cost of construction of new stopbanks;
2. Determine the risks to the temporary stopbanks during future earthquakes, flood events and daily tidal flows, and develop a decision tree with regards to modifying the form and location of ongoing temporary measures;
3. Investigate options for altering existing temporary stopbanks to extend their lifespan and make them more permanent whilst adhering to the objectives of the Flood Protection Activity Management Plan;

4. Highlight the potential recreational and landscape benefits of the temporary stopbank maintenance options; and
5. Produce an issues and options report detailing potential strategies for the temporary stopbanks, recommending a preferred option.

1.3 Risk Assessment Approach

The risk assessment procedure adopted in this report generally used the following procedure:

- Complete a site inspection of the Stopbank to familiarise the team members with the stopbank section types and general layout
- Hold a workshop with CCC to identify typical sections for analysis in the risk assessment
- Review the available data for the stopbank remedial works and carry out additional geotechnical investigation and testing to confirm material parameters for the foundations where required
- Define the levees sections and their appurtenant structures
- Screen the hazards to determine the applicable loading conditions to be considered in the risk assessment
- Quantify the seismic, flood and tidal loading conditions
- Assess the possible failure modes for each section considered in the risk assessment
- Develop event trees for each failure mode
- Determine the probability of each event in the event trees using the piping toolbox and various other available tools from which to assess the probability of stopbank failure for each section
- Estimate the population at risk and potential life loss (PLL) in the event of a breach for each section with consideration of flooding or tidal events
- Calculate the risk of failure as the product of the annual probability of failure and the PLL for the current temporary stopbank levees for 1, 5, 10 and 20 year design lives under the flood, tide and seismic loading
- Evaluate the risk based on current ANCOLD risk guidelines and make recommendations for ongoing maintenance works.

1.4 Scope and limitations

This report: has been prepared by GHD for Christchurch City Council and *may only be used and relied on by Christchurch City Council for the project requirements agreed between GHD and the Christchurch City Council as set out Section 1.2 of this report.*

GHD otherwise disclaims responsibility to any person other than Christchurch City Council arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD throughout this report and the reports referenced in this report. GHD disclaims liability arising from

GHD has prepared this report on the basis of information provided by Christchurch City Council and others who provided information to GHD (including Government authorities)], which GHD has not independently verified or checked beyond the agreed scope of work. GHD does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information.

1.5 Assumptions

The following assumptions have been made for the risk assessment:

- The construction of the present stopbank levee material complies with the design requirements
- Tidal events follow the same hydraulic gradient line as the 1 in 50 AEP event (from chainage 17900 to 19600 – provided to GHD by CCC) over the entire Avon River section under consideration

2. Available Information

2.1 Reports

As part of the risk assessment GHD undertook a review of any relevant information from construction supervision period and maintenance advice provided following construction of the stopbanks. The following reports were considered during this analysis:

- Work Package Concept Report, Lower Avon River Stopbanks – Engineering Review, August 2011, SCIRT WP0000290;
- Owles Terrace Rebuild, Draft Stopbank Concept Design Report, July 2011, by GHD for Fulton Hogan Limited.
- Lower Avon River Stopbanks, Geotechnical Review, August 2014

2.2 Surveys and River Modelling

The following information was provided by CCC;

- Crest level surveys from various dates undertaken by Davie Lovell Smith
- Bridge Street and Ferrymead 2011 tide spreadsheet data developed by Derek Goring
- DHI models provided by CCC
  - Avon_D12_5yr_0mSLR_PostDec_SB11pt2
  - Avon_D12_5yr_0mSLR1ytide_PostDec_SB11pt2
  - Avon_D12_10yr_0mSLR1ytide_PostDec_SB11pt2
  - Avon_D12_20yr_0mSLR2ytide_PostDec_SB11pt2
  - Avon_D12_50yr_0mSLR_PostDec_SB11pt2
  - Avon_D12_100yr_0mSLR_PostDec_SB11pt2
  - Avon_D12_200yr_0mSLR_PostDec_SB11pt2

3. Risk Assessment Analysis and Methodology

3.1 General

The Risk Assessment approach presented in this section of the report generally follows the methodology outlined in the ANCOLD Guidelines on Risk Assessment (ANCOLD 2003). The assessment was based on the information and documentation provided to GHD.

The risk assessment was competed using the following process, as shown on Figure 3-1.

- Complete a site inspection of the Stopbank to familiarise the team members with the stopbank section types and general layout
- Hold a workshop with CCC to identify typical sections for analysis in the risk assessment
- Review the available data for the stopbank remedial works and carry out additional geotechnical investigation and testing to confirm material parameters for the foundations where required
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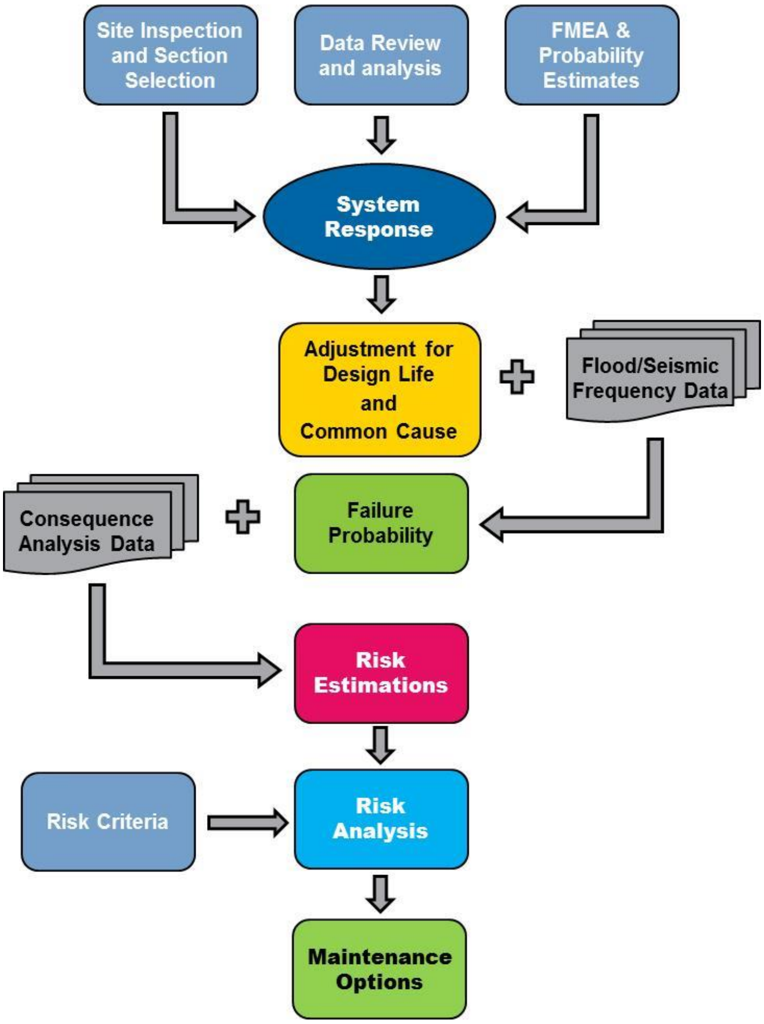


Figure 3-1 Avon Stopbank Risk Assessment Process

3.2 Definition of Risk Acceptance Criteria

The risk acceptance criteria have been adopted from the ANCOLD Risk Assessment Guidelines for Societal and Individual Risk.

3.2.1 Societal Risk

The societal risk curve for existing dams is shown on Figure 3-2.

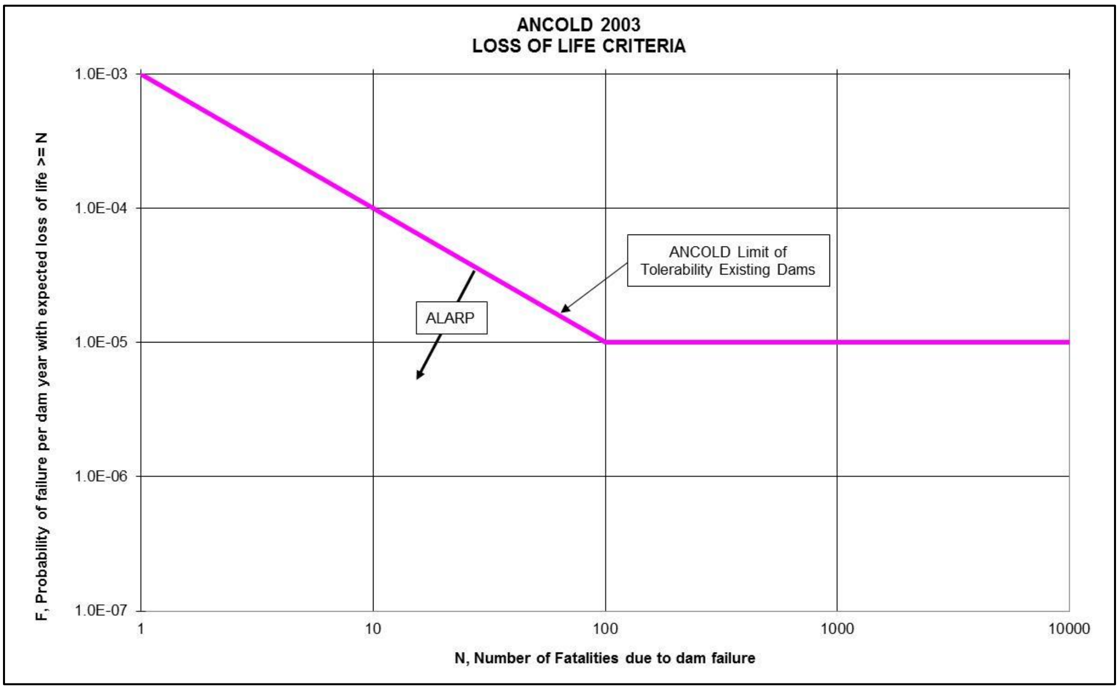


Figure 3-2 ANCOLD Societal Risk Criteria

Where the societal risk is above the Limit of Tolerability for existing dams, there is a requirement to lower the risk below the line. The ALARP (As Low As Reasonably Practicable) approach is then used to lower the risk below the line.

3.2.2 Individual Risk

The Individual risk criteria for existing dams that was applied to the Stopbank is as follows.

- An individual risk to the person or group, which is most at risk, that is higher than 10^{-4} per annum is unacceptable, except in exceptional circumstances.

3.3 Definition of Levees and Appurtenant Structures

3.3.1 Site Inspection

The available geotechnical information for the levees contained in the 2011 design reports was reviewed following which a site inspection was completed in July 2015 by the following personnel.

- Bob McKelvey GHD site engineer during remedial construction of the Levees following the seismic damage
- Malcolm Barker GHD Principal Engineer dams and risk analyst
- Darren Woods GHD geotechnical engineer

The purpose of the site inspection was to evaluate the condition of stopbanks and identify typical sections for the risk analysis. The sections selected are shown on Figure 3-4.

The site walkover notes are provided in Appendix B.

3.3.2 Workshop

Following the site inspection, a workshop was held with the following people present:

- GHD

- Samantha Webb Principal Engineering Geologist Christchurch
  - Jon Williams Principal Dams Engineer
  - Malcolm Barker Principal Dams Engineer
- Christchurch City Council
  - Karissa Hyde
  - Peter Christensen
  - Ramon Strong
  - Graham Harrington

The purpose of the workshop was as follows:

1 To confirm the scope and objectives of the study

2 To Present the Failure Modes identified for the Stopbank

3 To shortlist the failure modes for use in the study

4 To identify the Stopbank Types for which 20 sections were identified including two for buried services. An additional section was subsequently identified between Section 14 and 15 and was numbered Section 21

5 To discuss the consequences of failure based on the available Bathtub inundation mapping for RL 10.8 m and RL 11.0 m

6 To filter down the sections to the five key stopbank types / Failure Modes agreed on in the proposal

7 To discuss the next steps including the following:
   - Define the design lifetime which was agreed to be 1, 5, 10 and 20 years
   - Agree on the risk level acceptable to CCC
   - Obtain flood and tide combination data to be used for the study
   - Identify any gaps in the available data and obtain the data necessary to complete the study

3.3.3 Levee Geometry

The geometry and arrangement of the Avon River stopbank levees varies along the alignment of the river on both the left and right banks. A generalised schematic section of the River – Levee interface is shown in Figure 3-3 below.

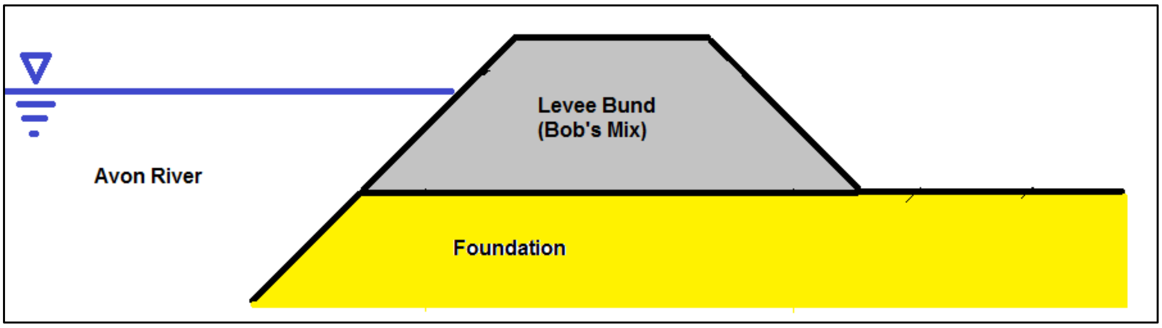


Figure 3-3 Generalised Schematic Section of River – Levee Interface

In addition to the items shown in Figure 3-3 above, several locations also include sandbags on the levee crest, trees on the crest, gabions and various other appurtenant structures.

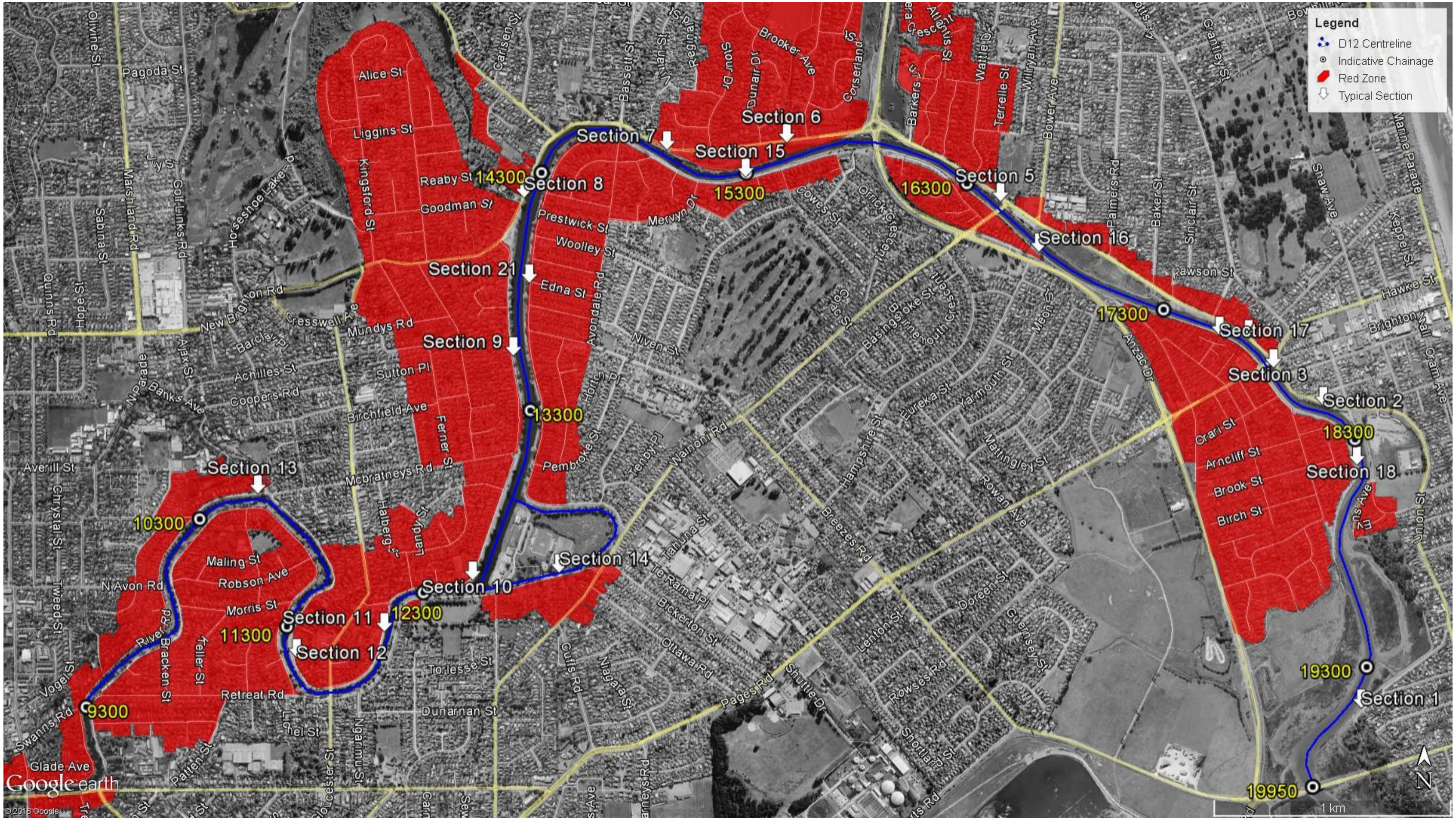


Figure 3-4 Indicative Section Locations Assessed as Part of the Risk Assessment (red zone properties)

3.3.4 Levee Embankment Configuration

During temporary stopbank construction, it was agreed with Council that for ease and rapid rate of construction, the standard stopbank configuration would be constructed as follows:

- Minimum crest elevation of RL 10.8 m;
- Trapezoidal cross section, crest width of 2.5 m and side slopes of 1:4 (V:H);
- Cutoff trench typically of depth 0.3 m to 1.5 m and 2.0 m wide to be taken into the original stopbank or founding material;
- With material comprising silty gravel with maximum particle size 200 mm and containing approximately 15% fines. The material was reasonably well graded and was easily compacted. The gravel/cobble component comprised rounded or sub-rounded material;
  - The material was sourced from a number of quarries and was blended at the Fulton Hogan's yard at Breezes Road. The material was placed and compacted to approximately 95% of maximum modified dry density; and
  - The permeability of this material as measured in the laboratory and an in situ measure was carried out and ranged from 10^{-9} m/s to 10^{-6} m/s.

Typical gradings of the material are shown on Figure 3-5.

Figure 3-5 Avon Stopbank material gradings

A photograph of a constructed Levee Section 15 is shown in Figure 3-6. Due to the working space constraints, certain sections of the stopbanks were not in accordance with the standard configuration. In certain areas, crest widths as little as 1.0 m have been constructed. In some instances side batters are as steep as approximately 1:1, or even near vertical if retained by Diamond Pro Block or portable segmented concrete barrier retaining walls. Compaction has also been compromised in some areas and in almost all locations compaction of the side slopes has not been performed. This results in superficial cracking of the slopes that may worsen through water ingress and will require routine maintenance to repair cracks where they develop and are seen to be increasing in size.

Geogrid, Triax TX160, and Bidim Geofabric has been used in some areas, particularly those with poor founding conditions. Sandbags have been used at several locations including Owles Terrace and New Brighton Road where the width of the stopbank was narrow owing to space constraints. Working in conjunction with CCC's arborists, significant trees have been protected from the new stopbank fill material.

Figure 3-6 Photograph of Typical Levee Section 15

3.4 Levee Data Evaluation and Analysis

3.4.1 Stability Analysis

Slope stability analyses had been completed for the 2011 emergency stopbank repairs, however, these did not cover the range of loads required for the risk analysis. Further slope stability analyses were, therefore, undertaken on five sections. Analysis was undertaken using SlopeW of the Geostudio 2012 software package. The following information was obtained for the analysis:

- Cross sectional profiles provided by survey undertaken by Davie Lovell-Smith Ltd on the 25 August 2015
- Soil profile provided by sonic boreholes to 105 m below ground level (bgl) with standard penetration tests at 1.5 m centres;
- Particle size distribution and plasticity index tests on samples retrieved from sonic boreholes;

Stability Cases Considered

- Static – No seismic load applied and water table at 1 m bgl.
- High water table – No seismic load applied and water at top of stopbank.
- Seismic – Seismic load of 0.15 g applied to slope, based on 0.5 x the pga (0.3 g) of the 23 December 2011 earthquake (USACE 1984).
- Seismic equilibrium – Seismic load applied to slope that generates a Factor of Safety of 1.

Material Parameters

The material parameters for the various zones were evaluated using the available CPT data together with the gradings and indicator test results and judgement for zones where no data was available. The parameters used for each section are shown on Table 3-1.

Table 3-1 Avon Stopbank Slope Stability analysis material parameters

Soil Type	Friction angle Φ (Degrees)	Effective strength Cohesion c' (kPa)	Density (kN/m^3)
Dirty pit run	30	1	18
Gabion Foundation Fill	30	1	19
Gabion	90	500	15
Sandy SILT	22	0	17
Clayey SILT	20	2	16
SILT	21	1	17
Loose silty fine to medium SAND	26	0	17
Loose fine to medium SAND	28	0	17
Medium Dense fine to medium SAND	30	0	18

Analysis results

The results for the slope stability analyses are presented on Table 3-2 and clearly show that the Stopbank sections are unlikely to fail under static or high water level conditions but have low factors of safety under seismic loads. This is indicative of deformation occurring, which is evidenced from past performance.

Table 3-2 Stopbank embankment factors of safety for selection sections

Section Location	Load Cases			
	Static	High Water Table	Seismic 0.15 g (0.5 x 0.3 g)	Seismic equilibrium pga (FoS = 1)
Section 2	1.588	1.942	1.006	0.15 g
Section 15	1.55	1.877	0.929	0.12 g
Section 16	1.179	1.259	0.688	0.05 g
Section 17	1.316	1.709	0.756	0.07 g
Section 18	0.912	0.963	0.753	Not found

Based on the slope stability results, the failure modes associated with normal and high water tables were dismissed for inclusion in the risk analysis as their contribution to the risk was expected to be significantly lower than the other failure modes.

3.4.2 Seismic Deformation Assessment using Historical Data

Seismic deformation analyses were completed for each Stopbank section using the available data and section geometry.

The raw data for the CPT’s has been obtained from the construction report and the recent geotechnical investigations. Additional cone penetrometer tests (CPT’s) including raw data near each selected Stopbank section were also obtained from the Canterbury Geotechnical Database.

Liquefaction assessment was done using CLiq[1] (CPT Liquefaction Assessment Software) with the Boulanger and Idriss 2014 method.

Assumptions made for the analysis process were as follows:

- Importance Level 2, 50-year design life, giving peak ground accelerations (PGA's) of:
  - 0.35 g for Ultimate Limit State (ULS), and
  - 0.13 g for Serviceability Limit State (SLS);
- Earthquake Magnitude 7.5;
- Groundwater levels at 0.0 m bgl.

Table 3-3 Historical Seismic Events Considered in the Assessment (Sections 15, 16, 17, 18 & 2 only)

Earthquake	Magnitude	PGA
4-Sep-10	7.1	0.17
22-Feb-11	6.2	0.34
13-Jun-11	6	0.25
16-Apr-11	5	0.15
23-Dec-11	5.9	0.3
SLS	7.5	0.13
ULS	7.5	0.35
MCE	6	0.19

The deformation analysis results obtained, as shown on Table 3-4 and Table 3-5 and Figure 3-7.

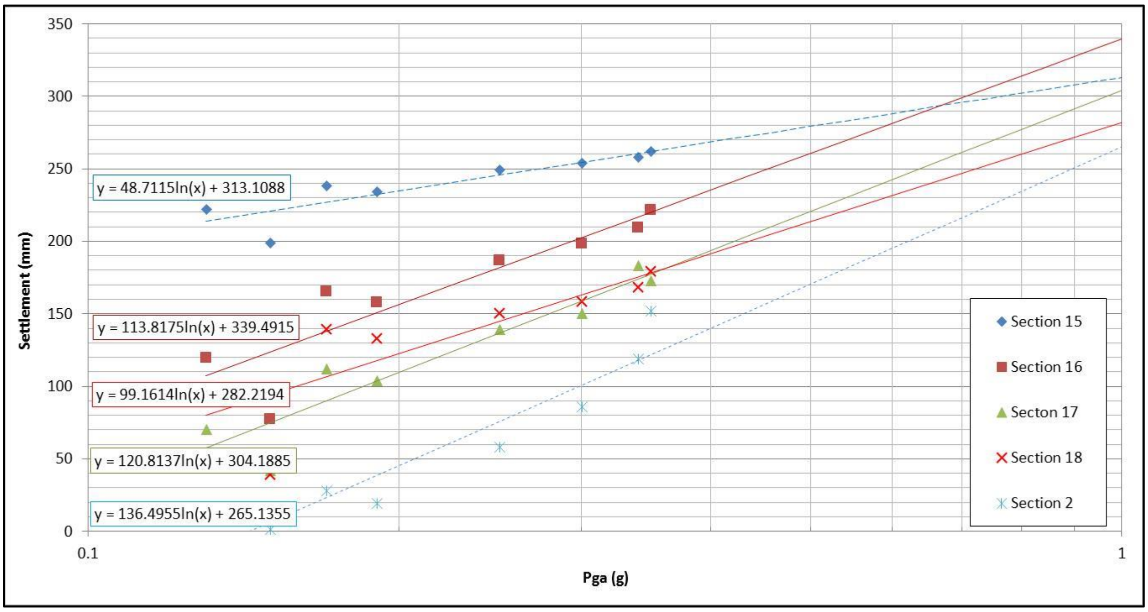


Figure 3-7 Avon Stopbanks typical deformation analysis results

The deformation results were used to estimate the likely crest settlement at each selected cross section from which to evaluate the overtopping potential given tidal fluctuations.

Table 3-4 Estimated Levee Deformations from Extrapolated Historical Seismic Data (1)

Return Period	PGA (g assumed)	Expected deformation								
		Section 15	Section 16	Section 17	Section 18	Section 2	Section 1	Section 3	Section 4	Section 5
20	0.07	184	37	0	19	0	0	55	0	56
50	0.11	206	88	38	63	0	0	85	0	76
75	0.14	217	116	67	87	0	0	100	0	87
200	0.22	239	167	121	132	58	5	130	2	106
475	0.31	256	206	163	166	105	10	152	5	121
1,000	0.40	268	235	193	191	140	14	169	7	133
2,000	0.50	279	261	220	213	171	17	184	9	142
5,000	0.64	291	289	250	238	204	21	200	11	153
10,000	0.77	300	310	273	256	229	24	212	12	161
20,000	0.90	308	327	291	272	251	26	222	13	168

Table 3-5 Estimated Levee Deformations from Extrapolated Historical Seismic Data (2)

Return Period	PGA (g assumed)	Expected deformation								
		Section 6	Section 7	Section 8	Section 9	Section 10	Section 11	Section 12	Section 13	Section 14
20	0.07	138	0	164	56	43	88	25	51	62
50	0.11	148	37	173	76	62	94	44	59	83
75	0.14	153	56	177	86	72	98	54	63	94
200	0.22	163	93	186	106	91	104	73	70	114
475	0.31	170	122	193	121	106	109	87	75	130
1,000	0.40	175	142	198	132	117	113	97	79	141
2,000	0.50	180	161	202	142	126	116	107	83	151
5,000	0.64	185	181	207	152	136	119	117	87	163
10,000	0.77	189	196	210	160	144	122	125	90	171
20,000	0.90	193	209	213	167	151	124	131	92	178

3.5 Failure Modes Effects Analysis (FMEA)

ANCOLD (2003) defines a failure mode as the way that a failure can occur, described as the means by which an element or component failure must occur to cause loss of the sub-system or system function.

Failure Modes and Effects Analysis (FMEA) is further defined by ANCOLD as an inductive method of analysis where particular initiating conditions are postulated, and the full range of effects thereof on the system is assessed, thereby revealing whether or not the particular initiating conditions would result in one or more potential failure modes.

The FMEA for the Avon River temporary stopbank levees has been completed using the following steps:

- Identification and screening of failure initiating events
- System identification including identification of dam components for evaluation of failure modes;
- Identification of potential failure modes for each component;
- Screening of failure modes for inclusion in the risk analysis

The FMEA was used to develop failure pathways that define the events or circumstances included in the risk assessment for the selected initiating events.

3.5.1 Identification of Failure Initiating Events

Failure initiating events are external threats to the proper functioning of the levee that originate outside the boundary of the levee and reservoir system and are beyond the control of the levee owner. The list of those credible failure initiating events applicable to Avon River temporary stopbank levees, which have been considered in the FMEA and risk assessment were screened for inclusion in the risk analysis using the criteria below:

Reference Criteria for Screening Initiating Events for the Avon River temporary stopbank levees

1. The event is of equal or lesser damage potential than the events for which the levee is designed. Design significantly exceeds requirement.
2. The event has a significantly lower mean frequency of occurrence than other events with similar uncertainties and could not result in worse consequences than those events.
3. The event cannot occur close enough to the levee to affect it.
4. The event is included in the definition of other event(s)
5. The event is judged to have an insignificant effect on the levee
6. Not an initiator

The identified potential failure initiating events for the Avon River temporary stopbank levees are presented in Table 3-6. A complete list of failure initiating events can be found in Appendix D.

Table 3-6 Avon River temporary stopbank levees – Screening of Initiating Events

Failure Initiating Events	Screening Criteria	Subsequent Events for Failure Pathways Analysis	Comments
Earthquake	POTENTIAL INITIATING EVENT	Earthquake causes one of the following: Longitudinal and transverse cracking. If depth of cracking extends below the water level then piping could initiate. Liquefaction. If post seismic strengh is low, leading to slope failure. If damaged zone extends below phreatic surface and filter is damaged, then piping could initiate slope failure.	
	POTENTIAL INITIATING EVENT	Internal erosion of the embankment core into the foundation if joints open during the earthquake and remain open	Drilling shows joints generally tight and fracturing is not open to the extent that piping can occur from the embankment core zone thorugh the foundation rock.
	POTENTIAL INITIATING EVENT	Slope instability owing to weak foundation layers or liquefaction results deformation. If deformation is greater than the available freeboard, then overtopping can occur or piping through the damaged embankment zone	
	POTENTIAL INITIATING EVENT	Piping through the possible shear zone in river bed	Shear zone is unlikely to be highly permeable
	POTENTIAL INITIATING EVENT	Conduit shear leading to seepage into conduit and possible sinkhole formation leading to failure	
	POTENTIAL INITIATING EVENT	Tower failure results in uncontrolled flow into the conduit causing flow from the access shaft to erode embankment and cause instability with potential for overtopping or piping	
	POTENTIAL INITIATING EVENT	Spillway gate failure	Gate failure owing to overstress
	POTENTIAL INITIATING EVENT	Ogee failure through low strength coal zones	
	5. The event is judged to have an insignificant effect on the levee.	Inlet channel slope failure	Slopes are cut into insitu weathered material and very unlikely to have significant slope failures affecting the spillway channel capacity.
	1. The event is of equal or lesser damage potential than the events for which the levee is designed. The design significantly exceeds the requirement.	Spillway channel wall failure	If the earthquake occurs a short time before the floods and the spillway cannot be operated leading to embankment overtopping
Hydrological / Flood and Tide (operating level rising)	POTENTIAL INITIATING EVENT	Flood causes operating level to rise; leading to overtopping of dam crest. Erosion of downstream slope causing steepening and sudden collapse of the embankment. Overtopping causing downcutting of the crest.	
	POTENTIAL INITIATING EVENT	Flood causes operating level to rise; leading to piping above sand filter layer or through the filter layer that could hold a crack	
	POTENTIAL INITIATING EVENT	Excessive pressures in the sandstone foundation seam reduces the embankment stability or leads to internal erosion along the foundation core interface.	

	POTENTIAL INITIATING EVENT	Rapid drawdown cases slope failure and regressive slope failure to point of failure.	Requires a flod to occur after the rapid drawn to overtop the failed embankment
	POTENTIAL INITIATING EVENT	Piping through the possible shear zone in river bed	Shear zone is unlikely to be highly permeable
	POTENTIAL INITIATING EVENT	Internal erosion through or at the foundation at the Sandstone core interface	Drilling shows joints generally tight and fracturing is not open to the extent that piping can occur thorugh the foundation rock. The core/foundation interface is a potential path for piping.
	POTENTIAL INITIATING EVENT	Outlet tower flotation leads to damage of conduit. Flooding of conduit causes either blowout of the end plug or flow through the downstream shaft. Resulting embankment erosion leads to embankment instability and potential overtopping	significant damage of the tower would be required for the flow to erode the embankment toe
	POTENTIAL INITIATING EVENT	Flood causes operating level to rise; leading to hydrostatic flood loading exceeding shear capacity of the ogee, leading to failure and erosion/downscutting of the spillway chute	Low strength coal seams in the foundation
	POTENTIAL INITIATING EVENT	Saturation of the approach channel cut slopes decreasing the effective stress and causing a slope failure. Reduced discharge capacity results in highere reservoir levels and embankment overtopping and possible dam breach.	Very unlikely that the slope failure will occur with sufficient volume to block the spillway.
	POTENTIAL INITIATING EVENT	Piping along the conduit	Silty filter may have been provided around the conduit casing downstream from the core. Cutoff collars may not be adequate. Piping along the conduit could occur.
	POTENTIAL INITIATING EVENT	Side walls overtop leading to backfill erosion and wall failure owing to turbulent flow and excessive internal pressure from flowing water. Wall failure leads to back cutting up the chute and potential failure of the ogee structure. More significant erosion could result in the embankment being affected but this is very unlikely.	CFD modelling shows walls overtop with PMF flood. Resulting risk may be low
	POTENTIAL INITIATING EVENT	Excessive uplift below spillway chute owing to hydraulic jump forming in the channel slope. Leads to excessive uplift and failure of anchors leading to erosion of the chute and back cutting in to the reservoir if the flood is of long enough duration	CFD modelling to evaluate location of hydraulic jump and pressures in the chute.
	POTENTIAL INITIATING EVENT	Erosion of the chute toe area during large and extreme floods	CFD modelling of the PMF shows that there are high velocities downsteam of the end sill greater than 6m/s and the rip rap protection may be inadequate.
	POTENTIAL INITIATING EVENT	Spillway flow causing embankment toe erosion	Spillway discharges downstream from the embankment. TWL may affect the embankment stability.

As shown in Table 3-6 above, the initiating events identified for further consideration in the risk analysis of the Avon River temporary stopbank levees included the following:

- Seismic events;
- Hydrological/Flood events

Note: Both hazard loading conditions are affected by the tidal level hence tidal loading was also considered in the analysis.

3.6 Failure Modes Analysis

Appendix E includes an evaluation of the potential failure modes, their cause and reason for either rejection. The failure modes accepted for the risk analysis are presented in Table 3-7 below.

Based on the failure modes analysis, the following failure modes have been evaluated in detailed for the risk analysis.

- Overtopping
  - Seismic deformation loss of freeboard and overtopping
  - Floods or tides overtopping the gravel embankment
  - Floods or tides overtopping the sandbag sections
- Piping
  - Seismic cracking
  - Cracks in embankment due to differential movement
  - Through the sand foundation
  - Through rotted tree roots
  - Through narrowed section caused by trees blowing over

Slope instability was evaluated and found to be significantly lower likelihood than the above failure modes and was dismissed for further analysis.

Table 3-7 Failure Modes Accepted for the Risk Analysis

Sub-system	ID No.	Components	ID No.	Hazard	ID No.	Failure Mode No.	Initiator	Consequence	Leading to	Leading to	Leading to	Leading to	Ultimate outcome	Rejection and Reason
Section 1	1	Embankment	1	Earthquake	1	1.1.1.1	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	
						1.1.1.3	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	
						1.1.1.4	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	
						1.1.1.5	Failure of sandbags	Loss of freeboard	Overtopping if tidal level above crest				Breach	Only applies to Types 6, 7, 8
						1.1.1.7	Differential movement around pipes	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	Only applies to generic services FM
				Hydrological / Flood	2	1.1.2.1	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	
						1.1.2.4	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	
						1.1.2.5	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	
						1.1.2.9	Sandbag deteriorates	Overtopping during extreme floods					Breach	Only applies to Types 6, 7, 8
						1.1.2.10	Tree roots rot	Open pipes to upstream	Pipe initiation through the embankment.	Continuation (No filter)	Progression with no intervention		Breach	
						1.1.2.11	Tree falls over	Removal of material from wall	Loss of freeboard	Overtopping			Breach	

3.7 Hazard Analysis and Partition Selection for the Risk Analysis

As shown in Section 3.5.1, the Avon Stopbank levees are subject to seismic and hydrological loading conditions. In addition to this, the levees are also subject to the tidal influence of the Avon River. This section of the report describes these loading conditions and their application in the risk assessment.

3.7.1 Tidal Influence

Available Data

The following information was used to develop the tidal loading conditions

- Bridge Street and Ferrymead 2011 tide spreadsheet data developed by Derek Goring
- DHI models provided by CCC
  - Avon_D12_5yr_0mSLR_PostDec_SB11pt2
  - Avon_D12_5yr_0mSLR1ytide_PostDec_SB11pt2
  - Avon_D12_10yr_0mSLR1ytide_PostDec_SB11pt2
  - Avon_D12_20yr_0mSLR2ytide_PostDec_SB11pt2
  - Avon_D12_50yr_0mSLR_PostDec_SB11pt2
  - Avon_D12_100yr_0mSLR_PostDec_SB11pt2
  - Avon_D12_200yr_0mSLR_PostDec_SB11pt2

Tide fluctuations along the Avon River vary significantly between the maximum and minimum water level on the stopbank levees. The peak tidal levels do not vary significantly, as shown on Figure 3-8. For this assessment, tides up to the 1 in 200 AEP event were considered as required for the CCC risk tolerance of 10% which is summarised in Table 3-8.

Table 3-8 CCC Risk Tolerance (probability of event occurring within design life of the structure)

Design Life	Tide Average Recurrence Interval (ARI) Years						
	2	5	10	20	50	100	200
1	50.0%	20.0%	10.0%	5.0%	2.0%	1.0%	0.5%
2	75.0%	36.0%	19.0%	9.8%	4.0%	2.0%	1.0%
5	96.9%	67.2%	41.0%	22.6%	9.6%	4.9%	2.5%
10	99.9%	89.3%	65.1%	40.1%	18.3%	9.6%	4.9%
20	100.0%	98.8%	87.8%	64.2%	33.2%	18.2%	9.5%

Each tidal level was combined with the design life period for the seismic and the flood frequency data. The CCC requested an analysis to be completed without floods and in this case, only the annual flood level data was combined with the tidal levels rather than the range of floods from the annual (1yr) to the 1 in 200 year event.

Bridge Street Tidal Data

Goring (2015) tidal levels at Bridge Street for an eight day period were provided to GHD by CCC. This data is presented in tabulated form in Appendix F and in graphical form in Figure 3-8 below. It includes tidal levels for the 1, 2, 5, 10, 20, 50, 100, 200 AEP tides and the median tide with no flood influence.

The data showed that tidal fluctuations varied up to 2.3 m water level between the peak of the high tide and the bottom of the low tide for a particular tidal event. Two full tidal oscillations were usually seen over a 24 hour period. To capture and better understand these tidal fluctuations, percentage time exceedance curves for the range of water levels at Bridge Street were developed for the 8 day tidal event data.

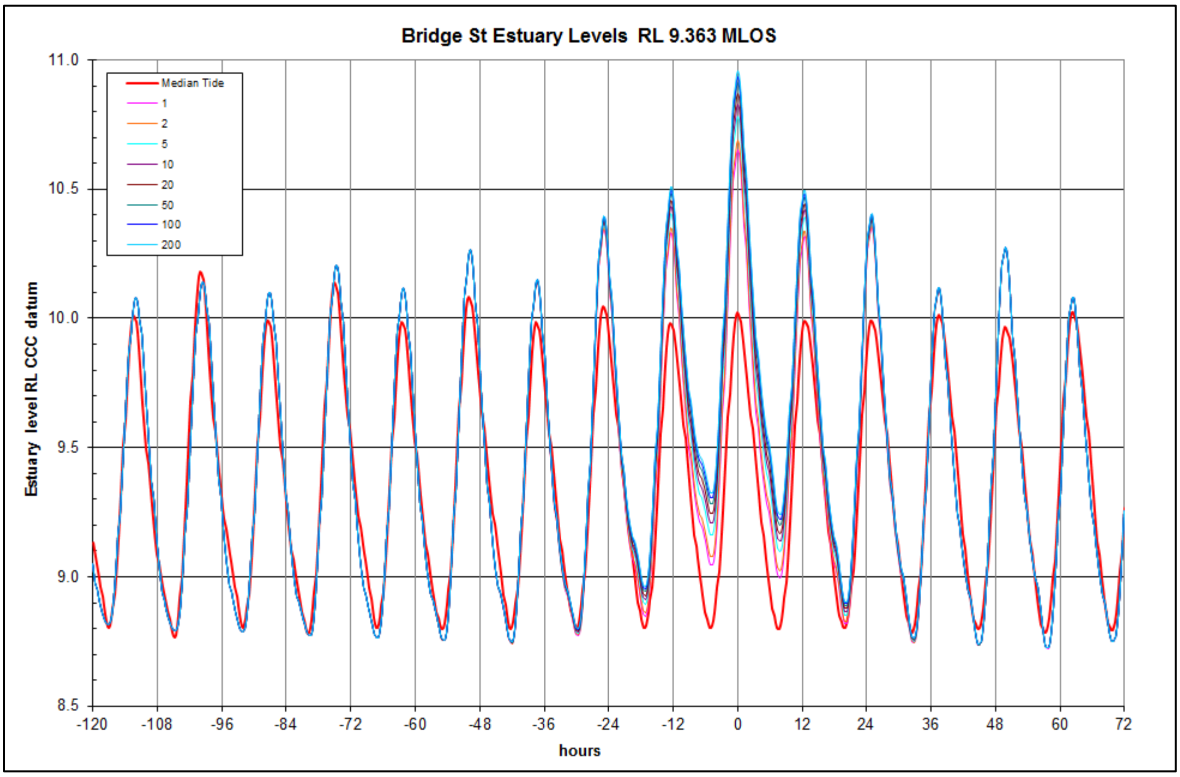


Figure 3-8 Tidal Data at Bridge Street (Goring 2015)

Figure 3-9 shows the % time exceedance curves for all tidal events presented in Figure 3-8. It can be seen that between tidal events, the amount of time a particular water level is exceeded varied up to ~10 hours. As the larger tidal events are of more concern to the integrity of the stopbank levees, the % time exceedance curves were looked at more closely for water levels above Rl 10 m and presented in Figure 3-10.

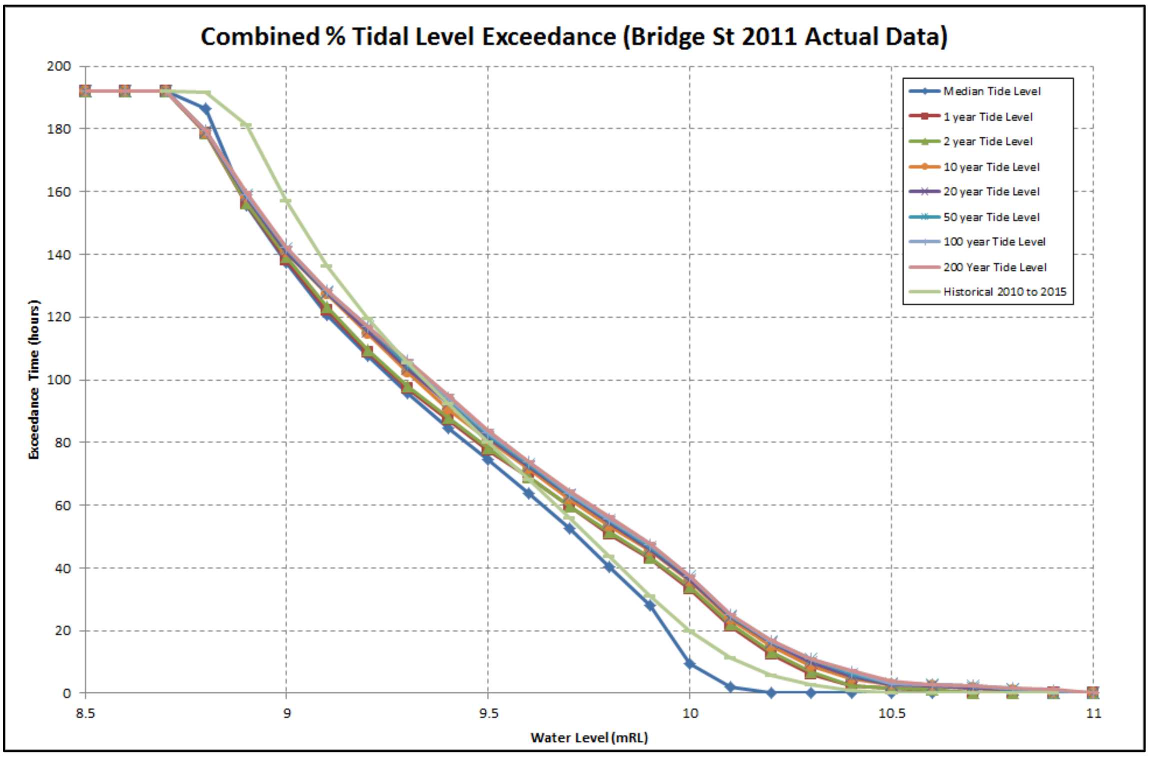


Figure 3-9 Percent Time Exceedance Curves for Data Presented in Figure 3-8

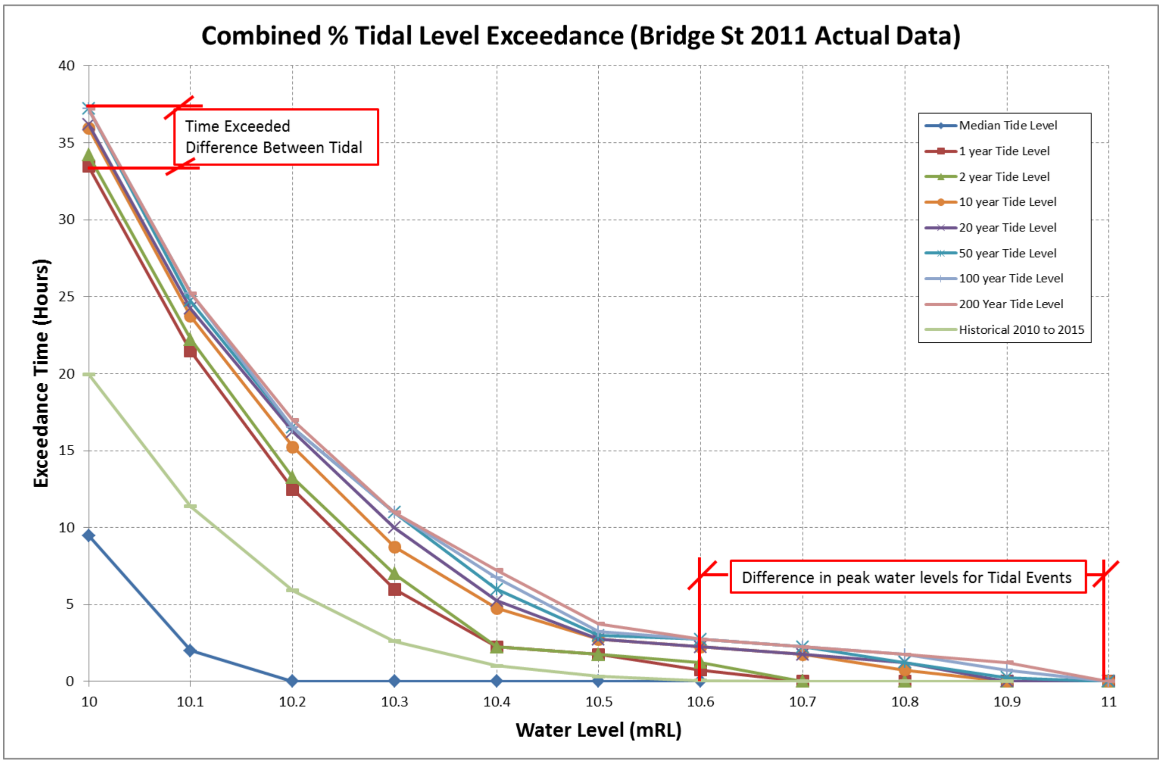


Figure 3-10 Percent Time Exceedance of Highest Water Levels

The percent time exceedance curves show that the higher water levels are exceeded for substantially less time than the lower water levels. Tidal fluctuations mean that peak water levels are experienced for short periods of time. To assess the stopbank levels under tidal levels with no floods, the peak water levels for the tidal events provided in Figure 3-9 were extrapolated upstream to chainage 9300 m. A hydraulic gradient between ~17,900 and Bridge Street was estimated from a 1 in 50 AEP tide coupled with a 1 in 5 AEP flood event hydrology model run. This hydraulic gradient was adopted for all of the tidal events under consideration and extrapolated data is summarised in Figure 3-11 below.

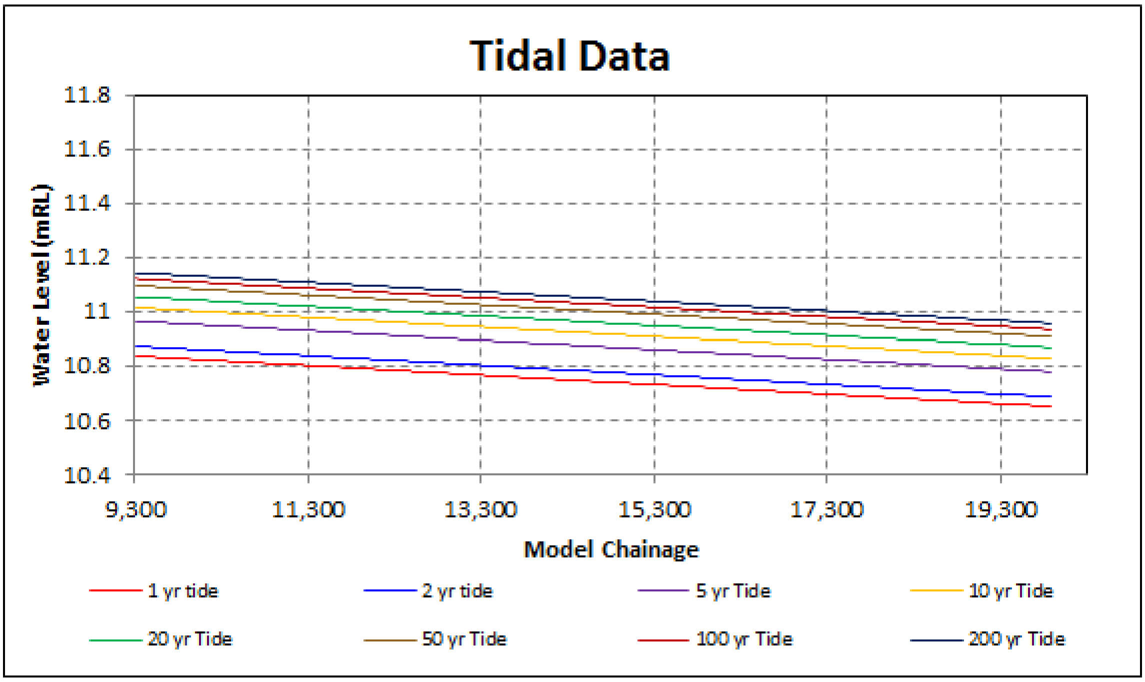


Figure 3-11 Extrapolated Tidal Data with no Flood Influence

3.7.2 Flood Loading

Hydrological/Flood loading was considered in the risk assessment as necessary from Section 3.5.1. Hydrological models were provided by CCC to GHD for up to the 1 in 200 AEP event. It should be noted that the flood events modelled were generally coupled with tidal events greater than the 1 in 1 yr AEP tide hence were not independent of tidal influence.

The following flood events were considered for the analysis

Table 3-9 Avon Stopbanks risk assessment flood events

Code	Return Period (years)	Annual Exceedance Probability (AEP)	Annual Probability Interval
FL1	1	1.00E+00	5.00E-01
FL2	2	5.00E-01	3.00E-01
FL3	5	2.00E-01	1.00E-01
FL4	10	1.00E-01	5.00E-02
FL5	20	5.00E-02	3.00E-02
FL6	50	2.00E-02	1.00E-02
FL7	100	1.00E-02	5.00E-03
FL8	200	5.00E-03	5.00E-03

A summary of the water levels associated with the floods considered in these analyses are presented in Figure 3-12 and Figure 3-13 for the left and right bank stopbanks respectively.

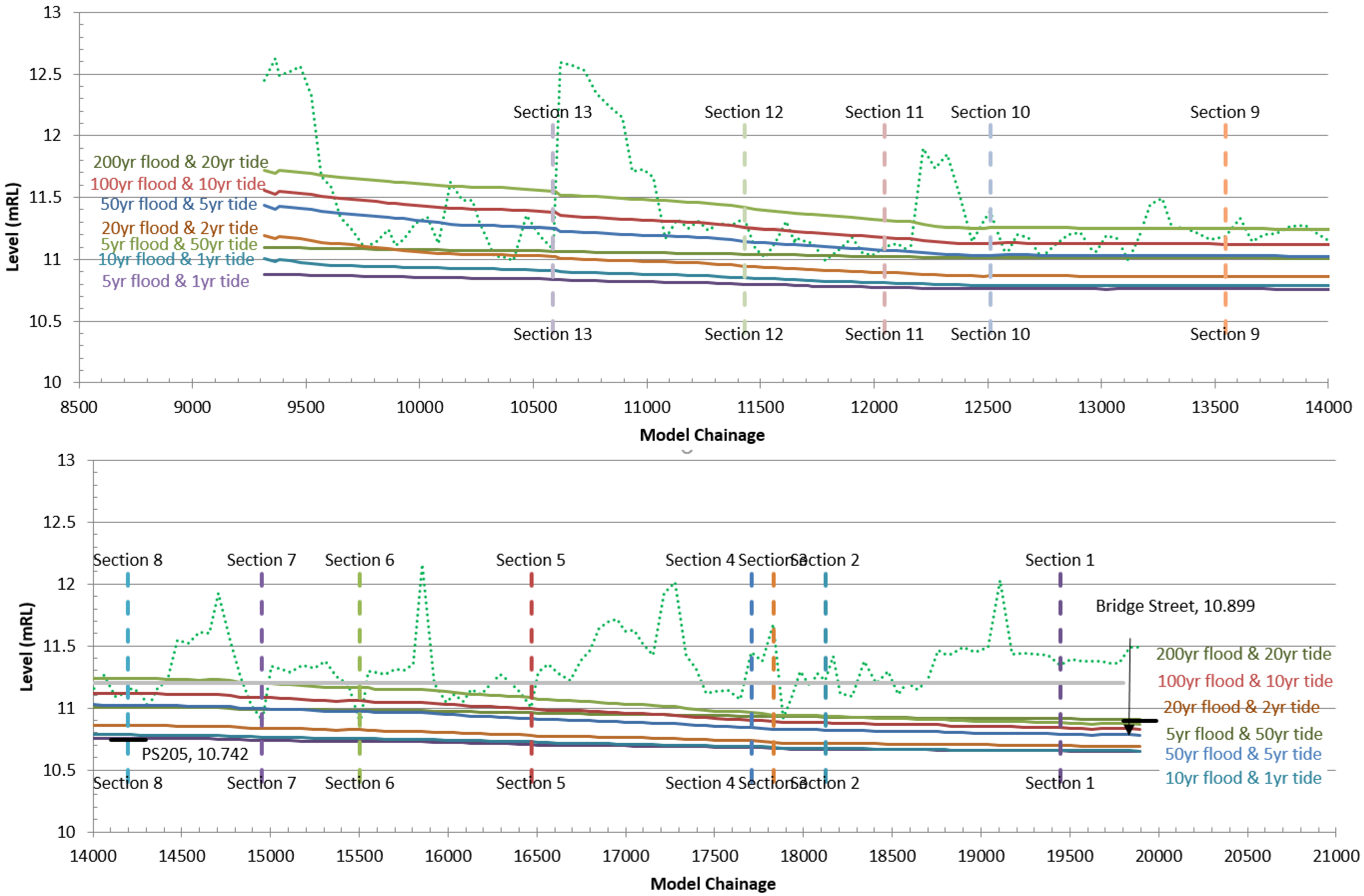
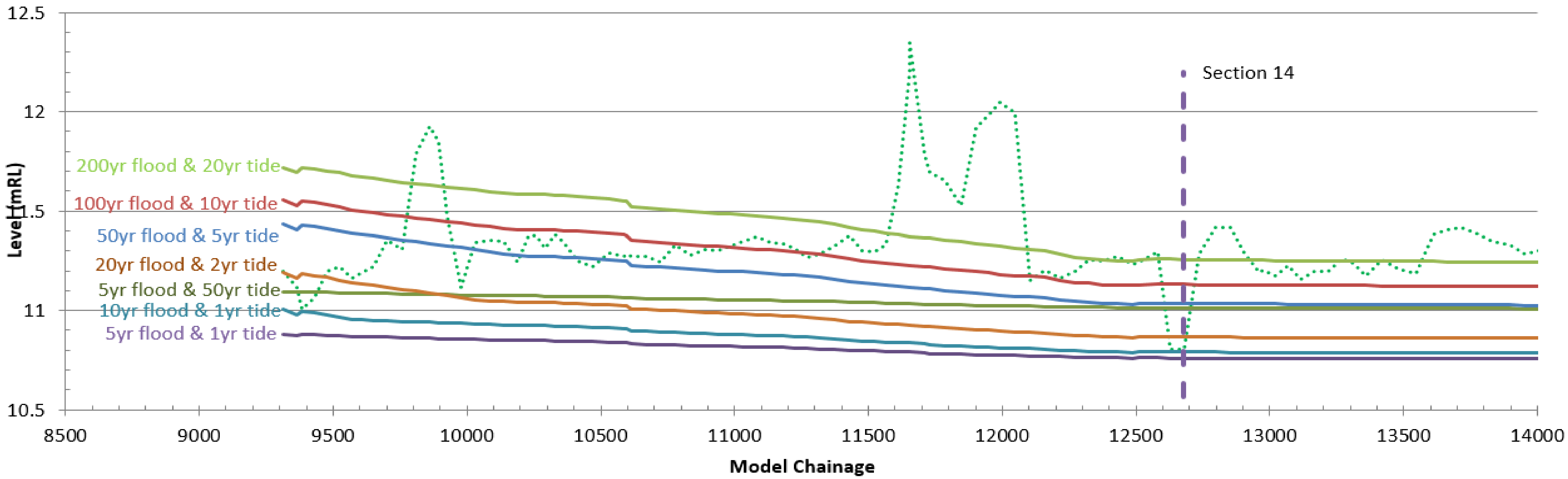


Figure 3-12 **Left Bank Flood and River Bed Levels**



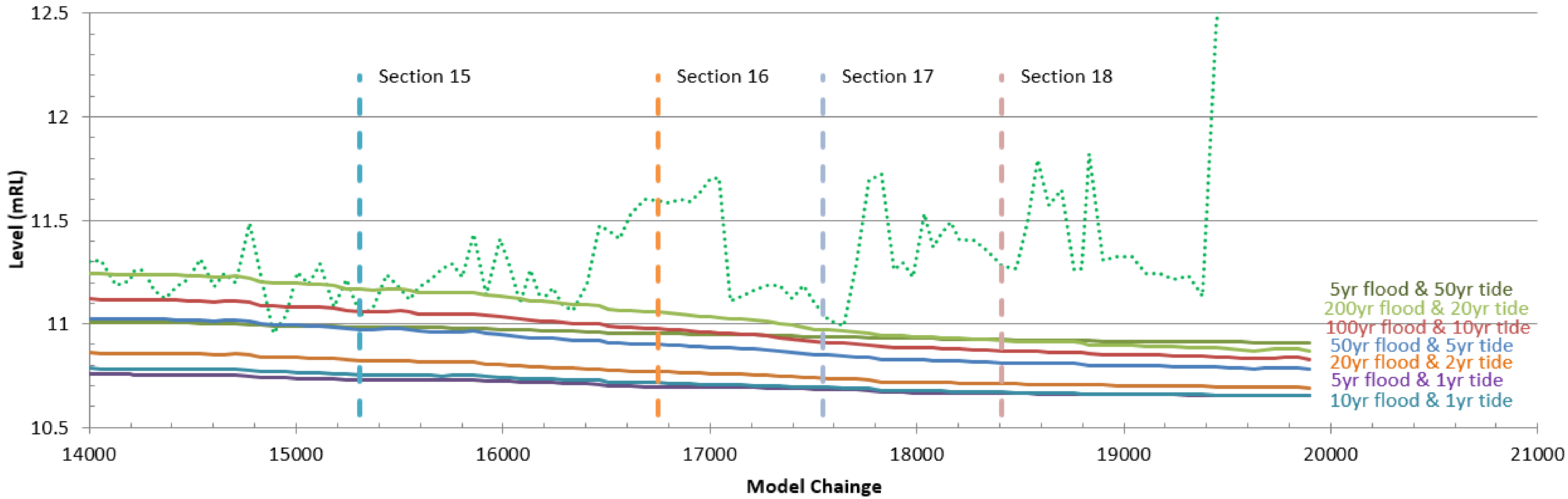


Figure 3-13 **Right Bank Flood and River Bed Levels**

Discussion of Flood and Tidal Influence Coupling

As described in Section 3.7.1, larger tidal events have the potential to drown out smaller flood events near the mouth of the river close to Bridge Street. The flood events shown in Figure 3-12 and Figure 3-13, showed that Chainage ~17,900 and 14,300 were potentially significant locations for flood and tide water level influence.

Between chainage Bridge Street and Chainage 17,900, the 1 in 50 AEP Tide with the 1 in 5 AEP indicates an almost linear hydraulic grade line. Considering all of the other flood events in the data set, the Hydraulic Grade Line (HGL) was almost the same in this section, hence tidal water level influence was considered dominant over flood water level influence. Chainage 17,900 was seen as a shifting point of this condition.

For all flood events provided in the data set, a difference in HGL slope could be seen when comparing Chainage 14,300 to 17,900 and Chainage 17,900 to Bridge Street (refer to Figure 3-12 and Figure 3-13). Considering the largest available flood event (the 1 in 200 AEP flood with the 1 in 20 AEP Tide) and the 1 in 50 AEP tide coupled with the 1 in 5 AEP flood, between chainage 9,300 to 17,900 it could be seen that the larger flood was creating higher water levels. Conversely, smaller floods were creating lower water levels than the larger tides in this location. Hence, for the flood events coupled with different tidal events, this section was considered as changing point and flood levels were compared against the tidal levels with no flood influence and the greater water level was adopted for the event under consideration. An example of this process is shown in Figure 3-14 below. The remainder of these curves are presented in Appendix G .

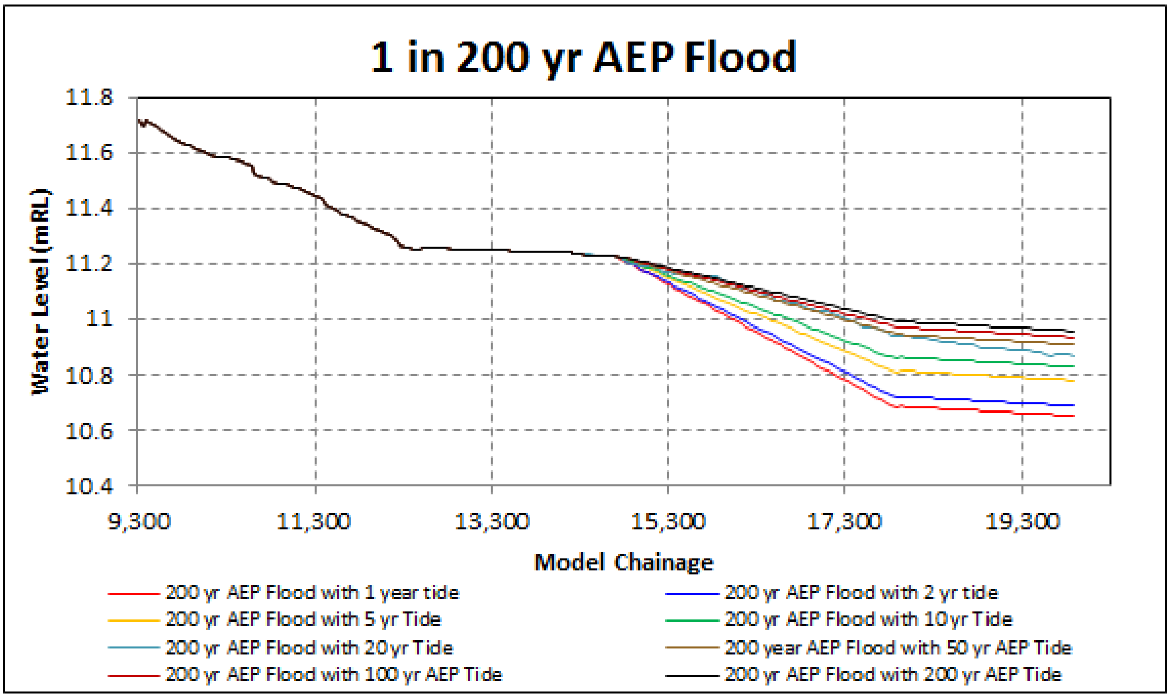


Figure 3-14 1 in 200 AEP Flood Event coupled with various tidal events

3.7.3 Seismic Loading

Seismic loading for the risk assessment was adopted from a literature source describing the seismic hazard of the Canterbury Region, New Zealand (Stirling et al. 2008). The seismic data for Christchurch obtained from the literature is shown in Table 3-10 below. PGA values for a spectral acceleration of 0 seconds were adopted for the seismic loading considered in the risk assessment. This data is shown on Table 3-11 and Figure 3-15 below and was was used to estimate levee crest deformations for each of the seismic events.

Table 3-10 Christchurch PGA vs Return Period (Adopted from Stirling et al (2008))

Table 1. Location-specific PGA (Period T = 0.0 sec), and response spectral acceleration (T = 0.075 to 3.0 sec) and MMI (last row) for various return periods (see column 1), and for class C (shallow soil) site conditions. The centres are listed in alphabetical order.

Christchurch
Latitude 43.53S Longitude 172.64E

T(s)	0.00	0.075	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.50	0.75	1.00	1.50	2.00	3.00
20 yrs	0.07	0.10	0.12	0.14	0.17	0.17	0.17	0.16	0.16	0.13	0.09	0.05	0.04	0.03	0.01
50 yrs	0.11	0.18	0.21	0.26	0.31	0.30	0.29	0.27	0.26	0.22	0.14	0.09	0.07	0.05	0.03
75 yrs	0.14	0.23	0.27	0.32	0.37	0.36	0.34	0.32	0.30	0.25	0.16	0.11	0.08	0.06	0.04
200 yrs	0.22	0.41	0.49	0.55	0.62	0.56	0.52	0.48	0.44	0.37	0.24	0.16	0.12	0.09	0.06
475 yrs	0.31	0.61	0.75	0.82	0.89	0.78	0.71	0.64	0.58	0.48	0.31	0.21	0.15	0.12	0.09
1,000 yrs	0.40	0.83	1.02	1.09	1.17	1.00	0.89	0.79	0.72	0.59	0.38	0.25	0.19	0.14	0.11
2,000 yrs	0.50	1.08	1.34	1.40	1.49	1.25	1.09	0.96	0.86	0.71	0.45	0.31	0.23	0.17	0.14
5,000 yrs	0.64	1.45	1.80	1.85	1.95	1.61	1.37	1.20	1.08	0.88	0.55	0.38	0.29	0.22	0.18
10,000 yrs	0.77	1.76	2.20	2.24	2.34	1.91	1.61	1.40	1.24	1.02	0.63	0.43	0.33	0.25	0.21
20,000 yrs	0.90	2.12	2.65	2.67	2.76	2.23	1.86	1.61	1.43	1.17	0.71	0.48	0.38	0.29	0.24

MMI 50 yrs = 6-7; 150 yrs = 7-8; 475 yrs = 7-8; 1,000 yrs = 8-9

Table 3-11 Avon Stopbanks risk assessment seismic events

Code	Return Period (years)	Annual Exceedance Probability (AEP)	Annual Probability Interval	Peak Ground Acceleration (g)
EQ1	20	5.00E-02	3.00E-02	0.07
EQ2	50	2.00E-02	6.67E-03	0.11
EQ3	75	1.33E-02	8.33E-03	0.14
EQ4	200	5.00E-03	2.89E-03	0.22
EQ5	475	2.11E-03	1.11E-03	0.31
EQ6	1,000	1.00E-03	5.00E-04	0.40
EQ7	2,000	5.00E-04	3.00E-04	0.50
EQ8	5,000	2.00E-04	1.00E-04	0.64
EQ9	10,000	1.00E-04	5.00E-05	0.77
EQ10	20,000	5.00E-05	5.00E-05	0.90

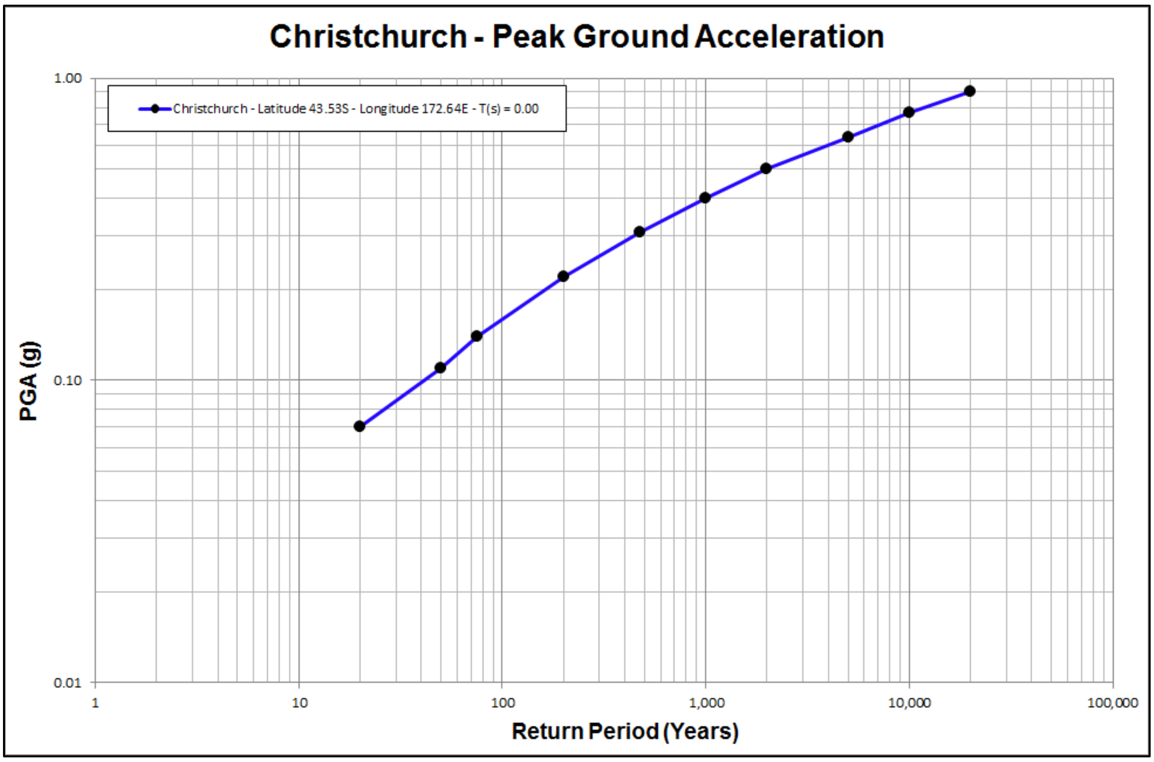


Figure 3-15 Christchurch PGA vs Return Period for T = 0s

3.8 Embankment Piping for Flood or Tidal events

3.8.1 General

Failures associated with internal erosion (piping) were assessed using the Piping Toolbox (USACE et al 2008). Other probabilities in the event trees were assigned using subjective engineering judgement and the probability data provided in Table 3-12 together with engineering analysis of the failure modes.

Table 3-12 Mapping Scheme after Barneich et al (1996) ANCOLD 2003 Table 8.1

Description of Condition or Event	Order of Magnitude Probability Assigned
Occurrence is virtually certain	1
Occurrences of the condition or event are observed in the database	10^{-1}
The occurrence of the condition or event is not observed, or is observed in one isolated instance, in the available database; several potential failure scenarios can be identified.	10^{-2}
The occurrence of the condition or event is not observed in the available database. It is difficult to think about any plausible failure scenario; however, a single scenario could be identified after considerable effort.	10^{-3}
The condition or event has not been observed, and no plausible scenario could be identified, even after considerable effort.	10^{-4}

3.8.2 Embankment Piping Failure Mode Sequence

The evaluation of the piping failure modes were mostly based on the generic sequence of events presented in Figure 3-16. The process depicted in this figure is specific to flood loading but is also applicable to seismic loading as the tidal water level of the river could be at any level at the time of seismic loading. The events are described in further detail below.

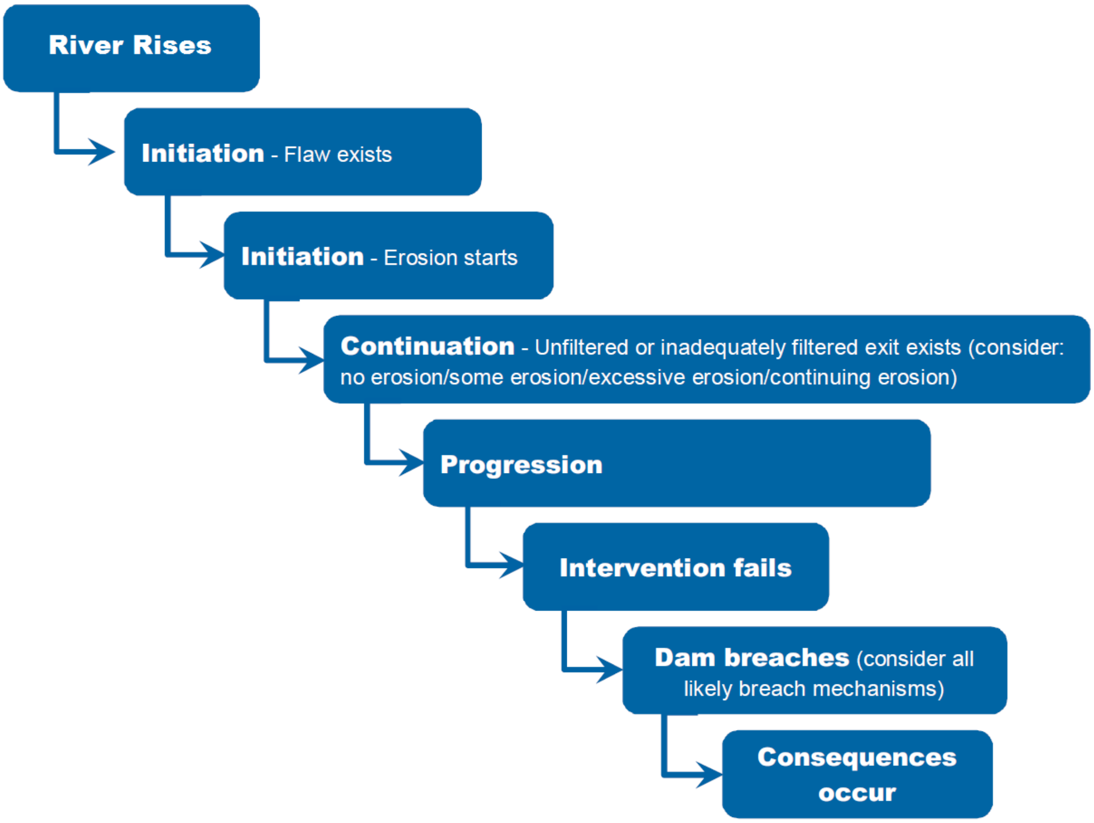


Figure 3-16 Generic Sequence of Events for Piping Failure Modes Analyses

3.8.3 Initiation

Initiation is the first phase and considers the existence of a flaw in the embankment or the foundation. The potential flaws within the embankment include a continuous crack or poorly compacted layer in which a concentrated leak may form. Flaws at the foundation comprise open defect or gaps within the in-filled defects or silty sands which can be prone to internal erosion under higher hydraulic gradients.

If a flaw exists, erosion must start to initiate for internal erosion to develop. There are several processes by which erosion can initiate in the embankment or foundation as follows;

- Concentrated leak erosion. Erosion can commence from the walls of a crack within the soil or within a poorly compacted layer.
- Scour at the embankment – foundation contact. Erosion of the soil may occur where it is in contact with seepage passing through the foundation either through a coarse grained soil or open joints in rock. In the case of the Avon Stopbanks, there is no rock foundation and the foundation is not coarse grained.
- Backward erosion. Backward erosion involves the detachment of soils particles when the seepage exits to a free unfiltered surface. The detached particles are carried away by the seepage flow and the process gradually works its way towards the upstream side of the embankment or its foundation until a continuous pipe is formed.

- Suffusion. This is a form of internal erosion which involves selective erosion of fine particles from the matrix of coarser particles (coarse particles are not floating in the fine particles). The fine particles are removed through the constrictions between the larger particles by seepage flow, leaving behind an intact soil skeleton formed by the coarser particles.

The potential for piping through the embankment has considered concentrated leak erosion and backward erosion estimated using the Piping Toolbox.

The Piping Toolbox initiating mechanisms were screened as follows.

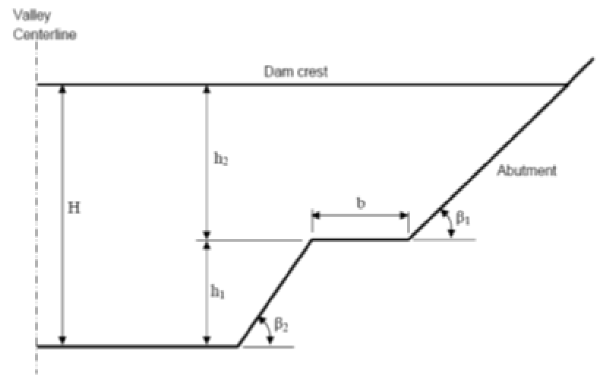
Transverse Cracks - Upper Parts of Embankment			
Initiating Mechanism	**Exclusions**	**Excludable (Yes/No)**	**Refer to**
IM1 - Transverse cracking due to cross valley differential settlement	No exclusions	No	IM1
IM2 - Transverse cracking due to differential settlement adjacent to a vertical cliff at the top of the embankment	Exclude if; (1) There is no vertical cliff with the embankment OR (2) A wide bench is present at the base of the cliff (Wb/Hw)>2.5 OR (3) The abutment slope below the cliff is gentle ($B1<25^0$) From Dimensions Entered: Excludable	Yes	IM2
IM3 - Transverse cracking due to cross valley arching	Exclude if; Width of valley to dam height ratio (Wv/Hw)>2 From Dimensions Entered: Excludable	Yes	IM3
IM4 - Transverse cracking resultant on cross section settlement	Exclude if; (1) The dam is zoning type homogeneous earthfill, earthfill with filter drains or zoned earthfill. OR (2) Evidence from relative settlements of core and shoulders that the materials have a similar modulus OR (3) Finite Element Analyses have demonstrated that stresses are such that hydraulic fracture is very unlikely.	Yes	IM4
IM5 - Transverse cracking due to differential settlements In the foundations beneath the core	Exclude if there is no compressible soil in the foundation below the core.	no	IM5
IM6 - Transverse cracking due to differential settlements due to embankment staging	Exclude if the embankment construction was not staged	Yes	IM6
IM7 - Cracking in the crest due to desiccation by drying	No exclusions	Yes	IM7
IM8 - Cracking on seasonal shutdown layers during construction and staged construction due to desiccation by drying	Exclude: (1) if the reservoir stage being considered is below the level of the seasonal shutdown surface. OR (2) This mechanism only applies above the level of saturation of the core. Below that any desiccation cracks should have swelled and closed. OR (3) This mechanism only applies where there has been a seasonal shutdown during construction, or the embankment has been staged. OR (4) Very good control and clean up practices used - desiccated layers removed from the embankment and replaced with new soil or adequately reworked to specified MC.	Yes	IM8
IM13 - Cracking due to earthquake	No exclusions *IM13A - Earthquake Hazard and Damage Class Rating* *IM13B - Probability of Transverse Cracking*	No	**IM13** IM13A IM13B

The following failure modes were evaluated for embankment piping, which included the Piping toolbox mechanisms together with the failure mechanisms associated with trees in the Stopbanks.

- Piping through cracks in embankment resulting from cross valley settlement and differential foundation settlement (Piping Toolbox IM1 and IM5)
- Piping through seismic induced cracks (Piping Toolbox IM13)
- Piping through rotted tree roots
- Piping through embankment narrowed section caused by trees blowing over

3.8.4 Piping Toolbox Base Data

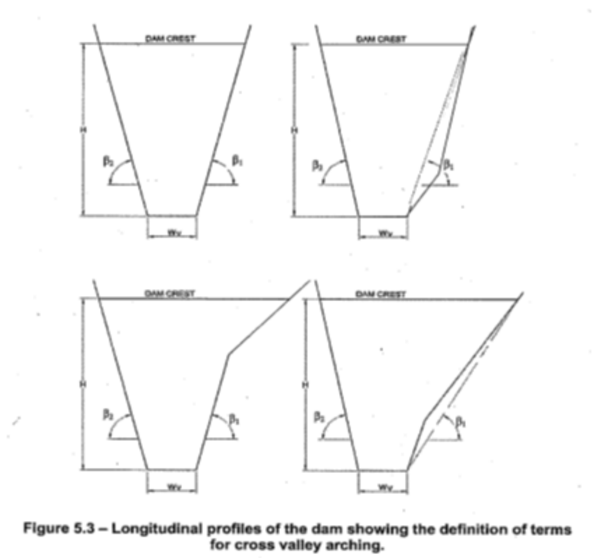
The use of the piping toolbox requires levee geometry to evaluate cross valley arching, transverse cracking due to differential foundation movements, hydraulic fracture, etc. While the stopbanks are not major structures, nevertheless, the foundation geometry, as shown by the river bed long section could result in differential movement and cracking through the levee. This was considered as follows.



Benches in the Foundation

h1	0.9
h2	
b	
B1	0.4
B2	0.4
H	0.9
b/h2	
H2/h1	
b/H	

Figure 3-17 Piping Toolbox Figure 5.1 for benching



Cross Valley Arching of the fill

B1	0.4
B2	0.4
Wv	20
H	0.9
Wv/H	22.22222

Figure 3-18 Piping Toolbox Figure 5.3 for cross valley arching

3.8.5 Crack formation

Cracking within the embankment may be the result of differential movements or settlement within the foundation or cracking due to seismic deformation.

Initiating mechanism IM1

This initiating mechanism was used for evaluating the piping potential through the embankment material.

The probability of cracks being present for IM1 was estimated as follows for the cracks above or below the Pool of record.

IM1 Transverse Cracking Due to Cross Valley Differential Settlement *(Table 5.2, 5.3 in book)*

Excludable:	No
Dam	
b/h2=	0.00
h2/h1=	0.00
***B1*=**	0.40
Dam Height=	0.90

			Likelihood Factor			
			Less Likely	Neutral	More Likely	Much More Likely
Factor	**Relative Importance Factor (RF)**	**Rating (1-4)**	**1**	**2**	**3**	**4**
Cross valley profile under embankment core	3	2	Uniform abutment profile without benches. Narrow bench very low in the abutment. b/h2<0.5 h2/h1>1.5	Wide bench, low in the abutment. b/h2>1 h2/h1>1	Wide bench in upper half to one third of the abutment. b/h2>1; 0.5<h2/h1<1 Or narrow bench in upper half to one third of the abutment. b/h2>0.5; h2/h1<0.25	Wide bench near the crest in the abutment. b/h2>1 0<h2/h1,0.5
Slope of abutments under embankment	2	1	Gentle abutment slope *B*1<30°	Moderate abutment slopes 30°<*B1*<45°	Steep abutments 45°<*B*1<60°	Very steep abutments *B*1>60°
Height of embankment	1	1	Dams less than 15 m high.	Dams 15 to 30 m	High dams 30 to 60 m	Very high dams >60 m (for dams higher than 120 m assign a likelihood factor of 5)
RF x LF		9				

Probability vs. RF*LF:

Below POR	0.00001	0.00005	0.00015	[0.0005]	0.005	0.02
Above POR	0.0001	0.0005	0.002	[0.007]	0.05	0.2
RF x LF	6	9	11	13	18	24

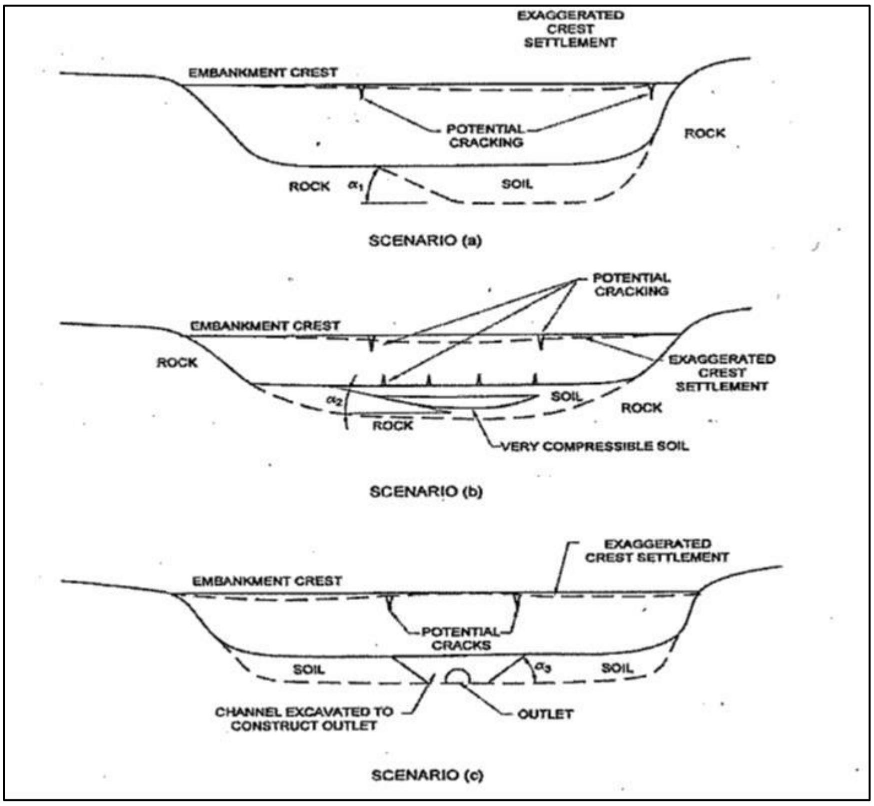
Probability:

Below POR	0.00005
Above POR	0.0005

Initiating mechanism IM5

This initiating mechanism was used for evaluating the piping potential through the foundation in the event that trees fall over, as discussed in Section 3.9.3.

Typical scenarios which may lead to differential settlement in foundations are shown below.



The probability of cracks being present for IM5 was estimated as follows for the cracks above or below the Pool of record.

IM5 Likelihood of Transverse Cracking Due to Differential Settlements in Soil in the Foundation

(Table 5.9, 5.10 in book)

Excludable: no
Dam Geometry:
α= See dia. Above
H= 0.9

Factor	Relative Importance Factor (RF)	Rating (1-4)	Less Likely 1	Neutral 2	More Likely 3	Much More Likely 4
			Likelihood Factor			
Foundation geology and geometry	3	3	Rock foundations or uniform soil foundations.[1]	Shallow soils or soils with gradual variation in depth and compressibility sufficient to cause differential settlement of less than 0.2% of the embankment height.	Moderate depth of compressible soil in the foundation sufficient to cause differential settlement of 0.3 to 0.5% of the embankment height.	Deep compressible soil in the foundation[2] sufficient to cause differential settlement of >0.5% of the embankment height.
Slope of the sides of the compressible	2	1	Gentle α <30°	Moderate 30° < α <45°	Steep 45°< α < 60°	Very steep α > 60°
Height of embankment	1	1	Dams less than 15 m high.	Dams 15 to 30 m	High dams 30 to 60 m	Very high dams >60 m
RF x LF		12				

Probability vs. RF*LF:

negligible	negligible	0.00005	0.0002	[0.0005]	0.003	0.02 Below POR
negligible	negligible	0.0005	0.002	[0.007]	0.03	0.2 Above POR
6	8	9	11	13	18	24 RF x LF

Notes:
essible soil in the foundation this mode does not apply.
h collapse on saturation and which have not been treated or

Note: "POR" refers to the Pool of Record level + 1 foot.

Probability:
Below POR 0.00035
Above POR 0.0035

Initiating Mechanism IM13

The initiation of piping for seismic events was completed as follows.

- Evaluate damage class for peak ground accelerations and magnitudes

The damage class for peak ground accelerations with representative magnitudes was evaluated for a range of events using Figure 3-19 and the results are shown on Table 3-13.

Table 3-13 Avon Stopbanks Seismic loading and damage class

Earthquake Peak Ground Acceleration	Representative Earthquake Magnitude	Damage Class (0-4) (From figures below)
0.07	5	0
0.11	5.5	0
0.14	6	0
0.22	6.5	1
0.31	7	2
0.4	7	3

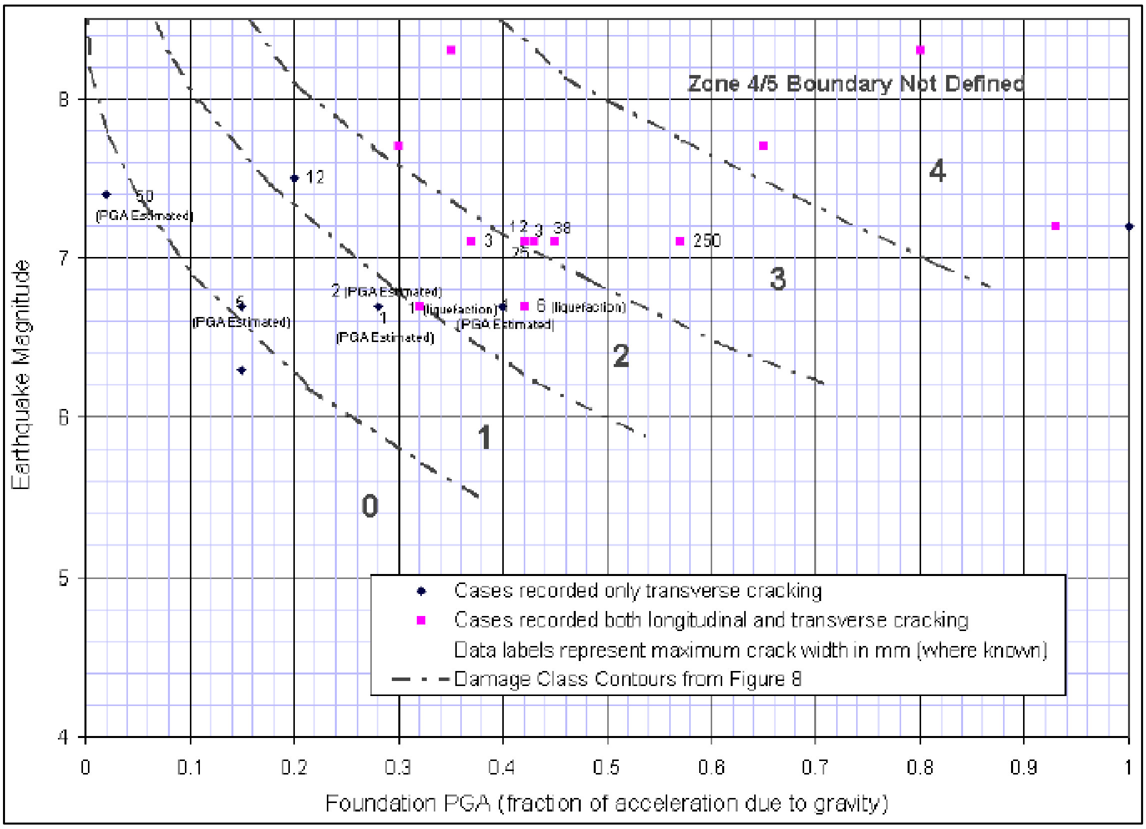


Figure 3-19 Incidence of transverse cracking versus seismic intensity and damage class contours for earthfill dams (Piping Toolbox Fig 5.8)

- Evaluate probability of cracks forming and crack widths at the Stopbank crest level.

The probability of crack formation and estimated maximum likely crack widths for each of the representative seismic events was evaluated using Table 5.39 of the Piping Toolbox as shown on Table 3-14 and the results are shown on Table 3-15.

Table 3-14 Probability of transverse cracks in an embankment caused by a Seismic event (Piping Toolbox Table 5.39)

Damage Class	For cases where cross valley or cross section cracking assessment is in lower three "boxes" i.e. RF x LF ≤ 12	
	Probability of transverse cracking	Maximum likely crack width
0	0.001	5
1	0.01	20
2	0.05	50
3	0.2	100
4	0.5	150

Table 3-15 Avon Stopbanks Probability of transverse cracks and likely maximum crack width for selected seismic events

Failure Mechanism	RF*LF	Earthquake Peak Ground Acceleration	Damage Class (0-4)	Probability of Transverse Cracking	Maximum Likely Crack Width at Crest (mm)
(IM1) / (IM5)	9 / 12	0.07	0	0.001	5
		0.11	0	0.001	5
		0.14	0	0.001	5
		0.22	1	0.01	20
		0.31	2	0.05	50
		0.4	3	0.2	100

The crack width at the crest was used to estimate the cracks at depth. Given the likely level of cracks and widths of cracks, the potential for piping was calculated using the hydraulic gradient at each level for tidal events with the material parameters appropriate to the stopbank material.

3.8.6 Cracking Factor

The cracking factor for adjusting the cracking potential was evaluated to be 1.0 using the following table taken from the piping toolbox

Factor	Influence on Likelihood			
	Less Likely	Neutral	More Likely	Much More Likely
Cracking observed in test pits to the top of or into the core	No cracking observed when large areas of the top of the core are exposed.	No test pits	Transverse cracks persistent across the top of the core and/or, extensive, open longitudinal cracking	Transverse cracks which pits show persist across the core, and extend below reservoir water level in the reservoir level partition being considered
Cracking Factor (A)	0.5 to 0.1 depending on the extent of exposure and how relevant the exposure is to the possible mechanism of cracking	1.0	5 to 100 depending on width(2) of cracking and whether they are in locations in which cracking might be expected	Probability of transverse crack = 1.0
Cracking in the surface of the crest, no test pits	No cracking observed, core exposed on the surface, careful inspection for cracking	No cracking observed, core covered with road pavement or other granular material	Narrow (<10mm) transverse cracks persistent across the crest and/or, extensive, narrow longitudinal cracking	Transverse cracks which persist across the crest and/or, extensive, wide longitudinal cracking.
Cracking Factor (B)	0.5 to 0.2 depending on the quality of exposure and whether they are in locations in which cracking might be expected	1.0	2 to 5 depending on and whether they are in locations in which cracking might be expected	2 to 20 depending on the width(2) of cracking and whether they are in locations in which cracking might be expected

Notes: (1) Apply either Cracking Factor (A) or Cracking Factor (B), whichever gives greatest probability of cracking
(2) The greater the crack width the more likely it represents cracking in the core.

3.8.7 Settlement Factor

The settlement factor for adjusting the cracking potential was evaluated to be 1.0 using the following table taken from the piping toolbox.

Factor		Influence on Likelihood			
		Less Likely	Neutral	More Likely	Much More Likely
Observed maximum settlements as percentage of embankment height					
- Core settlement during construction		< 1.5%	1.5% to 3%	3% to 4%	> 4%
- Post construction crest settlement at 10 years after construction dams with poorly compacted shoulders		<0.5%	0.5% to 1.0%	1.0% to 1.5%	> 1.5%
- Post construction crest settlement at 10 years after construction other dams		<0.25%	0.25% to 0.5%	0.5% to 1%	> 1%
- Long term settlement rates(% per log time cycle in years) dams with poorly compacted shoulders		< 0.15%	0.15% to 0.4%	0.4% to 0.7%	> 0.7%
- Long term settlement rates(% per log time cycle in years)-other dams		< 0.1%	0.1% to 0.25%	0.25% to 0.5%	> 0.5%
Settlement multiplication factors for cracking or hydraulic fracture in the upper part [(a)] of the embankment based on observed maximum settlements	**Dams with poorly compacted rockfill [(b)]**	0.05 to 0.2	0.2 to 0.5	1.0	2 to 5
	All other dams	0.2 to 0.5	1.0	2 to 10	10 to 20
Settlement multiplication factors for cracking or hydraulic fracture in the middle and lower parts [(c)(d)] of the embankment	**Dams with poorly compacted rockfill [(b)]**	0.2	0.2 to 0.5	1.0	2 to 5
	All other dams	0.5	1.0	2 to 5	5 to 10

Notes: (a) Multiplication factors to be applied to Probabilities from Sections 5.2.1, 5.2.2 and 5.2.3.
(b) Includes dumped rockfill, and rockfill and other granular zones compacted by tracking with bulldozers and by small rollers in thick layers
(c) To be applied to probabilities from Sections 5.3.1, 5.3.2 and 5.3.3
(d) Multiplication factors assumed to be half those for cracking in the upper part.

A summary of the crack formation for the initiation mechanisms IM1 and IM5 is shown on Table 3-16.

Table 3-16 Crack summary for piping initiating mechanisms IM1 and IM5

Initiation Mechanism	Partition	Pc (unfactored)	Settlement Factor	Cracking Factor	Probability of Crack (Pcrack)
IM1 - Transverse cracking due to cross valley differential settlement	1.00	0.00005	1	1	5.00E-05
	1.25	0.00005	1	1	5.00E-05
	1.50	0.00005	1	1	5.00E-05
	1.75	0.0005	1	1	5.00E-04
	2.00	0.0005	1	1	5.00E-04
IM5 - Transverse cracking due to differential settlements In the foundations beneath the core	1.00	0.00035	1	1	3.50E-04
	1.25	0.00035	1	1	3.50E-04
	1.50	0.00035	1	1	3.50E-04
	1.75	0.0035	1	1	3.50E-03
	2.00	0.0035	1	1	3.50E-03

3.8.8 Embankment Crack depth and size

Given the potential crack, the size of the crack was evaluated for Initiation mechanisms IM1 and IM5 using table 5.24 of the Piping toolbox as shown on Table 3-17. The theoretical maximum likely crack width was adjusted to the assumed width based on site observations.

Table 3-17 Avon Stopbank crack width at crest for Initiating mechanisms IM1 and IM5

Crack Formation Mechanism		RL*LF	Maximum likely crack width at the dam crest relative to RL*LF (mm)					Assumed Max likely Crack Width at Crest (mm)	Theory Max likely Crack Width at Crest (mm)
			6-9	9-11	11-13	13-18	18-24		
IM1	Cross Valley Differential Settlement	9	1	20	50	75	100	1	1
IM5	Differential settlement of the foundations	12	1	20	50	100	150	10	35

The likely crack width at depth was then calculated using Table 5.25 of the Piping Toolbox for which the cracks widths were estimated as shown on Table 3-18.

Table 3-18 Avon Stopbank crack width at depths below crest for Initiating mechanisms IM1 and IM5

Crack Formation Mechanism		Depth below crest level (m)				
		1.00	0.75	0.50	0.25	0.0
		Average crack width (mm)				
IM1	Cross Valley Differential Settlement	0.1	0.2	0.3	0.4	0.5
IM5	Differential settlement of the foundations	1.0	2.0	3.0	4.0	5.0

Table 3-19 Avon Stopbank crack width at depths below crest for Initiating mechanism IM13

Maximum crack width at crest	Depth below crest level (m)				
	1.00	0.75	0.50	0.25	0.0
	Average crack width (mm)				
5	1.0	2.0	3.0	4.0	5.0
20	7.3	10.5	13.7	16.8	20.0
50	25.0	31.3	37.5	43.8	50.0
100	70.0	77.5	85.0	92.5	100.0

Given the likely level of cracks and widths of cracks, the potential for piping was calculated using the hydraulic gradient at each level with the material parameters appropriate to the stopbank material.

3.8.9 Hydraulic Gradient for Embankment Piping

The hydraulic gradients used to assess the likelihood of piping through the embankment where cracks are initiated were calculated for a range of partition levels. Following the seismic events, cracks were observed at various locations along the levee alignment on both the left and right banks. These cracks were mapped and can be found in Appendix C. Transverse cracks were generally observed to be diagonal to axis of the levee rather than perpendicular hence the seepage length was taken as three times the transverse width (perpendicular to the axis of the levee). The estimated piping initiation level was taken as the levee crest level after settlement (initiated by seismic loading) minus half of the original height of the levee. This information is shown schematically in Figure 3-20 below.

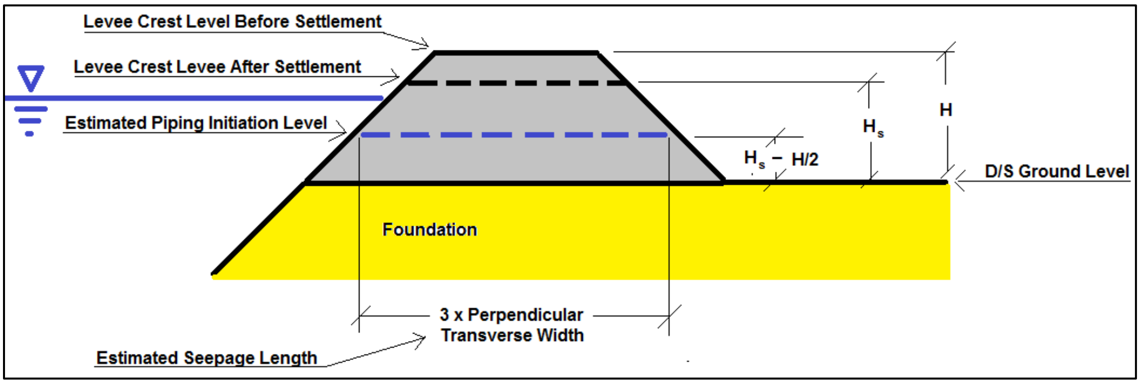


Figure 3-20 Schematic section showing the estimation of Hydraulic Gradient Initiating Piping

The hydraulic gradients were calculated for various core widths and defect levels as shown on Table 3-20.

Table 3-20 Avon Stopbanks hydraulic gradients for embankment piping

Defect level (m)	Core Width (m)	Hydraulic gradient across core when reservoir level is at a specific level			
		0.25	0.5	0.75	1
0.1	3.00	0.08	0.17	0.25	0.33
0.25	2.50		0.10	0.20	0.30
0.50	2.00			0.13	0.25
0.75	1.50				0.17
1.00	1.00				

These hydraulic gradients were used for estimating the initiation probabilities

3.8.10 Piping Initiation Probability Estimates

The probability of piping initiating in a crack through the embankment given an average hydraulic gradient was estimated for the cracks at various depths within the stopbanks using Table 5.29 of the Piping toolbox for a ML or SM soil with <30% fines copied below as Table 3-21.

Table 3-21 Estimation of probability of initiation in a crack for ML or SM with <30% fines soil types (Adopted from Table 5.29 USACE (2008) and extrapolated)

Estimated Crack Width (mm)	Probability of initiation of erosion for different seepage gradients							
	Average Hydraulic Gradient							
	0	0.01	0.1	0.25	0.5	1	2	5
0	0	0	0	0	0	0	0	0
0.5	0	0.00005	0.025	0.1	0.3	0.475	0.5	0.5
1	0	0.0001	0.05	0.2	0.6	0.95	1	1
2	0	0.001	0.1	0.6	0.9	1	1	1
5	0	0.005	0.6	1	1	1	1	1
10	0	0.01	0.9	1	1	1	1	1
25	0	0.1	1	1	1	1	1	1
50	0	0.15	1	1	1	1	1	1
75	0	0.2	1	1	1	1	1	1
100	0	0.5	1	1	1	1	1	1

The probability of piping initiation given the cracks for the failure initiating mechanisms IM1 and IM5 were estimated, as shown on Table 3-22.

Table 3-22 Avon Stopbank Probability of Piping initiation for Initiating mechanisms IM1 and IM5

Initiation Mechanism	Height above Base (m)	1m Crest Width		1.5m Crest Width		2m Crest Width	
		Initiation given crack P(Init)	P(Crack) *P(Init)	Initiation given crack P(Init)	P(Crack) *P(Init)	Initiation given crack P(Init)	P(Crack) *P(Init)
IM1	0.0	0.00E+00	1.00E-08	0.00E+00	1.00E-08	0.00E+00	1.00E-08
	0.25	3.53E-03	1.77E-07	2.87E-03	1.44E-07	2.38E-03	1.19E-07
	0.50	1.22E-02	6.11E-07	1.02E-02	5.12E-07	8.76E-03	4.38E-07
	0.75	3.00E-02	1.50E-05	2.29E-02	1.14E-05	1.86E-02	9.31E-06
	1.00	5.83E-02	2.92E-05	4.64E-02	2.32E-05	3.75E-02	1.88E-05
IM5	0.0	0.00E+00	1.00E-07	0.00E+00	1.00E-07	0.00E+00	1.00E-07
	0.25	3.58E-02	1.25E-05	2.93E-02	1.03E-05	2.44E-02	8.53E-06
	0.50	2.18E-01	7.62E-05	1.83E-01	6.40E-05	1.57E-01	5.48E-05
	0.75	5.06E-01	1.77E-03	4.54E-01	1.59E-03	4.03E-01	1.41E-03
	1.00	7.78E-01	2.72E-03	7.14E-01	2.50E-03	6.67E-01	2.33E-03

The probabilities of piping initiating through the cracks resulting from seismic deformation for mechanism IM13 were calculated using the crack widths and depths from Table 3-19 and the data shown on Table 3-21.

3.8.11 Piping Continuation

Continuation is the phase where the relationship of the particle size distribution between the base (core or infill materials within the foundation) and the filter controls determines whether or not erosion will continue. No filter materials make up the fill of the levee bunds and therefore, a probability of 1 was assigned to the occurrence of this event.

3.8.12 Piping Progression

Progression is the third phase of internal erosion, where hydraulic shear stresses within the eroding soil may or may not lead to the enlargement of the pipe. Increases of pore pressure and seepage occur. The main issues are whether the pipe will collapse and whether upstream zones may control the erosion process by flow limitation or crack filling. The likelihood of progression was evaluated using Table 11.1 of the Piping Toolbox copied below as Table 3-23.

Table 3-23 Probability of a soil being able to support a roof to an erosion pipe (Piping Toolbox Table 11.1)

Soil Classification	Percentage Fines	Plasticity of the Fines	Moisture Condition	Likelihood of Supporting a Roof
Clays, sandy clays (CL, CH, CL-CH)	> 50%	Plastic	Moist or saturated	1.0
ML or MH	>50%	Plastic or non-plastic	Moist or saturated	1.0
Sandy clays, Gravely clays, (SC, GC)	15% - 50%	Plastic	Moist or Saturated	1.0
Silty sands, Silty gravels, Silty sandy gravel (SM, GM)	> 15%	Non plastic	Moist Saturated	0.7 to 1.0 0.5 to 1.0
Granular soils with some cohesive fines (SC-SP, SC-SW, GC-GP, GC-GW)	5% to 15%	Plastic	Moist Saturated	0.5 to 1.0 0.2 to 0.5
Granular soils with some non plastic fines (SM-SP, SM-SW, GM-GP, GM-GW)	5% to 15%	Non plastic	Moist Saturated	0.05 to 0.1 0.02 to 0.05
Granular soils, (SP, SW, GP, GW)	< 5%	Non plastic Plastic	Moist and saturated Moist and saturated	0.0001 0.001 to 0.01

Notes: (1) Lower range of probabilities is for poorly compacted materials (i.e. not rolled), and upper bound for well compacted materials.
(2) Cemented materials give higher probabilities than indicated in the table. If soils are cemented, use the category that best describes the particular situation.

Given the granular nature of the embankment material, the probability was assessed to be 0.001 while for the foundation soils, the continuation was taken to be 0.5, as shown on Table 3-24.

Table 3-24 Avon Stopbank Piping Continuation probabilities

Stopbank Piping area	Height (m)			
	0.25 m	0.50 m	0.75	1.00
	Continuation Probability			
Embankment	0.001	0.001	0.001	0.001
Soil Foundation (Trees)	0.5	0.5	0.5	0.5

Consideration can also be given to the duration of the flood event that causes the piping initiation to determine whether the river level is sustained for the time required to progress the failure mode towards failure. At the present stage of the analysis, it has been assumed that the flood or tidal events have sufficient time to progress the failure.

3.8.13 Piping Intervention fails

Failure to intervene is the fourth phase of the failure pathway and this considers whether the internal erosion failure mechanism will be detected and whether intervention and repair will successfully stop the failure process. Given the rapid response to the previous seismic events, the likelihood of not intervening was taken to be 0.5 for the smaller seismic and flood events to 0.9 for the larger events.

3.8.14 Piping Related Breach

Levee Breach is the final phase of internal erosion and the following four phenomena were considered:

- Gross enlargement of the pipe (which may include the development of a sinkhole from the pipe to the crest of the embankment).
- Slope instability of the downstream slope.
- Unravelling of the downstream face.
- Overtopping (e.g. due to settlement of the crest from suffusion and/or due to the formation of a sinkhole from a pipe in the embankment).

No differentiation has been made with respect to the breach mechanism for the risk analysis, however, given the low height of the Stopbank and construction material, the most likely breach mechanism is expected to be sloughing or unravelling for which the likelihood was evaluated using Table 13.12 of the Piping Toolbox copied below. This indicates that the Probability could be between 0.1 to 1, depending on the amount of seepage that is likely to pass through the embankment zone. The probability of breach has, therefore, been taken to be 0.5 for the low flood events to 0.9 for the largest flood event.

Table 13.12			Likelihood Factor			
			Less Likely	Neutral	More Likely	Much More Likely
Factor	Relative Importance Factor (RF)	Rating (1-4)	1	2	3	4
Material in downstream zone	3	2	Cohesive Soils	Sandy Gravels (<20% fines)	Silty sand, silty sandy gravel, 20%-50% non plastic fines	As for more likely, but uncompacted materials
Freeboard at the time of incident	2	4	>4 m	3 m	2 m	1 m
Downstream Slope of the Embankment	1	4	3H:1V or flatter	2.5H:1V	2H:1V	Steeper than 1.8H:1V
RF x LF		18				

a. For internal erosion in the embankment, soil foundations and from embankment into foundation.

1.0	1.0	1.0	1.0	1.0	1.0	(CE)
0.01	0.05	0.1	0.5	0.9	1.0	(EE)
0.001	0.003	0.01	0.05	0.1	0.5	(SE)
6	9	11	13	18	24	

Note: Select the probability scale corresponding to the filter erosion condition being considered on the event tree.
CE = Continuing Erosion branch, EE = Excessive Erosion branch, and SE = Some Erosion branch.

3.9 Foundation Piping

The foundation was assessed for piping through the following:

- Silty Sands
- Rotted tree roots
- Embankment that has been narrowed by trees blowing over

3.9.1 Piping through Silty Sands

Piping through the silty foundation material is possible as the hydraulic gradient increases with higher tidal levels, particularly when the tide level is above any historical high level.

Sellmeijer et al. (2011) method was used to determine a critical hydraulic gradient for piping through the foundation for a range of applicable partition levels.

Water levels were adopted from the flood and tidal levels under consideration in the risk assessment. Levee geometry varied along the Avon river and was determined for each section under consideration. Figure 3-21 shows the general levee geometry and water levels used to estimate the critical hydraulic gradient required to initiate piping.

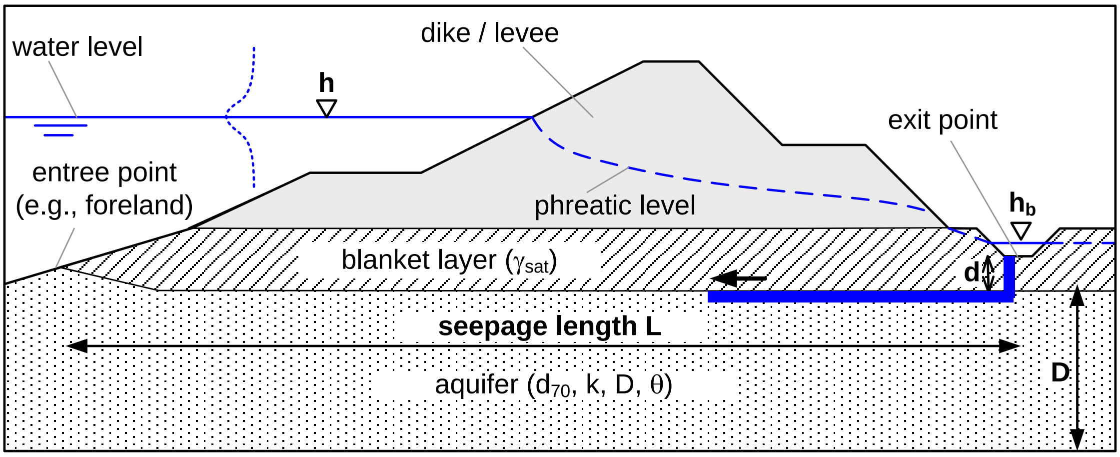


Figure 3-21 Geometry of backward erosion piping model

The formula used for evaluating the critical hydraulic gradient is shown below.

$$\frac{H_c}{L} = \frac{1}{c} = F_R F_S F_G$$

$$F_R = \eta \frac{\gamma'_p}{\gamma_w} \tan\vartheta \left(\frac{RD}{RD_m}\right)^{0.35}$$

$$F_S = \frac{d_{70}}{\sqrt[3]{\kappa L}} \left(\frac{d_{70m}}{d_{70}}\right)^{0.6}$$

$$F_G = 0.91 \left(\frac{D}{L}\right)^{\frac{0.28}{\left(\frac{D}{L}\right)^{2.8} - 1} + 0.04}$$

Notations

H_c	H_c critical head over the levee [m]
γ'_p	Volumetric underwater weight of particles [kN/m^3] $\gamma'_p = \gamma_p - \gamma_w$
γ_w	Volumetric weight of water [kN/m^3]
θ	Bedding angle [°]
η	White's coefficient (= 0,25) [-]
κ	Intrinsic permeability of the sand layer [m^2] $\kappa = \nu * k/g = 1{,}35*10^{-7}*k$
k	Darcy permeability [m/s]
ν	Kinematic viscosity [m^2/s]
g	Gravity acceleration (g = 9,81) [m/s^2]
d_{70}	Grain size at 70-percent cumulative weight [m]
d_{70m}	Mean d_{70} of small-scale tests ($d_{70m} = 2{,}08*10^{-4}$) [m]
D	Thickness of the sand bed [m]
L	Seepage length [m]

The critical hydraulic gradient was calculated using various seepage lengths appropriate to the bund height and crest width using the data shown on Table 3-25.

Table 3-25 Avon Stopbank input data for analysis of critical seepage gradient for initiation of piping in the foundation

Description	Factor
n Whites coefficient	0.25
Particle density	2.6
Water density	1
Friction angle (degrees)	30
d70 (m)	1.00E-04
d70m (m)	2.08E-04
Permeability (m/s)	3.00E-04
Intrinsic Permeability (m/s)	4.05E-11
Layer Thickness D (m)	3
Seepage Length (m)	Varies

The probability of piping was assumed to be 0.4 with the critical hydraulic gradient ration of Head/Hc of 1.0. The relationship of the head to critical hydraulic gradient (Head/Hc) was then evaluated, as shown on Figure 3-22. This relationship was then used for evaluating the probability of piping through the Stopbank sand foundations using 20% of the differential head from the river level to the ground level on the land side of the Stopbank. The factor of 20% allows for headloss through the foundation.

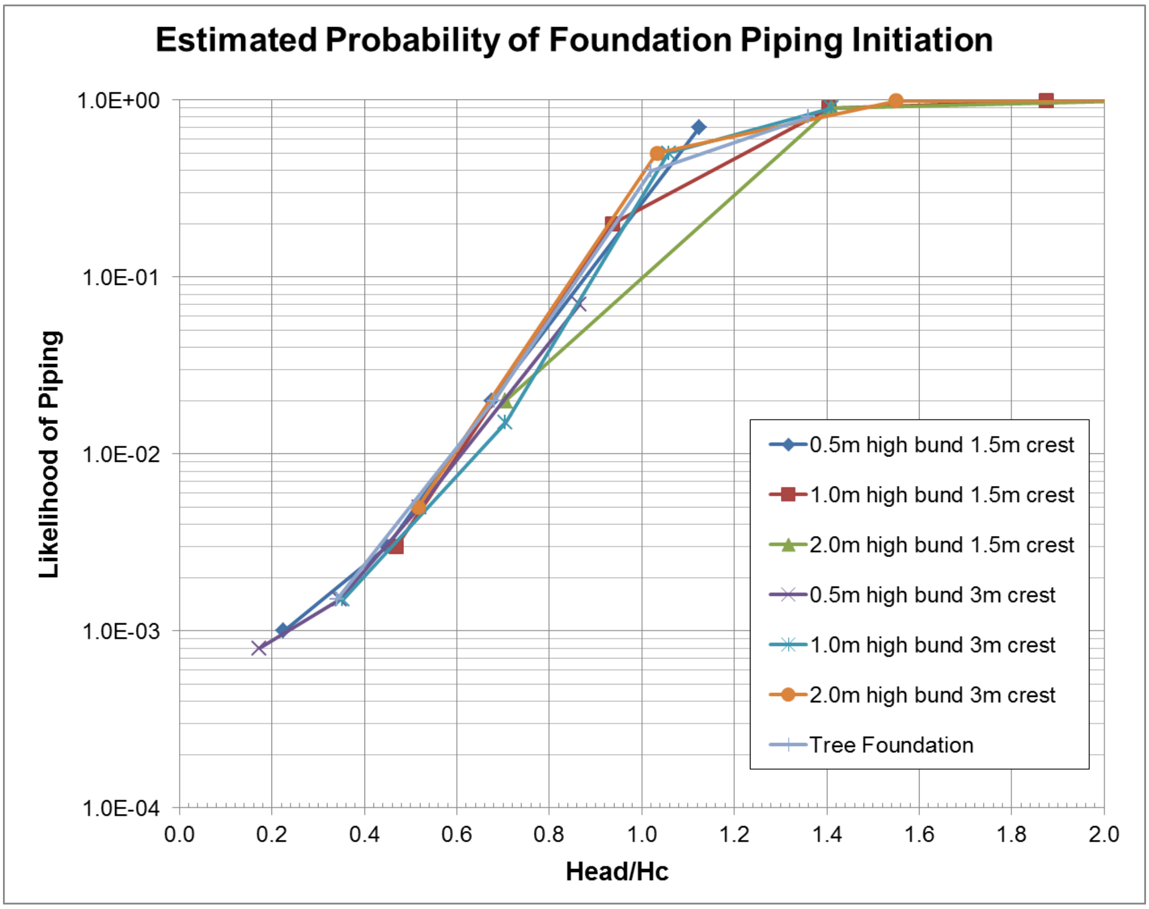


Figure 3-22 Estimated Probability of Foundation Piping Initiation for several bund geometries

The Stopbank sections where alluvial sands are present through which piping could occur were evaluated using the interpolation of the foundation probability with the head of the river above the bank level.

3.9.2 Piping through rotted tree roots

The foundation piping through rotted tree roots was evaluated using the same procedure as the piping through the silty sand with the exception that the layer thickness was reduced to 1 m and the seepage length was taken to be 12 m. The resulting conditional probability of failure and head to critical head ratio are shown on Figure 3-22 and Table 3-26.

Table 3-26 Conditional probability of Piping and Head to Critical head ratio for Stopbank with rotted tree roots

Head at toe area (m)	Conditional Probability of Piping	Head/Hc
0.0	1.00E-10	
0.5	1.50E-04	0.34
1.0	1.00E-02	0.68
1.5	4.00E-01	1.02
2.0	8.00E-01	1.36

The probability that the tree roots have rotted during each of the lifetimes being considered for the Stopbank were assumed to be as shown on Table 3-27 and this was combined with the conditional probability of piping given the tree roots have rotted.

Table 3-27 Probability that tree roots have rotted for each Stopbank Levee lifetime

Stopbank Lifetime (years)	Probability that the Tree Roots have rotted
1	0.001
5	0.005
10	0.01
20	0.1

3.9.3 Piping through embankment narrowed section caused by trees blowing over

The potential piping through the foundation with the trees blowing over and reducing the effective width of the piping seepage path was evaluated using the input data from Failure Initiating Mechanism IM5 (Table 3-22 in Section 3.8.10).

The head across Stopbank was used to interpret the piping initiation following which the continuation, progression, intervention and breach probabilities were evaluated using the same procedure as presented in Section 3.8.11 to Section 3.8.14.

3.10 Overtopping Failure

3.10.1 General

This failure mode is applicable whenever the river water level exceeds the crest level of the levee under consideration and has been assessed for all loading conditions including the following.

- Seismic deformation loss of freeboard and overtopping
- Floods or tides overtopping the gravel embankment
- Floods or tides overtopping the sandbag sections

Two failure modes were evaluated for the Stopbanks as follows.

Gravel Fill

The Avon stopbank levees have been constructed with gravel fill material, which is erodible hence with sufficient depth and velocity of overtopping flow, erosion of the levee could occur.

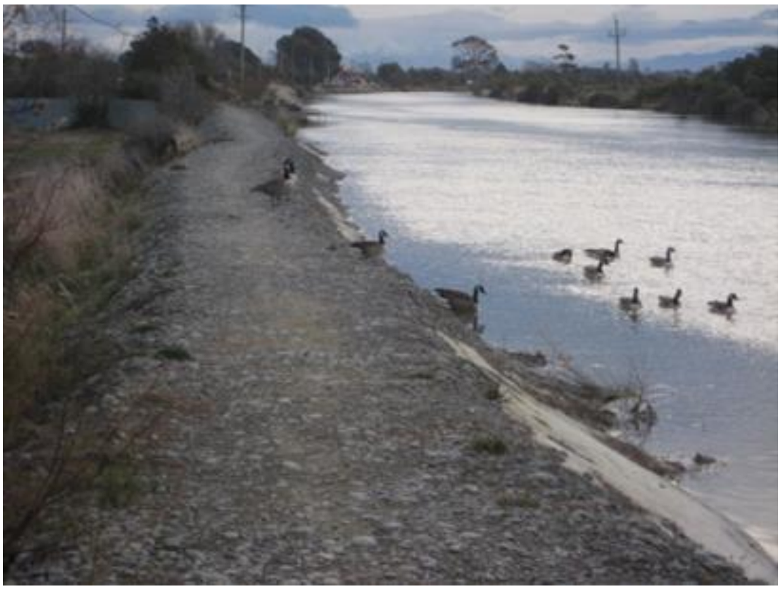


Figure 3-23 Section 17 Right Bank – Typical gravel fill Stopbank

Sandbags

In some areas, the land area was limited and sandbags were used to form the levee as shown in Figure 3-24 below. The degradation of these sandbags has been considered in the risk assessment.

Figure 3-24 Section 6 – Left Bank – Example of Sandbags

3.10.2 Overtopping Failure Probability Analysis

Overtopping failures were assessed where the water level in the Avon River exceeded the crest height of the stopbank levee under consideration. Overtopping flow up to 500 mm flow depth was assessed as this was close to the maximum caused by the flood events under consideration in this risk assessment.

Sections which had existing sandbags were assessed taking the top of the sand bag as the reported levee crest level from the LIDAR data provided to GHD by CCC.

The potential for overtopping erosion failure was evaluated using data from "The International Levee Handbook", (CIRIA 2013) as follows.

The critical velocity that would likely cause erosion of the levee crest was evaluated using the data shown on Table 8.10 and Table 8.11 of the Levee handbook copied below.

Table 3-28 CIRIA Levee handbook critical depth velocity table and adjustment factor

Table 8.10 Critical depth averaged velocities for loose granular material in water depth of 1 m

Material	Sieve size, *D* (mm)	Critical velocity *V* (m/s) for *h* = 1 m
Very coarse gravel	200–150	3.9–3.3
	150–100	3.3–2.7
Coarse gravel	100–75	2.7–2.4
	75–50	2.4–1.9
	50–25	1.9–1.4
	25–15	1.4–1.2
	15–10	1.2–1.0
	10–5	1.0–0.8
Gravel	5–2	0.8–0.6
Coarse sand	2–0.5	0.6–0.4
Fine sand	0.5–0.1	0.4–0.25
Very fine sand	0.1–0.02	0.25–0.20
Silt	0.02–0.002	0.20–0.15

Table 8.11 Velocity correction factors for water depths in range 0.3 m to 3 m

Depth, *h* (m)	0.3	0.6	1.0	1.5	2.0	2.5	3.0
Ki (-)	0.8	0.9	1.0	1.1	1.15	1.2	1.25

The data from the Levee handbook was then extended down to a depth of 0.05 m, as shown on Figure 3-25.

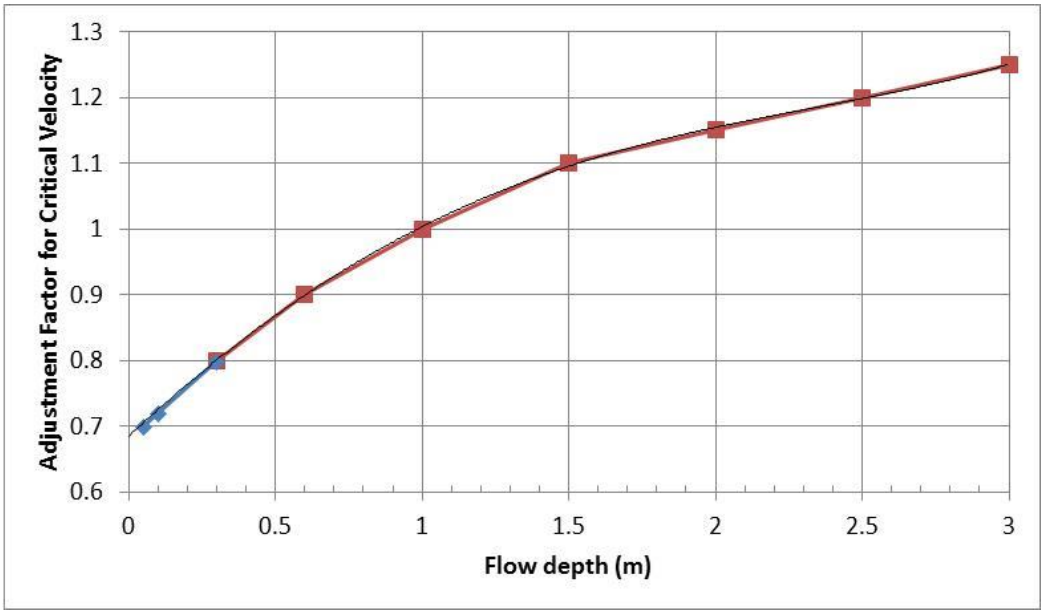


Figure 3-25 Adjustment factor for critical velocity of flow

The critical velocity of flow for each of the Stopbank material types was evaluated using the dat from Table 8.10 of the Levee handbook as shown on

Table 3-29 Avon Stopbank critical velocities for material types and 1 m depth of flow

Stopbank Material Zone	Critical Erosion Velocity (m/s)
Gravel 50-25 mm	1.5
Cementitious Sandbags, assume Coarse Sand	1.5
Regular Sand Bags, assume Fine Sand (deteriorated sandbags)	0.5

Weir flow discharge for various flow depths from 0.05 m to 0.5 m over the Stopbank crest was calculated from which the critical depth and velocity were calculated using the following formula.

For a rectangular channel $Q = qb$, $B = b$ and $A = by$, and taking $\alpha = 1$ this equation becomes

$$y_c = \left(\frac{q^2}{g}\right)^{1/3}$$

as $V_c\, y_c = q$

$$V_c = \sqrt{g y_c}$$

Equation 1.18

The allowable critical velocity was estimated for each of the Stopbank material types for the flow depths varying from 0.05 m to 0.5 m and compared with the actual critical velocity from which the probability of erosion failure was assessed, as shown on Table 3-30 and Figure 3-26.

Table 3-30 Critical Erosion Velocities Used to Estimate Probability of Overtopping Failure of Levee Bund Fill Material and Sandbags

Flow Depth (m)	Discharge (l/s/m)	Critical Depth (m)	Critical Velocity (m/s)	Levee Bund Fill Material and Sandbag Material		Deteriorated Sandbag Material	
				Levee Bund Fill Material and Sandbag Critical Erosion velocity	P (Erosion)	Regular Sandbag Material Critical Erosion velocity	P (Erosion)
0.05	16.2	0.03	0.54	1.05	0.050	0.35	0.999
0.10	45.9	0.06	0.77	1.08	0.075	0.36	0.999
0.15	84.2	0.09	0.94	1.11	0.130	0.37	0.999
0.20	129.7	0.12	1.08	1.14	0.250	0.38	0.999
0.25	181.3	0.15	1.21	1.17	0.400	0.39	0.999
0.30	238.3	0.18	1.33	1.20	0.600	0.40	0.999
0.35	300.2	0.21	1.43	1.23	0.800	0.41	0.999
0.40	366.8	0.24	1.53	1.25	0.900	0.42	0.999
0.45	437.7	0.27	1.63	1.28	0.950	0.43	0.999
0.50	512.7	0.30	1.71	1.30	0.999	0.43	0.999

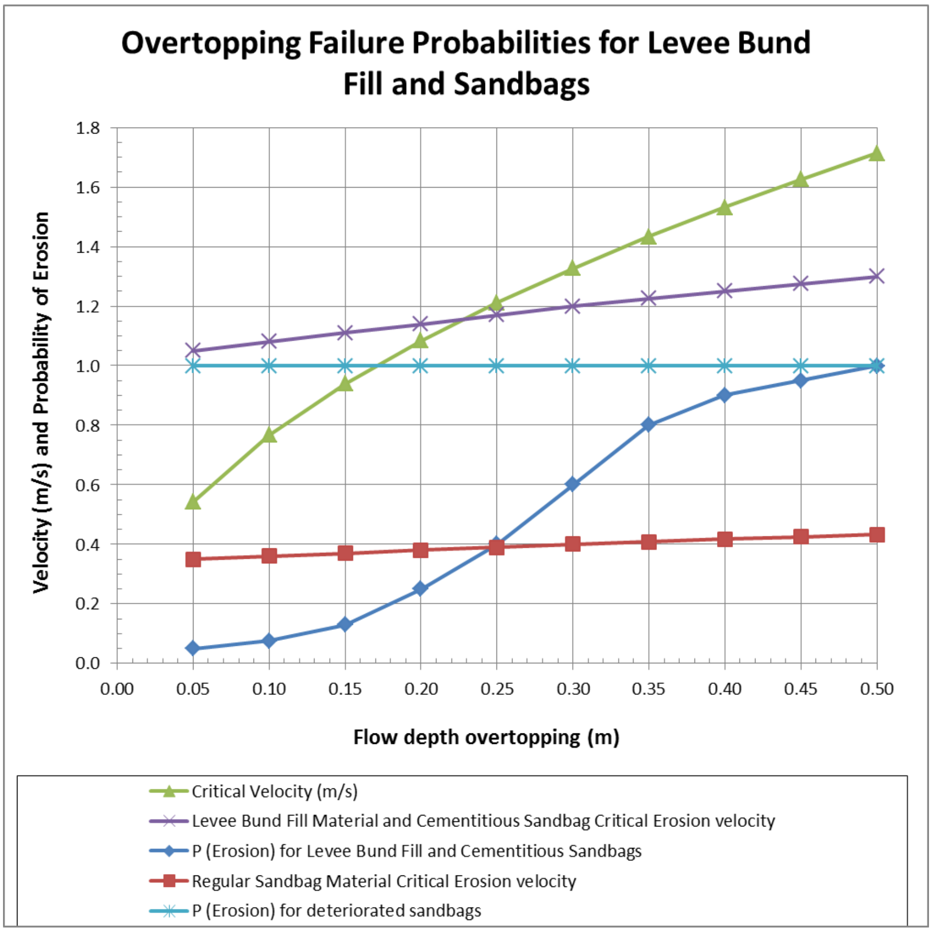


Figure 3-26 Estimated Probability of Overtopping Failure for Range of Overtopping Flow Depths

The depth of overtopping for each Stopbank section was calculated using the tidal levels with or without seismic deformation and the flood levels without seismic deformation. The depth was then used to interpolate the probability of overtopping erosion failure for the material type appropriate to each Section.

The sandbag overtopping failure was considered for the two cases of sandbag condition over the lifetimes being considered for the Stopbank, as shown on Table 3-31. The probability of failure for the two sand bag conditions shown on Table 3-30 was combined with the probability of the deteriorated sandbags for each lifetime being considered for the Stopbank.

Table 3-31 Avon Stopbank Sandbag deterioration over time

Stopbank Life (years)	Probability of Sandbag deterioration	Probability of Sandbag OK
1	0.2	0.8
5	0.9	0.1
10	0.99	0.01
20	0.999	0.001

3.11 Common Cause Adjustment

The common cause adjustment described below was applied to the lifetime failure probabilities rather than the individual failure modes for which it is commonly used. This was owing to expediency and simplification of the analysis process. Common cause adjustment is required where a flood or seismic event may cause multiple sections to fail with the same event.

The lifetime (1, 5,10, 20 years) failure probabilities for the various sections associated with the same seismic, flood or tidal event were, therefore, adjusted using the uni-modal bounds theorem (Ang and Tang, 1984) (de Morgan's rule).

The conditional probabilities for the failure modes that are not mutually exclusive can be adjusted for common cause occurrence by using the uni-modal bounds theorem. The unimodal bounds theorem (Ang and Tang, 1984) states that for k positively correlated failure modes, with conditional branch failure probabilities (system response probabilities), p_i, the system (total) branch failure probability, p_f, lies between the following upper (u) and lower (l) bounds:

$$max_i[p_i] \leq p_f \leq 1 - \prod_{i=1}^{k}(1 - p_i)$$

$$p_f^l \leq p_f \leq p_f^u$$

While the uni-modal bounds theorem provides an approach to bounding the total branch failure probability, it does not provide a direct means of bounding individual failure mode probabilities. This latter adjustment is normally needed because the consequences associated with each failure mode or section may differ. In the case of the Stopbank levees, the combined risk for each section with the Seismic and Flow or Tidal events have been adjusted rather than the individual failure modes.

While there is no unique approach to adjusting each system response probability, the following approach is proposed by Bowles et al (2001) was used to adjust the seismic, flood and tidal hazard data. The upper bound (u) was used to adjust the failure probabilities for each of the Stopbank lifetime failure probabilities, using the following formula:

$$p_i^u = p_i(p_f^u / p_f)$$

where p_f is the total probability of failure without the application of the uni-modal bounds theorem i.e. the total of the failure modes derived by addition. The adjustment was made simultaneously for all Stopbank sections for each lifetime and the resulting adjusted values used for the failure probability estimation for each lifetime.

The results for the seismic loading with the tidal events is shown on Table 3-32.

Table 3-32 Common Cause Adjustment for Seismic Loading with Tides

Section	Seismic Loading Lifetime Failure Probabilities				Adjusted Failure Probabilities for Lifetimes			
	1	5	10	20	1	5	10	20
1	8.04E-09	3.92E-08	7.60E-08	1.43E-07	7.97E-09	3.57E-08	6.50E-08	1.15E-07
2	1.02E-06	3.32E-06	5.45E-06	8.75E-06	1.01E-06	3.02E-06	4.66E-06	7.01E-06
3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	1.57E-08	7.52E-08	1.43E-07	2.61E-07	1.55E-08	6.84E-08	1.22E-07	2.09E-07
5	1.41E-04	6.63E-04	1.24E-03	2.21E-03	1.39E-04	6.03E-04	1.06E-03	1.77E-03
6	1.57E-02	1.24E-01	1.75E-01	2.19E-01	1.56E-02	1.13E-01	1.50E-01	1.75E-01
7	3.63E-03	5.00E-02	8.75E-02	1.28E-01	3.60E-03	4.55E-02	7.48E-02	1.02E-01
8	5.05E-03	6.71E-02	1.12E-01	1.56E-01	5.01E-03	6.10E-02	9.62E-02	1.25E-01
9	1.89E-06	6.65E-06	1.16E-05	2.02E-05	1.87E-06	6.05E-06	9.91E-06	1.62E-05
10	7.62E-09	3.72E-08	7.21E-08	1.36E-07	7.56E-09	3.38E-08	6.16E-08	1.09E-07
11	1.08E-04	5.17E-04	9.87E-04	1.81E-03	1.07E-04	4.70E-04	8.44E-04	1.45E-03
12	1.59E-03	2.59E-02	4.98E-02	8.10E-02	1.58E-03	2.36E-02	4.26E-02	6.49E-02
13	1.28E-04	6.12E-04	1.16E-03	2.09E-03	1.27E-04	5.57E-04	9.90E-04	1.67E-03
14	7.37E-08	3.23E-07	5.62E-07	8.97E-07	7.31E-08	2.94E-07	4.81E-07	7.19E-07
15	7.47E-04	3.17E-03	5.37E-03	8.37E-03	7.41E-04	2.88E-03	4.59E-03	6.71E-03
16	2.11E-07	7.06E-07	1.07E-06	1.49E-06	2.09E-07	6.42E-07	9.11E-07	1.19E-06
17	3.00E-06	8.62E-06	1.39E-05	2.23E-05	2.97E-06	7.84E-06	1.18E-05	1.78E-05
18	1.24E-06	3.02E-06	4.34E-06	6.12E-06	1.23E-06	2.75E-06	3.71E-06	4.90E-06
21	1.89E-07	7.69E-07	1.25E-06	1.86E-06	1.88E-07	7.00E-07	1.07E-06	1.49E-06
Sum	2.71E-02	2.72E-01	4.34E-01	5.98E-01	2.69E-02	2.47E-01	3.71E-01	4.79E-01
Common cause	2.69E-02	2.47E-01	3.71E-01	4.79E-01				
Factor	0.992	0.910	0.855	0.801				

4. Consequence Analysis

An assessment of consequence estimating the loss of life caused by levee failure was carried out as part of the risk assessment. The Reclamation Consequence Estimating Methodology (RCEM 2014) was used to undertake this assessment. The methodology relies on a graphical representation of fatality rate as a function of flood severity and warning time. The method has been based on analysis of dam failures, flash floods and regional floods.

The population at risk and potential loss of life was estimated for various areas along the river reach and the data applied to the Stopbank sections in each area.

4.1 Warning Times

Evacuation warning times can significantly reduce fatality rates associated with natural floods and floods caused by dam and levee failures. Where adequate warning time is provided to all of the Population at Risk (PAR), the Potential Loss of Life (PLL) has the potential to decrease to zero. Available warning times were considered in the consequence assessment. A schematic diagram of a dam/levee failure inflow hydrograph by Lang et al (2014) shown in Figure 4-1 below. Was used to consider the available warning time

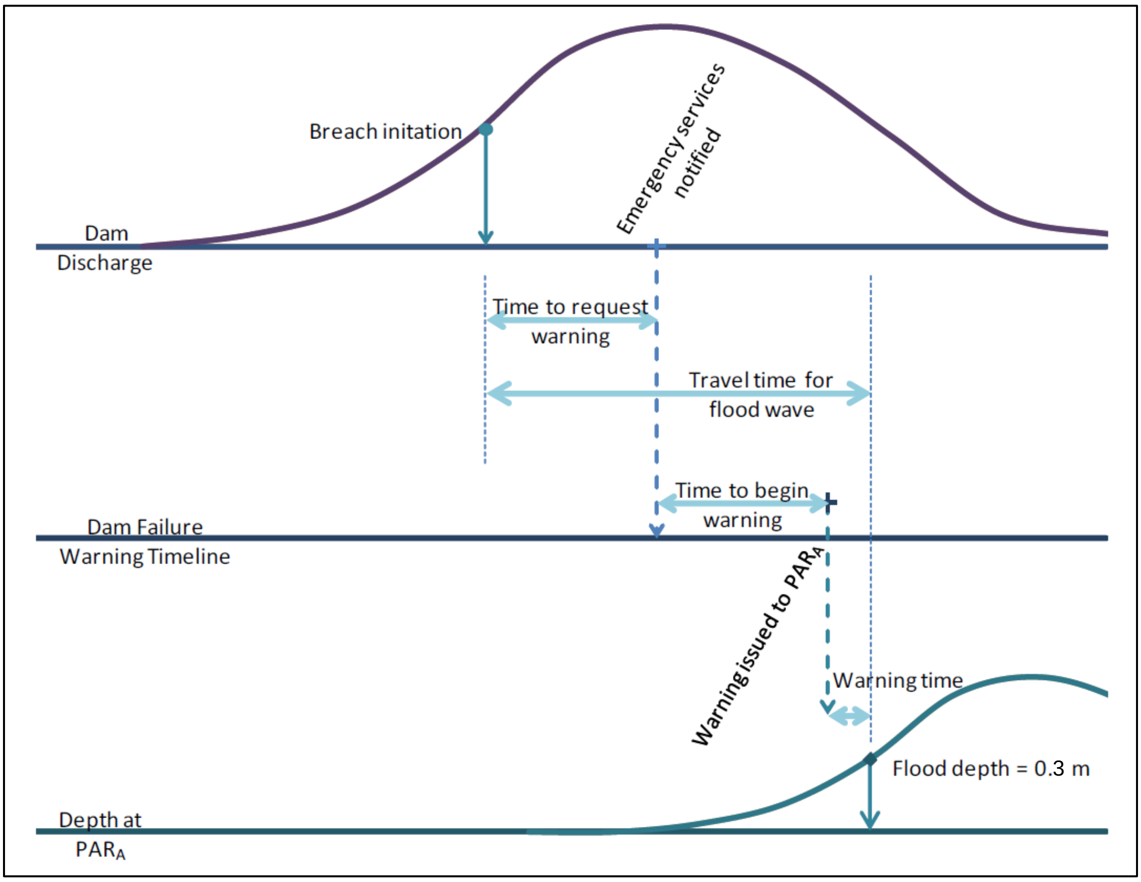


Figure 4-1 Estimating breach warning times for PAR

Figure 4-1 shows the common procedures involved in issuing a warning following an inflow event (caused by dam discharge in this case). Some literature suggests that up to 12 hours is required to request and begin a warning and therefore if less than 12 hours is available before 300 mm depth of inundation occurs at the PAR under consideration, than the warning time is considered zero.

It is thought that for large tidal events such as the 1 in 200 AEP tide, adequate warning time would be available as peak tides can be predicted and take several hours and some instances, days to develop. Hence, for tidal events only, adequate warning time was considered applicable for the loss of life assessment. Seismic and flood evets were considered to have no available warning time.

4.2 Population at Risk

Queensland Failure Impact Assessment Guidelines (DEWS, 2012) consider people as part of the PAR if:

- they occupy buildings or other places of occupation that lie within the failure impact zone and;
- any part of the ground where these buildings or other places of occupation are located would be covered by 300 mm or more of water.

This involves estimating the levee failure impact zone, determine the depth of flooding at each individual location, differentiating between building types and counting the number of properties inundated. Time of day also influences the PAR at a particular site due to the occupancy changing with business, school and other operating hours. For example, a detached house has a suggested night time equivalent PAR of 2.9. During day time business hours, the occupancy rate can be expected to decrease to ~1, decreasing the equivalent PAR to ~1. However at night, the members of the household can be expected to be present at home and therefore, the equivalent PAR should be taken as 2.9.

The majority of properties in the levee failure impact zone are detached houses. Several schools, shops, service stations and other buildings were in some of the failure impact zones. Table 4-1 shows the adopted equivalent PAR for the building types identified in the failure impact area. Only major schools and detached houses were considered in PAR due to making up the majority of the PAR.

After considering the larger flood extents, it was found that schools affected by inundation did not flood by more than 300 mm and hence only the equivalent PAR values for detached dwellings were used.

Table 4-1 Adopted Equivalent Population at Risk for Dwelling Types in Levee Failure Impact Zone

Nature of buildings or other places of occupation	Equivalent Population at Risk	
	Day	Night
Detached housing	1	3

4.3 Fatality Rates

Fatality rates are used to estimate the Potential Loss of Life (PLL) associated with flooding caused by levee failure. USBR (2014) and the UK Small Reservoirs Simplified Risk Assessment use graphical methods that have been refined over many years with data from dam failures and their associated consequences. The main factors influencing the fatality rate are the available warning time and the product of the depth and the velocity (DV) of flood water at each particular site.

As described in Section 4.1 above, warning time was considered available for tidal events and unavailable for flood and seismic events. Flood depths varied from 0 to 1.8 m in depth for the larger flood cases. The slope of the terrain adjacent to the stopbank levees and the driving head required to cause levee breach were used to estimate the velocity at each PAR location. It was estimated that a maximum DV of less than 1 m^2/s (11 ft^2/sec) would apply at each PAR location.

Using the data from the Small reservoirs simplified risk assessment methodology on Figure 4-2, the fatality rate is 0.5% or 0.005 for no warning with a DV value of 1 and 0.3% or 0.003 for no warning with a DV Value of 0.5.

Using the fatality charts shown on Figure 4-3 and Figure 4-4 for both adequate and partial warning times, this resulted in a fatality rate of less than 0.0015 for both cases.

The fatality rates for the day and night failure cases were selected as follows

Fatality rate Day	0.0015
Fatality rate Night	0.003

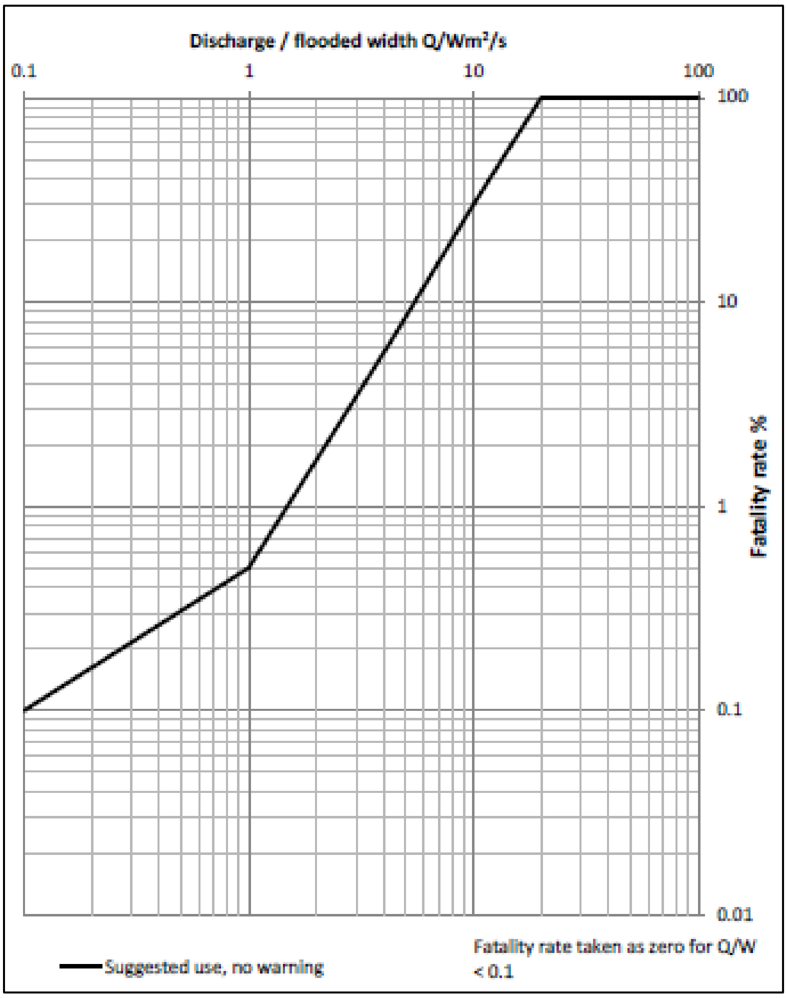


Figure 4-2 Fatality rate for No Warning (Small Reservoirs Simplified Risk Assessment Methodology Guidance Report, January 2014)

4.4 Potential Loss of Life

PAR values and the adopted fatality rate were then used to estimate the Potential Loss of Life for each of the bathtub flood models assessed. Two scenarios are presented to assess the potential of re-inhabiting properties (shown red in Figure 4-5 to Figure 4-7) evacuated properties.

- The estimated PLL for cases for the current PAR considering that red properties have been evacuated and consequently there is no PAR and PLL at red property locations
- The estimated PLL considering red properties are not evacuated and inhabited

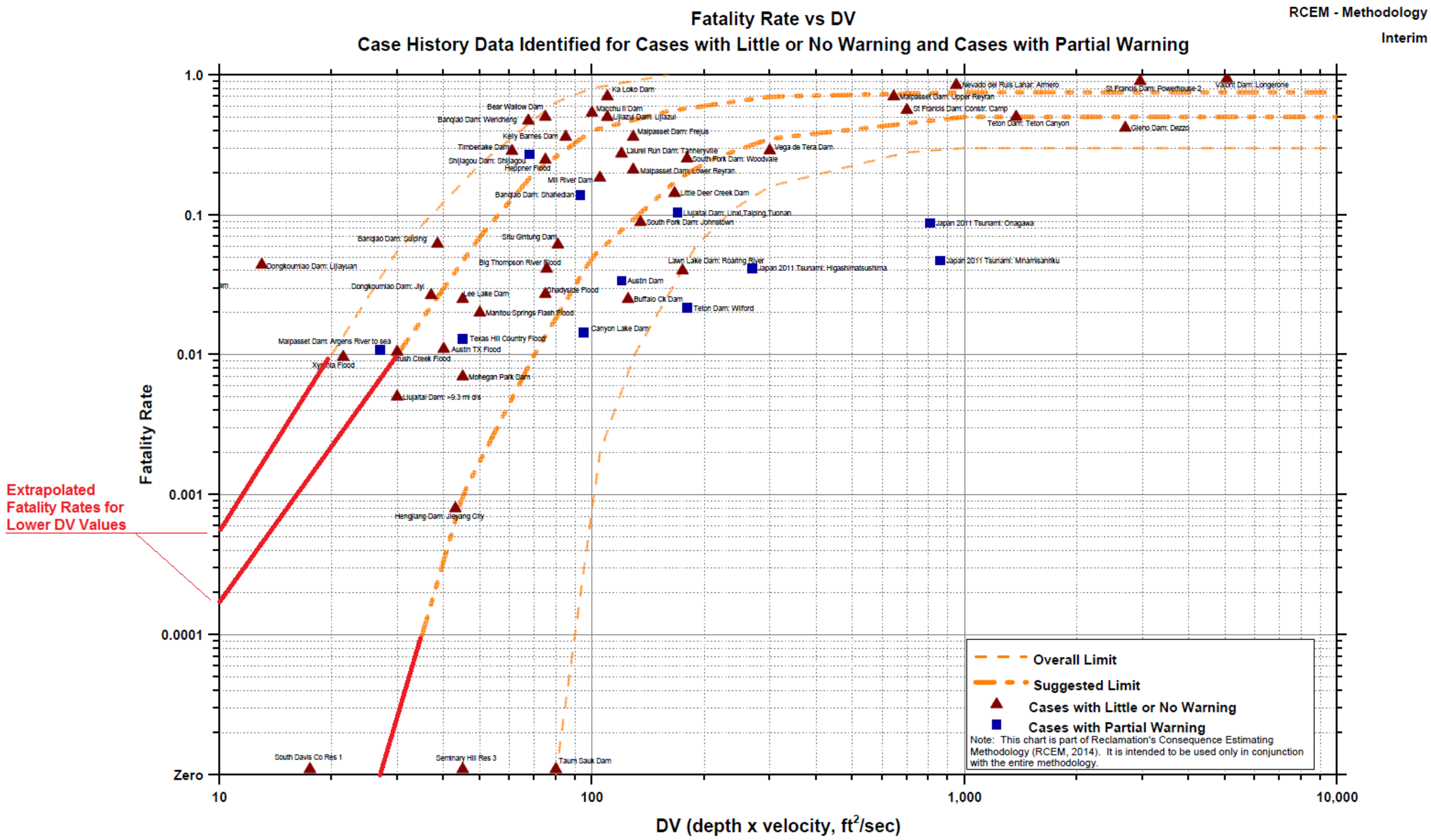


Figure 4-3 Fatality Rate vs DV – Case History Data Identified for Cases with Little or No Warning and Cases with Partial Warning (Adopted from USBR 2014)

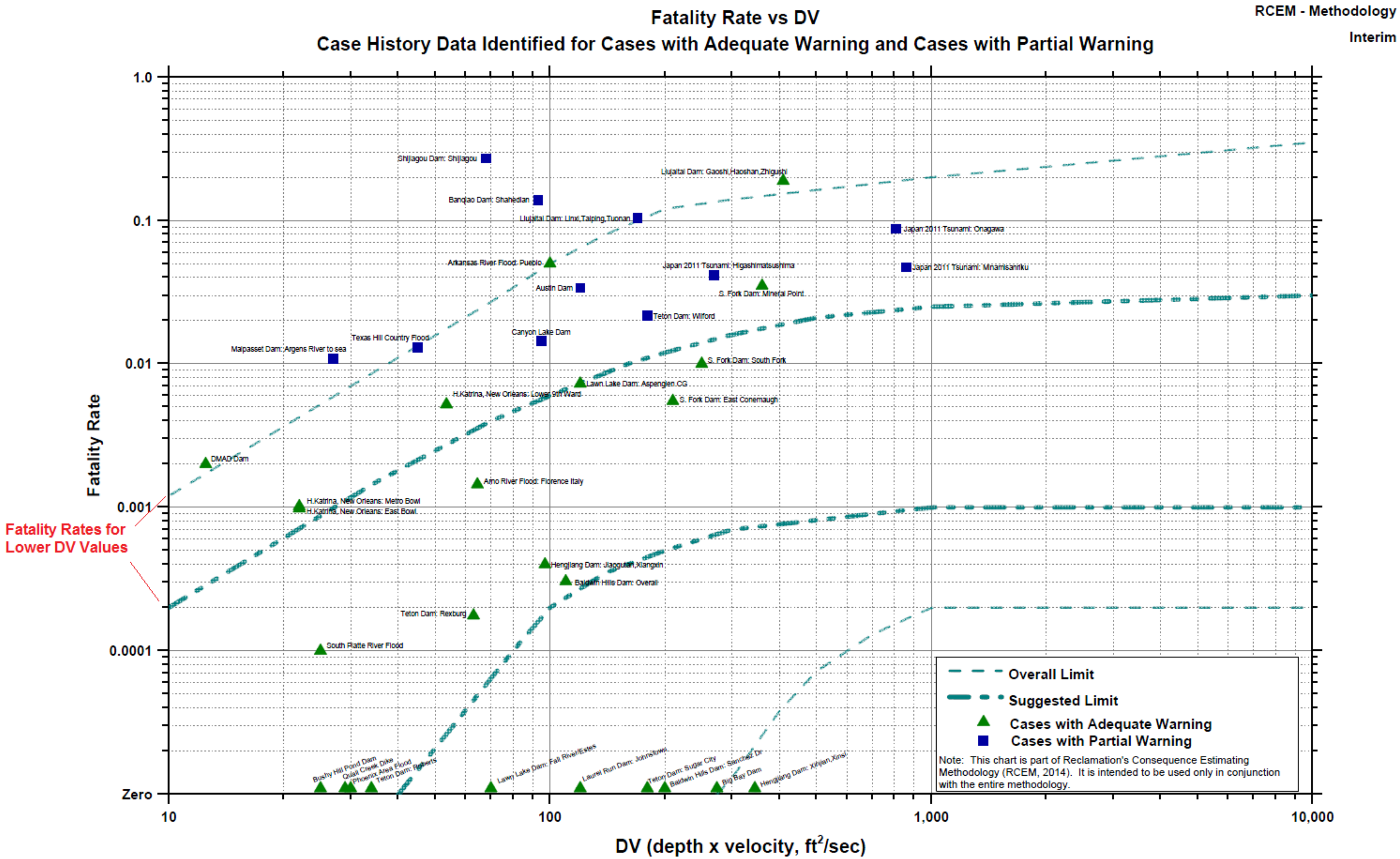


Figure 4-4 Fatality Rate vs DV – Case History Data Identified for Cases with Adequate Warning and Cases with Partial Warning (Adopted from USBR 2014)

4.5 Consequence Assessment for Flood Events

A simplified consequence assessment of the failure of sections of the stopbank levees was carried out. The method broadly involved modelling the inundation extents caused by a breached levee section along the left and right bank sections under consideration for an applicable water levels (estimated from the flood and tidal loading conditions presented in Section 3.7) and counting the number of properties affected by the flood extents.

Assumptions

The modelling assumed the following:

- There was enough flow to fill the "bathtub" (area of inundation extent caused by breached levee) which may be conservative for a peak water level as tidal fluctuations could restrict water flow through a breach levee section.
- An upper bound of the properties effected
- Limited connectivity to small areas, but large connectivity to large areas
- Houses are at the average ground level at the centre of the building
- No differentiation between sheds, garages or any other commercial, industrial or school buildings
- GIS area for 11.0 m RL and 10.8 m RL was truncated to the north and in the estuary
- Does not consider the breach effects of sections that were not analysed in the risk assessment
- No connectivity to lower areas by storm water network

Water Levels Flood Extents Assessed in Bathtub Flood Models

The flooding extent of three water levels was assessed using the bathtub model to estimate the Population At Risk (PAR) for various water levels. Bathtub water levels of 11.2 m RL, 11.0 m RL and 10.8 m RL were adopted for the assessment and the model outputs for these cases can be seen in Figure 4-5, Figure 4-6 and Figure 4-7 respectively. The depth of inundation and the number of properties affected by the inundation for each of the cases are summarised in Appendix H. Red properties represent properties that have been evacuated by CCC and are no longer inhabited. Green properties represent properties that are currently inhabited and have not been evacuated.

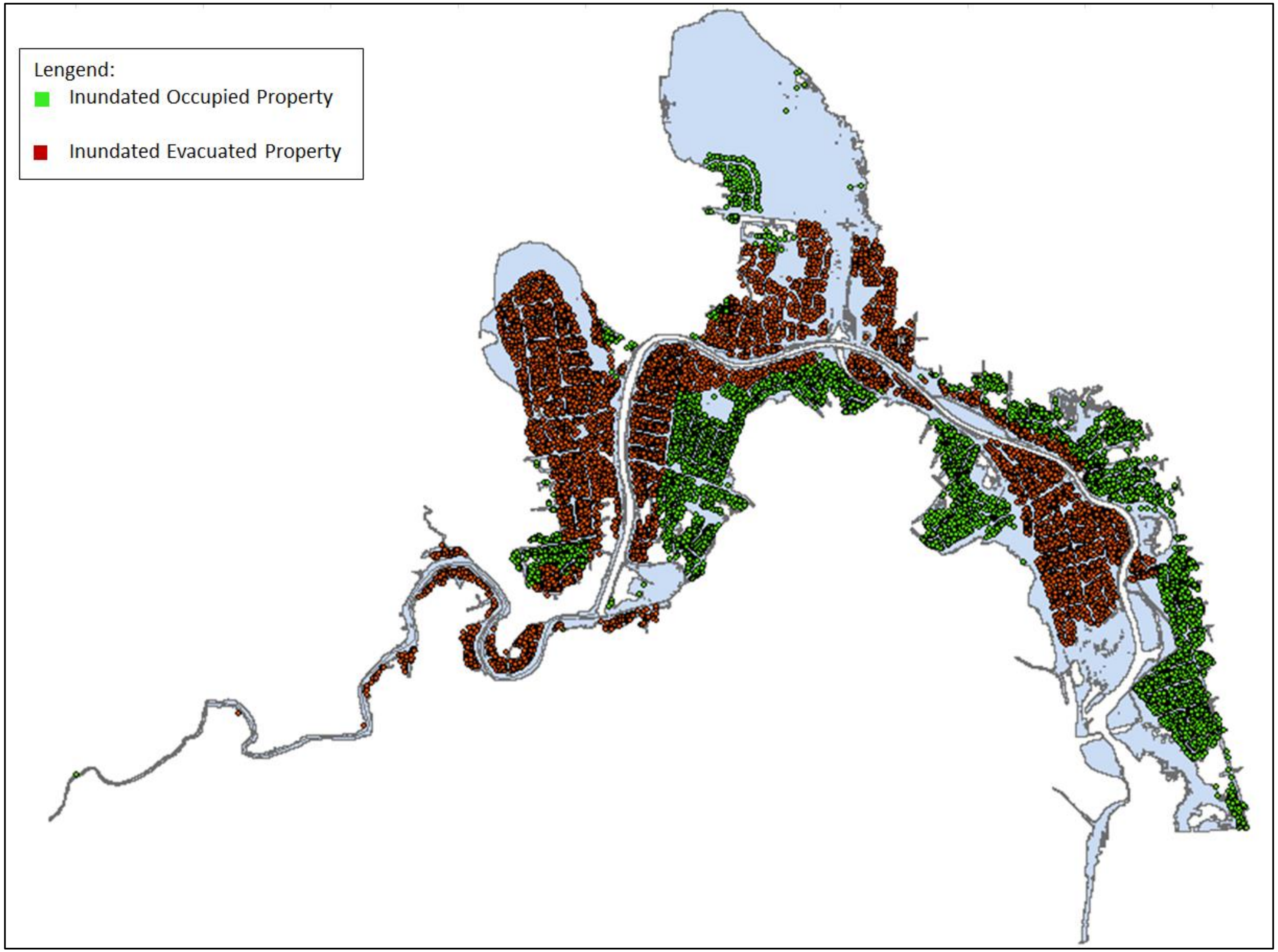


Figure 4-5 Bathtub Model Flooding Extent for 11.2 m RL Water Level

Figure 4-6 Bathtub Model Flooding Extent for 11.0 m RL Water Level

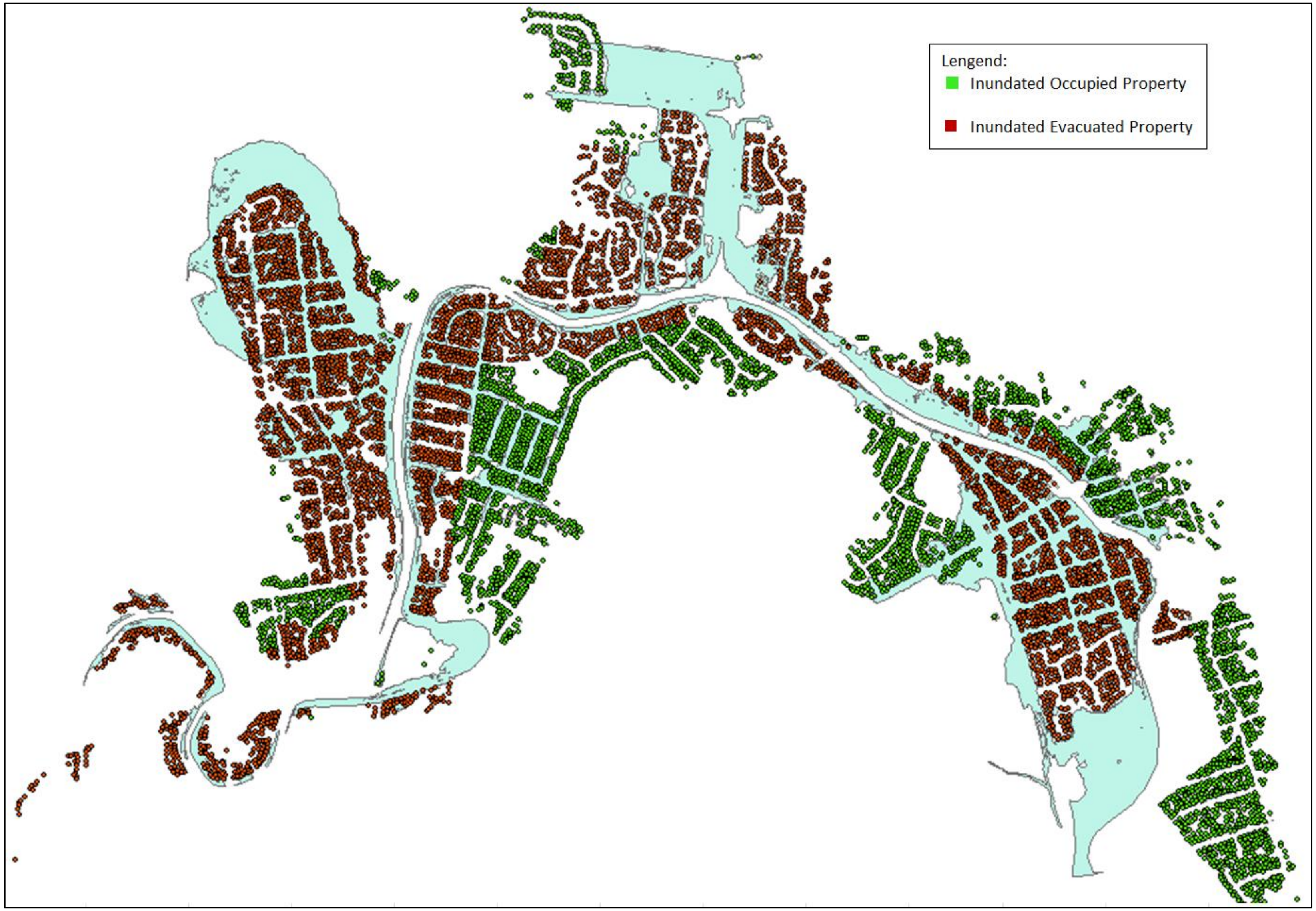


Figure 4-7 Bathtub Model Flooding Extent for 10.8 m RL Water Level

Estimated Population at Risk and Loss of Life for Flood Cases

The results of the PAR and PLL assessment for the green and red properties are summarised in Table 4-2 and Table 4-3 respectively.

Table 4-2 Estimated PAR and PLL for Green Properties in Flood Scenarios

Chainage and Side of Bank	Estimated PAR		Estimated PLL	
	Day	Night	Day	Night
11.2 m RL Bathtub Flood				
Left Bank				
14,700-18,900 and 19,300-19,900	846	2538	1.3	7.6
9,000-14,700	77	231	0.1	0.7
Right Bank				
9,000-19,900	1047	3141	1.6	9.4
11.0 m RL Bathtub Flood				
Left Bank				
10,900-14,500	1	3	0.0015	0.009
14,500-19,900	439	1317	0.7	4.0
Right Bank				
12,700-15,900	352	1056	0.53	3.2
16,500-19,900	149	447	0.2	1.3
10.8 m RL Bathtub Flood				
Left Bank				
9,800-10,900	1	3	0.002	0.009
10,900-12,300	3	9	0.005	0.027
12,300-14,600	560	1680	0.840	5.040
14,600-16,900	35	105	0.053	0.315
16,900-19,900	98	294	0.147	0.882
Right Bank				
9,800-11800	4	12	0.006	0.036
11,800-12,750	12	36	0.018	0.108
12,750-15900	105	315	0.158	0.945
15,900-16500	18	54	0.027	0.162
16,500-19900	942	2826	1.413	8.478

Table 4-3 Estimated PAR and PLL for Red Properties in Flood Scenarios (Assuming the Red Properties are Re-Inhabited)

Chainage and Side of Bank	Estimated PAR		Estimated PLL	
	Day	Night	Day	Night
11.2 m RL Bathtub Flood				
Left Bank				
14,700-18,900 and 19,300-19,900	585	1755	0.9	5.3
9,000-14,700	1446	4338	2.2	13.0
Right Bank				
9,000-19,900	2081	6243	3.1	18.7
11.0 m RL Bathtub Flood				
Left Bank				
9,400-10,900	10	30	0.015	0.0900
10,900-12,300	40	120	0.06	0.3600
12,300-14,500	968	2904	1.452	8.7120
14,500-19,900	282	846	0.423	2.5380
Right Bank				
9,400-11,700	18	54	0.027	0.1620
11,700-12,700	21	63	0.0315	0.1890
12,700-15,900	451	1353	0.6765	4.0590
15,900-16,500	37	111	0.0555	0.3330
16,500-19,900	1043	3129	1.5645	9.3870
10.8 mRL Bathtub Flood				
Left Bank				
9,800-10,900	1	3	0.002	0.009
10,900-12,300	3	9	0.005	0.027
12,300-14,600	560	1680	0.840	5.040
14,600-16,900	35	105	0.053	0.315
16,900-19,900	98	294	0.147	0.882
Right Bank				
9,800-11,800	4	12	0.006	0.036
11,800-12,750	12	36	0.018	0.108
12,750-15,900	105	315	0.158	0.945
15,900-16,500	18	54	0.027	0.162
16,500-19,900	942	2826	1.413	8.478

4.6 Consequence Assessment for Tidal Events

A breach assessment of the levees for tidal events was conducted for the 200 year and 50 year tides without the influence of flooding or seismicity causing levee crest slumping. Both overtopping and piping flow was considered in the breach assessment and the resulting extent of flooding was used to estimate the PAR and PLL.

Estimated Population at Risk and Potential Loss of Life for Tidal Cases

The results of the PAR and PLL assessment for the green and red properties are summarised in Table 4-4 and Table 4-5 respectively.

Table 4-4 Estimated PAR and PLL for Green Properties in 200 yr Tide with no Flood or Seismic Loading

Section	Chainage	Green Properties			
		Estimated PAR		Estimated PLL	
		Day	Night	Day	Night
Left Bank					
2	16,564	2	6	0.0030	0.0180
5	16,468	0	0	0	0
6	15,504	0	0	0	0
8	14,198	1	3	0.0015	0.0090
9	13,546	0	0	0	0
Right Bank					
14	12,679	0	0	0	0
15	15,179	352	1056	0.528	3.168
16	16,564	0	0	0	0
21	13,000	0	0	0	0

Table 4-5 Estimated PAR and PLL for Red Properties in 200 yr Tide with no Flood or Seismic Loading

Section	Chainage	Red Properties			
		Estimated PAR		Estimated PLL	
		Day	Night	Day	Night
Left Bank					
2	16,564	1	3	0	0
5	16,468	0	0	0	0
6	15,504	0	0	0	0
8	14,198	968	2904	1.5	8.7
9	13,546	246	738	0.4	2.2
Right Bank					
14	12,679	9	27	0.0	0.1
15	15,179	451	1353	0.7	4.1
16	16,564	3	9	0	0
21	13,000	1	3	0.002	0.009

Table 4-6 Estimated PAR and PLL for Green Properties in 50 yr Tide with no Flood or Seismic Loading

Section	Chainage	Green Properties			
		Estimated PAR		Estimated PLL	
		Day	Night	Day	Night
Left Bank					
2	16,564	0	0	0	0
5	16,468	0	0	0	0
6	15,504	0	0	0	0
8	14,198	0	0	0	0
9	13,546	0	0	0	0
Right Bank					
14	12,679	0	0	0	0
15	15,179	352	1056	0.528	3.168
16	16,564	0	0	0	0
21	13,000	0	0	0	0

Table 4-7 Estimated PAR and PLL for Red Properties in 50 yr Tide with no Flood or Seismic Loading

Section	Chainage	Red Properties			
		Estimated PAR		Estimated PLL	
		Day	Night	Day	Night
Left Bank					
2	16,564	0	0	0	0
5	16,468	0	0	0	0
6	15,504	0	0	0	0
8	14,198	0	0	0	0
9	13,546	246	738	0.4	2.2
Right Bank					
14	12,679	0	0	0	0
15	15,179	451	1353	0.7	4.1
16	16,564	0	0	0	0
21	13,000	0	0	0	0

4.7 Consequence Assessment for Seismic Events

A breach assessment of the levees for tidal events coupled with the ULS earthquake was conducted for the 200 yr tide. No flood influence was considered in this assessment. Both overtopping and piping flow was considered in the breach assessment and the resulting extent of flooding was used to estimate the PAR and PLL.

Estimated Population at Risk and Potential Loss of Life for Tidal Cases

The results of the PAR and PLL assessment for the green and red properties with the 200 year tide and seismic events are summarised in Table 4-4 and Table 4-5 respectively.

Table 4-8 Estimated PAR and PLL for Green Properties in 200 yr Tide with ULS Seismic Loading

Section	Chainage	Green Properties			
		Estimated PAR		Estimated PLL	
		Day	Night	Day	Night
Left Bank					
2	16,564	2	6	0.003	0.018
5	16,468	0	0	0	0
9	13,546	0	0	0	0
Right Bank					
15	15,179	352	1056	0.528	3.168
16	16,564	0	0	0	0
21	13,000	337	1011	0.506	3.033

Table 4-9 Estimated PAR and PLL for Red Properties in 200 yr Tide with ULS Seismic Loading

Section	Chainage	Red Properties			
		Estimated PAR		Estimated PLL	
		Day	Night	Day	Night
Left Bank					
2	16,564	1	3	0.0015	0.009
5	16,468	0	0	0.0	0.0
9	13,546	246	738	0.4	2.2
Right Bank					
15	15,179	451	1353	0.7	4.1
16	16,564	3	9	0.005	0.027
21	13,000	438	1314	0.7	3.9

4.8 Combination of Day and Night PLL

The PLL estimates for day and night were combined to give an overall PLL using the following assumptions for the exposure of the population at risk.

Day time exposure 6 days 8 hours = 48 hours Factor = 0.285

Night Time remainder of the week = 120 hours Factor = 0.715

The PLL estimated for the overall Tidal events with and without seismic events are shown on Table 4-10 and the PLL estimates for the Bathtub flood events are shown on Table 4-11.

Table 4-10 Combined day and night PLL for Tidal events

Section	Tide ARI (years)			Tide ARI (years)		
	20	50	200	20	50	200
	PLL Tide with No Earthquake			PLL Tide with Earthquake		
Section 1		0	0.014		0	0.014
Section 2		0	0.014		0	0.014
Section 3		0	0.014		0	0.014
Section 4		0	0.014		0	0.014
Section 5		0	0.000		0	0.000
Section 6		0	0.000		0	0.000
Section 7		0	0.000		0	0.000
Section 8		0	0.007		0	0.007
Section 9		0	0.000		0	0.000
Section 10		0	0.000		0	0.000
Section 11		0	0.000		0	0.000
Section 12		0	0.000		0	0.000
Section 13		0	0.000		0	0.000
Section 14		0	0.000		0	0.000
Section 15	0	2.414	2.414	0	2.414	2.414
Section 16		0	0.000		0	0.000
Section 17		0	0.000		0	0.000
Section 18		0	0.000		0	0.000
Section 21		0.000	0.000		0	2.311

It should be noted that the PLL estimate for Section 15 has a significant effect on the outcomes of the risk assessment for the Tidal events, as discussed below.

Table 4-11 Combined day and night PLL for Bathtub Flood events

Cross Section	Level 11.2 m			Level 11 m			Level 10.8 m		
	Day	Night	Combined	Day	Night	Combined	Day	Night	Combined
Section 1	1.269	7.614	5.80	0.6585	3.951	3.01	0.165	0.99	0.75
Section 2	1.269	7.614	5.80	0.6585	3.951	3.01	0.165	0.99	0.75
Section 3	1.269	7.614	5.80	0.6585	3.951	3.01	0.165	0.99	0.75
Section 4	1.269	7.614	5.80	0.6585	3.951	3.01	0.165	0.99	0.75
Section 5	1.269	7.614	5.80	0.6585	3.951	3.01	0.0045	0.027	0.02
Section 6	1.269	7.614	5.80	0.6585	3.951	3.01	0.0045	0.027	0.02
Section 7	1.269	7.614	5.80	0.6585	3.951	3.01	0.0045	0.99	0.71
Section 8	0.1155	0.693	0.53	0.0015	0.009	0.01	0	0	0
Section 9	0.1155	0.693	0.53	0.0015	0.009	0.01	0	0	0
Section 10	0.1155	0.693	0.53	0.0015	0.009	0.01	0	0	0
Section 11	0.1155	0.693	0.53	0	0	0	0	0	0
Section 12	0.1155	0.693	0.53	0	0	0	0	0	0
Section 13	0.1155	0.693	0.53	0	0	0	0	0	0
Section 14	1.5705	9.423	7.18	0.528	3.168	2.41	0.0795	0.477	0.36
Section 15	1.5705	9.423	7.18	0.528	3.168	2.41	0.0795	0.477	0.36
Section 16	1.5705	9.423	7.18	0.2235	1.341	1.02	0.1335	0.801	0.61
Section 17	1.5705	9.423	7.18	0.2235	1.341	1.02	0.1335	0.801	0.61
Section 18	1.5705	9.423	7.18	0.2235	1.341	1.02	0.1335	0.801	0.61
Section 21	1.5705	9.423	7.18	0.528	3.168	2.41	0.0795	0.477	0.36

5. Risk Analysis Results

5.1 Scenarios

The Stopbanks were originally constructed to mitigate against tidal flooding of the lower areas along the Avon river. Given that floods have occurred subsequent to the Stopbank reinstatement that overtopped the stopbanks, the risk analysis was also completed for flood events.

Two scenarios were, therefore evaluated as follows:

- Floods and earthquakes
- Tides and earthquakes

The probability of failure for the stopbanks was calculated for these scenarios for the 1, 5, 10 and 20 year operating durations.

The Societal and Individual risk was calculated for the 1 year duration of operation only as the criteria for evaluation relate only to an annual probability of failure rather than failure over a lifetime period.

5.2 Floods and Earthquakes

5.2.1 Probabilities of Failure

The results for the failure probabilities for each section with the 1, 5, 10 and 20 year operating lifetimes for the seismic and flood events are shown on Figure 5-1 and Figure 5-2 for the Seismic and flood events respectively. Figure 5-3 and Table 5-1 provide details of the combined flood and seismic events probabilities of failure for each of the selected lifetimes.

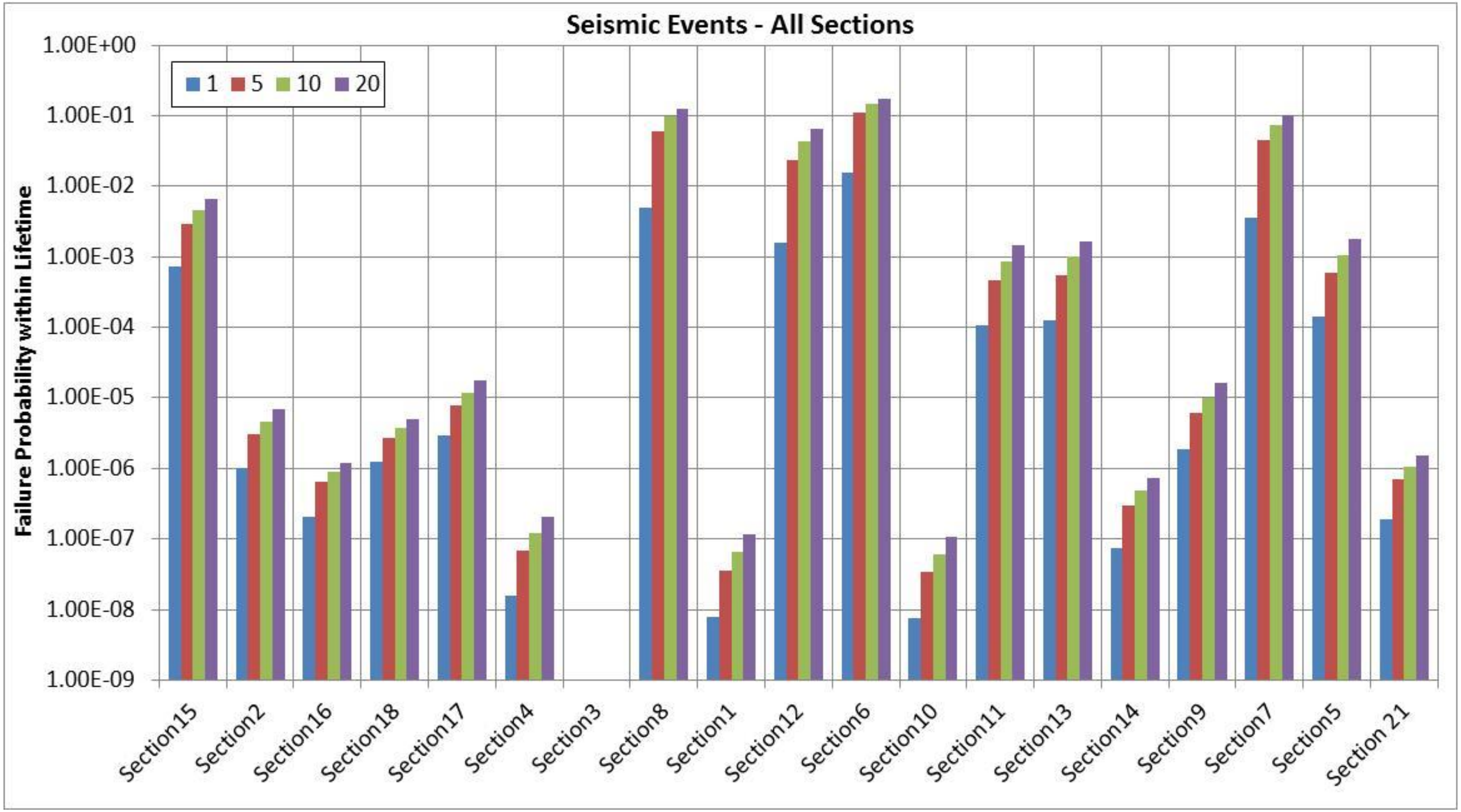


Figure 5-1 Avon Stopbank Seismic Events Probability of failure for sections within 1, 5, 10, 20 year lifetimes

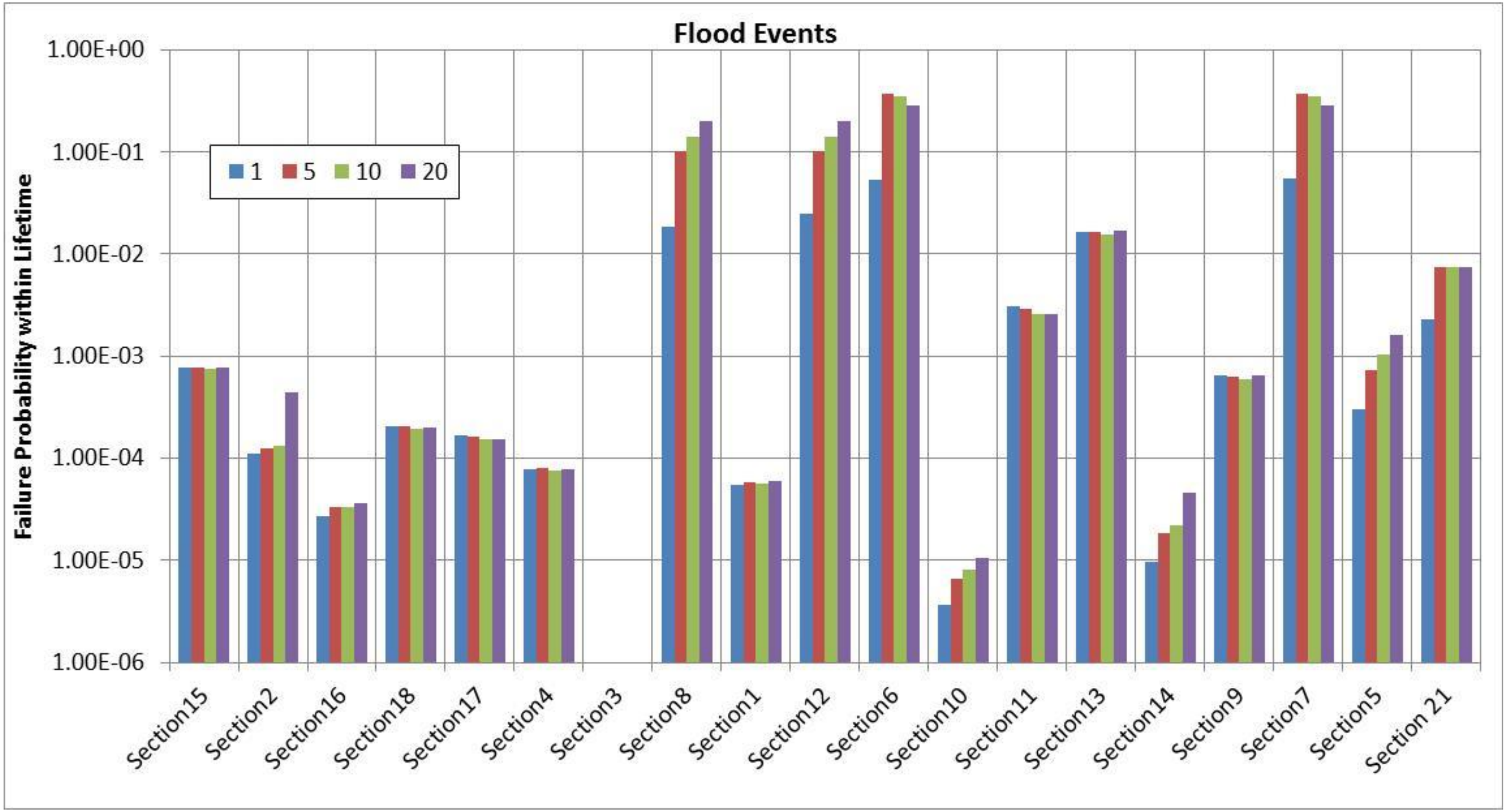


Figure 5-2 Avon Stopbank Flood Events Probability of failure for sections within 1, 5, 10, 20 year lifetimes

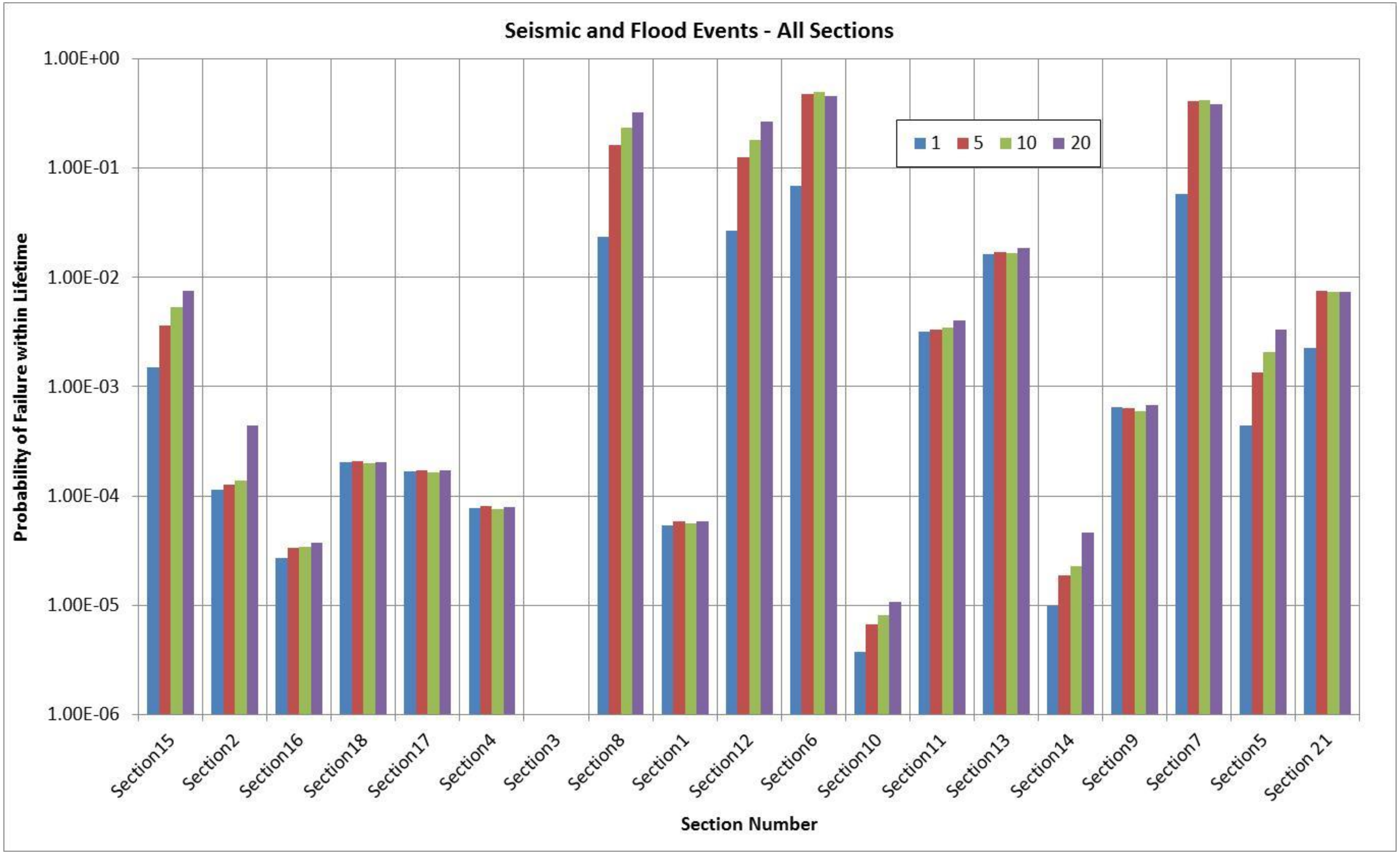


Figure 5-3 Avon Stopbank Seismic and Flood Events Total Probability of failure for sections within 1, 5, 10, 20 year lifetimes

Table 5-1 Avon Stopbanks Risk Analysis results for probability of failure for sections within 1, 5, 10, 20 year lifetimes with Floods and seismic events

Section No.	Seismic Events (lifetime)				Tides and Floods (lifetime)				Total (lifetime)			
	1	5	10	20	1	5	10	20	1	5	10	20
	Left Bank											
1	7.97E-09	3.57E-08	6.50E-08	1.15E-07	5.43E-05	5.86E-05	5.65E-05	5.88E-05	5.43E-05	5.86E-05	5.65E-05	5.90E-05
2	1.01E-06	3.02E-06	4.66E-06	7.01E-06	1.12E-04	1.24E-04	1.33E-04	4.38E-04	1.13E-04	1.27E-04	1.37E-04	4.45E-04
3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	1.55E-08	6.84E-08	1.22E-07	2.09E-07	7.77E-05	8.05E-05	7.62E-05	7.83E-05	7.78E-05	8.05E-05	7.63E-05	7.85E-05
5	1.39E-04	6.03E-04	1.06E-03	1.77E-03	3.00E-04	7.34E-04	1.03E-03	1.59E-03	4.39E-04	1.34E-03	2.09E-03	3.36E-03
6	1.56E-02	1.13E-01	1.50E-01	1.75E-01	5.28E-02	3.69E-01	3.46E-01	2.85E-01	6.84E-02	4.82E-01	4.96E-01	4.60E-01
7	3.60E-03	4.55E-02	7.48E-02	1.02E-01	5.49E-02	3.69E-01	3.46E-01	2.85E-01	5.85E-02	4.15E-01	4.21E-01	3.87E-01
8	5.01E-03	6.10E-02	9.62E-02	1.25E-01	1.83E-02	1.01E-01	1.39E-01	1.99E-01	2.33E-02	1.62E-01	2.35E-01	3.24E-01
9	1.87E-06	6.05E-06	9.91E-06	1.62E-05	6.43E-04	6.28E-04	5.87E-04	6.56E-04	6.45E-04	6.34E-04	5.97E-04	6.72E-04
10	7.56E-09	3.38E-08	6.16E-08	1.09E-07	3.69E-06	6.63E-06	8.12E-06	1.06E-05	3.70E-06	6.66E-06	8.18E-06	1.07E-05
11	1.07E-04	4.70E-04	8.44E-04	1.45E-03	3.07E-03	2.88E-03	2.61E-03	2.61E-03	3.18E-03	3.35E-03	3.46E-03	4.07E-03
12	1.58E-03	2.36E-02	4.26E-02	6.49E-02	2.51E-02	1.02E-01	1.40E-01	2.01E-01	2.67E-02	1.26E-01	1.82E-01	2.66E-01
13	1.27E-04	5.57E-04	9.90E-04	1.67E-03	1.64E-02	1.63E-02	1.57E-02	1.69E-02	1.65E-02	1.69E-02	1.67E-02	1.86E-02
	Right Bank											
14	7.31E-08	2.94E-07	4.81E-07	7.19E-07	9.78E-06	1.85E-05	2.21E-05	4.58E-05	9.85E-06	1.87E-05	2.26E-05	4.65E-05
15	7.41E-04	2.88E-03	4.59E-03	6.71E-03	7.68E-04	7.81E-04	7.44E-04	7.77E-04	1.51E-03	3.66E-03	5.34E-03	7.48E-03
16	2.09E-07	6.42E-07	9.11E-07	1.19E-06	2.70E-05	3.30E-05	3.32E-05	3.59E-05	2.72E-05	3.36E-05	3.42E-05	3.71E-05
17	2.97E-06	7.84E-06	1.18E-05	1.78E-05	1.66E-04	1.63E-04	1.51E-04	1.52E-04	1.69E-04	1.71E-04	1.63E-04	1.70E-04
18	1.23E-06	2.75E-06	3.71E-06	4.90E-06	2.04E-04	2.06E-04	1.94E-04	1.97E-04	2.05E-04	2.09E-04	1.97E-04	2.02E-04
21	1.88E-07	7.00E-07	1.07E-06	1.49E-06	2.26E-03	7.49E-03	7.41E-03	7.39E-03	2.26E-03	7.49E-03	7.41E-03	7.39E-03

The escalation ratio of the total probability of failure for each section for the 5, 10 and 20 year lifetime compared with the 1 year probability varied as shown on Table 5-2 and Figure 5-4.

The ratio shows a considerable variation in the escalation for the various sections with the average being as shown on Table 5-2. This clearly shows a significant increase in the failure probability after one year with the greatest increase being for the Sections 6, 7, 8, 12, 21 and 5 for which the ratio was greater than 2 after 5 years.

Table 5-2 Avon Stopbank Failure escalation factors for each section Failure probability compared with the 1 year period for Seismic Floods and Tidal events

Section Number	Stopbank Lifetime (years)			
	1	5	10	20
Section 7	1.00	7.09	7.20	6.61
Section 6	1.00	7.04	7.25	6.73
Section 8	1.00	6.96	10.09	13.87
Section 12	1.00	4.72	6.83	9.95
Section 21	1.00	3.31	3.27	3.26
Section 5	1.00	3.04	4.76	7.65
Section 15	1.00	2.43	3.54	4.96
Section 14	1.00	1.90	2.30	4.72
Section 10	1.00	1.80	2.21	2.89
Section 16	1.00	1.24	1.26	1.36
Section 2	1.00	1.12	1.21	3.93
Section 1	1.00	1.08	1.04	1.09
Section 11	1.00	1.05	1.09	1.28
Section 4	1.00	1.04	0.98	1.01
Section 18	1.00	1.02	0.96	0.98
Section 13	1.00	1.02	1.01	1.13
Section 17	1.00	1.01	0.96	1.00
Section 9	1.00	0.98	0.92	1.04
Section 3				
Overall Average	1.00	2.66	3.16	4.08

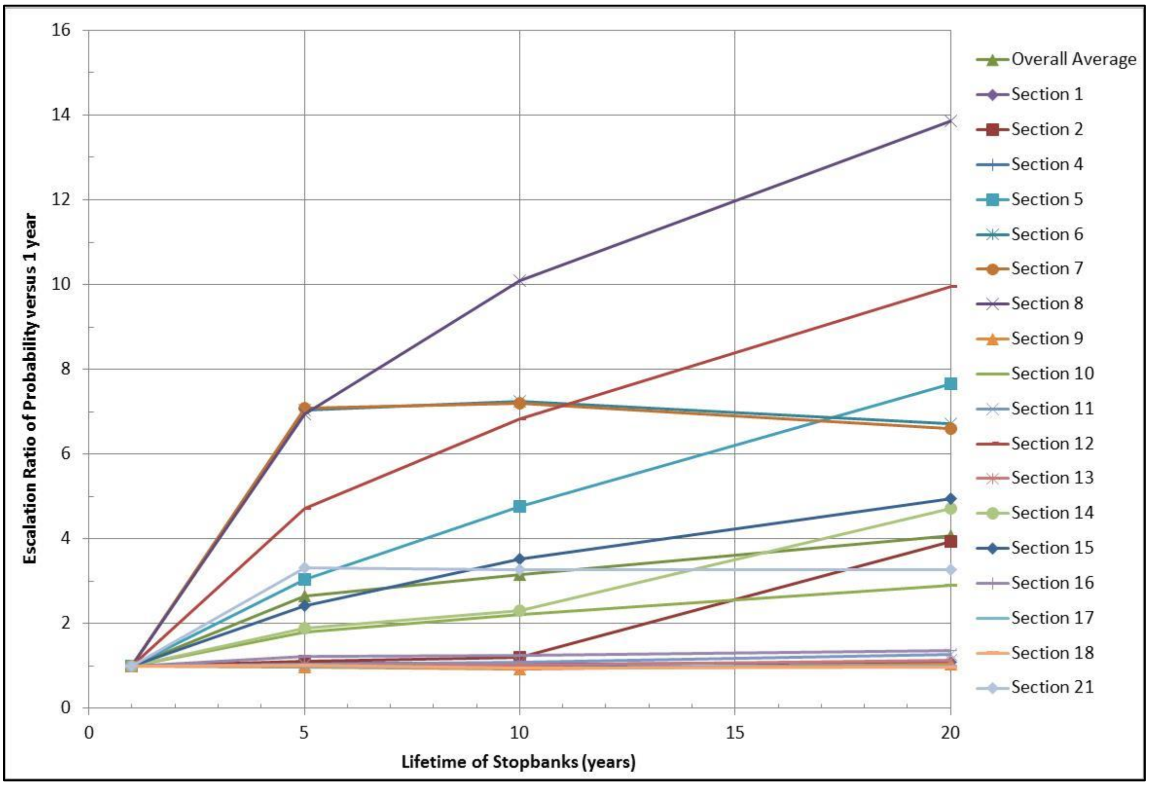


Figure 5-4 Avon Stopbank Failure escalations factors versus lifetime

5.2.2 Societal and Individual Risk

Societal Risk

The societal risk was calculated for the Stopbank with the flood and seismic events, as shown on Figure 5-5, which clearly indicates that the risk is above the tolerable limit for which upgrade works are required.

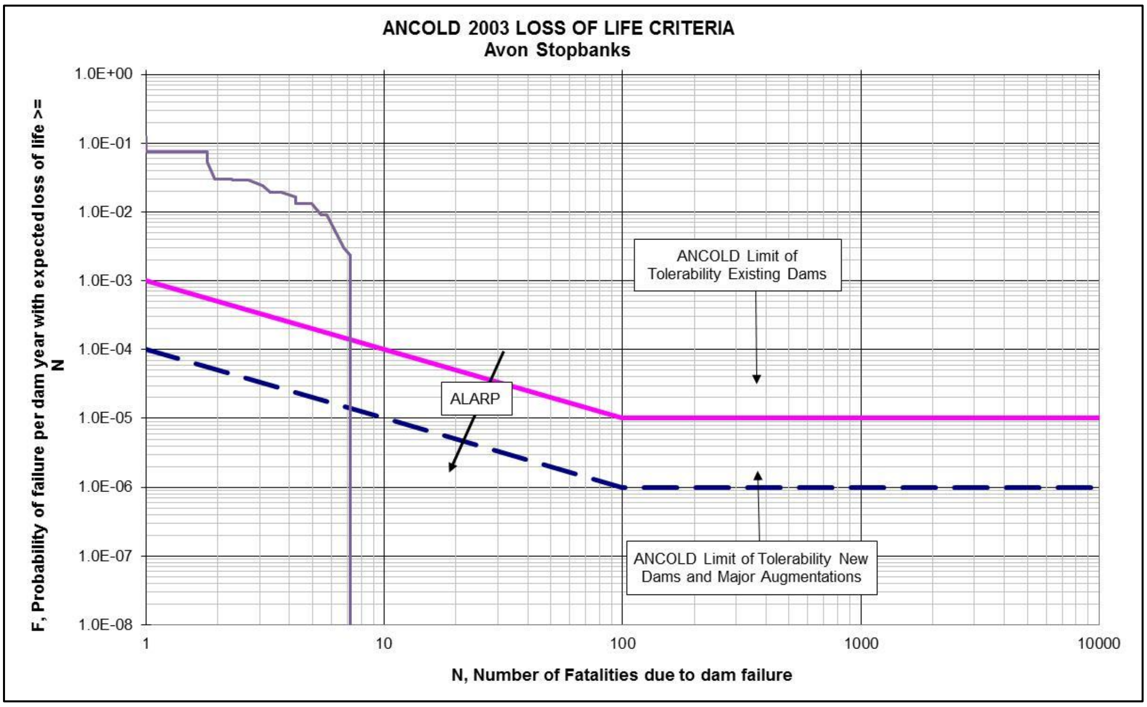


Figure 5-5 Avon Stopbanks Societal Risk for Floods and Seismic events

The risk analysis results for the failure modes of each section have been ranked according to the highest total risk, as shown on Table 5-3 and Figure 5-6.

Table 5-3 Avon Stopbanks Risk Analysis results (lives/annum) for each Section

Section Number	Seismic Overtopping	Seismic Piping	Flood Overtopping	Piping Foundatio n	Piping Embankment	Tree roots rot	Trees fall over	Total	Percentage Total Risk	Individual Risk
7	0.00E+00	0.00E+00	6.80E-02	0.00E+00	0.00E+00	2.90E-07	3.54E-06	6.80E-02	47.60%	2.13E-04
6	0.00E+00	0.00E+00	4.38E-02	0.00E+00	0.00E+00	1.04E-07	1.87E-06	4.38E-02	30.66%	3.28E-04
13	0.00E+00	0.00E+00	9.11E-03	1.73E-06	1.01E-11	7.73E-09	5.78E-07	9.11E-03	6.38%	5.41E-05
12	0.00E+00	0.00E+00	7.13E-03	4.72E-05	5.07E-10	2.96E-06	2.03E-05	7.20E-03	5.04%	9.70E-05
15	4.68E-04	2.49E-07	4.14E-03	1.20E-04	4.92E-09	0.00E+00	0.00E+00	4.73E-03	3.31%	9.95E-06
21	0.00E+00	2.70E-08	4.18E-03	9.45E-05	3.98E-10	3.73E-07	2.60E-05	4.30E-03	3.01%	7.30E-06
8	9.38E-07	1.43E-10	2.11E-03	0.00E+00	0.00E+00	1.92E-09	3.24E-08	2.11E-03	1.48%	1.10E-04
11	0.00E+00	0.00E+00	1.64E-03	7.98E-06	9.50E-11	4.54E-08	5.50E-06	1.66E-03	1.16%	1.10E-05
5	0.00E+00	0.00E+00	1.03E-03	1.76E-05	1.99E-11	0.00E+00	0.00E+00	1.05E-03	0.74%	2.37E-06
9	0.00E+00	0.00E+00	2.82E-04	8.01E-06	9.76E-11	4.84E-08	4.47E-06	2.94E-04	0.21%	2.09E-06
2	1.71E-10	2.03E-10	5.12E-05	1.08E-04	1.03E-09	2.05E-06	7.60E-05	2.37E-04	0.17%	3.72E-07
17	0.00E+00	0.00E+00	0.00E+00	1.15E-04	3.49E-09	0.00E+00	0.00E+00	1.15E-04	0.08%	5.67E-07
4	0.00E+00	6.14E-11	0.00E+00	7.86E-05	2.55E-10	0.00E+00	0.00E+00	7.86E-05	0.06%	2.51E-07
18	0.00E+00	0.00E+00	0.00E+00	7.02E-05	2.40E-10	0.00E+00	0.00E+00	7.02E-05	0.05%	6.71E-07
1	0.00E+00	4.73E-11	0.00E+00	5.12E-05	6.88E-11	0.00E+00	0.00E+00	5.12E-05	0.04%	1.75E-07
14	0.00E+00	0.00E+00	0.00E+00	2.87E-05	5.67E-11	2.31E-07	2.63E-06	3.15E-05	0.02%	3.23E-08
16	0.00E+00	0.00E+00	0.00E+00	2.01E-05	2.53E-11	0.00E+00	0.00E+00	2.01E-05	0.01%	8.92E-08
10	0.00E+00	0.00E+00	0.00E+00	6.71E-07	1.87E-12	0.00E+00	0.00E+00	6.71E-07	0.00%	1.20E-08
3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00%	0.00E+00
Totals	4.69E-04	2.77E-07	1.41E-01	7.69E-04	1.12E-08	6.11E-06	1.41E-04	1.43E-01	100.00%	
Percentage Contribution	0.3283%	0.0002%	99.0303%	0.5383%	0.0000%	0.0043%	0.0987%			

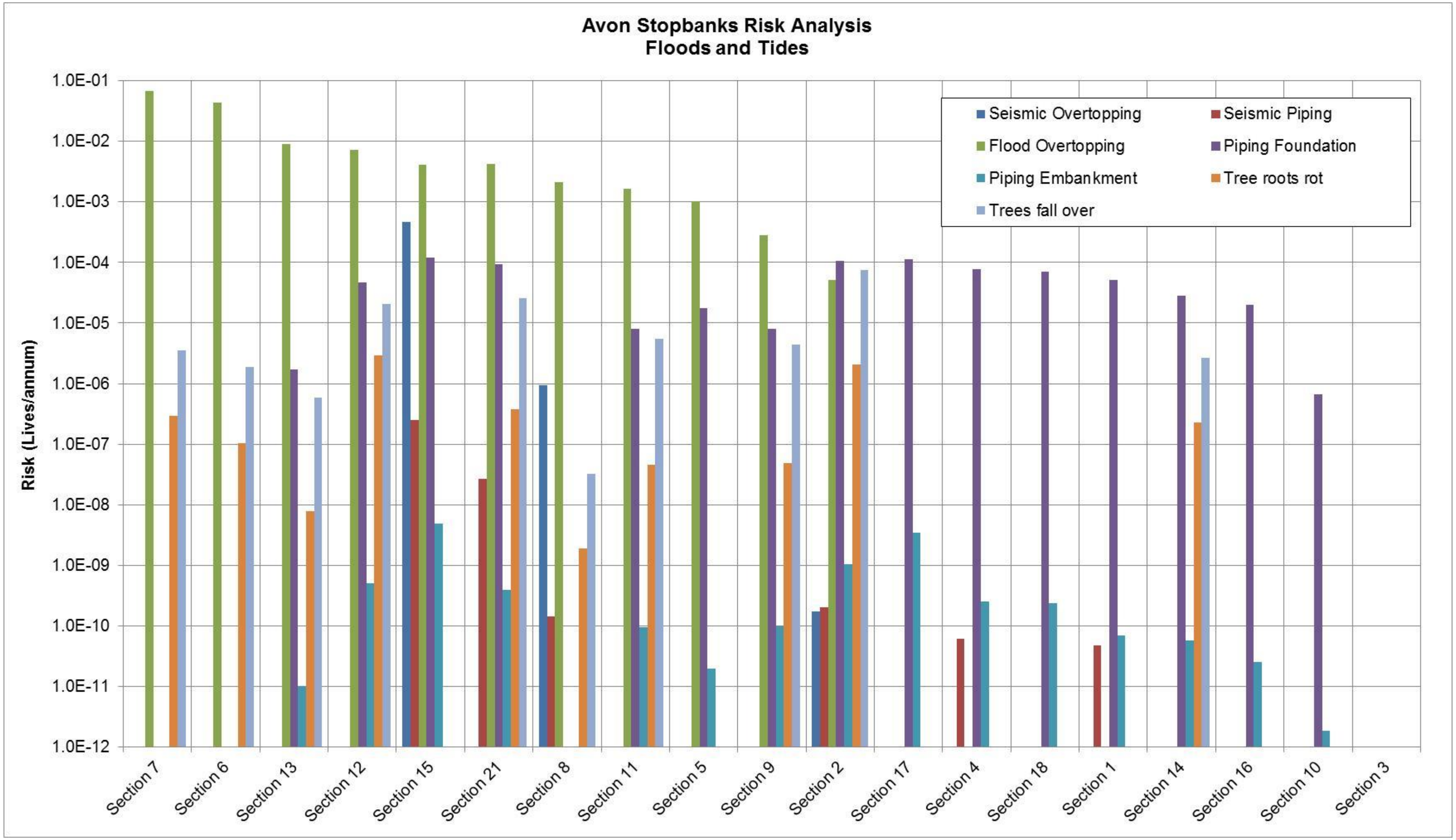


Figure 5-6 Avon Stopbanks Annual Risk (Lives/yr) for each failure mode and Section location for Floods and Seismic Events

The risk analysis results clearly show that the risk is dominated by the flood overtopping with the sections having sandbags contributing the highest proportion of the risk, as shown on Figure 5-7.

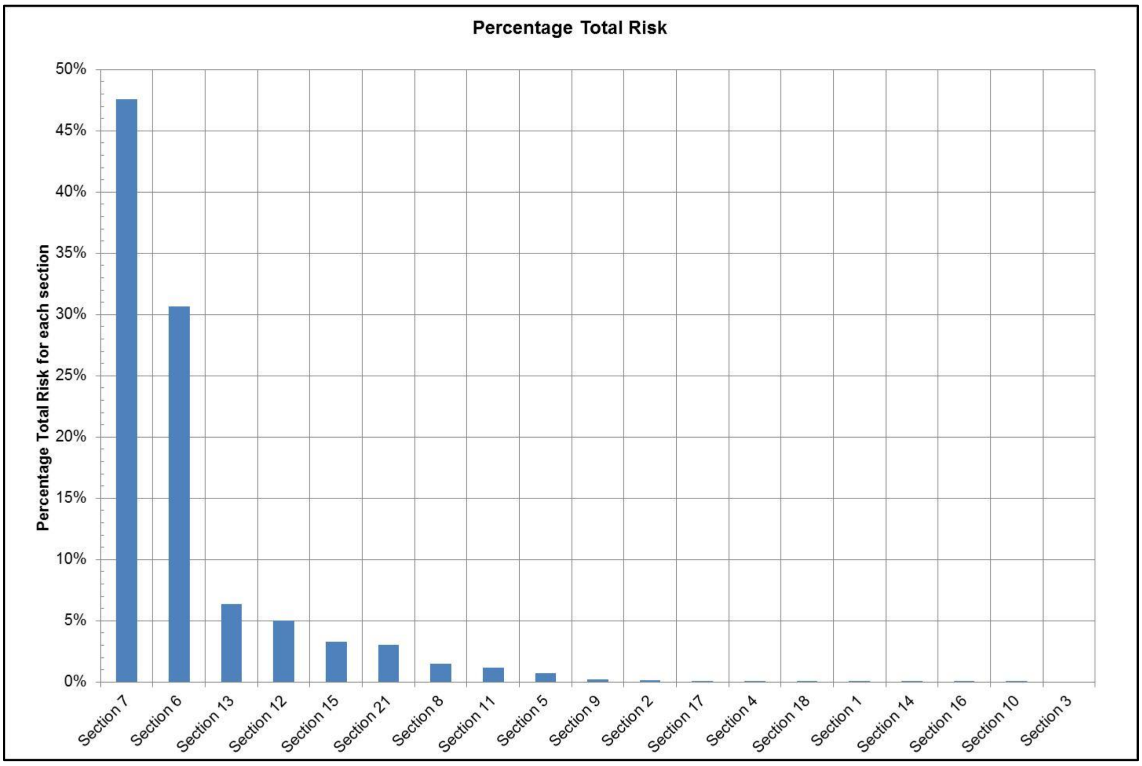


Figure 5-7 Avon Stopbank Percentage total risk ranked for each section

Individual Risk

The Individual risk was calculated for each section, as shown on Figure 5-8, which indicates that Sections 6, 7, 8 and 12 are at or exceed the ANCOLD limit of tolerability of 1E-4.

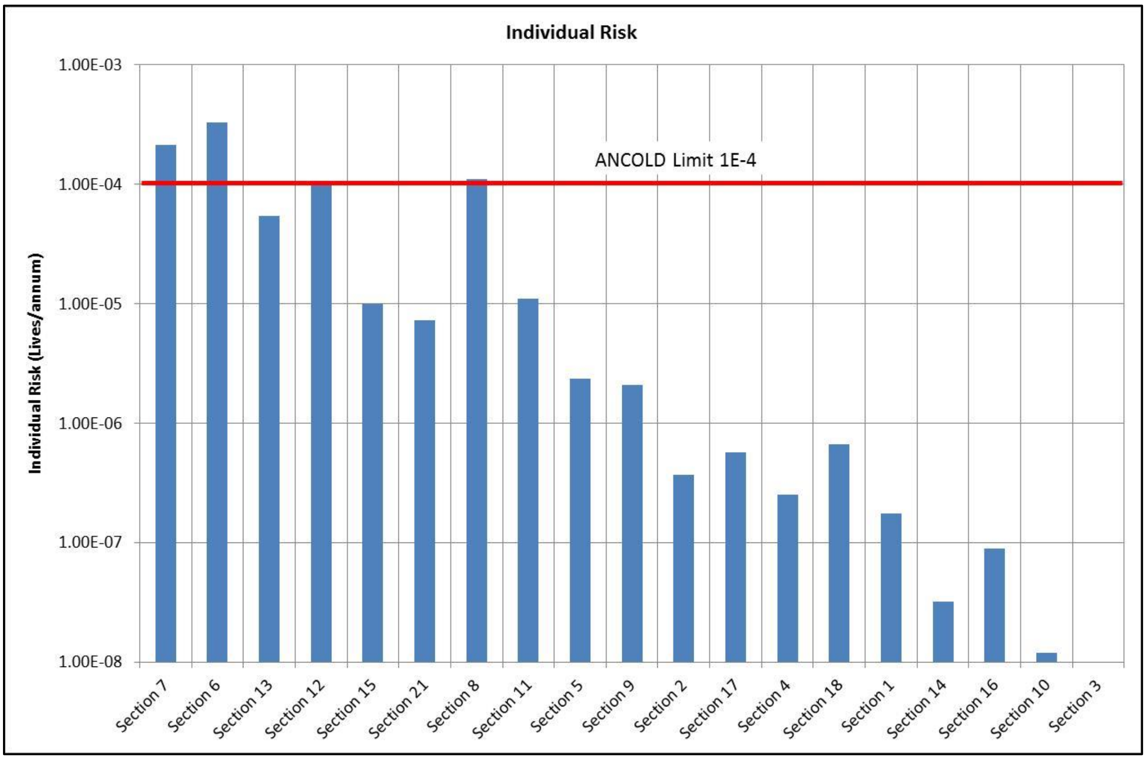


Figure 5-8 Avon Stopbank Individual Risk

5.3 Tides and earthquakes

5.3.1 Probabilities of Failure

The results for the failure probabilities for each section with the 1, 5, 10 and 20 year operating lifetimes for the seismic and tidal events are shown on Figure 5-9 and Figure 5-10 for the Seismic and flood events respectively. Figure 5-11 and Table 5-4 provide details of the combined flood and seismic events probabilities of failure for each of the selected lifetimes.

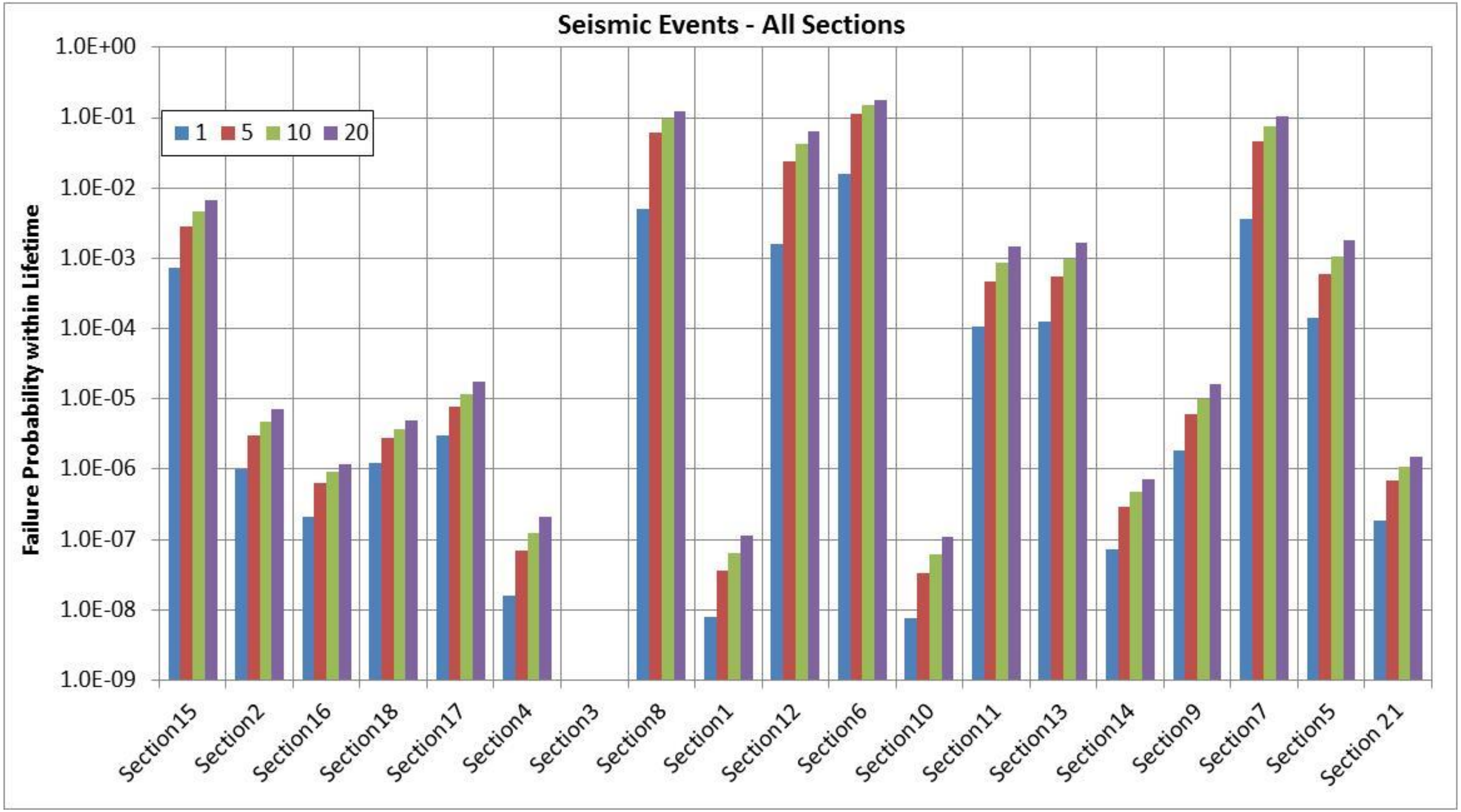


Figure 5-9 Avon Stopbank Seismic Events Probability of failure for sections within 1, 5, 10, 20 year lifetimes with Tidal Events

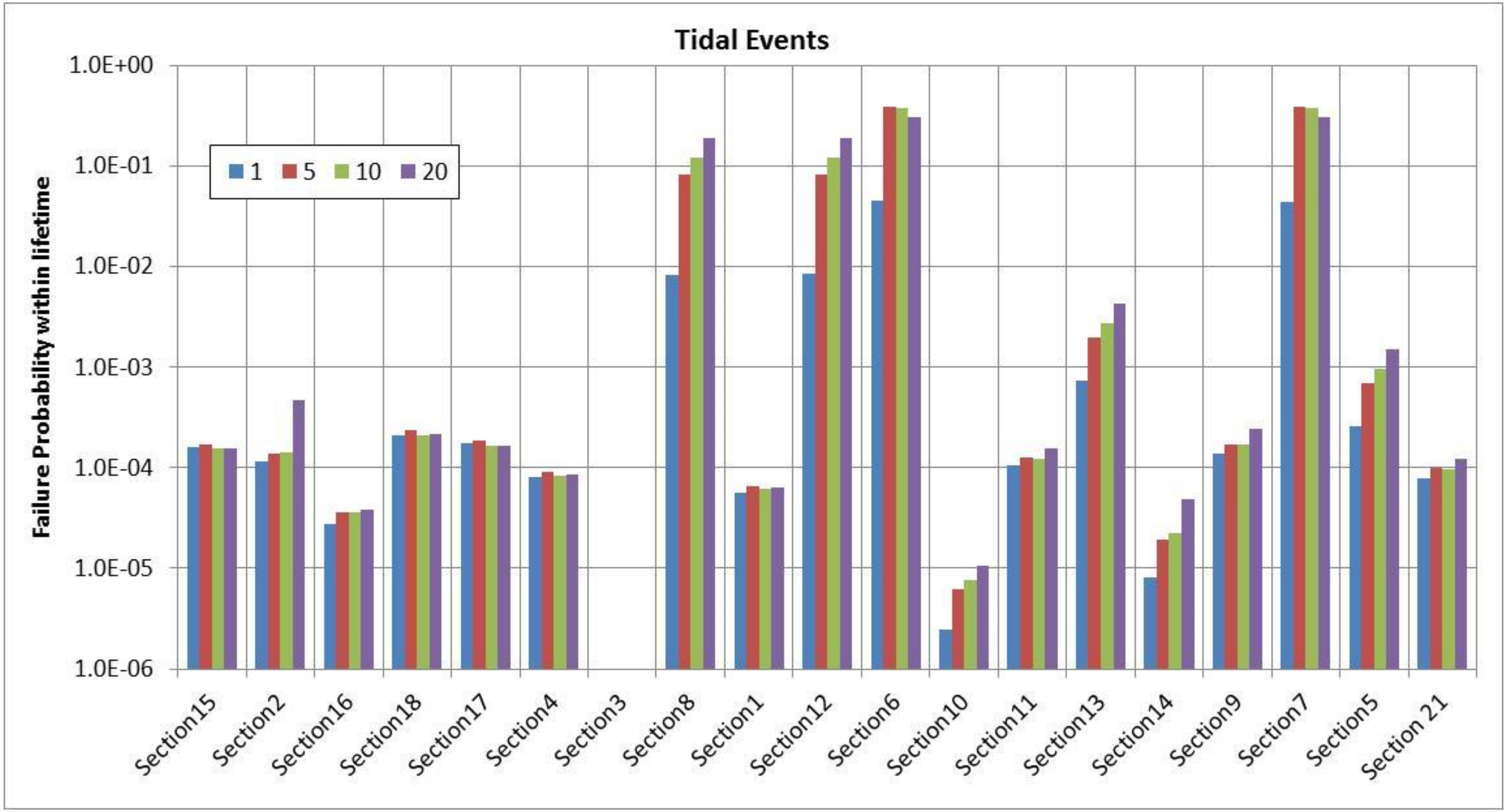


Figure 5-10 Avon Stopbank Tidal Events Probability of failure for sections within 1, 5, 10, 20 year lifetimes

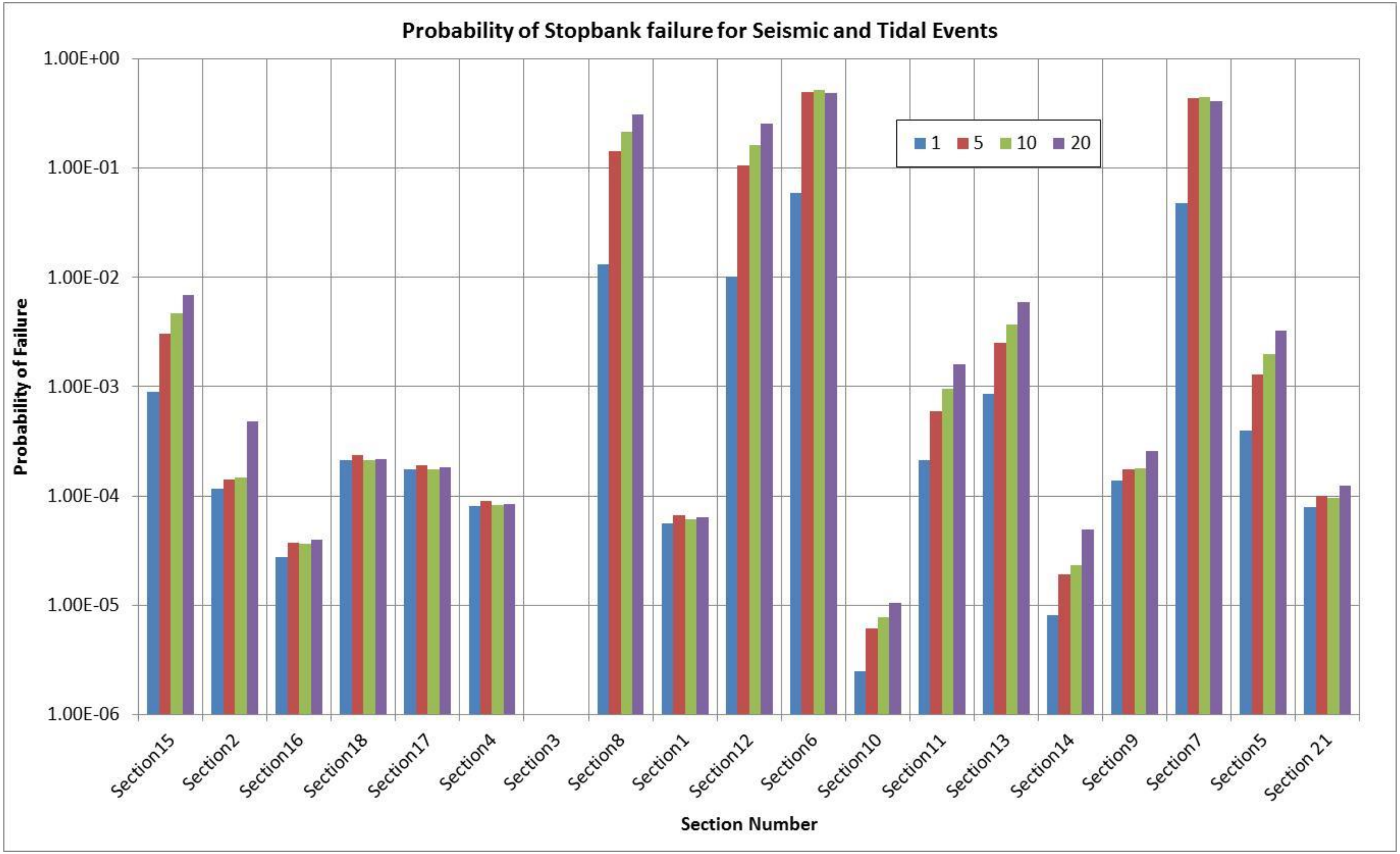


Figure 5-11 Avon Stopbank Seismic and Tidal Events Total Probability of failure for sections within 1, 5, 10, 20 year lifetimes

Table 5-4 Avon Stopbanks Tidal and seismic probability of failure for sections within 1, 5, 10, 20 year lifetimes

Section No.	Seismic Events (lifetime)				Tides (lifetime)				Total (lifetime)			
	1	5	10	20	1	5	10	20	1	5	10	20
	Left Bank											
1	7.97E-09	3.57E-08	6.50E-08	1.15E-07	5.63E-05	6.60E-05	6.13E-05	6.37E-05	5.63E-05	6.60E-05	6.13E-05	6.38E-05
2	1.01E-06	3.02E-06	4.66E-06	7.01E-06	1.16E-04	1.40E-04	1.44E-04	4.74E-04	1.17E-04	1.43E-04	1.49E-04	4.81E-04
2	1.88E-07	7.00E-07	1.07E-06	1.49E-06	7.89E-05	9.89E-05	9.49E-05	1.21E-04	7.91E-05	9.96E-05	9.60E-05	1.23E-04
3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	1.55E-08	6.84E-08	1.22E-07	2.09E-07	8.05E-05	9.05E-05	8.26E-05	8.47E-05	8.05E-05	9.06E-05	8.28E-05	8.49E-05
5	1.39E-04	6.03E-04	1.06E-03	1.77E-03	2.54E-04	6.87E-04	9.47E-04	1.50E-03	3.93E-04	1.29E-03	2.01E-03	3.27E-03
6	1.56E-02	1.13E-01	1.50E-01	1.75E-01	4.44E-02	3.90E-01	3.76E-01	3.08E-01	6.00E-02	5.02E-01	5.25E-01	4.83E-01
7	3.60E-03	4.55E-02	7.48E-02	1.02E-01	4.40E-02	3.90E-01	3.76E-01	3.08E-01	4.76E-02	4.35E-01	4.50E-01	4.10E-01
8	5.01E-03	6.10E-02	9.62E-02	1.25E-01	8.10E-03	8.21E-02	1.22E-01	1.87E-01	1.31E-02	1.43E-01	2.18E-01	3.12E-01
9	1.87E-06	6.05E-06	9.91E-06	1.62E-05	1.36E-04	1.70E-04	1.68E-04	2.43E-04	1.38E-04	1.76E-04	1.78E-04	2.59E-04
10	7.56E-09	3.38E-08	6.16E-08	1.09E-07	2.46E-06	6.14E-06	7.71E-06	1.04E-05	2.46E-06	6.18E-06	7.77E-06	1.05E-05
11	1.07E-04	4.70E-04	8.44E-04	1.45E-03	1.07E-04	1.27E-04	1.20E-04	1.55E-04	2.14E-04	5.97E-04	9.64E-04	1.61E-03
12	1.58E-03	2.36E-02	4.26E-02	6.49E-02	8.58E-03	8.25E-02	1.22E-01	1.89E-01	1.02E-02	1.06E-01	1.65E-01	2.54E-01
13	1.27E-04	5.57E-04	9.90E-04	1.67E-03	7.24E-04	1.97E-03	2.72E-03	4.30E-03	8.51E-04	2.53E-03	3.71E-03	5.97E-03
	Right Bank											
14	7.31E-08	2.94E-07	4.81E-07	7.19E-07	8.04E-06	1.89E-05	2.25E-05	4.82E-05	8.12E-06	1.92E-05	2.30E-05	4.89E-05
15	7.41E-04	2.88E-03	4.59E-03	6.71E-03	1.60E-04	1.71E-04	1.53E-04	1.54E-04	9.01E-04	3.06E-03	4.75E-03	6.86E-03
16	2.09E-07	6.42E-07	9.11E-07	1.19E-06	2.72E-05	3.65E-05	3.55E-05	3.84E-05	2.74E-05	3.71E-05	3.65E-05	3.96E-05
17	2.97E-06	7.84E-06	1.18E-05	1.78E-05	1.72E-04	1.84E-04	1.64E-04	1.64E-04	1.75E-04	1.91E-04	1.76E-04	1.82E-04
18	1.23E-06	2.75E-06	3.71E-06	4.90E-06	2.12E-04	2.32E-04	2.10E-04	2.13E-04	2.13E-04	2.35E-04	2.14E-04	2.18E-04

The escalation ratio of the total probability of failure for each section for the 5, 10 and 20 year lifetime compared with the 1 year probability varied as shown on Table 5-5 and Figure 5-12.

The ratio shows a considerable variation in the escalation for the various sections with the average being as shown on Table 5-5. This clearly shows a significant increase in the failure probability after one year with the majority of the sections having a ratio of greater than 2 after 5 years.

Table 5-5 Avon Stopbank tidal and seismic Failure escalation factors for each section failure probability compared with the 1 year period

Section Number	Stopbank Lifetime (years)			
	1	5	10	20
Section 8	1.00	10.92	16.63	23.82
Section 12	1.00	10.45	16.22	25.02
Section 7	1.00	9.15	9.47	8.62
Section 6	1.00	8.38	8.76	8.06
Section 15	1.00	3.39	5.27	7.61
Section 5	1.00	3.28	5.11	8.32
Section 13	1.00	2.97	4.36	7.02
Section 11	1.00	2.79	4.51	7.53
Section 10	1.00	2.51	3.15	4.28
Section 14	1.00	2.37	2.83	6.02
Section 16	1.00	1.36	1.33	1.45
Section 9	1.00	1.28	1.29	1.88
Section 21	1.00	1.26	1.21	1.56
Section 2	1.00	1.22	1.27	4.10
Section 1	1.00	1.17	1.09	1.13
Section 4	1.00	1.12	1.03	1.05
Section 18	1.00	1.10	1.00	1.02
Section 17	1.00	1.09	1.00	1.04
Section 3				
Average	1.00	3.66	4.75	6.64

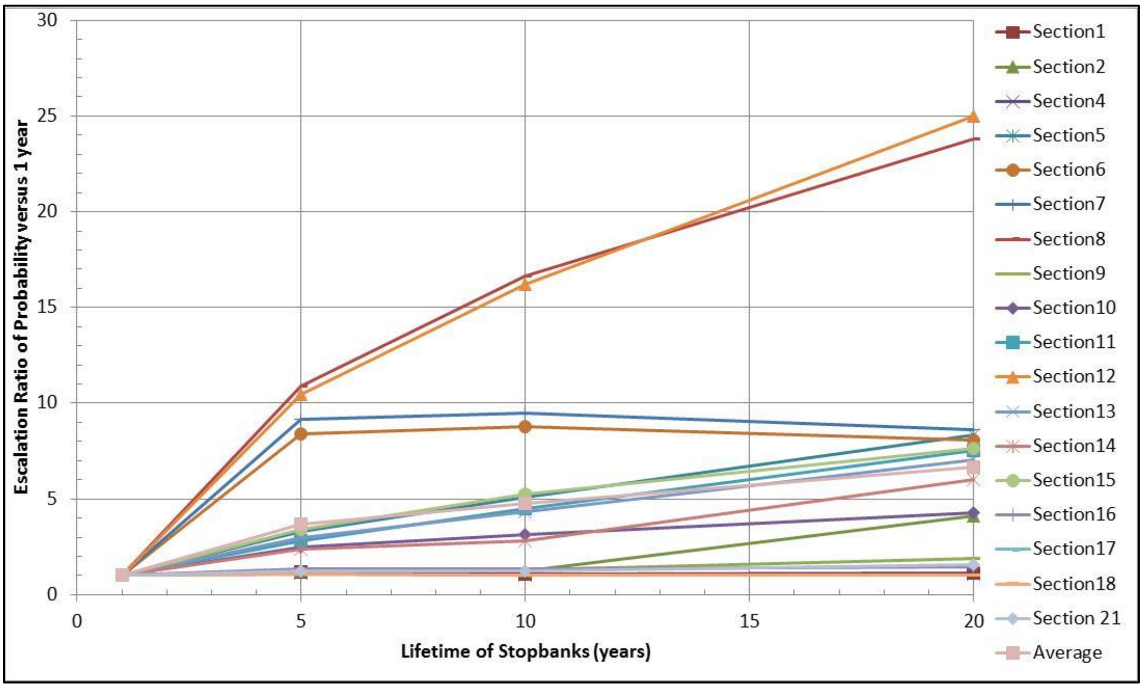


Figure 5-12 Avon Stopbank Failure escalations factors versus lifetime for Tidal and Seismic Events

5.3.2 Societal and Individual Risk

Societal Risk

The societal risk was calculated for the Stopbank with the tides and seismic events, as shown on Figure 5-13, which includes the societal risk for floods and seismic events. The figure clearly indicates that the risk is below the tolerable limit for which upgrade works are required to be considered on an ALARP basis.

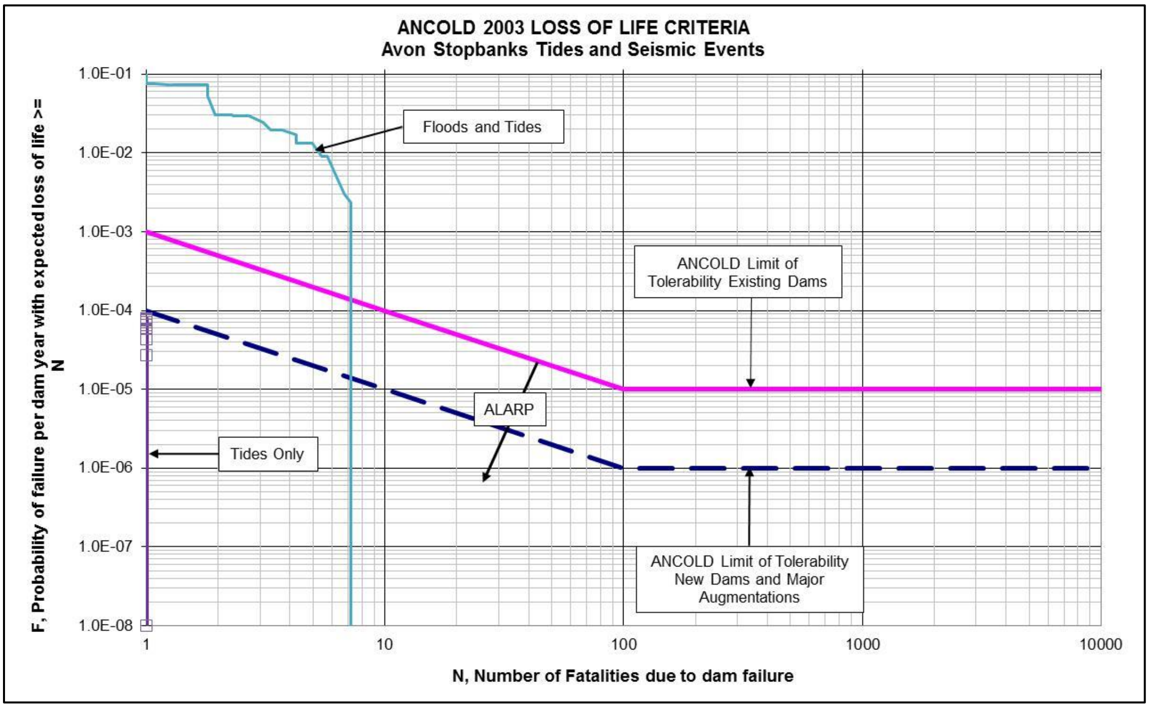


Figure 5-13 Avon Stopbanks Societal Risk for Tides and Seismic events and Floods and seismic events

The risk analysis results for the failure modes of each section have been ranked according to the highest total risk, as shown on Table 5-6 and Figure 5-14.

Table 5-6 Avon Stopbanks Risk Analysis results (lives/annum) for each Section with Tides and Seismic events

Section Number	Seismic Overtopping	Seismic Piping	Flood Overtopping	Piping Foundation	Piping Embankment	Tree roots rot	Trees fall over	Total	Percentage Total Risk	Individual Risk
Section15	4.68E-04	2.49E-07	0.00E+00	9.77E-06	3.67E-10	0.00E+00	0.00E+00	4.78E-04	99.08%	7.97E-06
Section8	9.38E-07	1.43E-10	3.43E-06	0.00E+00	0.00E+00	1.03E-11	4.92E-14	4.37E-06	0.91%	7.57E-05
Section 21	0.00E+00	2.70E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.70E-08	0.01%	2.47E-07
Section2	1.71E-10	2.03E-10	8.39E-09	1.28E-08	3.55E-13	7.71E-10	5.19E-11	2.24E-08	0.00%	3.72E-07
Section4	0.00E+00	6.14E-11	0.00E+00	1.02E-08	1.62E-13	0.00E+00	0.00E+00	1.03E-08	0.00%	2.51E-07
Section1	0.00E+00	4.73E-11	0.00E+00	8.39E-09	2.74E-14	0.00E+00	0.00E+00	8.43E-09	0.00%	1.75E-07
Section7	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00%	1.73E-04
Section6	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00%	2.95E-04
Section13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00%	3.53E-06
Section12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00%	4.26E-05
Section11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00%	1.41E-06
Section5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00%	2.19E-06
Section9	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00%	4.41E-07
Section17	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00%	5.66E-07
Section18	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00%	6.71E-07
Section14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00%	2.58E-08
Section16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00%	8.66E-08
Section10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00%	7.72E-09
Section3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00%	0.00E+00
Totals	4.69E-04	2.77E-07	3.44E-06	9.80E-06	3.68E-10	7.81E-10	5.20E-11	4.82E-04	100.00%	
Percentage Contribution	97.1975%	0.0574%	0.7126%	2.0323%	0.0001%	0.0002%	0.0000%			

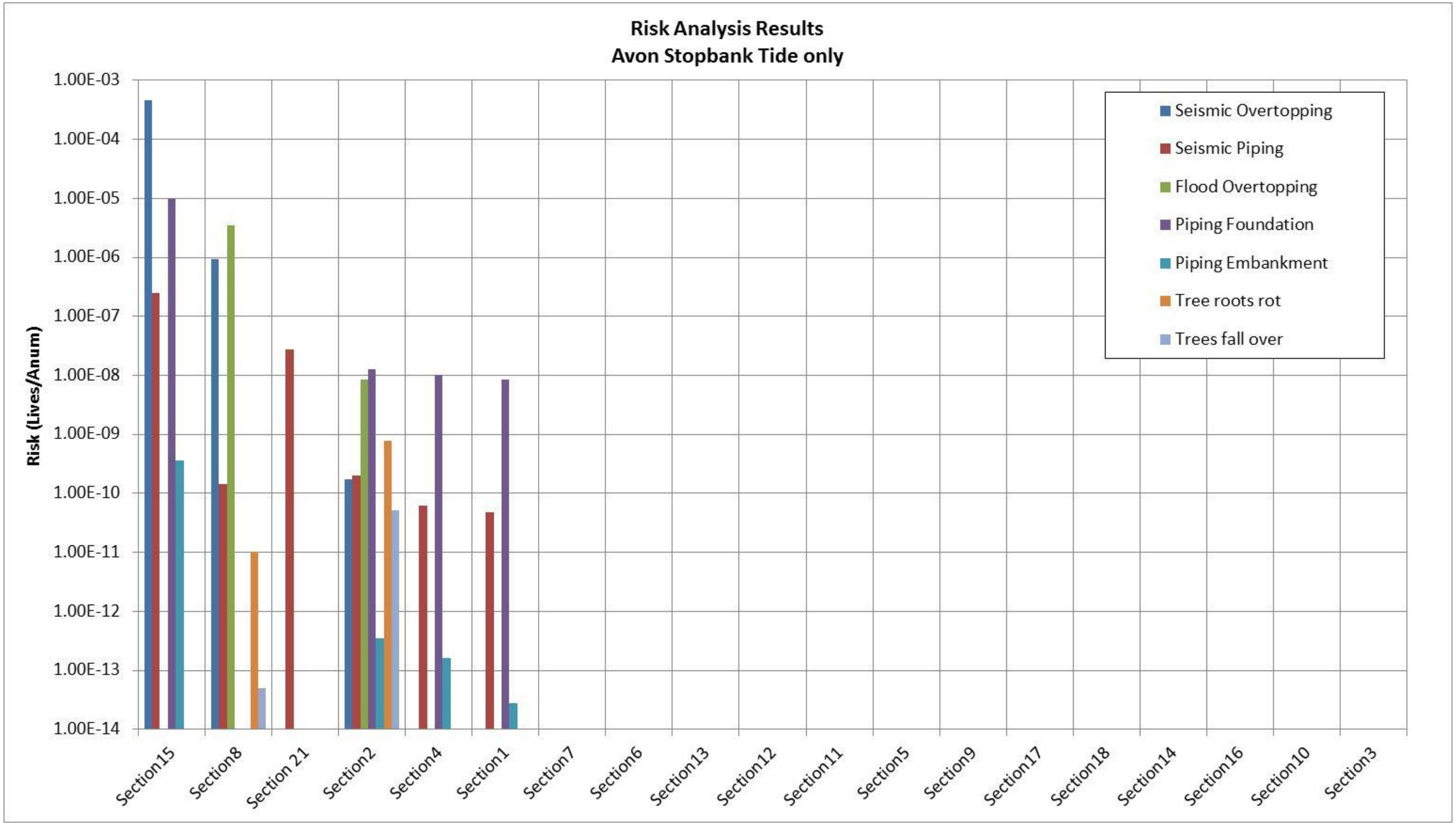


Figure 5-14 Avon Stopbanks Annual Risk (Lives/yr) for each failure mode and Section location for tides and seismic events

The risk analysis results clearly show that the risk is dominated by the seismic deformation and tidal overtopping for Section 15, as shown on Table 5-6. This is owing mainly to the Potential Loss of Life resulting from failure of this section being relatively high for the more frequent tidal events when compared with the other sections.

Individual Risk

The Individual risk was calculated for each section, as shown on Figure 5-15, which indicates that Sections 6, 7 and 8 are at or exceed the ANCOLD limit of tolerability of 1E-4.

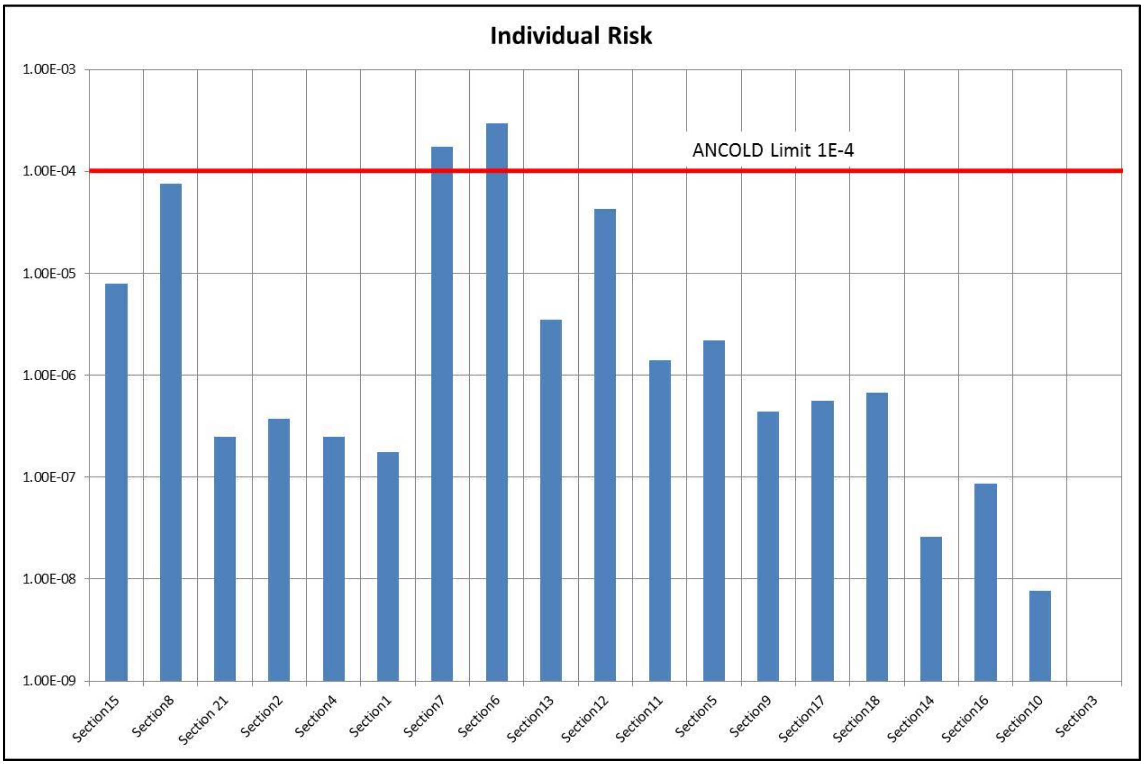


Figure 5-15 Avon Stopbank Individual Risk for Tides and Seismic events

5.4 Stopbank Upgrade Option

Given that the highest risk is associated with floods overtopping the stopbanks or tides overtopping the embankments following a seismic event, the most significant risk reduction can be achieved by raising the stopbanks as shown on Table 5-7 to prevent overtopping for floods up to the 1 in 200 AEP.

Table 5-7 Overtopping prevention embankment sections raise

Section	Centreline Chainage (m)	Stopbank Crest Level (m)	Max Embankment raise for flood and seismic events (m)	Raise Type
Left Bank				
5	16468	11.01	0.18	Fill material raise
6	15504	10.88	0.35	Replace sandbags with embankment
7	14952	10.90	0.35	Replace sandbags with embankment
8	14314	11.01	0.26	Replace sandbags with embankment and use Concrete section on road side to limit encroachment on the road

9	13546	11.18	0.06	Raise Embankment and flatten land side slope
11	12048	11.11	0.21	Raise Embankment and flatten land side slope
12	11520	11.02	0.39	Replace land side sandbags with embankment
13	10587	11.09	0.46	Raise embankment and use Concrete section on road side to limit encroachment on the road if necessary
Right Bank				
15	15179	11.08	0.27	Raise Embankment and flatten land side slope
17	17450	11.19	0.11	Raise Embankment and flatten land side slope if possible
18	17982	11.23	0.04	Fill material raise
21	13360	11.18	0.07	Raise embankment and use Concrete section on road side to limit encroachment on the road if necessary

The resulting Societal risk after completion of the upgrade works is as shown on Figure 5-16, which indicates that the risk is reduced to below the ANCOLD Tolerable limit and further upgrade works should be considered based on the ALARP principle.

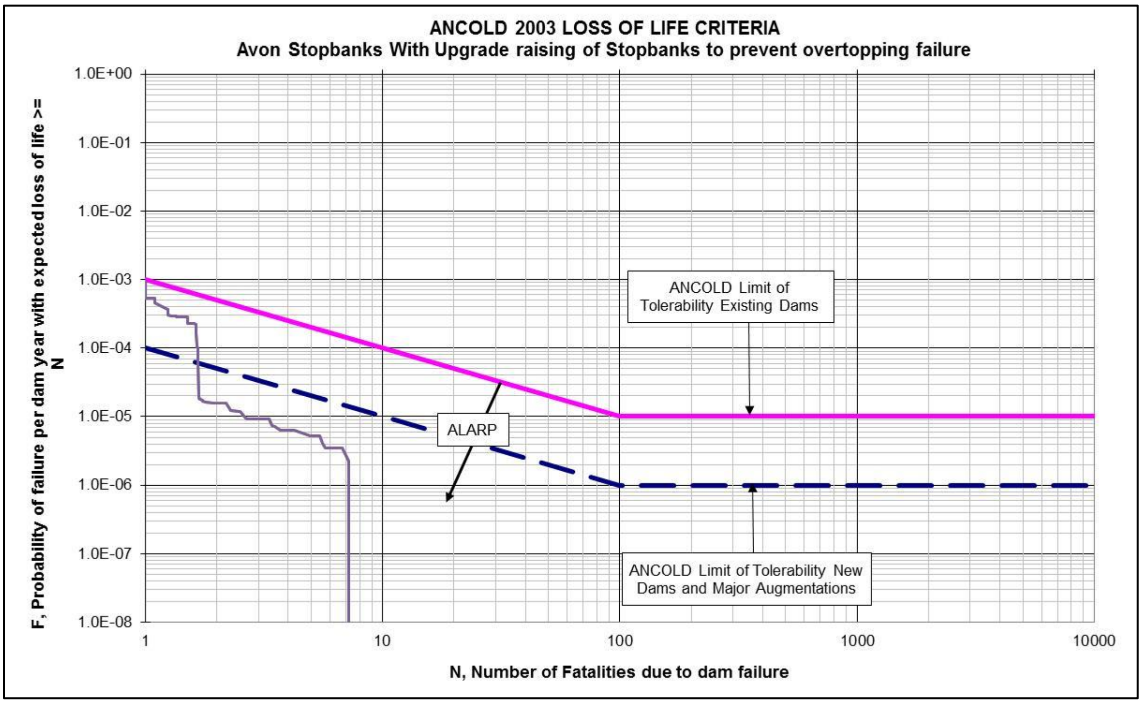


Figure 5-16 Avon Stopbanks Societal Risk after raising stopbanks to prevent overtopping

The Individual risk is as presented on Figure 5-17 clearly shows that the risk is acceptable.

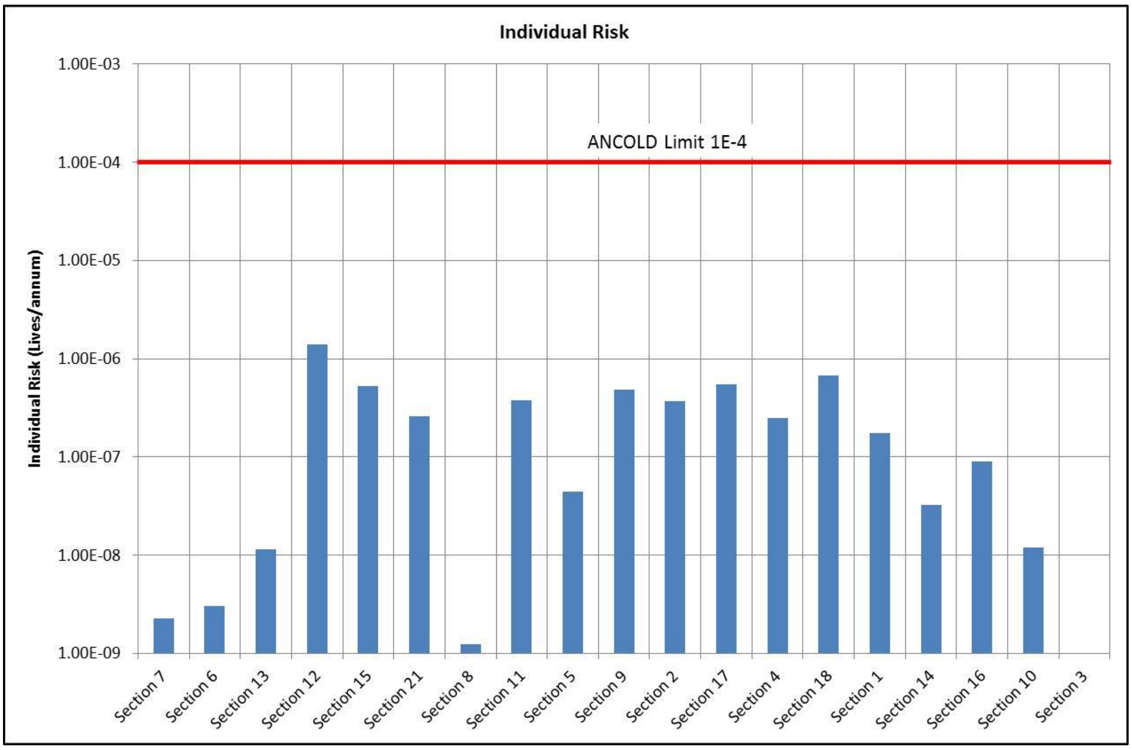


Figure 5-17 Avon Stopbank Individual Risk for Floods, Seismic and Tidal events after raising stopbanks to prevent overtopping

6. Risk Assessment Conclusions

The risk analysis has been completed for the Avon Stopbanks with consideration of the following hazards:

- Seismic events with tidal levels varying from the annual tidal level to the 200 year ARI event.
- Tidal events alone varying from the annual tidal level to the 200 year ARI event
- Flood events alone with floods varying from the annual event to the 200 year ARI event.

The Societal Risk for the Stopbanks as presented on Figure 6-1 confirms the following:

- The Societal risk is well in excess of the ANCOLD Tolerable limit for the seismic, floods and tidal events and confirms the need for prevention of overtopping failure of the stopbanks resulting from flood events.
- The Societal risk is acceptable for the Tides and Seismic events, and confirms that remedial works are required to satisfy the As Low As Reasonably Practicable (ALARP) criteria.

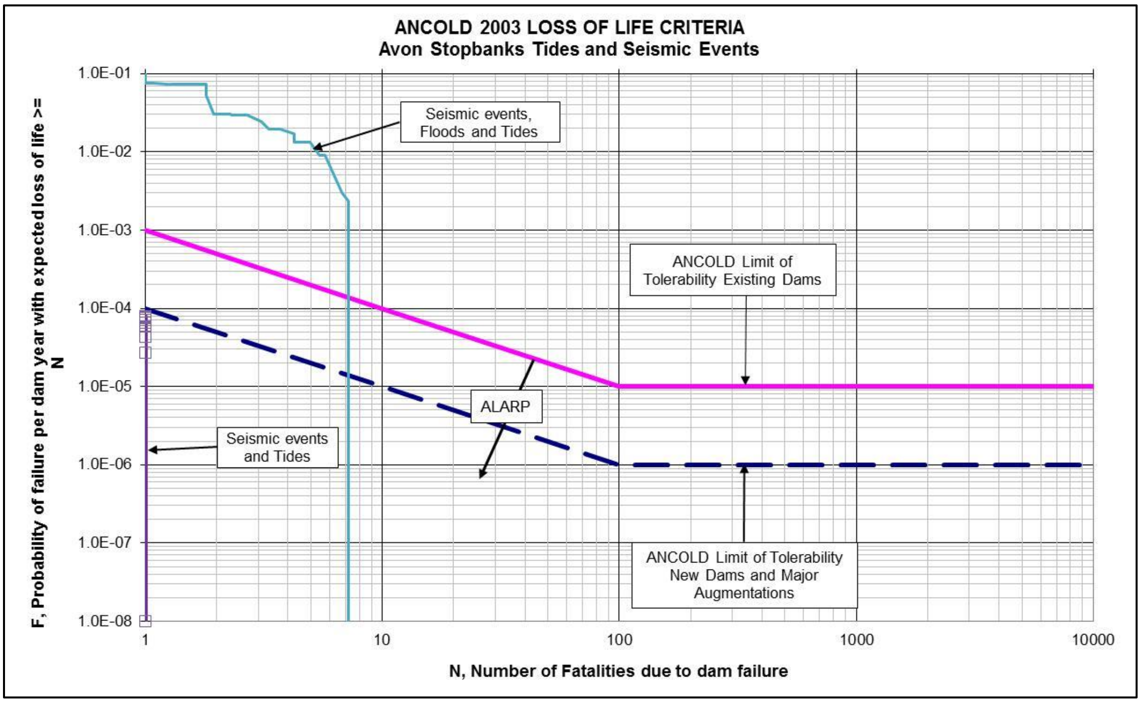


Figure 6-1 Avon Stopbanks Societal Risk for Seismic events with Tides and Tides and Floods

The results clearly show that the individual risk for the Avon Stopbanks is above the tolerable limit of 1.0E-4 lives/annum for the following sections and hazards.

Table 6-1 Avon Stopbanks Individual Risks above or close to the ANCOLD limit of Tolerability

Section	Tides and Seismic events	Tides, Floods and Seismic Events
Section 6	2.95 E-4	3.28E-4

Section 7	1.73E-4	2.13E-4
Section 8	7.57E-5	1.10E-4
Section 12	4.26E-5	9.70E-5

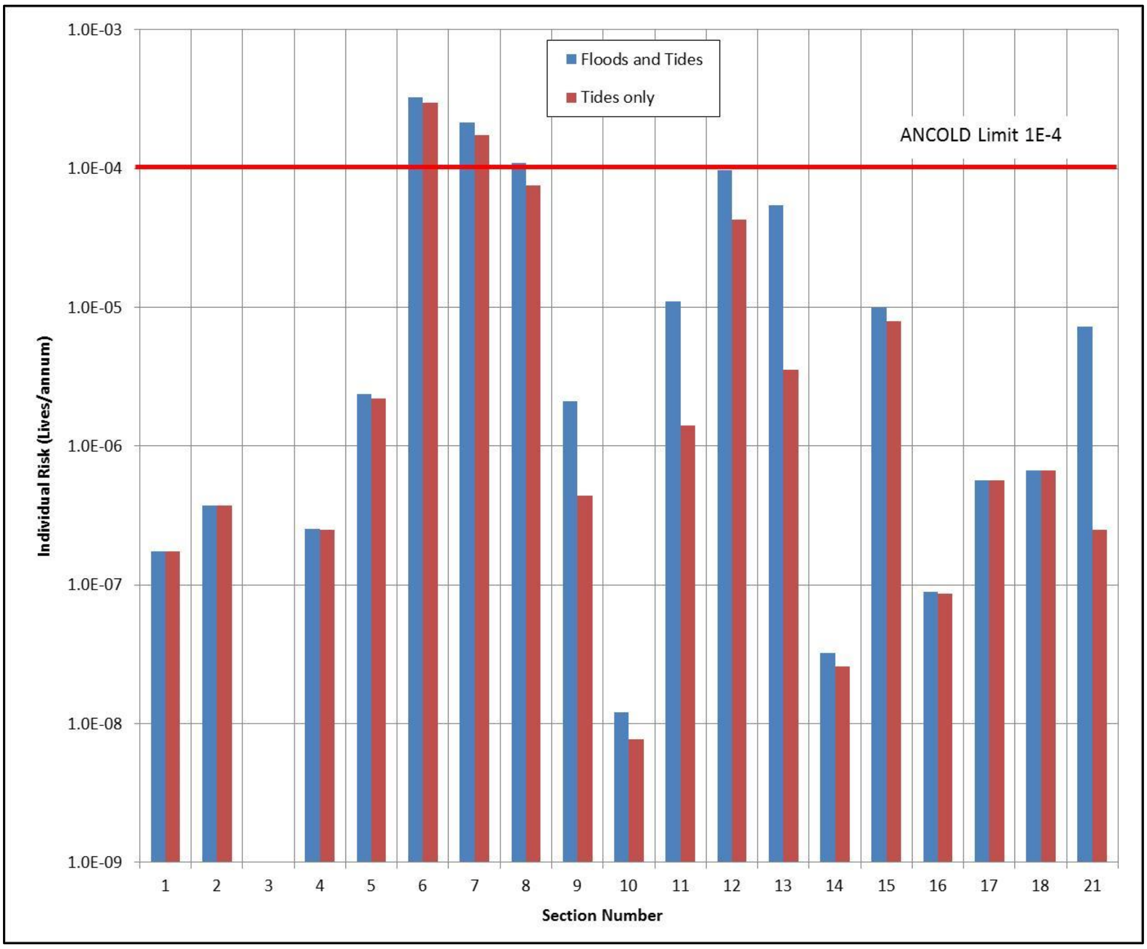


Figure 6-2 Avon Stopbanks Individual Risk

The results show a significant escalation in potential failure of the stopbank sections within the next five years of between 8 to 11 for Sections 6, 7, 8 and 12 where sandbags have been used for tidal protection. Section 2, which also has sand bags, has a lower increase of about 1.2 owing to the use of the more substantial sandbags combined with earthfill at this section. The overall increase in failure potential is 3.66 times the annual failure probability within the next 5 years of operation (Table 5-5).

The failure potential and resulting risk for tidal and seismic events is dominated by the seismic deformation resulting in overtopping failure contributing 97.2% of the total risk for the annual events.

The trees within the embankments do not contribute significantly to the failure probabilities or risk.

There are a number of areas where the Stopbank levels are below the design level of RL 11.2 m which exacerbates the overtopping failure resulting from tides or tides and flood events.

The upgrade option for raising the embankment reduces the Societal risk below the ANCOLD Tolerable limit, as shown on Figure 5-16 and further upgrade works are to consider the ALARP principle. The individual risk for the raised embankment sections is lowered to below the ANCOLD limit of tolerability for all sections, as shown on Figure 5-17.

7. Management Plan Recommendations

Based on the results of the risk analysis, the following are recommended for management of the Stopbanks.

7.1 Immediate Action and Ongoing Maintenance

- Reinstate the stopbank levels to the design level of RL 11.2 m
- Ongoing maintenance of the sandbag sections 6, 7, 8 and 12.

The cost for the ongoing maintenance is as follows:

Cost Estimate from Samantha

7.2 Five Year Management Plan

The overall risk posed by the Stopbanks with seismic, tidal and flood events is above the tolerable limit. Furthermore there is a significant increase in potential failure within the next five years.

The five year management plan is therefore is to raise the embankments to prevent overtopping by floods or tides following seismic events, as per Table 5-7.

The cost for the raising is as follows:

Cost Estimate from Samantha

Raising the Stopbanks has the adverse effect of confining the flow. In the case of the Stopbanks, the raise amounts are not significant, however, the following works should be considered for the design level of the embankments:

- Use "glass wall" stopbank levels which do not permit any overtopping to occur for the design level to be considered.
- Complete additional hydrological and hydraulic analyses to determine the flood levels along the Stopbank
- Complete a cost analysis for raising and potentially re-aligning the Stopbanks to provide the optimal solution for the Stopbanks based on a cost benefit analysis

7.3 20 Year Management Plan

The Stopbanks can be considered as being permanent for as long as they stand given that their construction material is very unlikely to degrade. The temporary nature is a function of the immediate need for the stopbanks following the 2011 event and the limited area available for the construction of more robust structures. The embankments will stand for as long as they are not affected by seismic loading or overtopping or piping failure modes. The permanent sections will be more robust structures in areas not prone to the lateral spreading or bank slope failure.

The main issue with respect to the temporary or permanent nature of the stopbanks is the level, which allows for overtopping failures resulting from seismic lateral spreading or settlement followed by tidal movement or floods overtopping the existing embankment.

Superficial cracking of the slopes that may worsen through water ingress and will require routine maintenance to repair cracks where they develop and are seen to be increasing in size.

The failure escalations factors versus lifetime for Tidal and Seismic Events, as given on Figure 5-12, show that, in general, the long term likelihood of failure is not significantly increased after the first five years of operation. The long term management options, therefore, include the following:

a. ongoing maintenance of the raised and original embankment sections after the 5 year management plan construction works are completed. This will require annual survey of the crest and topping up of the sections where settlement may have occurred.

b. relocation of the stopbanks to permanent locations as per the plan developed by GHD and presented in report ?????. Risk levels would change with permanent stopbanks with respect to piping failure modes through the foundation and embankment where greater effort could be put to reducing seepage gradients and prevention of piping failure initiating. The overtopping failure mode could be reduced, depending on the construction of the permanent structures. The relocation will allow for the potential recreational and landscape development of the zone between the new embankment and the river. These areas will be subject to flooding and the landscaping and development should account for this.

Cost Estimates for comparison of these options are as follows.

from Samantha

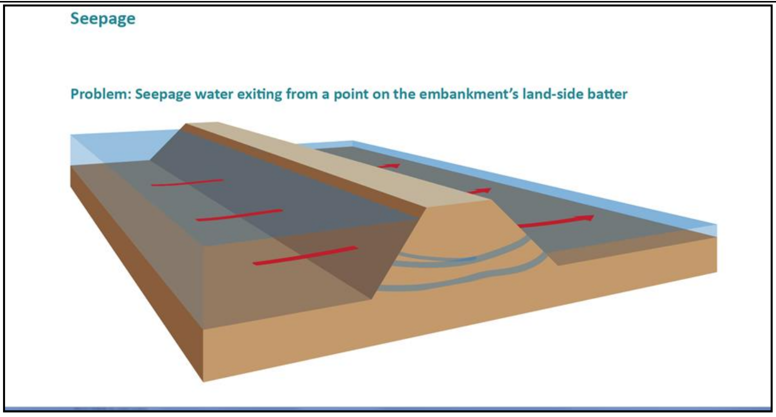
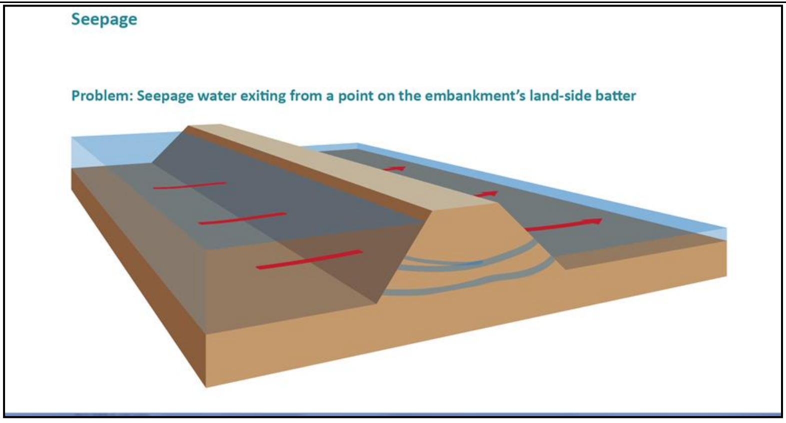
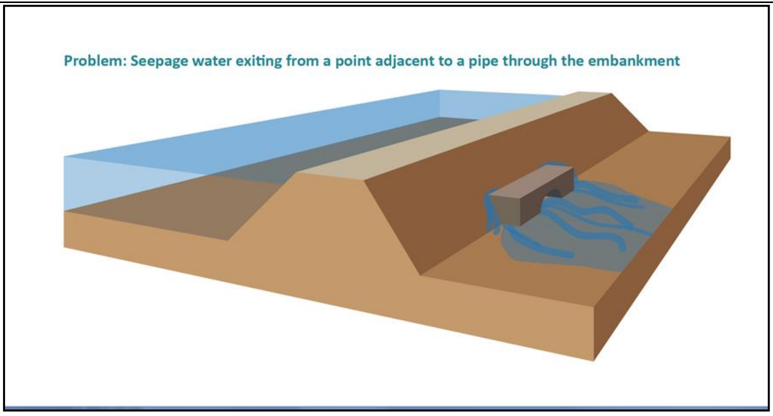
8. References

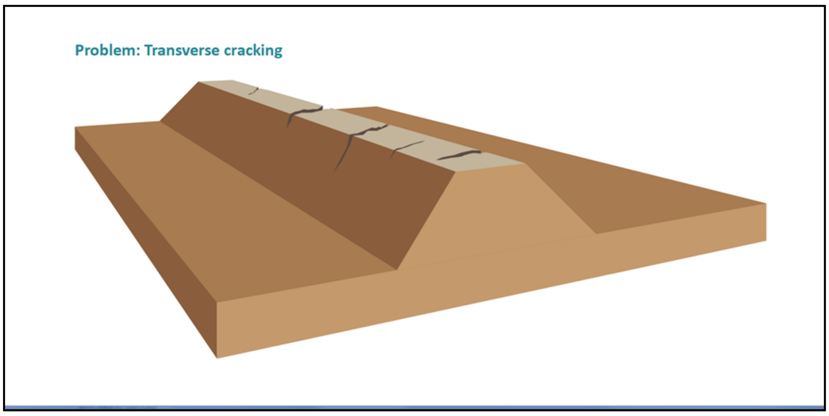
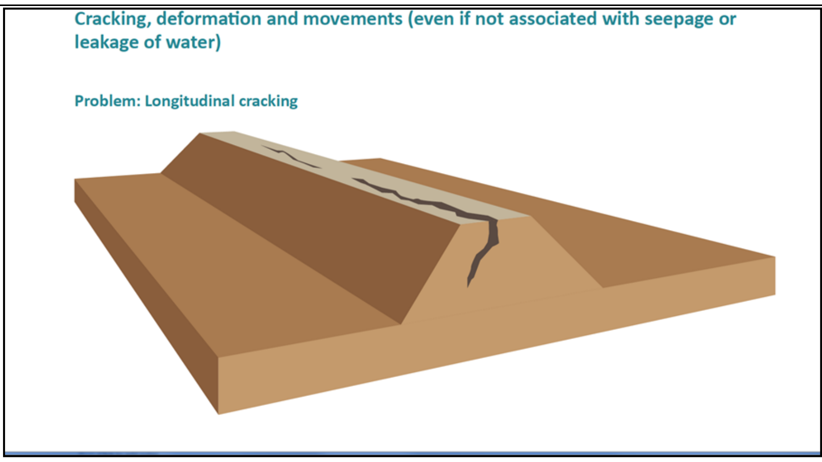
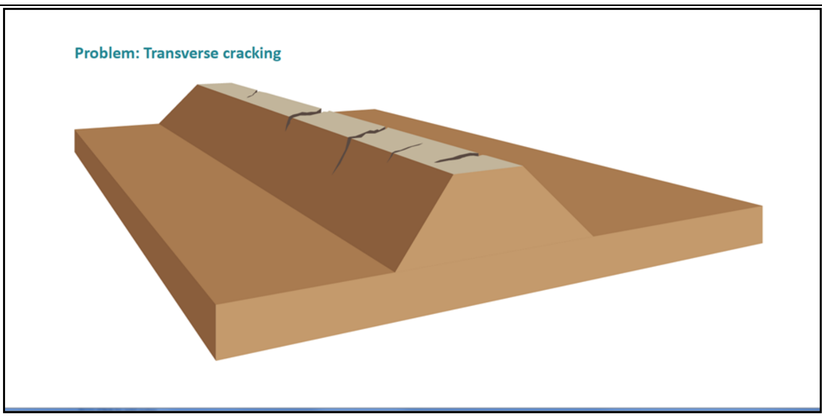
Stirling, M et al (2008), *“Seismic Hazard of the Canterbury Region, New Zealand: New Earthquake Source Model and Methodology”* – Bulletin of the New Zealand and Society for Earthquake Engineering, Vol. 41, No. 2

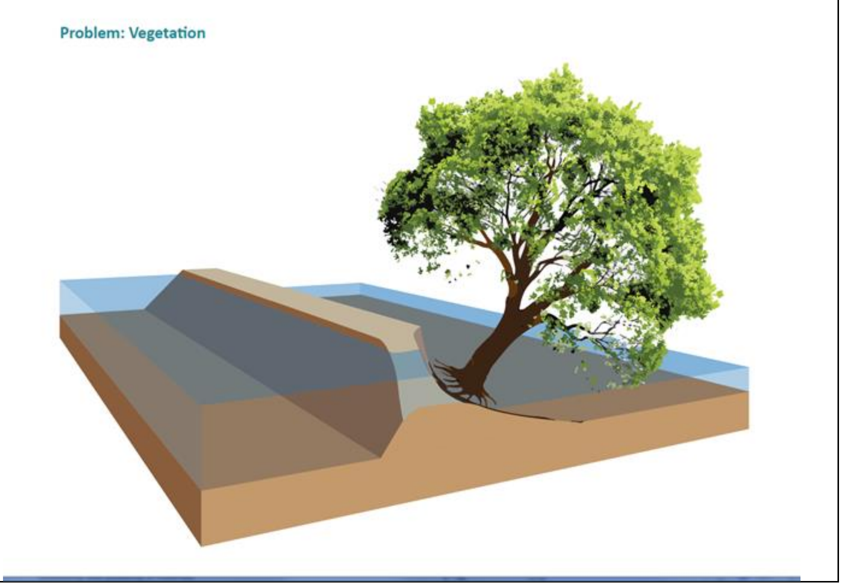
U.S. Department of the Interior Bureau of Reclamation (USBR), (2014), *“RCEM – Reclamation Consequence Estimating Methodology – Interim – Guidelines for Estimating Life Loss for Dam Safety Risk Analysis”*

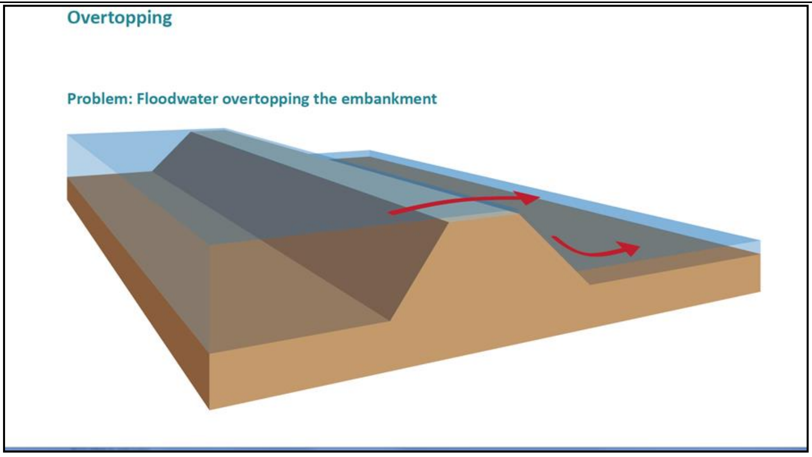
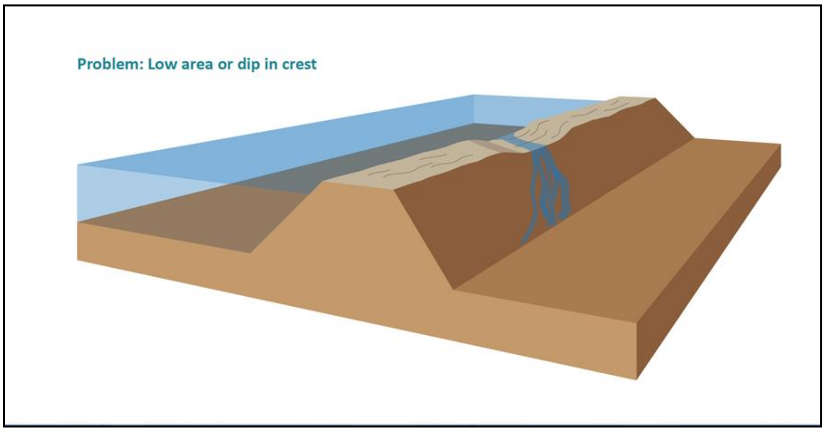
Appendices

Appendix A – Summary of Applicable Failure Modes

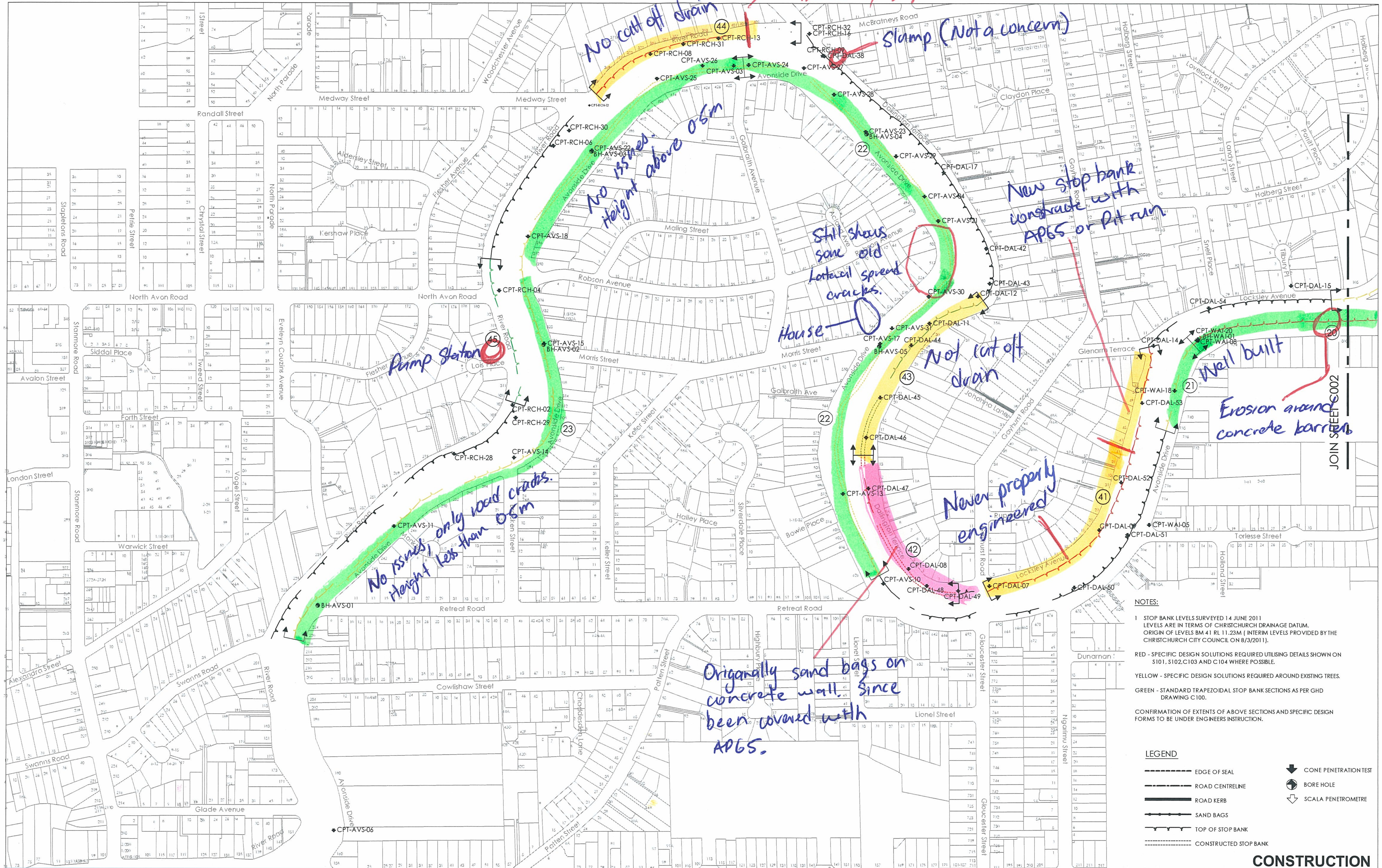
Event	Initiating Event	Generalized Schematic Diagram
Piping		
Seepage through embankment	*Hydrological / Flood*	
Seepage through foundation sands	*Hydrological / Flood*	
Seepage along stormwater pipes	*Hydrological / Flood*	

Transverse cracking of the wall - Differential movement around pipes	*Earthquake / Flood*	
Transverse cracking of the wall - Differential foundation conditions	*Earthquake / Flood*	
Longitudinal cracks - Translation (Lateral Spreading)	*Earthquake*	
Transverse cracking of the wall - Slope failure through weak foundation layers	*Earthquake*	

Tree roots rot - Opening Pipes to upstream	*Hydrological / Flood*	

Event	Initiating Event	Schematic Drawing
Overtopping		
Loss of Freeboard - Failure of Sandbags	*Earthquake*	
Loss of Freeboard - Slumping (stopbank or foundation)	*Flood*	
Overtopping during extreme floods causing lack of freeboard (settlement) - Sandbag deteriorates	*Hydrological / Flood*	
Overtopping during extreme floods or tide - Settlement	*Hydrological / Flood*	
Longitudinal cracks - Translation (Lateral Spreading)	*Earthquake / Flood*	
Removal of material from wall - Trees fall over	*Hydrological / Flood*	

Appendix B – Inspection Notes



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CONFIRMATION OF EXTENTS OF ABOVE SECTIONS AND SPECIFIC DESIGN FORMS TO BE UNDER ENGINEERS INSTRUCTION.

LEGEND

- EDGE OF SEAL
- ROAD CENTRELINE
- ROAD KERB
- SAND BAGS
- TOP OF STOP BANK
- CONSTRUCTED STOP BANK
- CONE PENETRATION TEST
- BORE HOLE
- SCALA PENETROMETRE

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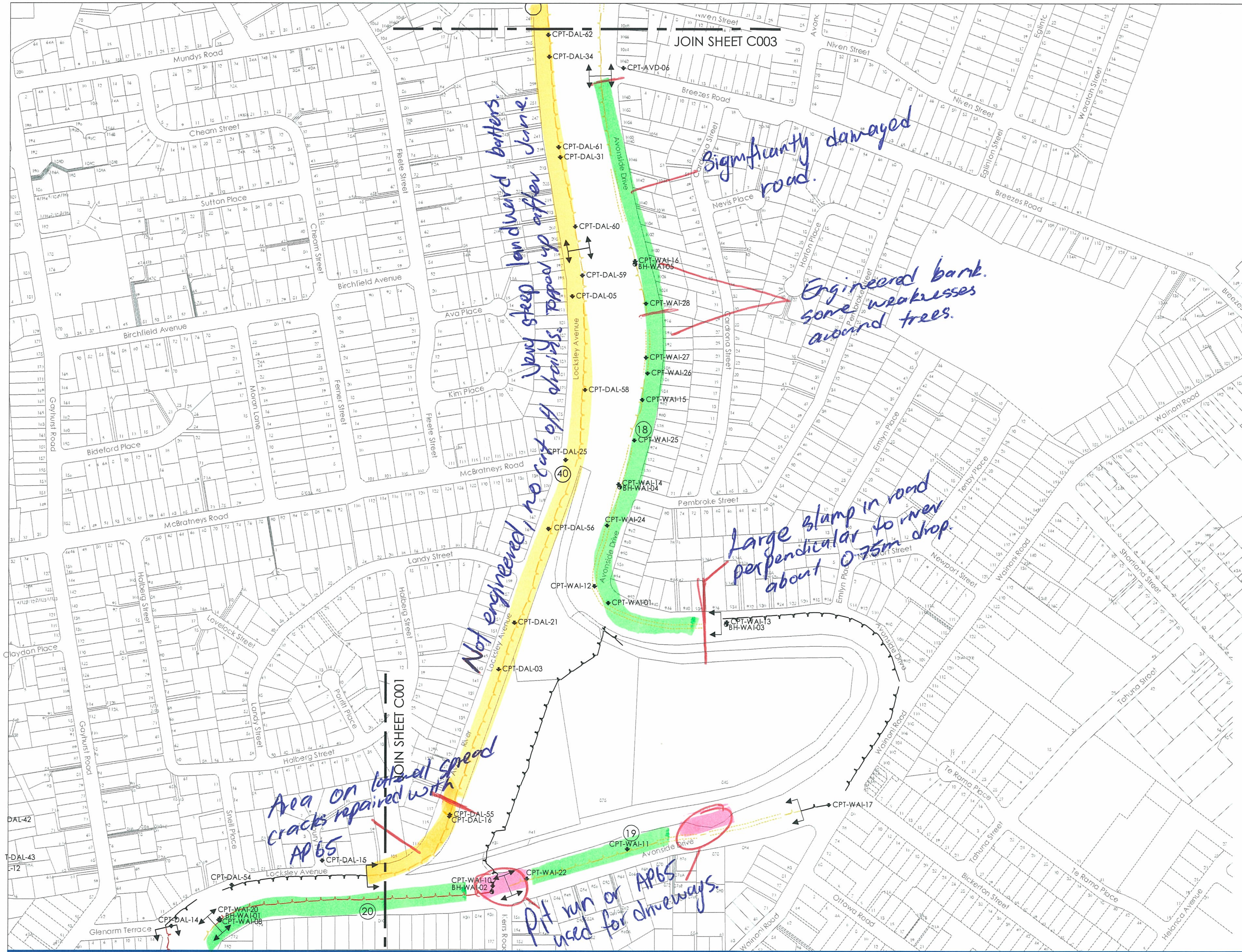

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- ROAD KERB
- SAND BAGS
- TOP OF STOP BANK
- CONSTRUCTED STOP BANK
- CONE PENETRATION TEST
- BORE HOLE
- SCALA PENETROMETRE

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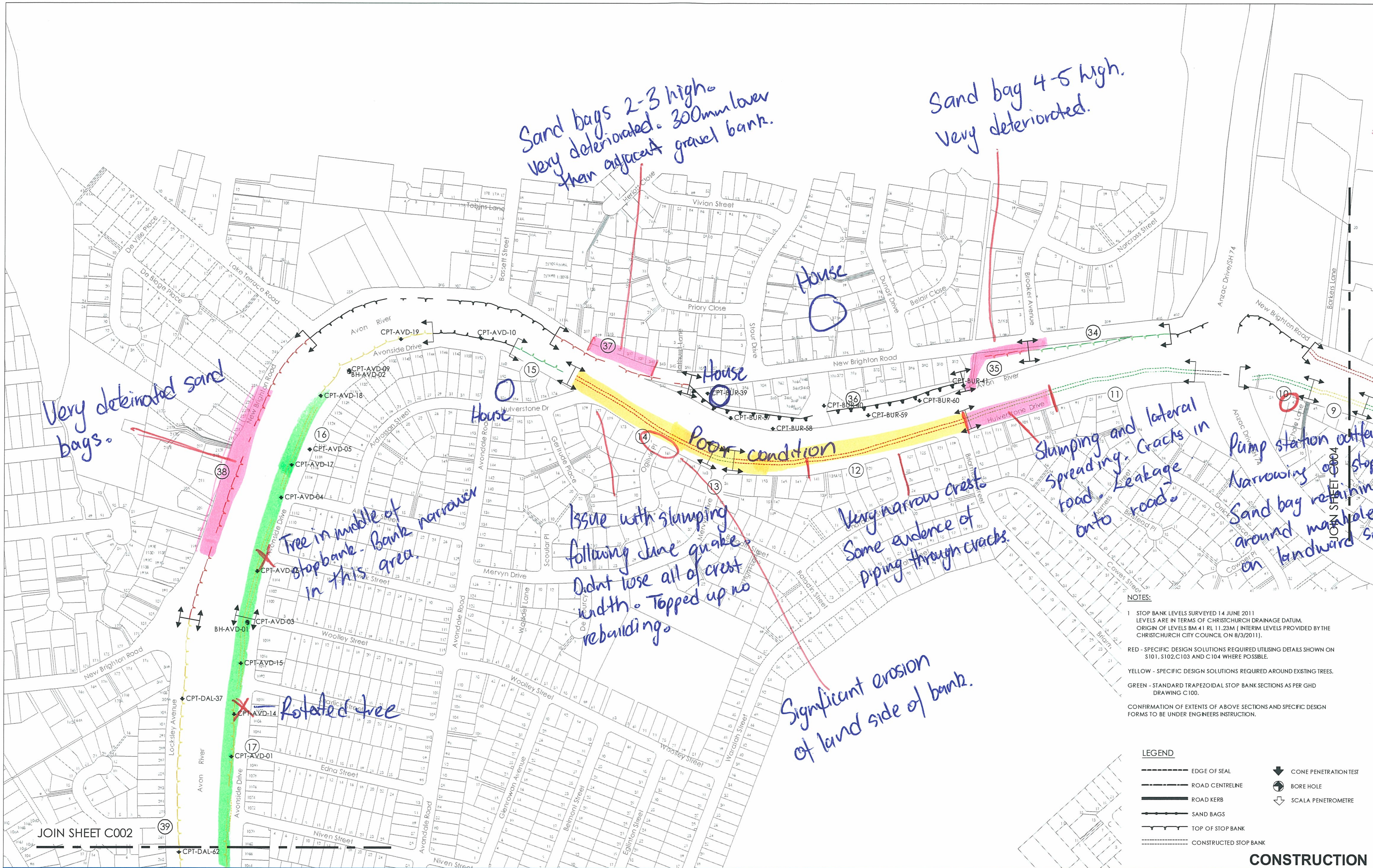

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LEGEND

EDGE OF SEAL
ROAD CENTRELINE
ROAD KERB
SAND BAGS
TOP OF STOP BANK
CONSTRUCTED STOP BANK
CONE PENETRATION TEST
BORE HOLE
SCALA PENETROMETRE

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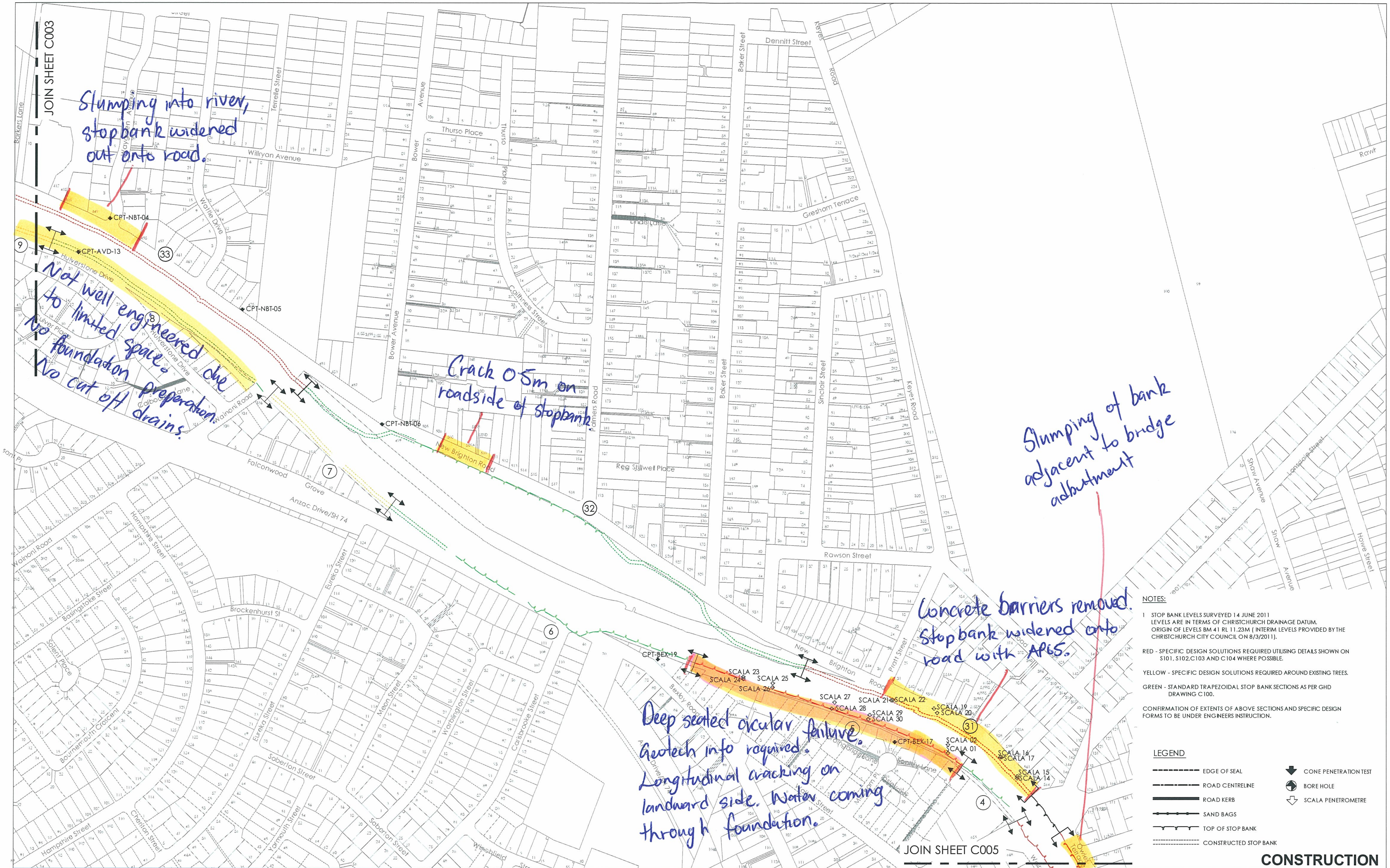

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- ROAD KERB
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- TOP OF STOP BANK
- CONSTRUCTED STOP BANK
- CONE PENETRATION TEST
- BORE HOLE
- SCALA PENETROMETRE

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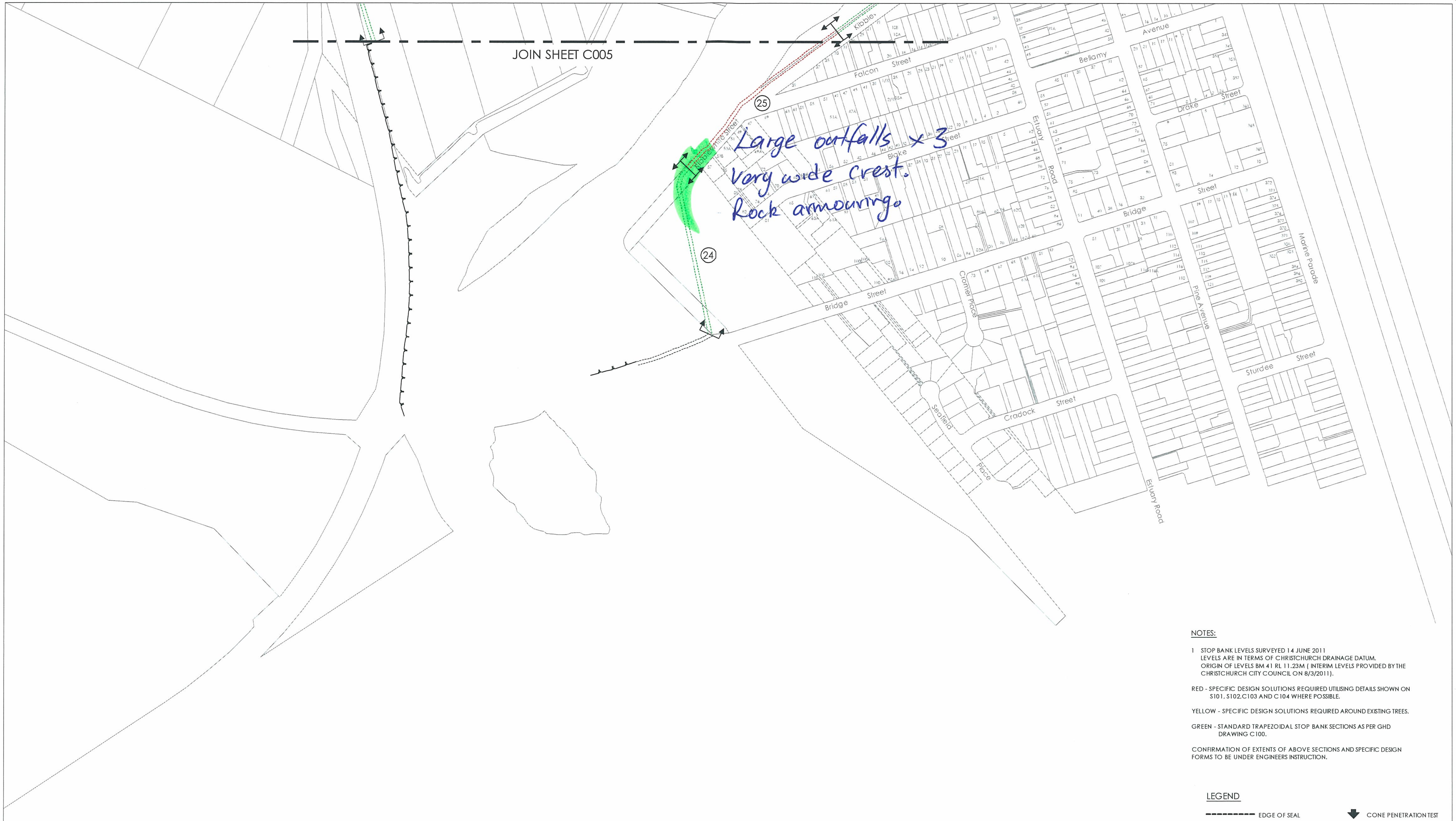

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LEGEND

- EDGE OF SEAL
- ROAD CENTRELINE
- ROAD KERB
- SAND BAGS
- TOP OF STOP BANK
- CONSTRUCTED STOP BANK
- CONE PENETRATION TEST
- BORE HOLE
- SCALA PENETROMETRE

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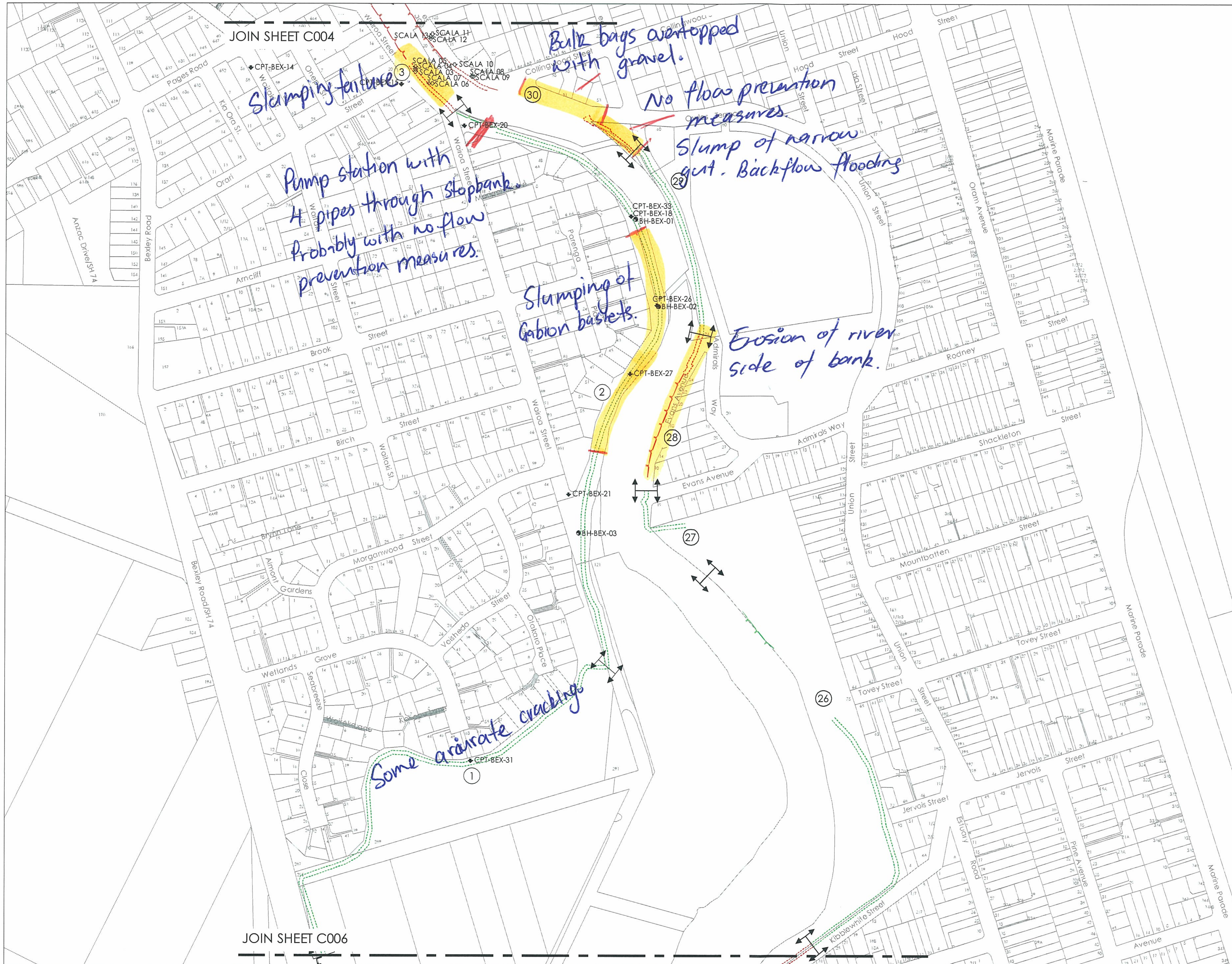

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LEGEND

EDGE OF SEAL	CONE PENETRATION TEST
ROAD CENTRELINE	BORE HOLE
ROAD KERB	SCALA PENETROMETRE
SAND BAGS	
TOP OF STOP BANK	
CONSTRUCTED STOP BANK	

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Appendix C – Crack Mapping and Levee Section Sketches


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Any Database user has read and agrees to the terms of use for the Database;
Any Database user has read any explanatory text accompanying this map; and
The "Important notice" accompanying the map and data must be reproduced whenever the map or data are reproduced.
Observed Crack Locations
Post 22 Feb 2011
(for lateral spreading)
> 200 mm Cracks
50 to 200 mm Cracks
10 to 50 mm Cracks
< 10 mm Cracks
Unclassified Cracks
4 Sept 2010 to 22 Feb 2011
(many properties unmapped)
> 100 mm Cracks
50 to 100 mm Cracks
< 50 mm Cracks
Section 1
Section 2
Section 3
Section 4
Section 5
Section 6
Section 7
Section 8
Section 9
Section 10
Section 11
Section 12
Section 13
Section 14
Section 15
Section 16
Section 17
Section 18
CERA
EQC
Tonkin & Taylor


Observed Crack Locations
Post 22 Feb 2011 (for lateral spreading)
> 200 mm Cracks
50 to 200 mm Cracks
10 to 50 mm Cracks
< 10 mm Cracks
Unclassified Cracks
4 Sept 2010 to 22 Feb 2011 (many properties unmapped)
> 100 mm Cracks
50 to 100 mm Cracks
< 50 mm Cracks
Section 1
Section 2
Section 3
Section 4
Section 5
Section 6
Section 7
Section 8
Section 9
Section 10
Section 11
Section 12
Section 13
Section 14
Section 15
Section 16
Section 17
Section 18
Important notice
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Appendix D – Identification of Failure Initiating Events

Failure Initiating Events	Screening Criteria	Subsequent Events for Failure Pathways Analysis	Comments
Aircraft Impact	3. The event cannot occur close enough to the levee to affect it.		No major flight paths directly over dam
Avalanche	3. The event cannot occur close enough to the levee to affect it.		No snow
Chemical Reaction	6. Not an initiator.		No indication of chemical action
Earthquake	POTENTIAL INITIATING EVENT	Earthquake causes one of the following: Longitudinal and transverse cracking. If depth of cracking extends below the water level then piping could initiate. Liquefaction. If post seismic strengh is low, leading to slope failure. If damaged zone extends below phreatic surface and filter is damaged, then piping could initiate slope failure.	
	POTENTIAL INITIATING EVENT	Internal erosion of the embankment core into the foundation if joints open during the earthquake and remain open	Drilling shows joints generally tight and fracturing is not open to the extent that piping can occur from the embankment core zone thorugh the foundation rock.
	POTENTIAL INITIATING EVENT	Slope instability owing to weak foundation layers or liquefaction results deformation. If deformation is greater than the available freeboard, then overtopping can occur or piping through the damaged embankment zone	
	POTENTIAL INITIATING EVENT	Piping through the possible shear zone in river bed	Shear zone is unlikely to be highly permeable
	POTENTIAL INITIATING EVENT	Conduit shear leading to seepage into conduit and possible sinkhole formation leading to failure	
	POTENTIAL INITIATING EVENT	Tower failure results in uncontrolled flow into the conduit causing flow from the access shaft to erode embankment and cause instability with potential for overtopping or piping	
	POTENTIAL INITIATING EVENT	Spillway gate failure	Gate failure owing to overstress
	POTENTIAL INITIATING EVENT	Ogee failure through low strength coal zones	
	5. The event is judged to have an insignificant effect on the levee.	Inlet channel slope failure	Slopes are cut into insitu weathered material and very unlikely to have significant slope failures affecting the spillway channel capacity.
	1. The event is of equal or lesser damage potential than the events for which the levee is designed. The design significantly exceeds the requirement.	Spillway channel wall failure	If the earthquake occurs a short time before the floods and the spillway cannot be operated leading to embankment overtopping
Fire	5. The event is judged to have an insignificant effect on the levee.		
Hail	5. The event is judged to have an insignificant effect on the levee.		
Human Error	4. The event is included in the definition of other event(s).	Error in spillway gate operation	Included in Hydrological / Flood events

Hydrological / Flood and Tide (operating level rising)	POTENTIAL INITIATING EVENT	Flood causes operating level to rise; leading to overtopping of dam crest. Erosion of downstream slope causing steepening and sudden collapse of the embankment. Overtopping causing downcutting of the crest.	
	POTENTIAL INITIATING EVENT	Flood causes operating level to rise; leading to piping above sand filter layer or through the filter layer that could hold a crack	
	POTENTIAL INITIATING EVENT	Excessive pressures in the sandstone foundation seam reduces the embankment stability or leads to internal erosion along the foundation core interface.	
	POTENTIAL INITIATING EVENT	Rapid drawdown cases slope failure and regressive slope failure to point of failure.	Requires a flod to occur after the rapid drawn to overtop the failed embankment
	POTENTIAL INITIATING EVENT	Piping through the possible shear zone in river bed	Shear zone is unlikely to be highly permeable
	POTENTIAL INITIATING EVENT	Internal erosion through or at the foundation at the Sandstone core interface	Drilling shows joints generally tight and fracturing is not open to the extent that piping can occur thorugh the foundation rock. The core/foundation interface is a potential path for piping.
	POTENTIAL INITIATING EVENT	Outlet tower flotation leads to damage of conduit. Flooding of conduit causes either blowout of the end plug or flow through the downstream shaft. Resulting embankment erosion leads to embankment instability and potential overtopping	significant damage of the tower would be required for the flow to erode the embankment toe
	POTENTIAL INITIATING EVENT	Flood causes operating level to rise; leading to hydrostatic flood loading exceeding shear capacity of the ogee, leading to failure and erosion/downscutting of the spillway chute	Low strength coal seams in the foundation
	POTENTIAL INITIATING EVENT	Saturation of the approach channel cut slopes decreasing the effective stress and causing a slope failure. Reduced discharge capacity results in highere reservoir levels and embankment overtopping and possible dam breach.	Very unlikely that the slope failure will occur with sufficient volume to block the spillway.
	POTENTIAL INITIATING EVENT	Piping along the conduit	Silty filter may have been provided around the conduit casing downstream from the core. Cutoff collars may not be adequate. Piping along the conduit could occur.
	POTENTIAL INITIATING EVENT	Side walls overtop leading to backfill erosion and wall failure owing to turbulent flow and excessive internal pressure from flowing water. Wall failure leads to back cutting up the chute and potential failure of the ogee structure. More significant erosion could result in the embankment being affected but this is very unlikely.	CFD modelling shows walls overtop with PMF flood. Resulting risk may be low
	POTENTIAL INITIATING EVENT	Excessive uplift below spillway chute owing to hydraulic jump forming in the channel slope. Leads to excessive uplift and failure of anchors leading to erosion of the chute and back cutting in to the reservoir if the flood is of long enough duration	CFD modelling to evaluate location of hydraulic jump and pressures in the chute.

	POTENTIAL INITIATING EVENT	Erosion of the chute toe area during large and extreme floods	CFD modelling of the PMF shows that there are high velocities downsteam of the end sill greater than 6m/s and the rip rap protection may be inadequate.
	POTENTIAL INITIATING EVENT	Spillway flow causing embankment toe erosion	Spillway discharges downstream from the embankment. TWL may affect the embankment stability.
Ice	6. Not an initiator.		No ice at this location
Intrinsic Deficiencies	4. The event is included in the definition of other event(s).	Inadequate embankment filters.	
Lightning	5. The event is judged to have an insignificant effect on the levee.		
Meteor Strike	2. The event has a significantly lower mean frequency of occurrence than other events with similar uncertainties and could not result in worse consequences than those events.		
Pore Pressures (Levee Wall)	4. The event is included in the definition of other event(s).	Build up through cracks or poor zones	Slope instability - overtopping or piping
Pore Pressures (Foundations)	4. The event is included in the definition of other event(s).	Could exacerbate piping	
Reservoir Level Fluctuations	4. The event is included in the definition of other event(s).	Could exacerbate piping	Piping through the embankment if reservoir fluctuates significantly causing increased seepage gradient
Reservoir Rim Slope Failure	2. The event has a significantly lower mean frequency of occurrence than other events with similar uncertainties and could not result in worse consequences than those events.		Landslide generated wave less likely than hydrologic flood and covered by hydrologic flood load
Temperature	6. Not an initiator.		
Terrorism / Sabotage	2. The event has a significantly lower mean frequency of occurrence than other events with similar uncertainties and could not result in worse consequences than those events.		
Toxic Gas	6. Not an initiator.		
Transportation Accident	3. The event cannot occur close enough to the dam to affect it.		No roads near dam
Vandalism	2. The event has a significantly lower mean frequency of occurrence than other events with similar uncertainties and could not result in worse consequences than those events.	Unauthorised release of water; no impact on dam wall	Business risk
Volcanic Activity	3. The event cannot occur close enough to the levee to affect it.		None in the area
Wind	4. The event is included in the definition of other event(s).	Erosion of the U/S embankment crest during floods	

Appendix E – Failure Modes Effects Analysis

Sub-system	ID No.	Components	ID No.	Hazard	ID No.	Failure Mode No.	Initiator	Consequence	Leading to	Leading to	Leading to	Leading to	Ultimate outcome	Rejection and Reason
Section 1	1	Embankment	1	Earthquake	1	1.1.1.1	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	
						1.1.1.2	~~Slope failure through weak foundation layers~~	~~Settlement of the embankment~~	~~Overtopping~~	~~Collapse of embankent~~	-	-	~~Breach~~	Combined with 1 above
						1.1.1.3	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	
						1.1.1.4	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	
						1.1.1.5	Failure of sandbags	Loss of freeboard	Overtopping if tidal level above crest				Breach	Only applies to Types 6, 7, 8
						1.1.1.6	~~Liquefaction~~	~~Slope failure through weak foundation layers~~	~~Transverse cracking of the wall~~	~~Piping initiation~~	~~Continuation (No filter)~~	~~Progression with no intervention~~	~~Breach~~	Included in settlement above
						1.1.1.7	Differential movement around pipes	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	Only applies to generic services FM
						~~1.1.1.8~~	~~Differential movement in foundation~~	~~Transverse cracking of the wall~~	~~Piping initiation~~	~~Continuation (No filter)~~	~~Progression with no intervention~~	-	Breach	Not likely based on current data
				Hydrological / Flood	2	1.1.2.1	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	
						~~1.1.2.2~~	~~Settlement~~	~~Loss of freeboard~~	~~Overtopping with high tide~~	~~Downcutting of crest or downstream slope~~	-	-	Breach	Combined with 1 above

						~~1.1.2.3~~	~~Slope instability with increasing embankment pore pressure or pressure rise in foundation~~	~~Cracking of the core leads to seepage~~	~~Piping initiation~~	~~Continuation (No filter)~~	~~Progression with no intervention~~	-	Breach	Unlikely as granular fill
						1.1.2.4	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	
						1.1.2.5	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	
						~~1.1.2.6~~	~~Transverse cracking due to differential settlements in the foundation alluvial layers~~	~~Pipe initiation through the embankment.~~	~~Continuation (No filter)~~	~~Progression with no intervention~~	-	-	Breach	Not likely based on current data
						~~1.1.2.7~~	~~Cracking in the crest due to desiccation by drying~~	~~Pipe initiation in the upper part of the embankment~~	~~Continuation (No filter)~~	~~Progression with no intervention~~	-	-	Breach	Unlikely as granular fill
						~~1.1.2.8~~	~~Poorly compacted layers~~	~~Piping initiates through poorly compacted layers.~~	~~Continuation (No filter)~~	~~Progression with no intervention~~	-	-	Breach	Unlikely as 4 years of service has not higlighted seepage
						1.1.2.9	Sandbag deteriorates	Overtopping during extreme floods					Breach	Only applies to Types 6, 7, 8
						1.1.2.10	Tree roots rot	Open pipes to upstream	Pipe initiation through the embankment.	Continuation (No filter)	Progression with no intervention		Breach	
						1.1.2.11	Tree falls over	Removal of material from wall	Loss of freeboard	Overtopping			Breach	

Appendix F - Goring (2015) Bridge Street Tidal Data

Conditional Formatting Key	
Tidal Level (RL CCC Datum)	**Cell Format**
<9.65	XXXX
9.65 to 9.85	XXXX
9.85 to 9.95	XXXX
>9.95	XXXX

	Tide Water Level (RL CCC datum)								
	Tide (AEP)								
Time (hours)	**Mean Tide**	**1**	**2**	**5**	**10**	**20**	**50**	**100**	**200**
-114.00	9.609	9.607	9.607	9.607	9.607	9.607	9.607	9.607	9.607
-113.75	9.705	9.698	9.698	9.698	9.698	9.698	9.698	9.698	9.698
-113.50	9.795	9.785	9.785	9.785	9.785	9.785	9.785	9.785	9.785
-113.25	9.875	9.865	9.865	9.865	9.865	9.865	9.865	9.865	9.865
-113.00	9.940	9.937	9.937	9.937	9.937	9.937	9.937	9.937	9.937
-112.75	9.987	9.996	9.996	9.996	9.996	9.996	9.996	9.996	9.996
-112.50	10.011	10.042	10.042	10.042	10.042	10.042	10.042	10.042	10.042
-112.25	10.011	10.070	10.070	10.070	10.070	10.070	10.070	10.070	10.070
-112.00	9.987	10.081	10.081	10.081	10.081	10.081	10.081	10.081	10.081
-111.75	9.943	10.072	10.072	10.072	10.072	10.072	10.072	10.072	10.072
-111.50	9.883	10.044	10.044	10.044	10.044	10.044	10.044	10.044	10.044
-111.25	9.814	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000
-111.00	9.743	9.941	9.941	9.941	9.941	9.941	9.941	9.941	9.941
-110.75	9.673	9.874	9.874	9.874	9.874	9.874	9.874	9.874	9.874
-110.50	9.608	9.800	9.800	9.800	9.800	9.800	9.800	9.800	9.800
-110.25	9.549	9.725	9.725	9.725	9.725	9.725	9.725	9.725	9.725
-110.00	9.493	9.651	9.651	9.651	9.651	9.651	9.651	9.651	9.651
-109.75	9.440	9.578	9.578	9.578	9.578	9.578	9.578	9.578	9.578
-102.00	9.574	9.467	9.467	9.467	9.467	9.467	9.467	9.467	9.467
-101.75	9.679	9.569	9.569	9.569	9.569	9.569	9.569	9.569	9.569
-101.50	9.782	9.670	9.670	9.670	9.670	9.670	9.670	9.670	9.670
-101.25	9.881	9.767	9.767	9.767	9.767	9.767	9.767	9.767	9.767
-101.00	9.972	9.858	9.858	9.858	9.858	9.858	9.858	9.858	9.858
-100.75	10.052	9.941	9.941	9.941	9.941	9.941	9.941	9.941	9.941
-100.50	10.116	10.012	10.012	10.012	10.012	10.012	10.012	10.012	10.012
-100.25	10.161	10.069	10.069	10.069	10.069	10.069	10.069	10.069	10.069
-100.00	10.182	10.111	10.111	10.111	10.111	10.111	10.111	10.111	10.111
-99.75	10.178	10.136	10.136	10.136	10.136	10.136	10.136	10.136	10.136
-99.50	10.149	10.142	10.142	10.142	10.142	10.142	10.142	10.142	10.142
-99.25	10.100	10.128	10.128	10.128	10.128	10.128	10.128	10.128	10.128
-99.00	10.034	10.095	10.095	10.095	10.095	10.095	10.095	10.095	10.095
-98.75	9.959	10.046	10.046	10.046	10.046	10.046	10.046	10.046	10.046
-98.50	9.881	9.984	9.984	9.984	9.984	9.984	9.984	9.984	9.984
-98.25	9.806	9.912	9.912	9.912	9.912	9.912	9.912	9.912	9.912
-98.00	9.736	9.835	9.835	9.835	9.835	9.835	9.835	9.835	9.835
-97.75	9.672	9.757	9.757	9.757	9.757	9.757	9.757	9.757	9.757
-97.50	9.614	9.679	9.679	9.679	9.679	9.679	9.679	9.679	9.679
-97.25	9.559	9.602	9.602	9.602	9.602	9.602	9.602	9.602	9.602
-89.00	9.616	9.640	9.640	9.640	9.640	9.640	9.640	9.640	9.640
-88.75	9.709	9.737	9.737	9.737	9.737	9.737	9.737	9.737	9.737
-88.50	9.795	9.830	9.830	9.830	9.830	9.830	9.830	9.830	9.830
-88.25	9.870	9.914	9.914	9.914	9.914	9.914	9.914	9.914	9.914
-88.00	9.930	9.986	9.986	9.986	9.986	9.986	9.986	9.986	9.986
-87.75	9.972	10.043	10.043	10.043	10.043	10.043	10.043	10.043	10.043
-87.50	9.992	10.083	10.083	10.083	10.083	10.083	10.083	10.083	10.083
-87.25	9.990	10.102	10.102	10.102	10.102	10.102	10.102	10.102	10.102
-87.00	9.966	10.100	10.100	10.100	10.100	10.100	10.100	10.100	10.100
-86.75	9.924	10.077	10.077	10.077	10.077	10.077	10.077	10.077	10.077
-86.50	9.869	10.035	10.035	10.035	10.035	10.035	10.035	10.035	10.035
-86.25	9.806	9.977	9.977	9.977	9.977	9.977	9.977	9.977	9.977
-86.00	9.742	9.907	9.907	9.907	9.907	9.907	9.907	9.907	9.907
-85.75	9.678	9.832	9.832	9.832	9.832	9.832	9.832	9.832	9.832
-85.50	9.618	9.754	9.754	9.754	9.754	9.754	9.754	9.754	9.754
-85.25	9.561	9.677	9.677	9.677	9.677	9.677	9.677	9.677	9.677
-85.00	9.505	9.602	9.602	9.603	9.603	9.603	9.603	9.603	9.603
-77.00	9.562	9.515	9.515	9.515	9.515	9.515	9.515	9.515	9.515
-76.75	9.666	9.621	9.621	9.621	9.621	9.621	9.621	9.621	9.621
-76.50	9.768	9.726	9.726	9.726	9.726	9.726	9.726	9.726	9.726
-76.25	9.865	9.828	9.828	9.828	9.828	9.828	9.828	9.828	9.828
-76.00	9.953	9.923	9.923	9.923	9.923	9.923	9.923	9.923	9.923
-75.75	10.028	10.010	10.010	10.010	10.010	10.010	10.010	10.010	10.010
-75.50	10.087	10.085	10.085	10.085	10.085	10.085	10.085	10.085	10.085
-75.25	10.124	10.145	10.145	10.145	10.145	10.145	10.145	10.145	10.145
-75.00	10.138	10.186	10.186	10.186	10.186	10.186	10.186	10.186	10.186

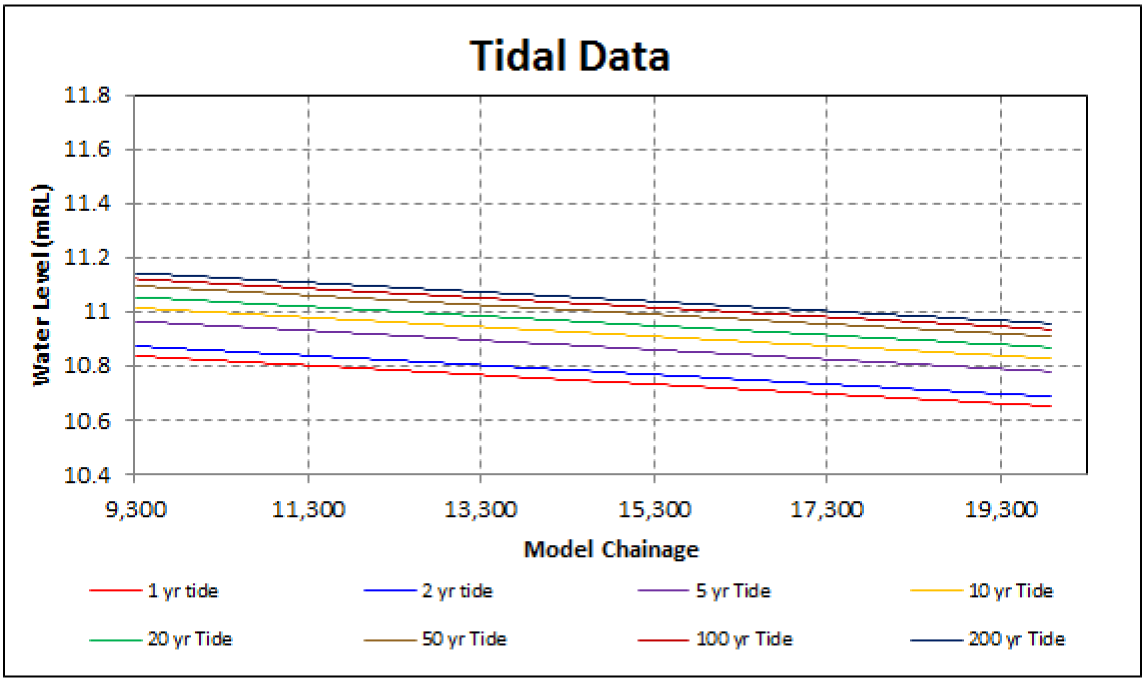
Time (hours)	Tide Water Level (RL CCC datum)								
	Tide (AEP)								
	Mean Tide	1	2	5	10	20	50	100	200
-74.75	10.128	10.206	10.206	10.206	10.206	10.206	10.206	10.206	10.206
-74.50	10.096	10.203	10.203	10.203	10.203	10.203	10.203	10.203	10.203
-74.25	10.046	10.177	10.177	10.177	10.177	10.177	10.177	10.177	10.177
-74.00	9.984	10.129	10.129	10.129	10.129	10.129	10.129	10.129	10.129
-73.75	9.917	10.064	10.064	10.064	10.064	10.064	10.064	10.064	10.064
-73.50	9.850	9.986	9.986	9.987	9.987	9.987	9.987	9.987	9.987
-73.25	9.787	9.902	9.902	9.902	9.902	9.902	9.902	9.902	9.902
-73.00	9.729	9.816	9.816	9.816	9.817	9.817	9.817	9.817	9.817
-72.75	9.675	9.732	9.732	9.732	9.732	9.732	9.732	9.732	9.732
-72.50	9.623	9.652	9.652	9.652	9.652	9.652	9.652	9.652	9.652
-72.25	9.572	9.575	9.575	9.575	9.575	9.575	9.575	9.575	9.575
-64.25	9.521	9.572	9.572	9.572	9.572	9.572	9.572	9.572	9.572
-64.00	9.616	9.677	9.677	9.677	9.677	9.677	9.677	9.677	9.677
-63.75	9.707	9.777	9.777	9.777	9.777	9.777	9.777	9.777	9.777
-63.50	9.791	9.870	9.870	9.870	9.870	9.870	9.870	9.870	9.870
-63.25	9.865	9.952	9.953	9.953	9.953	9.953	9.953	9.953	9.953
-63.00	9.925	10.021	10.021	10.022	10.022	10.022	10.022	10.022	10.022
-62.75	9.966	10.074	10.074	10.074	10.074	10.074	10.074	10.074	10.074
-62.50	9.986	10.106	10.106	10.106	10.107	10.107	10.107	10.107	10.107
-62.25	9.983	10.117	10.117	10.117	10.118	10.118	10.118	10.118	10.118
-62.00	9.960	10.106	10.106	10.106	10.106	10.106	10.106	10.106	10.106
-61.75	9.919	10.072	10.072	10.072	10.072	10.072	10.073	10.073	10.073
-61.50	9.867	10.019	10.019	10.020	10.020	10.020	10.020	10.020	10.020
-61.25	9.808	9.952	9.952	9.952	9.952	9.952	9.952	9.952	9.952
-61.00	9.747	9.874	9.874	9.874	9.874	9.875	9.875	9.875	9.875
-60.75	9.687	9.792	9.792	9.793	9.793	9.793	9.793	9.793	9.793
-60.50	9.630	9.710	9.710	9.711	9.711	9.711	9.711	9.711	9.711
-60.25	9.576	9.631	9.631	9.631	9.631	9.631	9.631	9.632	9.632
-52.00	9.552	9.558	9.558	9.559	9.559	9.560	9.560	9.560	9.560
-51.75	9.653	9.672	9.672	9.673	9.673	9.674	9.674	9.674	9.674
-51.50	9.750	9.785	9.786	9.786	9.786	9.787	9.787	9.787	9.787
-51.25	9.841	9.895	9.895	9.896	9.896	9.896	9.896	9.897	9.897
-51.00	9.923	9.997	9.997	9.998	9.998	9.999	9.999	9.999	9.999
-50.75	9.991	10.088	10.089	10.089	10.090	10.090	10.090	10.090	10.091
-50.50	10.043	10.164	10.165	10.165	10.166	10.166	10.166	10.166	10.167
-50.25	10.075	10.221	10.221	10.222	10.222	10.223	10.223	10.223	10.223
-50.00	10.085	10.255	10.255	10.256	10.256	10.257	10.257	10.257	10.257
-49.75	10.075	10.263	10.263	10.264	10.265	10.265	10.265	10.265	10.266
-49.50	10.047	10.245	10.245	10.246	10.247	10.247	10.247	10.247	10.248
-49.25	10.004	10.203	10.203	10.204	10.204	10.204	10.205	10.205	10.205
-49.00	9.952	10.139	10.139	10.140	10.141	10.141	10.141	10.142	10.142
-48.75	9.896	10.061	10.061	10.062	10.062	10.063	10.063	10.063	10.063
-48.50	9.840	9.974	9.974	9.975	9.975	9.976	9.976	9.976	9.977
-48.25	9.786	9.884	9.884	9.885	9.886	9.886	9.887	9.887	9.887
-48.00	9.733	9.797	9.797	9.798	9.798	9.799	9.799	9.799	9.800
-47.75	9.682	9.713	9.714	9.715	9.715	9.716	9.716	9.716	9.716
-47.50	9.631	9.635	9.635	9.636	9.637	9.637	9.638	9.638	9.638
-39.25	9.529	9.605	9.606	9.609	9.610	9.611	9.612	9.613	9.614
-39.00	9.625	9.710	9.711	9.714	9.715	9.717	9.718	9.719	9.719
-38.75	9.717	9.811	9.812	9.815	9.816	9.818	9.819	9.820	9.820
-38.50	9.802	9.905	9.906	9.909	9.910	9.912	9.913	9.914	9.915
-38.25	9.875	9.988	9.989	9.992	9.994	9.995	9.996	9.997	9.998
-38.00	9.932	10.057	10.058	10.061	10.063	10.064	10.065	10.066	10.067
-37.75	9.969	10.107	10.108	10.111	10.113	10.115	10.116	10.117	10.118
-37.50	9.985	10.135	10.137	10.140	10.142	10.143	10.145	10.146	10.147
-37.25	9.979	10.140	10.141	10.144	10.146	10.148	10.149	10.150	10.151
-37.00	9.954	10.119	10.120	10.123	10.125	10.127	10.128	10.129	10.130
-36.75	9.914	10.074	10.075	10.079	10.081	10.083	10.084	10.085	10.086
-36.50	9.865	10.010	10.011	10.015	10.017	10.019	10.021	10.022	10.022
-36.25	9.812	9.932	9.934	9.937	9.940	9.941	9.943	9.944	9.945
-36.00	9.759	9.847	9.848	9.852	9.855	9.856	9.858	9.859	9.860
-35.75	9.706	9.760	9.762	9.766	9.768	9.770	9.772	9.773	9.774
-35.50	9.656	9.676	9.678	9.682	9.684	9.686	9.688	9.689	9.690
-35.25	9.606	9.597	9.599	9.604	9.606	9.608	9.610	9.611	9.612
-27.25	9.443	9.529	9.533	9.544	9.551	9.555	9.561	9.564	9.567
-27.00	9.538	9.650	9.655	9.667	9.673	9.678	9.683	9.687	9.689
-26.75	9.633	9.773	9.777	9.789	9.796	9.801	9.807	9.810	9.813
-26.50	9.724	9.892	9.897	9.910	9.916	9.922	9.927	9.931	9.934
-26.25	9.810	10.006	10.011	10.024	10.031	10.036	10.042	10.046	10.049
-26.00	9.887	10.110	10.115	10.128	10.135	10.141	10.147	10.151	10.154
-25.75	9.952	10.200	10.205	10.219	10.226	10.232	10.238	10.242	10.245
-25.50	10.002	10.272	10.277	10.291	10.299	10.305	10.311	10.315	10.319
-25.25	10.034	10.322	10.327	10.342	10.349	10.355	10.362	10.366	10.369
-25.00	10.047	10.346	10.351	10.366	10.374	10.381	10.387	10.392	10.395
-24.75	10.040	10.343	10.349	10.364	10.372	10.379	10.386	10.390	10.394

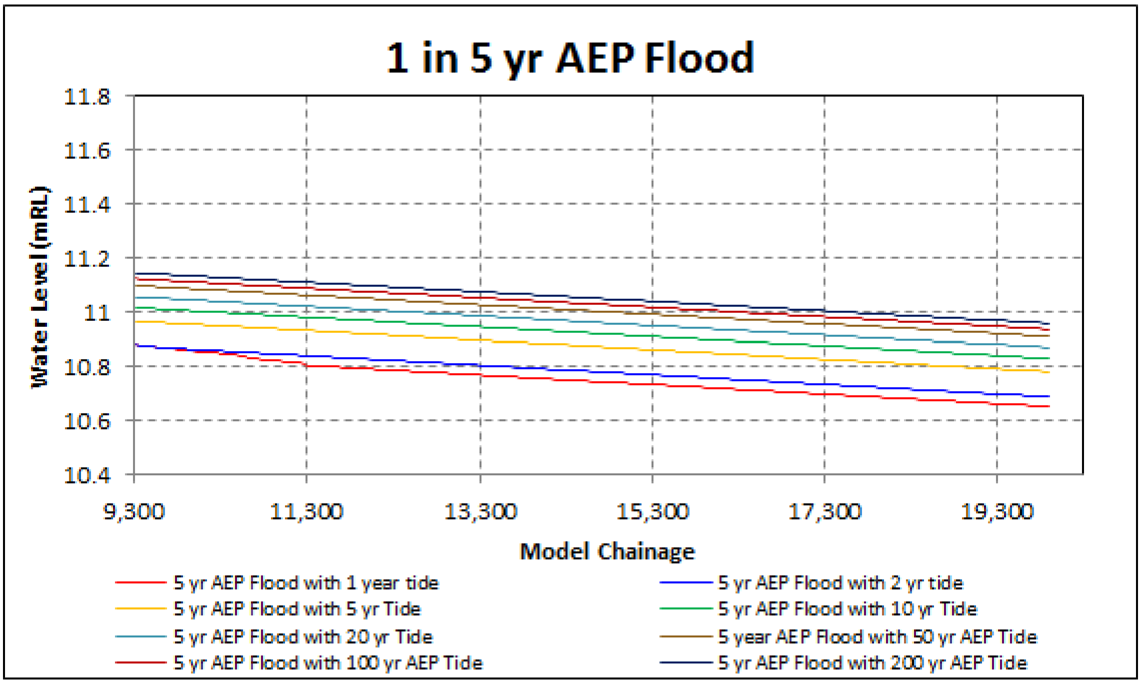
	Tide Water Level (RL CCC datum)								
	Tide (AEP)								
Time (hours)	**Mean Tide**	**1**	**2**	**5**	**10**	**20**	**50**	**100**	**200**
-24.50	10.015	10.314	10.320	10.336	10.344	10.351	10.358	10.362	10.366
-24.25	9.978	10.261	10.267	10.283	10.292	10.299	10.306	10.311	10.314
-24.00	9.933	10.189	10.196	10.212	10.221	10.228	10.236	10.241	10.245
-23.75	9.883	10.106	10.113	10.130	10.139	10.146	10.154	10.159	10.163
-23.50	9.831	10.017	10.024	10.042	10.051	10.058	10.066	10.071	10.076
-23.25	9.780	9.928	9.935	9.953	9.963	9.971	9.979	9.984	9.988
-23.00	9.729	9.842	9.849	9.868	9.878	9.886	9.894	9.900	9.904
-22.75	9.679	9.761	9.769	9.788	9.798	9.806	9.815	9.820	9.825
-22.50	9.628	9.684	9.692	9.712	9.722	9.730	9.739	9.745	9.750
-22.25	9.577	9.610	9.618	9.639	9.649	9.658	9.667	9.673	9.678
-22.00	9.527	9.539	9.547	9.568	9.579	9.588	9.597	9.603	9.608
-15.00	9.266	9.446	9.462	9.505	9.527	9.546	9.565	9.577	9.587
-14.75	9.360	9.554	9.571	9.615	9.638	9.656	9.676	9.688	9.699
-14.50	9.457	9.666	9.683	9.728	9.751	9.770	9.791	9.803	9.814
-14.25	9.555	9.779	9.797	9.842	9.866	9.886	9.906	9.919	9.930
-14.00	9.650	9.891	9.909	9.956	9.980	10.000	10.021	10.034	10.046
-13.75	9.739	9.999	10.018	10.065	10.091	10.111	10.132	10.146	10.157
-13.50	9.820	10.100	10.118	10.167	10.193	10.214	10.236	10.249	10.261
-13.25	9.887	10.188	10.207	10.257	10.283	10.304	10.327	10.341	10.352
-13.00	9.938	10.258	10.278	10.329	10.356	10.377	10.400	10.415	10.427
-12.75	9.970	10.307	10.327	10.379	10.407	10.429	10.452	10.467	10.479
-12.50	9.982	10.331	10.351	10.404	10.432	10.455	10.479	10.494	10.506
-12.25	9.976	10.327	10.348	10.402	10.430	10.453	10.478	10.493	10.506
-12.00	9.953	10.297	10.318	10.373	10.402	10.426	10.451	10.466	10.479
-11.75	9.919	10.243	10.265	10.321	10.351	10.375	10.400	10.416	10.429
-11.50	9.877	10.173	10.195	10.252	10.282	10.307	10.333	10.349	10.362
-11.25	9.832	10.092	10.115	10.173	10.204	10.229	10.255	10.272	10.286
-11.00	9.786	10.009	10.032	10.091	10.123	10.148	10.175	10.192	10.206
-10.75	9.739	9.928	9.951	10.012	10.044	10.070	10.097	10.114	10.129
-10.50	9.691	9.853	9.877	9.938	9.971	9.997	10.025	10.043	10.057
-10.25	9.641	9.784	9.809	9.872	9.905	9.932	9.960	9.978	9.993
-10.00	9.588	9.722	9.746	9.810	9.844	9.871	9.901	9.918	9.934
-9.75	9.534	9.663	9.688	9.753	9.788	9.815	9.845	9.863	9.878
-9.50	9.479	9.606	9.632	9.698	9.733	9.761	9.791	9.810	9.826
-9.25	9.423	9.551	9.577	9.645	9.680	9.709	9.739	9.758	9.774
-9.00	9.368	9.498	9.524	9.593	9.629	9.658	9.689	9.708	9.724
-8.75	9.313	9.446	9.473	9.543	9.580	9.609	9.641	9.660	9.677
-8.50	9.261	9.399	9.426	9.497	9.534	9.564	9.596	9.616	9.632
-3.50	9.022	9.309	9.343	9.432	9.478	9.516	9.556	9.580	9.601
-3.25	9.092	9.408	9.442	9.531	9.578	9.616	9.656	9.681	9.702
-3.00	9.169	9.516	9.550	9.639	9.687	9.725	9.765	9.790	9.811
-2.75	9.253	9.630	9.665	9.755	9.802	9.840	9.881	9.906	9.927
-2.50	9.342	9.749	9.784	9.875	9.922	9.961	10.002	10.027	10.048
-2.25	9.433	9.872	9.907	9.998	10.045	10.084	10.125	10.151	10.172
-2.00	9.526	9.995	10.030	10.122	10.170	10.208	10.250	10.275	10.297
-1.75	9.618	10.118	10.153	10.244	10.293	10.331	10.373	10.398	10.420
-1.50	9.708	10.236	10.271	10.363	10.411	10.450	10.492	10.518	10.539
-1.25	9.793	10.347	10.382	10.474	10.523	10.562	10.604	10.629	10.651
-1.00	9.869	10.447	10.483	10.575	10.623	10.663	10.704	10.730	10.752
-0.75	9.933	10.532	10.567	10.660	10.708	10.748	10.790	10.815	10.837
-0.50	9.982	10.597	10.632	10.725	10.774	10.813	10.855	10.881	10.903
-0.25	10.011	10.638	10.674	10.766	10.815	10.854	10.896	10.922	10.944
0.00	10.021	10.652	10.688	10.780	10.829	10.869	10.910	10.936	10.958
0.25	10.012	10.638	10.674	10.766	10.815	10.854	10.896	10.922	10.944
0.50	9.987	10.597	10.632	10.725	10.774	10.813	10.855	10.881	10.903
0.75	9.951	10.533	10.568	10.661	10.709	10.749	10.791	10.816	10.838
1.00	9.908	10.452	10.487	10.579	10.628	10.667	10.709	10.735	10.756
1.25	9.861	10.360	10.396	10.488	10.536	10.575	10.617	10.643	10.665
1.50	9.814	10.266	10.301	10.393	10.441	10.480	10.522	10.547	10.569
1.75	9.766	10.172	10.207	10.299	10.347	10.386	10.427	10.453	10.475
2.00	9.719	10.083	10.118	10.209	10.258	10.296	10.338	10.363	10.384
2.25	9.671	9.999	10.034	10.125	10.173	10.212	10.253	10.278	10.299
2.50	9.623	9.920	9.955	10.045	10.093	10.131	10.172	10.198	10.219
2.75	9.574	9.845	9.879	9.969	10.017	10.055	10.096	10.121	10.142
3.00	9.524	9.772	9.807	9.896	9.943	9.981	10.022	10.047	10.068
3.25	9.473	9.703	9.737	9.826	9.873	9.910	9.951	9.975	9.996
3.50	9.422	9.637	9.671	9.759	9.806	9.843	9.883	9.908	9.929
3.75	9.369	9.575	9.609	9.697	9.743	9.780	9.820	9.845	9.865
4.00	9.316	9.519	9.553	9.640	9.686	9.723	9.762	9.787	9.807
4.25	9.263	9.469	9.502	9.588	9.634	9.671	9.710	9.734	9.754
4.50	9.211	9.424	9.457	9.542	9.587	9.624	9.662	9.686	9.707
4.75	9.160	9.383	9.416	9.501	9.545	9.582	9.620	9.644	9.664
5.00	9.112	9.347	9.379	9.463	9.508	9.544	9.582	9.605	9.625
9.75	9.213	9.434	9.459	9.524	9.558	9.586	9.616	9.634	9.649
10.00	9.304	9.532	9.557	9.621	9.655	9.682	9.711	9.729	9.744
10.25	9.399	9.636	9.661	9.724	9.757	9.784	9.812	9.830	9.845

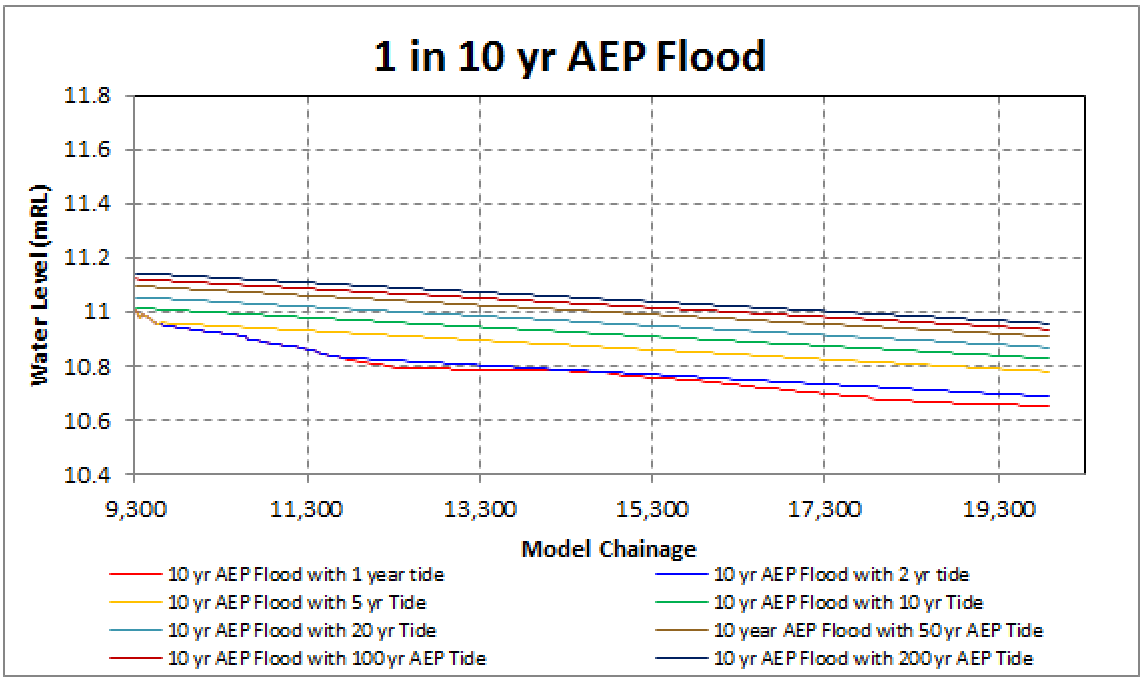
	Tide Water Level (RL CCC datum)								
	Tide (AEP)								
Time (hours)	Mean Tide	1	2	5	10	20	50	100	200
10.50	9.494	9.744	9.768	9.830	9.862	9.889	9.917	9.934	9.949
10.75	9.588	9.853	9.876	9.937	9.969	9.995	10.023	10.039	10.054
11.00	9.678	9.960	9.983	10.042	10.074	10.099	10.126	10.143	10.157
11.25	9.762	10.061	10.083	10.142	10.173	10.198	10.224	10.241	10.254
11.50	9.838	10.152	10.174	10.231	10.261	10.286	10.312	10.328	10.342
11.75	9.901	10.227	10.249	10.305	10.335	10.359	10.384	10.400	10.413
12.00	9.949	10.282	10.304	10.359	10.388	10.412	10.437	10.452	10.465
12.25	9.979	10.314	10.334	10.389	10.417	10.440	10.465	10.480	10.493
12.50	9.991	10.318	10.338	10.391	10.419	10.442	10.466	10.481	10.493
12.75	9.987	10.295	10.315	10.367	10.394	10.417	10.440	10.455	10.467
13.00	9.967	10.248	10.267	10.318	10.345	10.367	10.390	10.404	10.416
13.25	9.937	10.181	10.200	10.250	10.276	10.297	10.320	10.334	10.345
13.50	9.900	10.101	10.120	10.168	10.194	10.215	10.237	10.250	10.262
13.75	9.858	10.015	10.033	10.081	10.106	10.127	10.148	10.162	10.173
14.00	9.812	9.929	9.947	9.994	10.019	10.039	10.060	10.073	10.084
14.25	9.764	9.848	9.865	9.911	9.935	9.955	9.975	9.988	9.999
14.50	9.714	9.772	9.789	9.834	9.857	9.876	9.897	9.909	9.920
14.75	9.661	9.701	9.718	9.761	9.785	9.803	9.823	9.835	9.845
15.00	9.607	9.634	9.650	9.693	9.715	9.733	9.753	9.765	9.775
15.25	9.551	9.568	9.584	9.626	9.648	9.665	9.684	9.696	9.706
15.50	9.496	9.503	9.519	9.560	9.581	9.598	9.617	9.628	9.638
22.50	9.351	9.516	9.524	9.544	9.554	9.563	9.572	9.577	9.582
22.75	9.444	9.633	9.641	9.660	9.670	9.678	9.687	9.692	9.697
23.00	9.537	9.751	9.759	9.777	9.787	9.795	9.804	9.809	9.813
23.25	9.629	9.869	9.876	9.894	9.904	9.912	9.920	9.925	9.929
23.50	9.717	9.983	9.990	10.008	10.017	10.025	10.033	10.038	10.042
23.75	9.798	10.091	10.097	10.114	10.123	10.131	10.139	10.143	10.147
24.00	9.869	10.186	10.192	10.209	10.218	10.225	10.233	10.237	10.241
24.25	9.927	10.265	10.271	10.287	10.296	10.303	10.310	10.315	10.319
24.50	9.967	10.322	10.328	10.344	10.352	10.359	10.366	10.370	10.374
24.75	9.989	10.353	10.359	10.374	10.382	10.389	10.396	10.400	10.403
25.00	9.993	10.355	10.360	10.375	10.383	10.390	10.396	10.400	10.404
25.25	9.980	10.327	10.333	10.348	10.355	10.361	10.368	10.372	10.375
25.50	9.954	10.274	10.279	10.294	10.301	10.307	10.313	10.317	10.321
25.75	9.920	10.200	10.205	10.219	10.226	10.232	10.238	10.242	10.245
26.00	9.881	10.112	10.117	10.131	10.138	10.143	10.149	10.153	10.156
26.25	9.839	10.018	10.023	10.036	10.043	10.049	10.054	10.058	10.061
26.50	9.796	9.925	9.930	9.942	9.949	9.954	9.960	9.963	9.966
26.75	9.751	9.836	9.840	9.852	9.859	9.864	9.870	9.873	9.876
27.00	9.705	9.753	9.757	9.769	9.775	9.780	9.786	9.789	9.792
27.25	9.656	9.676	9.680	9.692	9.698	9.703	9.708	9.711	9.714
27.50	9.606	9.604	9.608	9.619	9.625	9.630	9.635	9.638	9.641
35.50	9.535	9.544	9.546	9.550	9.552	9.554	9.556	9.557	9.558
35.75	9.626	9.655	9.657	9.661	9.663	9.665	9.667	9.668	9.669
36.00	9.715	9.763	9.765	9.769	9.771	9.773	9.774	9.776	9.777
36.25	9.797	9.864	9.865	9.869	9.871	9.873	9.875	9.876	9.877
36.50	9.871	9.953	9.955	9.958	9.960	9.962	9.964	9.965	9.966
36.75	9.932	10.026	10.028	10.031	10.033	10.035	10.037	10.038	10.038
37.00	9.977	10.079	10.080	10.084	10.086	10.087	10.089	10.090	10.091
37.25	10.004	10.107	10.109	10.112	10.114	10.115	10.117	10.118	10.119
37.50	10.012	10.109	10.111	10.114	10.116	10.117	10.119	10.120	10.120
37.75	10.004	10.086	10.087	10.091	10.092	10.094	10.095	10.096	10.097
38.00	9.982	10.041	10.042	10.045	10.047	10.048	10.049	10.050	10.051
38.25	9.950	9.978	9.979	9.982	9.984	9.985	9.987	9.987	9.988
38.50	9.911	9.905	9.906	9.909	9.911	9.912	9.913	9.914	9.915
38.75	9.868	9.828	9.829	9.832	9.833	9.834	9.836	9.836	9.837
39.00	9.822	9.751	9.752	9.755	9.756	9.757	9.758	9.759	9.760
39.25	9.774	9.677	9.678	9.681	9.682	9.683	9.685	9.685	9.686
39.50	9.723	9.608	9.609	9.611	9.613	9.614	9.615	9.616	9.616
39.75	9.672	9.542	9.543	9.545	9.546	9.548	9.549	9.549	9.550
40.00	9.618	9.478	9.479	9.481	9.482	9.484	9.485	9.485	9.486
47.75	9.481	9.582	9.583	9.584	9.584	9.584	9.585	9.585	9.585
48.00	9.571	9.702	9.703	9.704	9.704	9.705	9.705	9.705	9.705
48.25	9.657	9.822	9.822	9.823	9.823	9.824	9.824	9.824	9.824
48.50	9.737	9.936	9.936	9.937	9.938	9.938	9.938	9.939	9.939
48.75	9.809	10.041	10.042	10.043	10.043	10.043	10.044	10.044	10.044
49.00	9.871	10.132	10.133	10.134	10.134	10.134	10.135	10.135	10.135
49.25	9.919	10.204	10.205	10.205	10.206	10.206	10.206	10.207	10.207
49.50	9.951	10.252	10.252	10.253	10.253	10.254	10.254	10.254	10.254
49.75	9.966	10.272	10.272	10.273	10.273	10.273	10.274	10.274	10.274
50.00	9.965	10.263	10.263	10.264	10.264	10.265	10.265	10.265	10.265
50.25	9.950	10.227	10.227	10.228	10.229	10.229	10.229	10.229	10.229
50.50	9.925	10.169	10.169	10.170	10.170	10.170	10.171	10.171	10.171
50.75	9.892	10.095	10.095	10.095	10.096	10.096	10.096	10.097	10.097
51.00	9.854	10.012	10.012	10.012	10.013	10.013	10.013	10.014	10.014
51.25	9.812	9.926	9.927	9.927	9.928	9.928	9.928	9.928	9.928

	Tide Water Level (RL CCC datum)								
	Tide (AEP)								
Time (hours)	Mean Tide	1	2	5	10	20	50	100	200
51.50	9.767	9.844	9.844	9.845	9.845	9.845	9.846	9.846	9.846
51.75	9.720	9.766	9.767	9.767	9.768	9.768	9.768	9.768	9.768
52.00	9.670	9.694	9.694	9.695	9.695	9.695	9.696	9.696	9.696
52.25	9.617	9.626	9.626	9.626	9.627	9.627	9.627	9.627	9.627
60.50	9.596	9.535	9.536	9.536	9.536	9.536	9.536	9.536	9.536
60.75	9.687	9.645	9.645	9.645	9.645	9.645	9.645	9.645	9.645
61.00	9.774	9.751	9.751	9.751	9.751	9.751	9.751	9.751	9.751
61.25	9.853	9.850	9.850	9.850	9.850	9.850	9.850	9.850	9.850
61.50	9.920	9.937	9.937	9.937	9.938	9.938	9.938	9.938	9.938
61.75	9.973	10.008	10.008	10.008	10.008	10.009	10.009	10.009	10.009
62.00	10.007	10.058	10.058	10.058	10.058	10.058	10.058	10.058	10.058
62.25	10.024	10.083	10.083	10.083	10.083	10.083	10.083	10.083	10.083
62.50	10.023	10.081	10.081	10.082	10.082	10.082	10.082	10.082	10.082
62.75	10.008	10.055	10.055	10.055	10.056	10.056	10.056	10.056	10.056
63.00	9.981	10.008	10.008	10.009	10.009	10.009	10.009	10.009	10.009
63.25	9.948	9.946	9.946	9.947	9.947	9.947	9.947	9.947	9.947
63.50	9.909	9.876	9.876	9.876	9.876	9.876	9.876	9.876	9.876
63.75	9.867	9.802	9.803	9.803	9.803	9.803	9.803	9.803	9.803
64.00	9.823	9.731	9.731	9.731	9.731	9.731	9.731	9.731	9.731
64.25	9.775	9.662	9.662	9.662	9.662	9.662	9.662	9.662	9.662
64.50	9.725	9.597	9.597	9.597	9.597	9.597	9.597	9.597	9.597
64.75	9.673	9.535	9.535	9.535	9.535	9.535	9.535	9.535	9.535
65.00	9.617	9.475	9.475	9.475	9.475	9.475	9.475	9.475	9.475

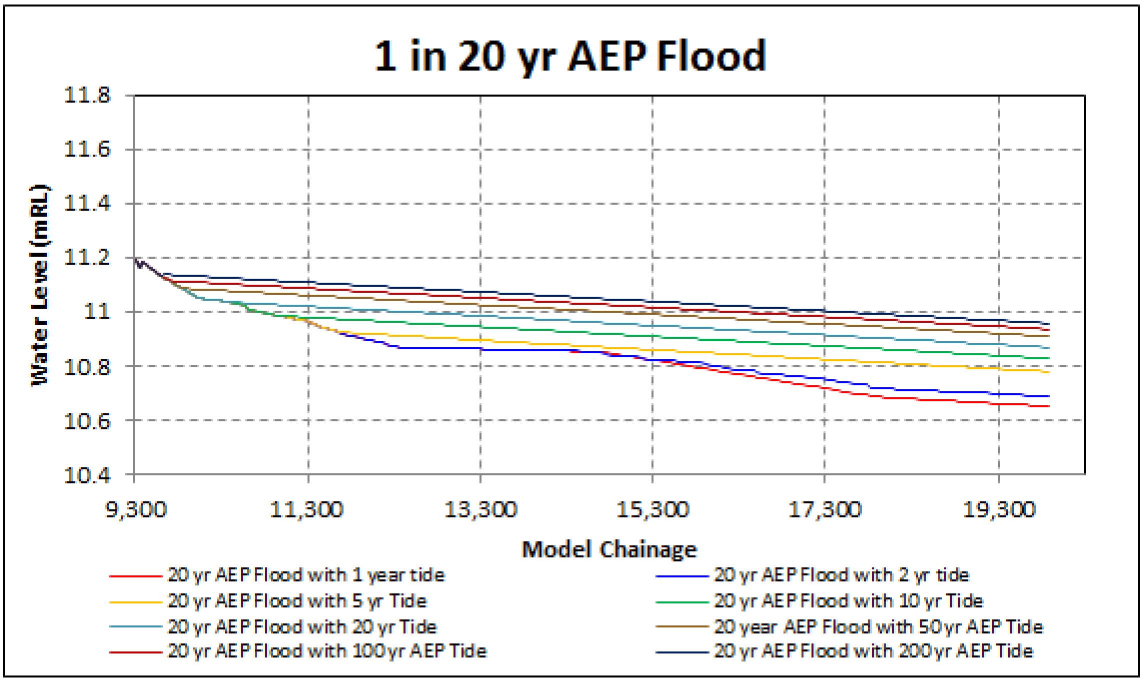
Appendix G – Combined Flood and Tidal Level Curves



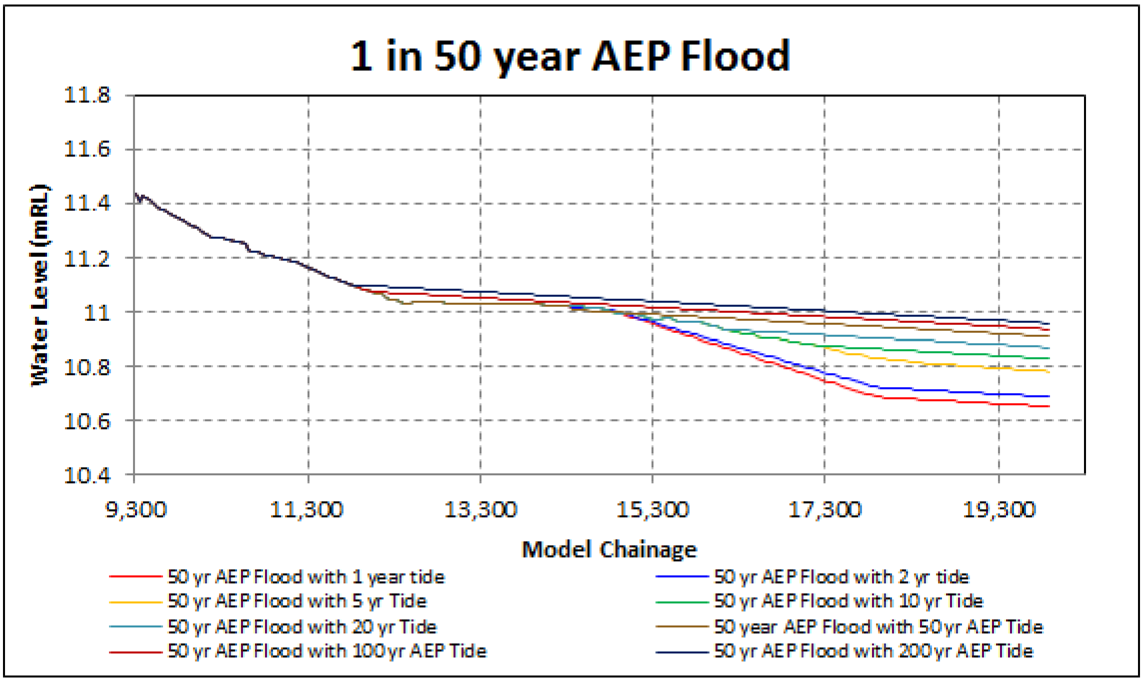


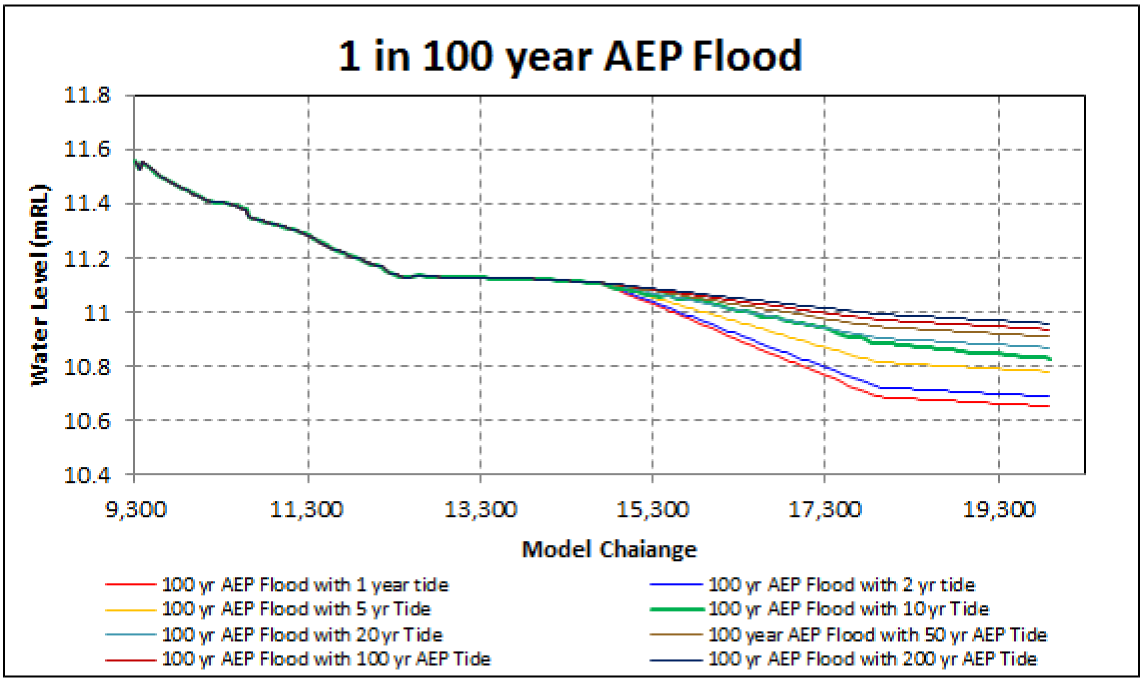


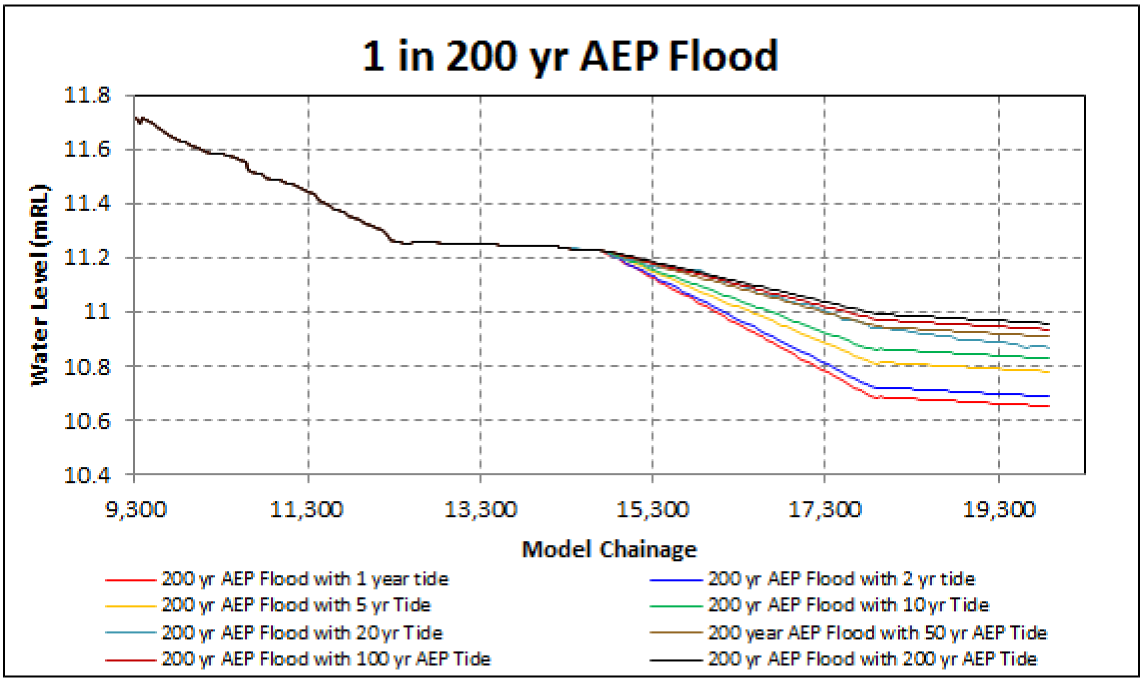
1 in 10 yr AEP Flood
Water Level (mRL)
11.8
11.6
11.4
11.2
11
10.8
10.6
10.4
9,300
11,300
13,300
15,300
17,300
19,300
Model Chainage
10 yr AEP Flood with 1 year tide
10 yr AEP Flood with 2 yr tide
10 yr AEP Flood with 5 yr Tide
10 yr AEP Flood with 10 yr Tide
10 yr AEP Flood with 20 yr Tide
10 year AEP Flood with 50yr AEP Tide
10 yr AEP Flood with 100yr AEP Tide
10 yr AEP Flood with 200yr AEP Tide



1 in 20 yr AEP Flood
Water Level (mRL)
11.8
11.6
11.4
11.2
11
10.8
10.6
10.4
9,300
11,300
13,300
15,300
17,300
19,300
Model Chainage
20 yr AEP Flood with 1 year tide
20 yr AEP Flood with 2 yr tide
20 yr AEP Flood with 5 yr Tide
20 yr AEP Flood with 10 yr Tide
20 yr AEP Flood with 20 yr Tide
20 year AEP Flood with 50yr AEP Tide
20 yr AEP Flood with 100yr AEP Tide
20 yr AEP Flood with 200yr AEP Tide


1 in 50 year AEP Flood
Water Level (mRL)
11.8
11.6
11.4
11.2
11
10.8
10.6
10.4
9,300
11,300
13,300
15,300
17,300
19,300
Model Chainage
50 yr AEP Flood with 1 year tide
50 yr AEP Flood with 2 yr tide
50 yr AEP Flood with 5 yr Tide
50 yr AEP Flood with 10 yr Tide
50 yr AEP Flood with 20 yr Tide
50 year AEP Flood with 50yr AEP Tide
50 yr AEP Flood with 100yr AEP Tide
50 yr AEP Flood with 200yr AEP Tide


1 in 100 year AEP Flood
Water Level (mRL)
11.8
11.6
11.4
11.2
11
10.8
10.6
10.4
9,300
11,300
13,300
15,300
17,300
19,300
Model Chainage
100 yr AEP Flood with 1 year tide
100 yr AEP Flood with 2 yr tide
100 yr AEP Flood with 5 yr Tide
100 yr AEP Flood with 10yr Tide
100 yr AEP Flood with 20yr Tide
100 year AEP Flood with 50 yr AEP Tide
100 yr AEP Flood with 100 yr AEP Tide
100 yr AEP Flood with 200 yr AEP Tide


1 in 200 yr AEP Flood
Water Level (mRL)
11.8
11.6
11.4
11.2
11
10.8
10.6
10.4
9,300
11,300
13,300
15,300
17,300
19,300
Model Chainage
200 yr AEP Flood with 1 year tide
200 yr AEP Flood with 2 yr tide
200 yr AEP Flood with 5 yr Tide
200 yr AEP Flood with 10yr Tide
200 yr AEP Flood with 20yr Tide
200 year AEP Flood with 50 yr AEP Tide
200 yr AEP Flood with 100 yr AEP Tide
200 yr AEP Flood with 200 yr AEP Tide

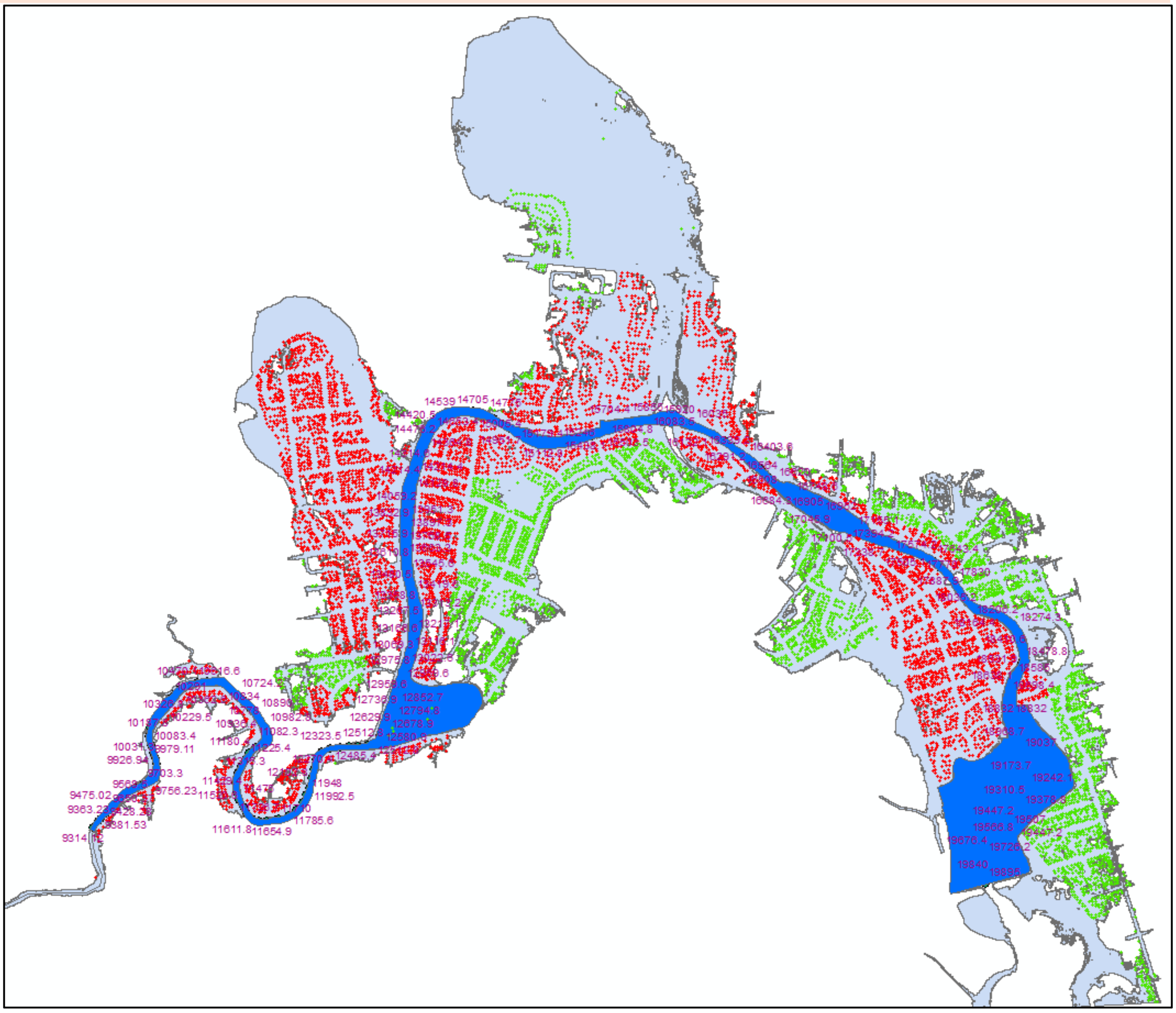
Appendix H – Population at Risk data

Appendix H 1 - Bath Tub Counts

Building count for constant elevation of 11.2m

11.2m Green Zone only					
Chainage	**0-0.1**	**0.1-03**	**0.3-0.5**	**0.5+**	**Total**
Left Bank					
14700-18900 and 19300-19900	521	547	407	439	**1914**
9000-14700	92	85	67	10	**254**
Right Bank					
9000-19900	365	433	546	501	**1845**
Grand Total	**978**	**1065**	**1020**	**950**	**4013**

11.2m Red Zone only					
Chainage	**0-0.1**	**0.1-03**	**0.3-0.5**	**0.5+**	**Total**
Left Bank					
14700-18900 and 19300-19900	180	270	302	283	**1035**
9000-14700	230	335	420	1026	**2011**
Right Bank					
9000-19900	156	338	511	1570	**2575**
Total	**566**	**943**	**1233**	**2879**	**5621**

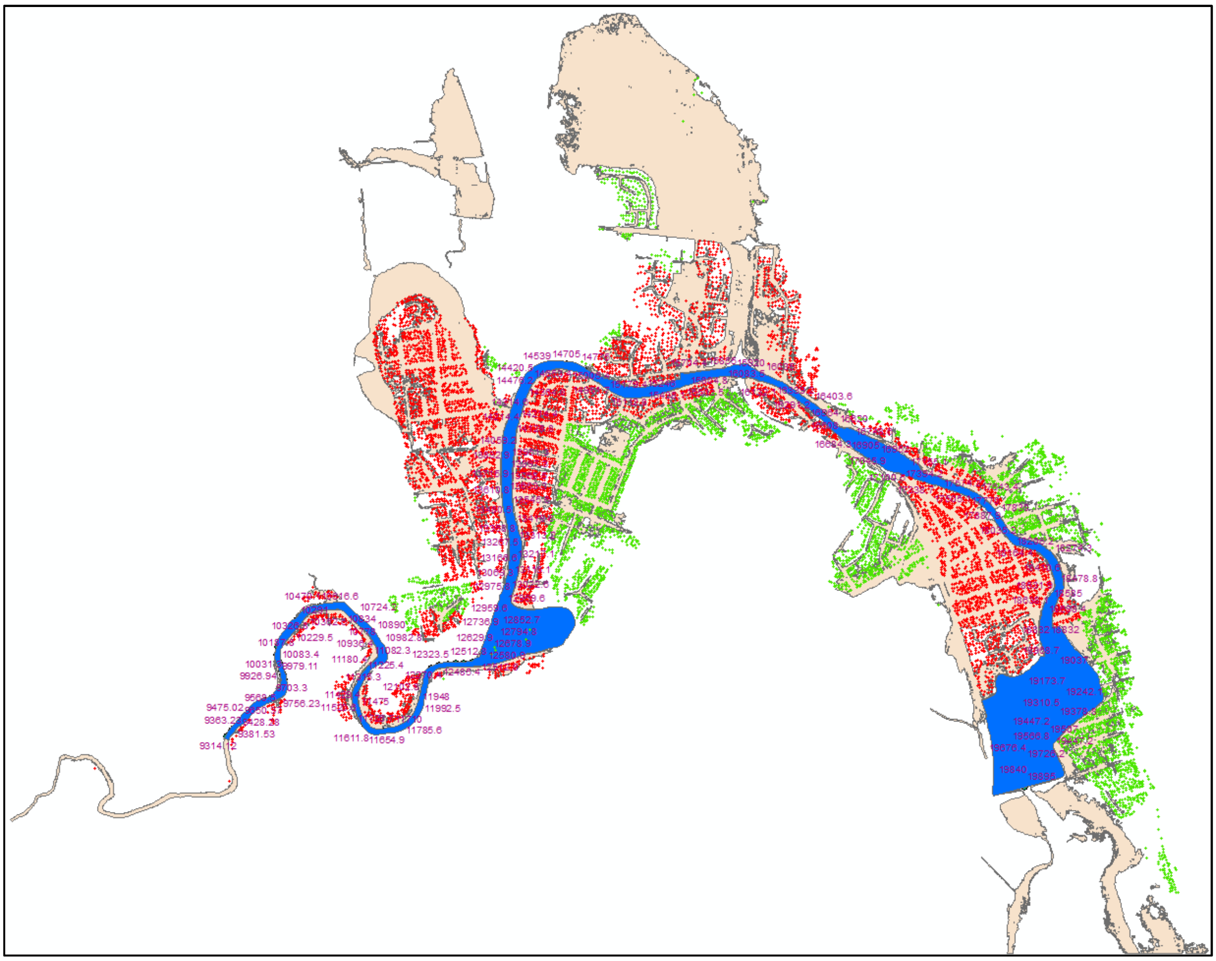


RL 11.2 m Bath Tub extent polygon

Building count for constant elevation of 11.0m

	11.0m Green Zone only				
Chainage	0-0.1	0.1-03	0.3-0.5	0.5+	Total
LEFT Bank					
12300-14600	1	1	0	0	2
14600-16900	5	5	1	2	13
16900-19900	166	321	101	9	597
RIGHT Bank	**222**	**359**	**79**	**63**	**723**
12750-15900	188	299	53	0	540
16500-19900	34	60	26	63	183
Total	**3247**	**694**	**182**	**74**	**4197**

	11.0 m Red Zone only				
Chainage	0-0.1	0.1-03	0.3-0.5	0.5+	Total
LEFT Bank					
10900-12300	19	37	3	0	59
12300-14600	183	408	332	228	1151
14600-16900	115	98	28	7	248
16900-19900	25	51	51	47	174
9800-10900	2	9	1	0	**12**
RIGHT Bank					
11800-12750	3	9	4	8	**24**
12750-15900	153	346	89	16	**604**
15900-16500	27	19	16	2	**64**
16500-19900	66	101	75	867	**1109**
9800-11800	16	14	4	0	**34**
Total	**2812**	**1100**	**604**	**1175**	**5691**

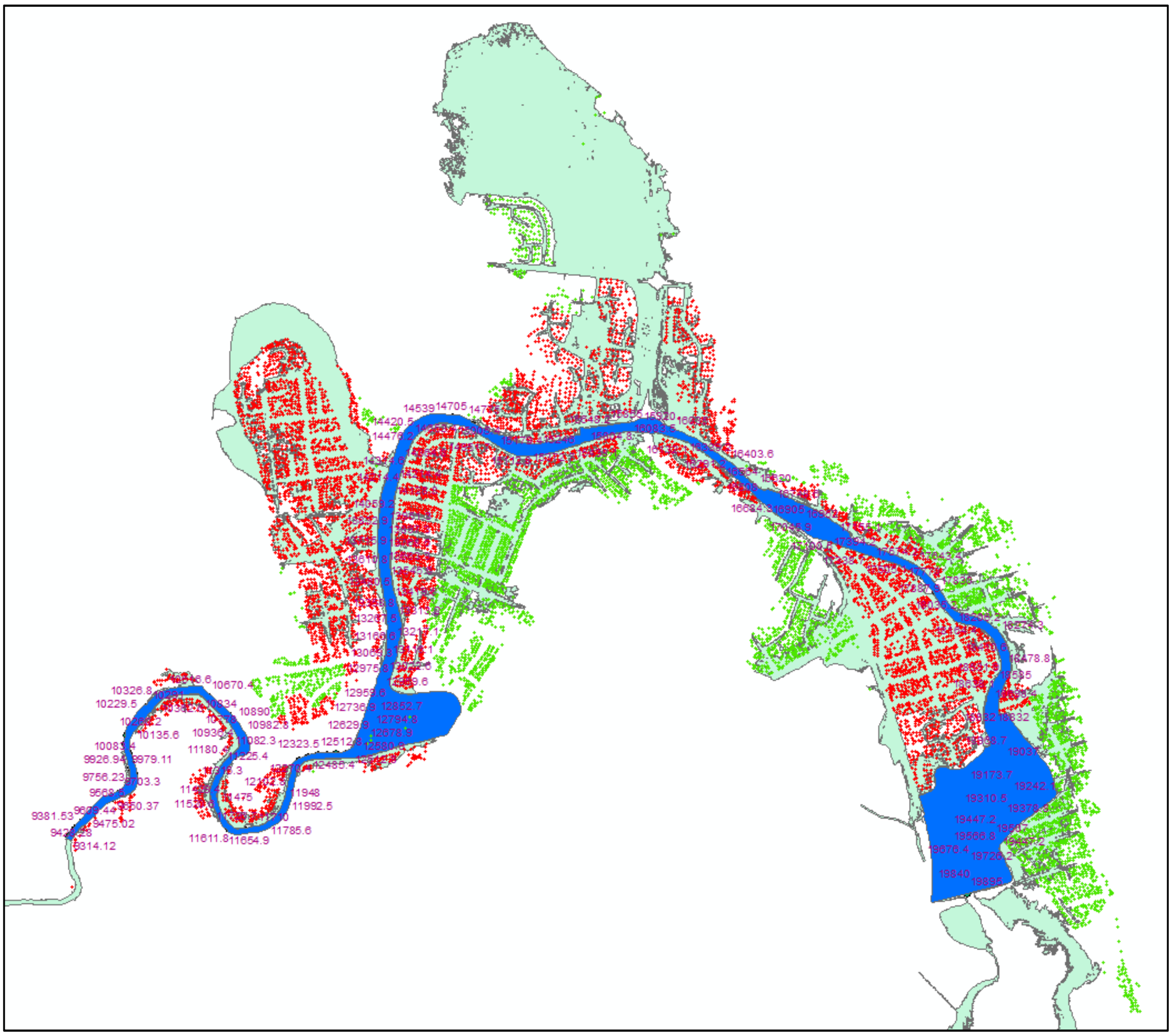


11.0m Bath tub extent polygon

Building count for constant elevation of 10.8m

10.8m Green Zone only					
Chainage	0-0.1	0.1-03	0.3-0.5	0.5+	Total
LEFT Bank	**0**	**172**	**327**	**113**	**612**
12300-14500	0	1	1	0	2
14500-19900	0	171	326	113	610
RIGHT Bank	**0**	**232**	**359**	**142**	**733**
12700-15900	0	190	299	53	542
16500-19900	0	42	60	89	191
Total	**2227**	**1020**	**694**	**256**	**4197**

Red Zone only					
Chainage	0-0.1	0.1-03	0.3-0.5	0.5+	Total
LEFT Bank					
10900-12300	0	19	37	3	59
12300-14500	0	183	408	560	1151
14500-19900	0	140	149	133	422
9400-10900	0	2	9	1	12
RIGHT Bank					
11700-12700	0	3	9	12	24
12700-15900	0	153	346	105	604
15900-16500	0	27	19	18	64
16500-19900	0	69	101	942	1112
9400-11700	0	16	14	4	34
Total	**1579**	**1233**	**1100**	**1779**	**5691**



10.8m Bath tub extent polygon

Appendix H 2 - Tide Breach Building Counts

Base Section Information Use in Counts									
Section	**14**	**6**	**8**	**15**	**5**	**2**	**21**	**9**	**16**
Bank	Right Bank	Left Bank	Left Bank	Right Bank	Left Bank	Left Bank	Right Bank	Left Bank	Right Bank
Chainage	12679	15504	14198	15179	16468	16564	13000	13546	16564
Bank Height (RL)	11.23	10.85	11.11	11.08	11.01	11.28	11.35	11.18	11.41
Ground Level (RL)	10.48	10.52	9.54	10.04	10.73	10.20	10.91	10.46	10.63
Tide Adjust Factor %	101.15%	100.70%	101%	100.76%	100.55%	100.29%	101.49%	101.01%	100.54%

200yr Tide Breach									
Section	**14**	**6**	**8**	**15**	**5**	**2**	**21**	**9**	**16**
Weir Width	30	80	80	80	80	80	80	80	80
Crest Width	NA	2000	NA	NA	80	NA	NA	NA	NA
Volume (m3)	118,020	29,497	755,378	514,806	16,130	529,628	2,127	288,062	97,009
Elevation (m)	10.66	10.02	11.04	11.01	10.00	10.47	10.49	10.62	10.71
Crest Weir Flow	NA	Yes	NA	NA	Yes	NA	NA	NA	NA

200yr Tide Breach Green Zone Building Counts									
Ground level Depth (m)	**14**	**6**	**8**	**15**	**5**	**2**	**21**	**9**	**16**
0.5+	0	0	0	53	0	2	0	0	0
0.3-0.5	0	0	1	299	0	0	0	0	0
0.1-0.3	0	0	1	190	0	0	0	0	0
0-0.1	0	2	0	0	2	2	12	24	0
Total	0	2	2	542	2	4	12	24	0

200yr Tide Breach Red Zone Building Count									
Ground level Depth (m)	**14**	**6**	**8**	**15**	**5**	**2**	**21**	**9**	**16**
0.5+	0	0	560	105	0	0	0	75	0
0.3-0.5	9	0	408	346	0	1	1	171	3
0.1-0.3	5	0	183	153	0	8	26	337	15
0-0.1	7	0	0	0	0	27	72	652	16
Total	21	0	1151	604	0	36	99	1235	34

200yr Tide Breach + EQ ULS Settlement									
Section	**14**	**6**	**8**	**15**	**5**	**2**	**21**	**9**	**16**
Bank Height			10.9	10.82	10.86	11.13	11.29	11.18	11.188
Weir Width			0	80.00	80.00	80.00	80.00	80	80
Crest Width			0	100.00	80.00	NA	NA	150	NA
Volume (m3)			775,651	930,389	16,130	569,798	17,097	288,062	97,009
Elevation			11.06	11.04	10.00	10.50	11.00	10.62	10.71
Crest Weir Flow			NA	Yes	Yes	NA	NA	Yes	NA

200yr Tide + EQ ULS Settlement Green Zone Building Count									
Ground level Depth (m)	**14**	**6**	**8**	**15**	**5**	**2**	**21**	**9**	**16**
0.5+				53	0	2	53	0	0
0.3-0.5				299	0	0	299	0	0
0.1-0.3				190	0	0	190	0	0
0-0.1				0	2	2	0	24	0
Total				542	2	4	542	24	0

200yr Tide + EQ ULS Settlement Red Zone Building Count									
Ground level Depth (m)	**14**	**6**	**8**	**15**	**5**	**2**	**21**	**9**	**16**
0.5+				105	0	0	105	75	0
0.3-0.5				346	0	1	346	171	3
0.1-0.3				153	0	8	153	337	15
0-0.1				0	0	27	0	652	16
Total				604		36	604	1235	34

50yr Tide Breach									
Section	14	6	8	15	5	2	21	9	16
Weir Width				80			No breach depth for 50T or 100T	80	
Crest Width				NA			NA	NA	
Volume (m3)				409,701			0	211,857	
Elevation				11.00			0	10.59	
Crest Weir Flow				NA			0	NA	

50yr Tide Breach Green Zone Building Count									
Ground level Depth (m)	14	6	8	15	5	2	21	9	16
0.5+				53			0	0	
0.3-0.5				299			0	0	
0.1-0.3				190			0	1	
0-0.1				0			0	0	
Total				542			0	1	

50yr Tide Breach Red Zone Building Count									
Ground level Depth (m)	14	6	8	15	5	2	21	9	16
0.5+				105			0	75	
0.3-0.5				346			0	171	
0.1-0.3				153			0	337	
0-0.1				0			0	652	
Total				604			0	1235	

Appendix C: Breach Analysis Hydrographs

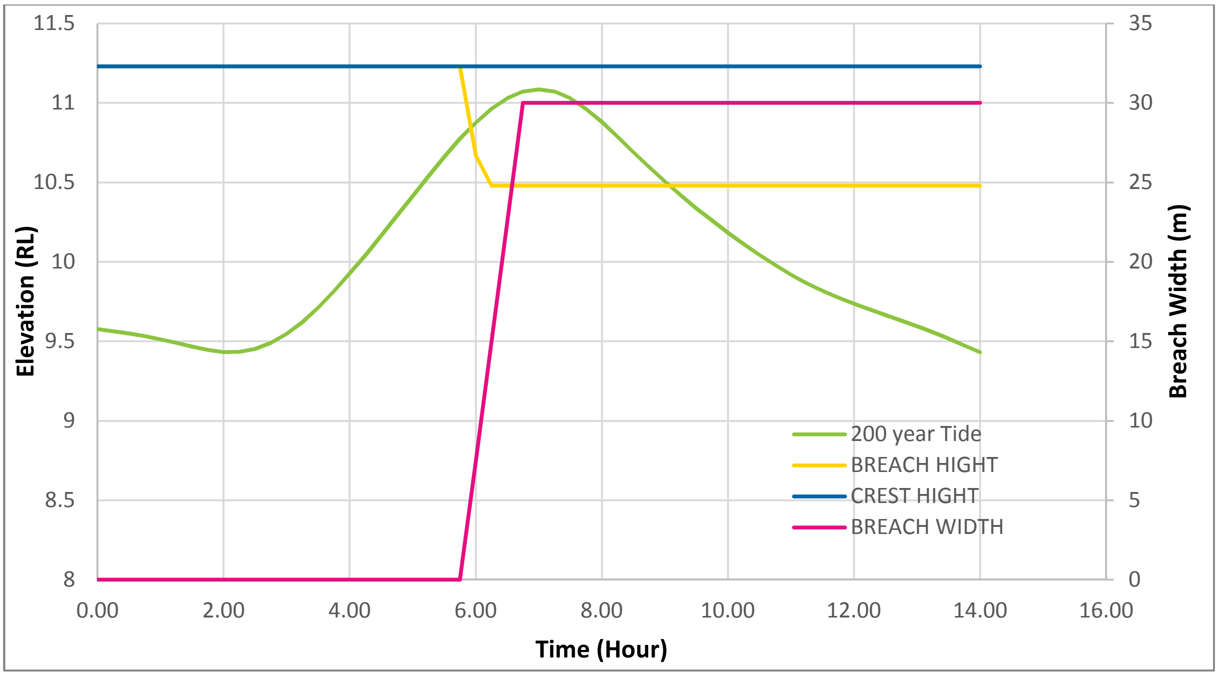


Figure 1: Breach elevation to volume relationship for Section 14 – 200yr Tide

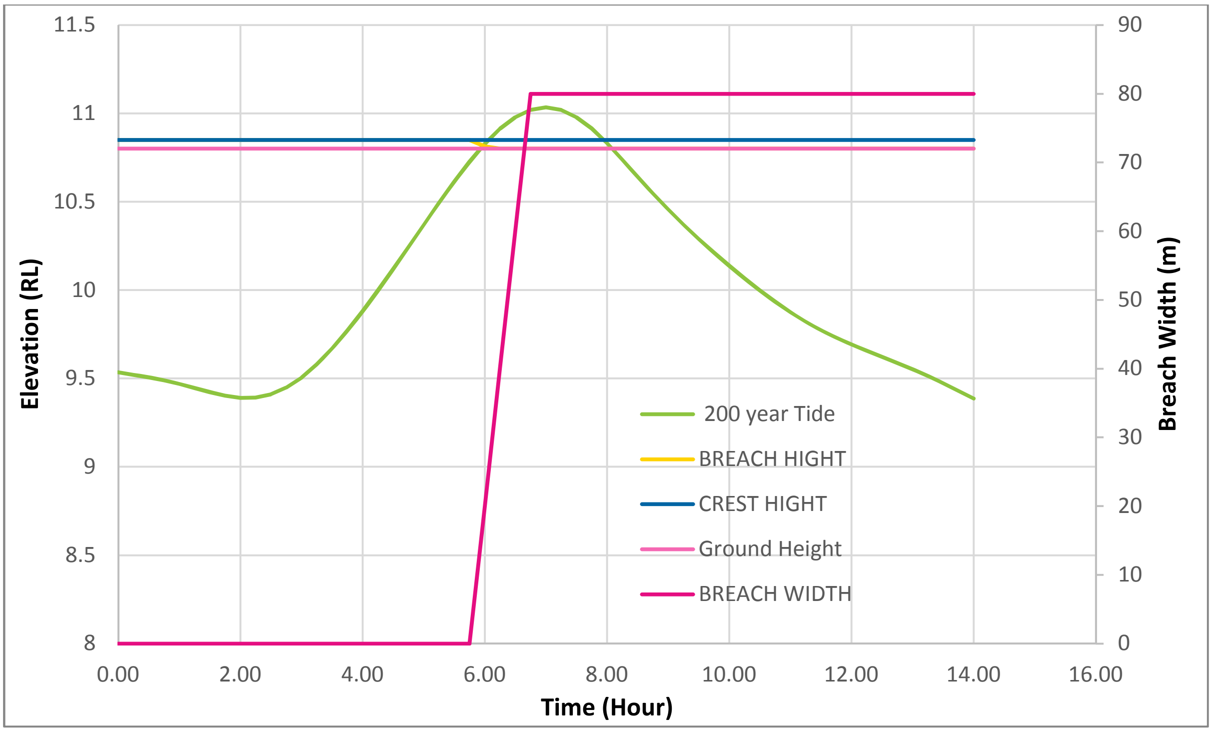


Figure 2: Breach elevation to volume relationship for Section 6 – 200yr Tide

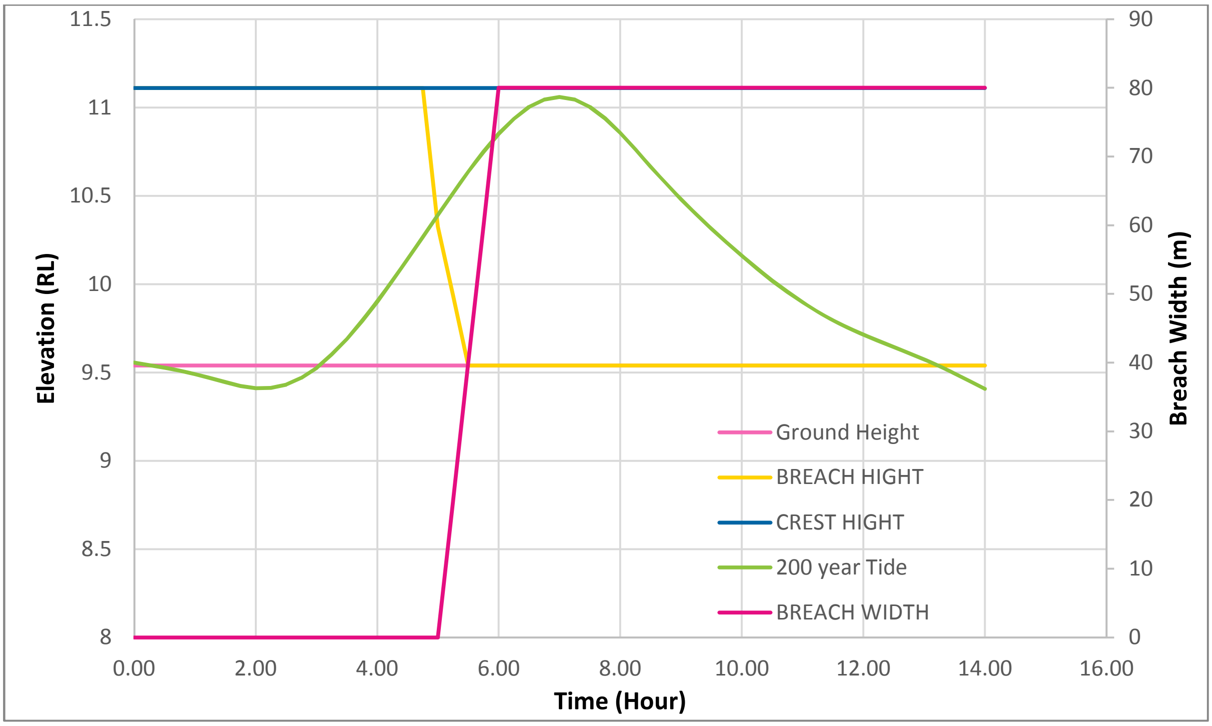


Figure 3: Breach elevation to volume relationship for Section 8 – 200yr Tide

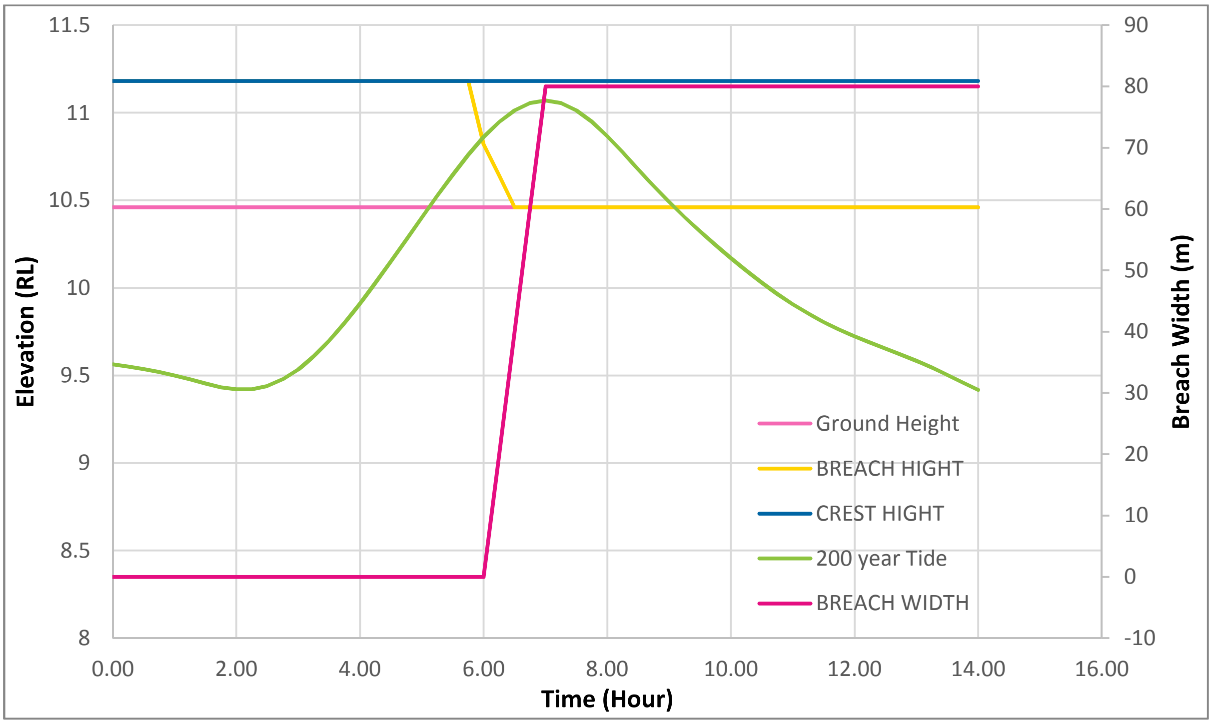


Figure 4: Breach elevation to volume relationship for Section 9 – 200yr Tide

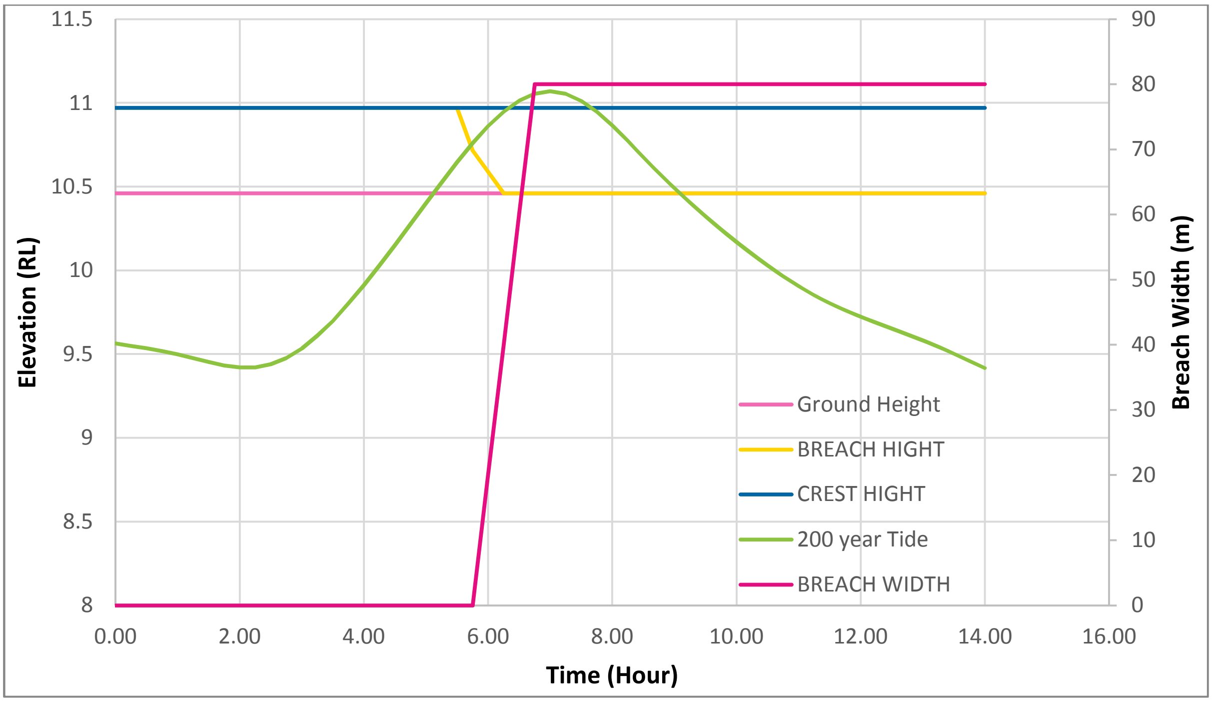


Figure 5: Breach elevation to volume relationship for Section 9 – 200yr Tide + EQ ULS

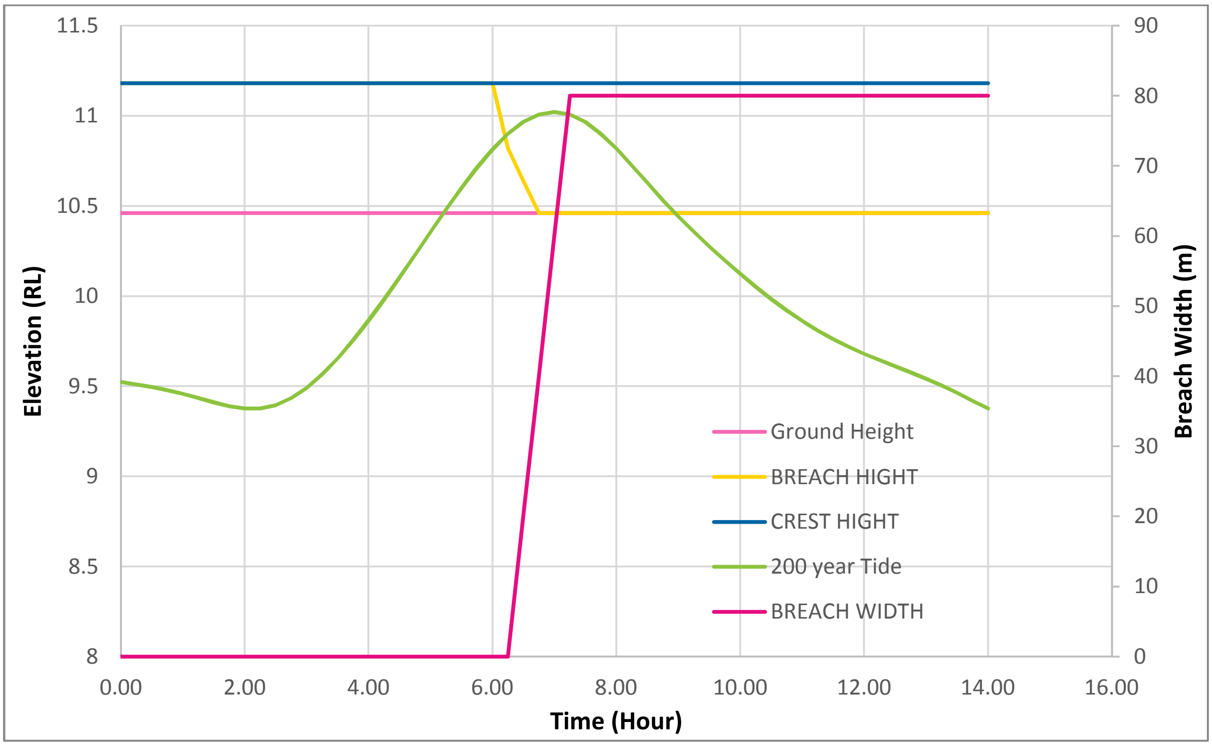


Figure 6: Breach elevation to volume relationship for Section 9 – 50yr Tide

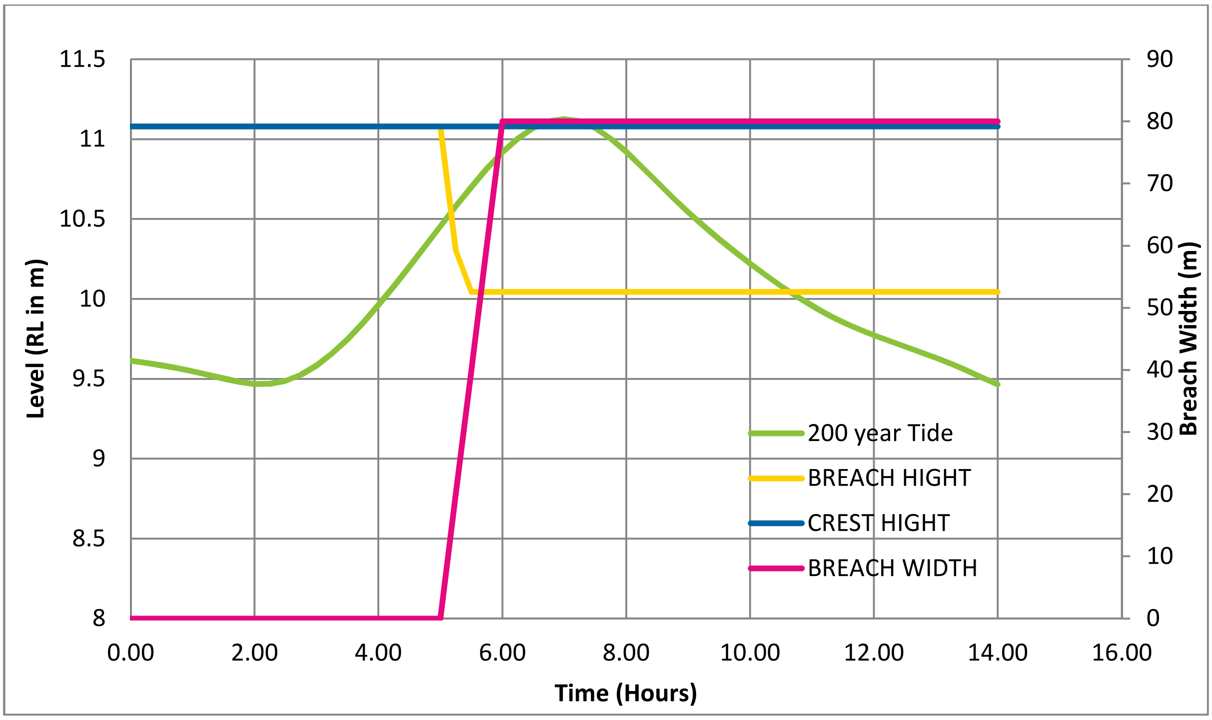


Figure 7: Breach elevation to volume relationship for Section 15 – 200yr Tide

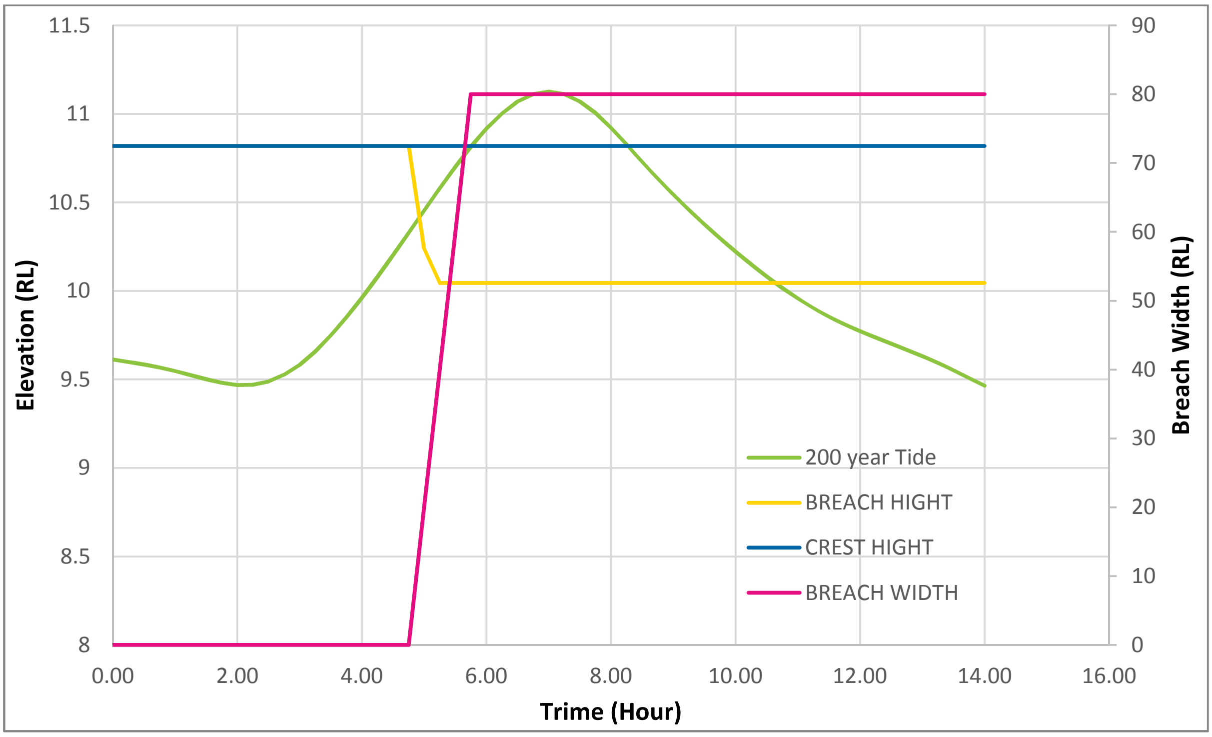


Figure 8: Breach elevation to volume relationship for Section 15 – 200yr Tide + EQ ULS

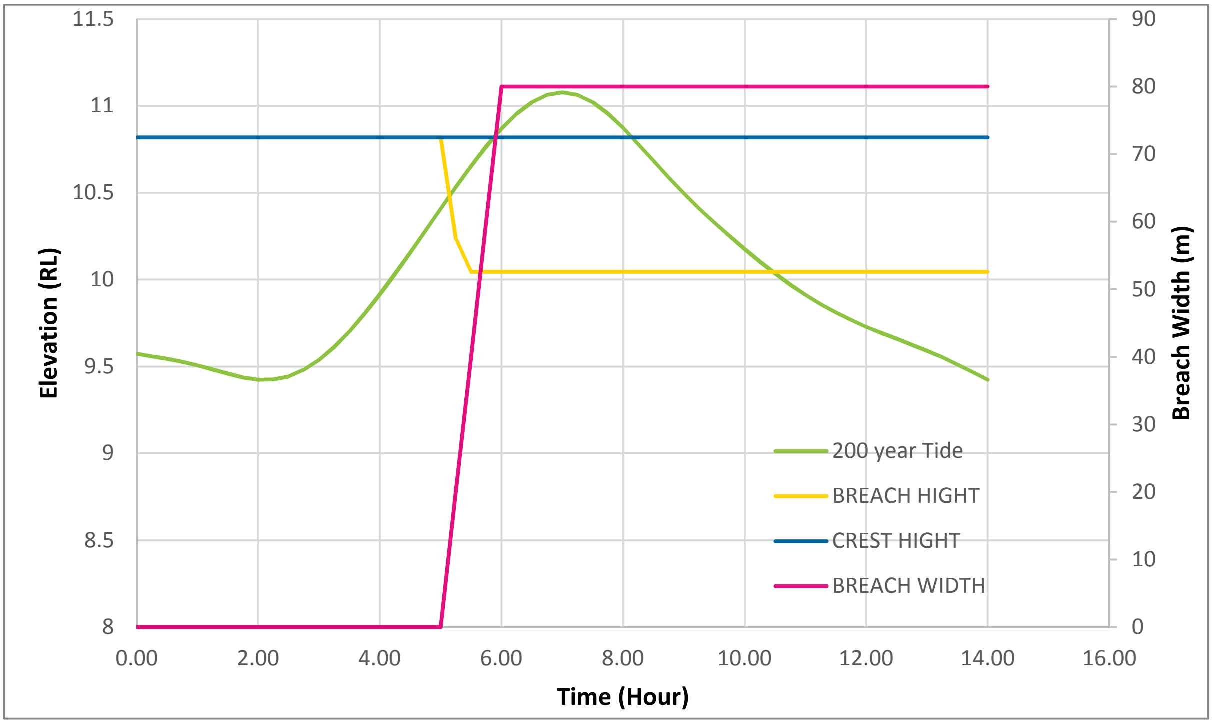


Figure 9: Breach elevation to volume relationship for Section 15 – 50yr Tide

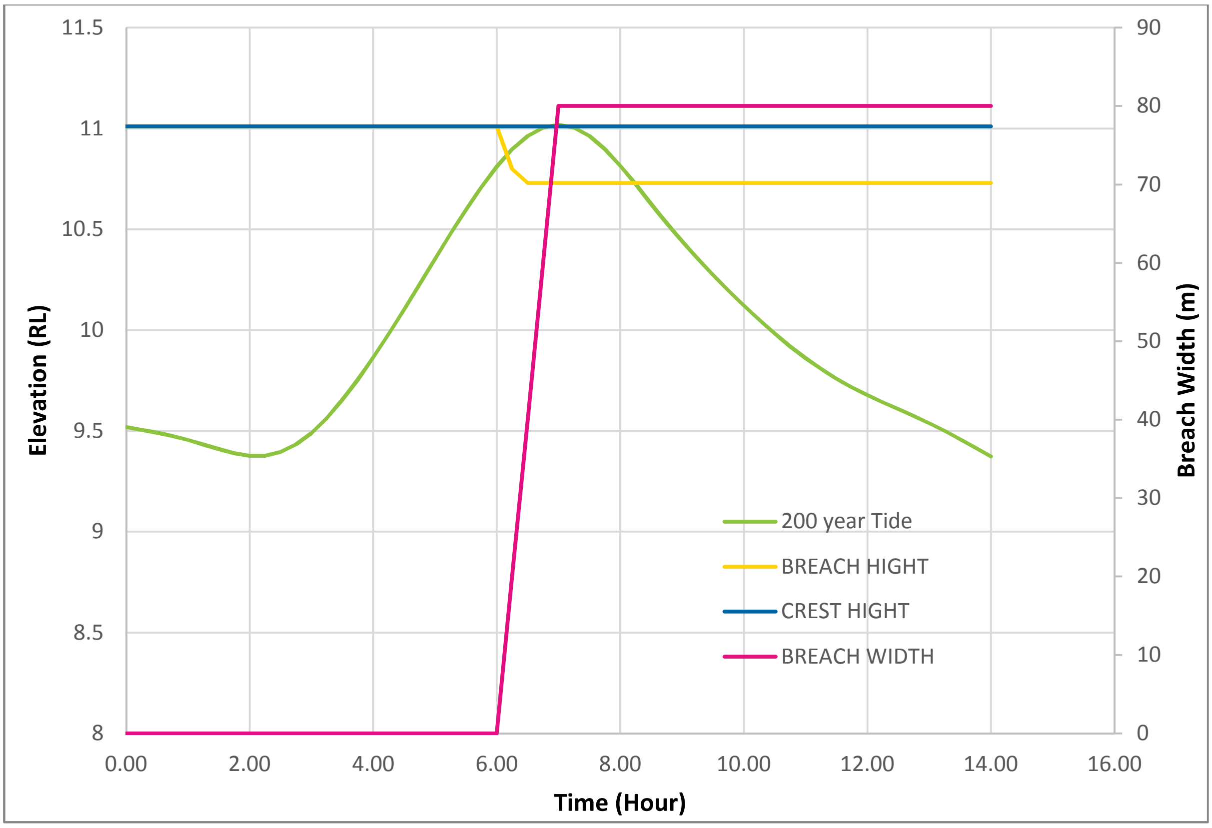


Figure 10: Breach elevation to volume relationship for Section 5 – 200yr Tide

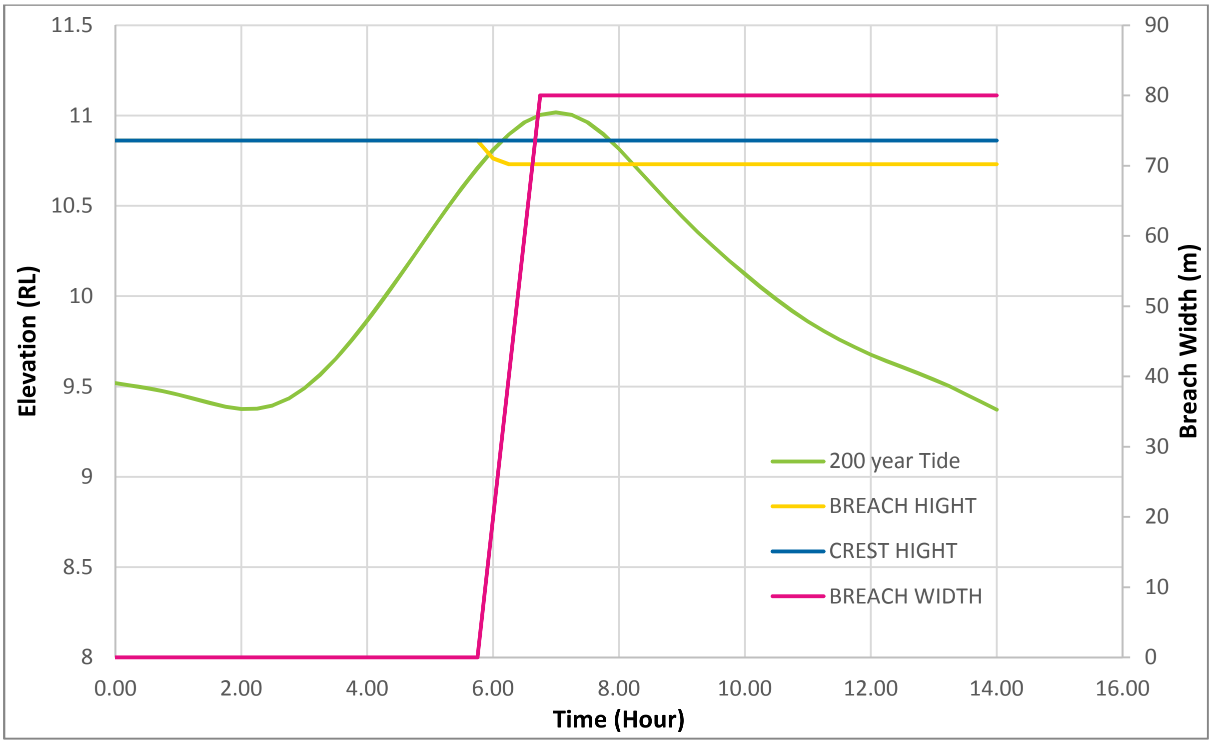


Figure 11: Breach elevation to volume relationship for Section 5 – 200yr Tide + EQ ULS

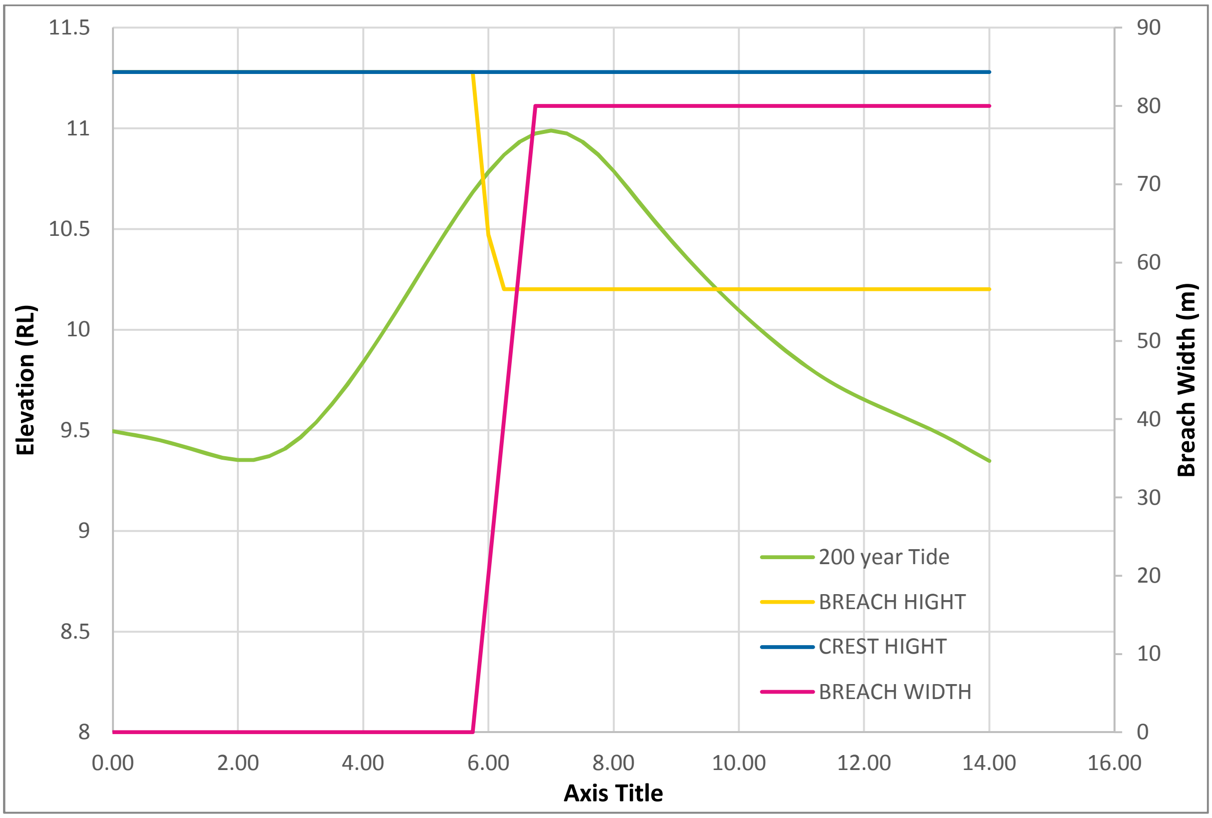


Figure 12: Breach elevation to volume relationship for Section 2 – 200yr Tide

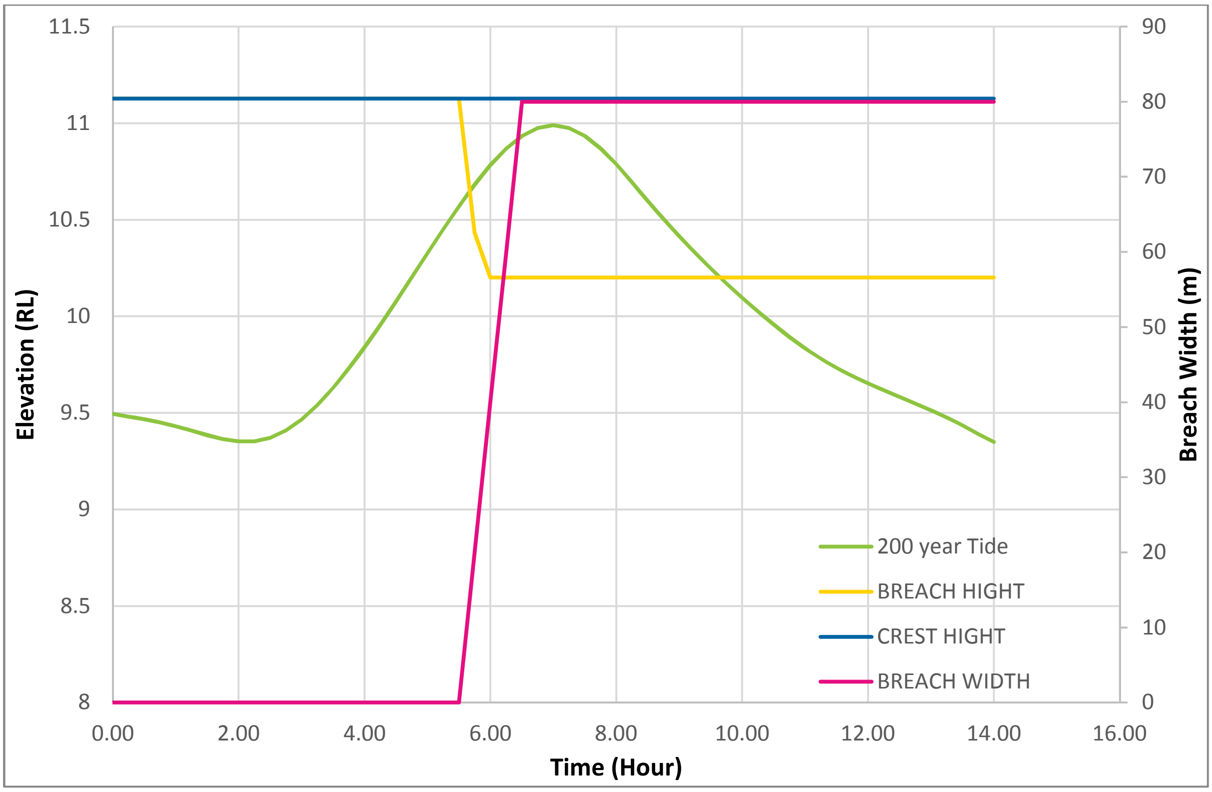


Figure 13: Breach elevation to volume relationship for Section 2 – 200yr Tide + EQ ULS

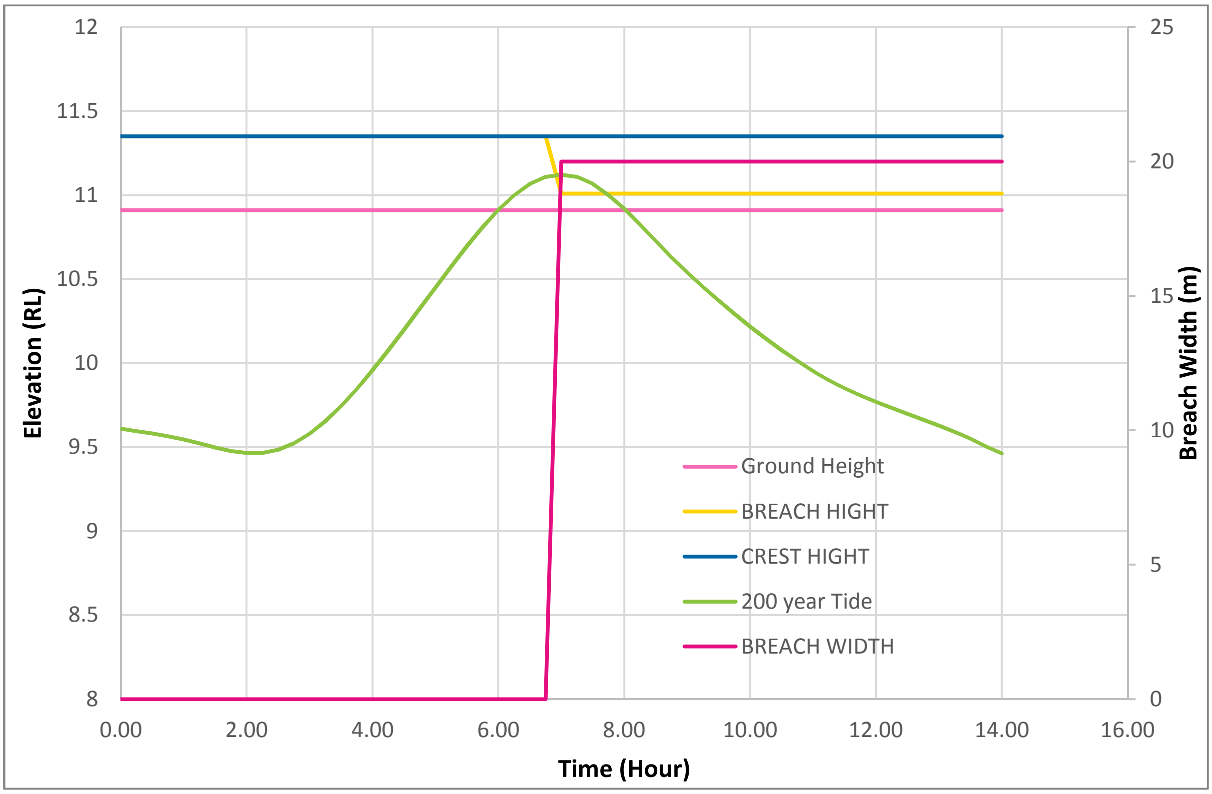


Figure 14: Breach elevation to volume relationship for Section 21 – 200yr Tide

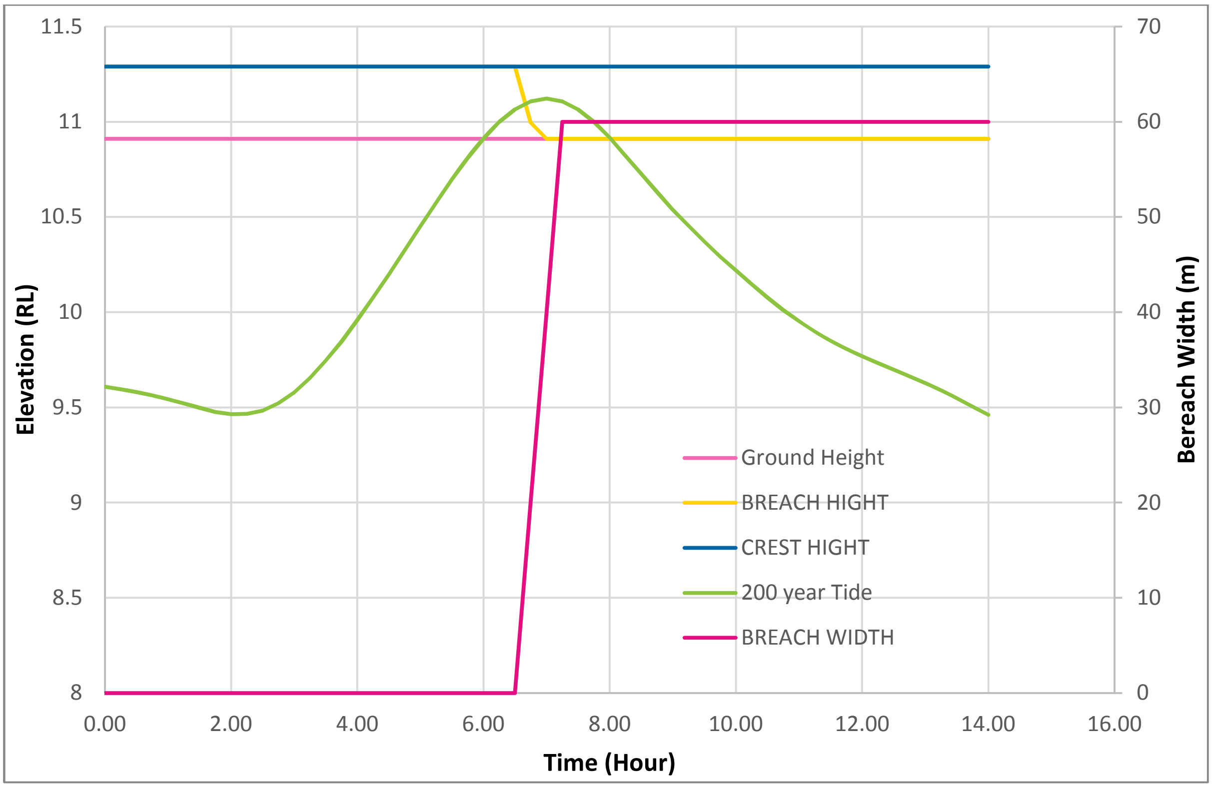


Figure 15: Breach elevation to volume relationship for Section 21 – 200yr Tide + EQ ULS

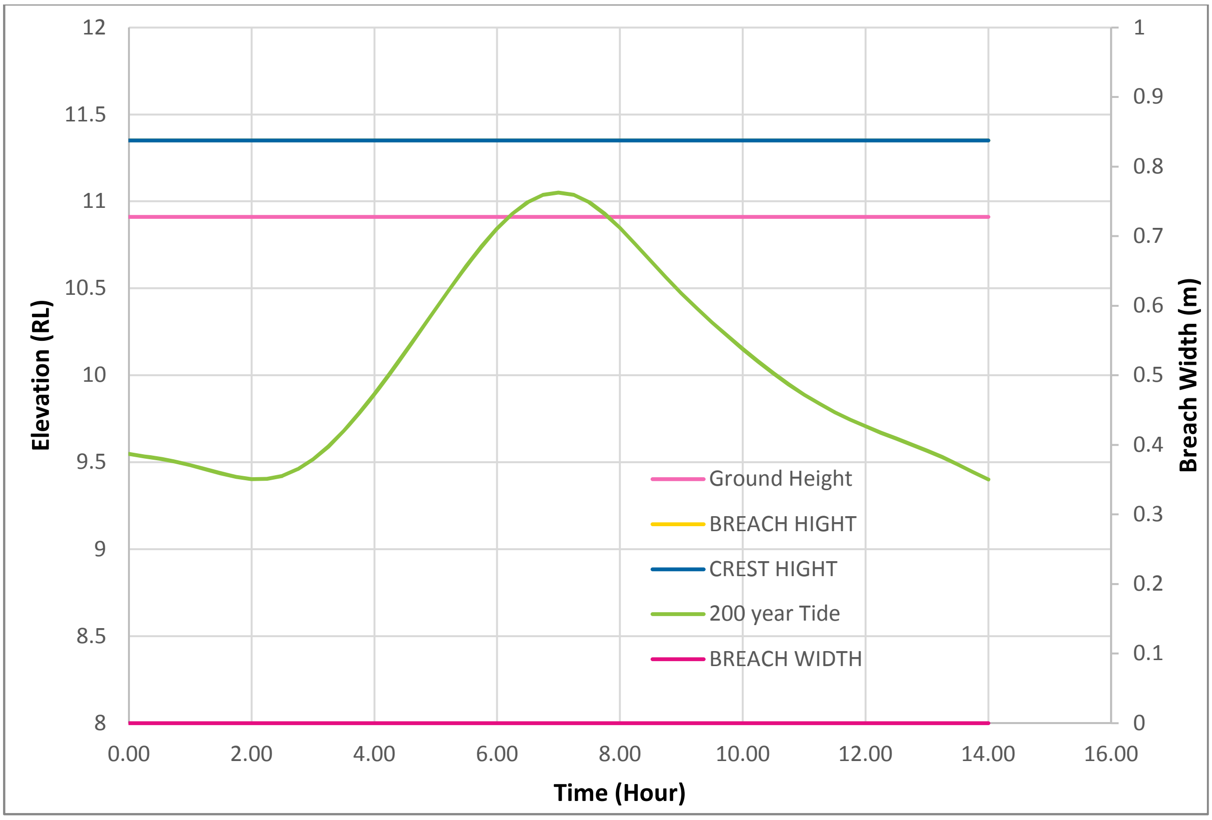


Figure 16: Breach elevation to volume relationship for Section 21 – 50yr Tide

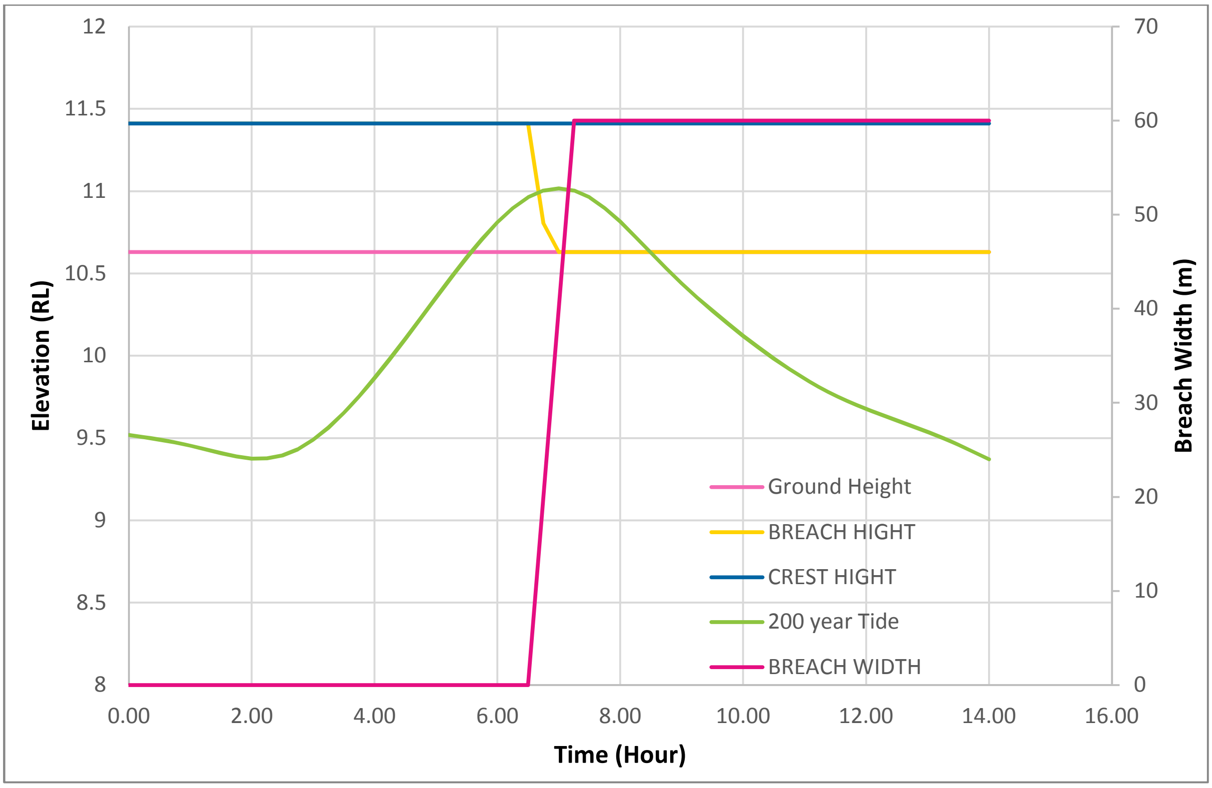


Figure 17: Breach elevation to volume relationship for Section 16 – 200yr Tide

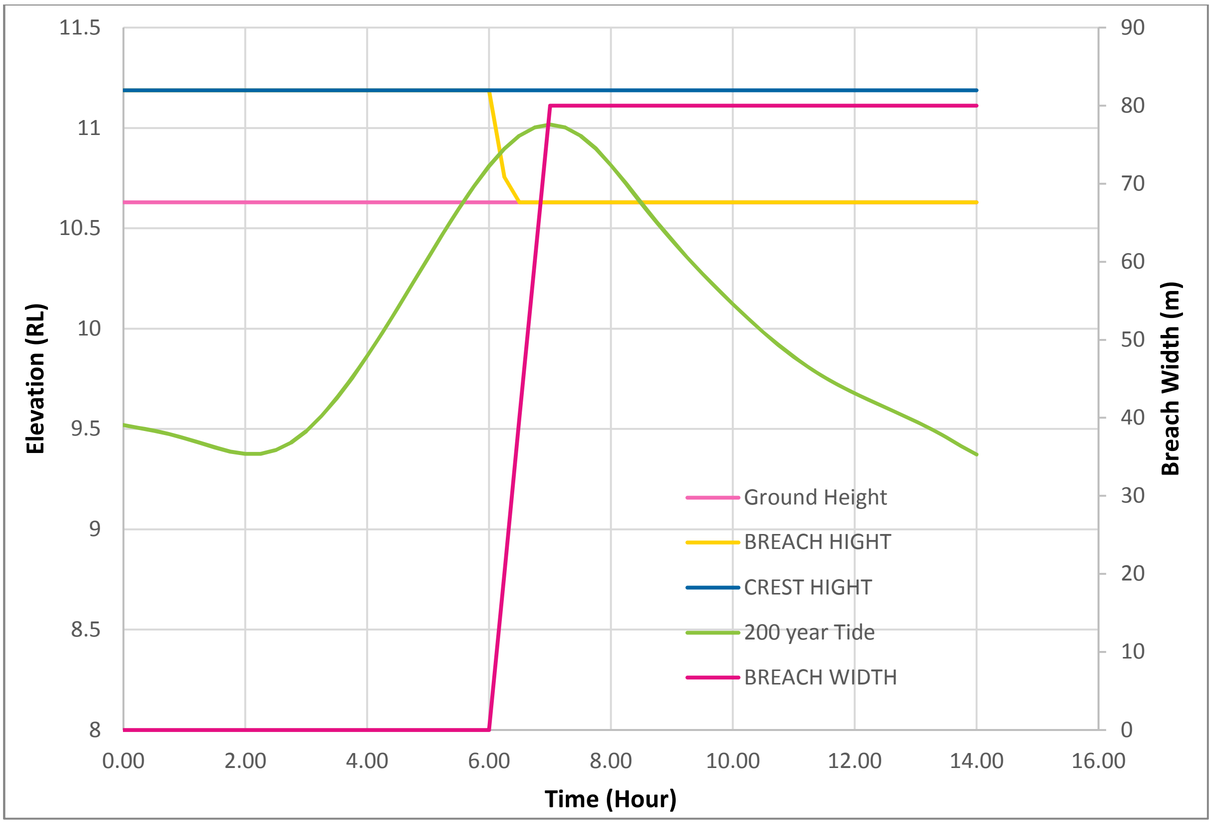


Figure 18: Breach elevation to volume relationship for Section 16 – 200yr Tide + EQ ULS

Appendix D: Volume Elevation Graphs

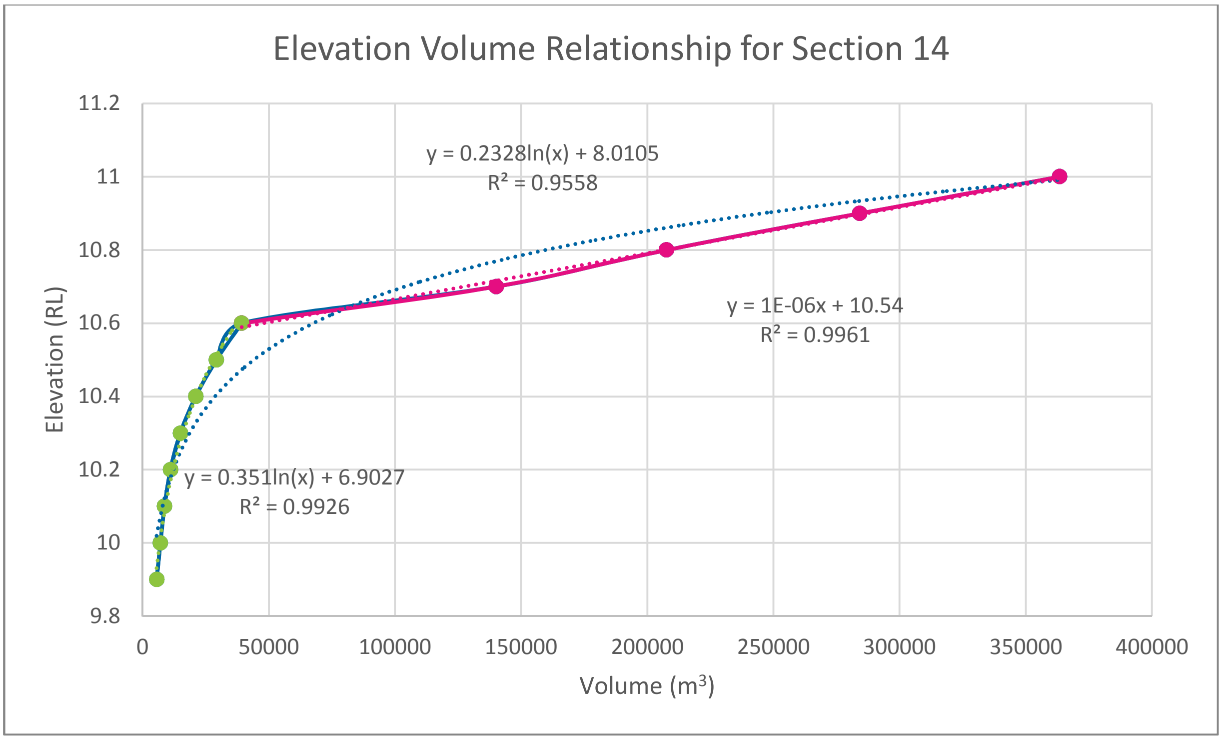


Figure 19: Breach elevation to volume relationship for Section 14

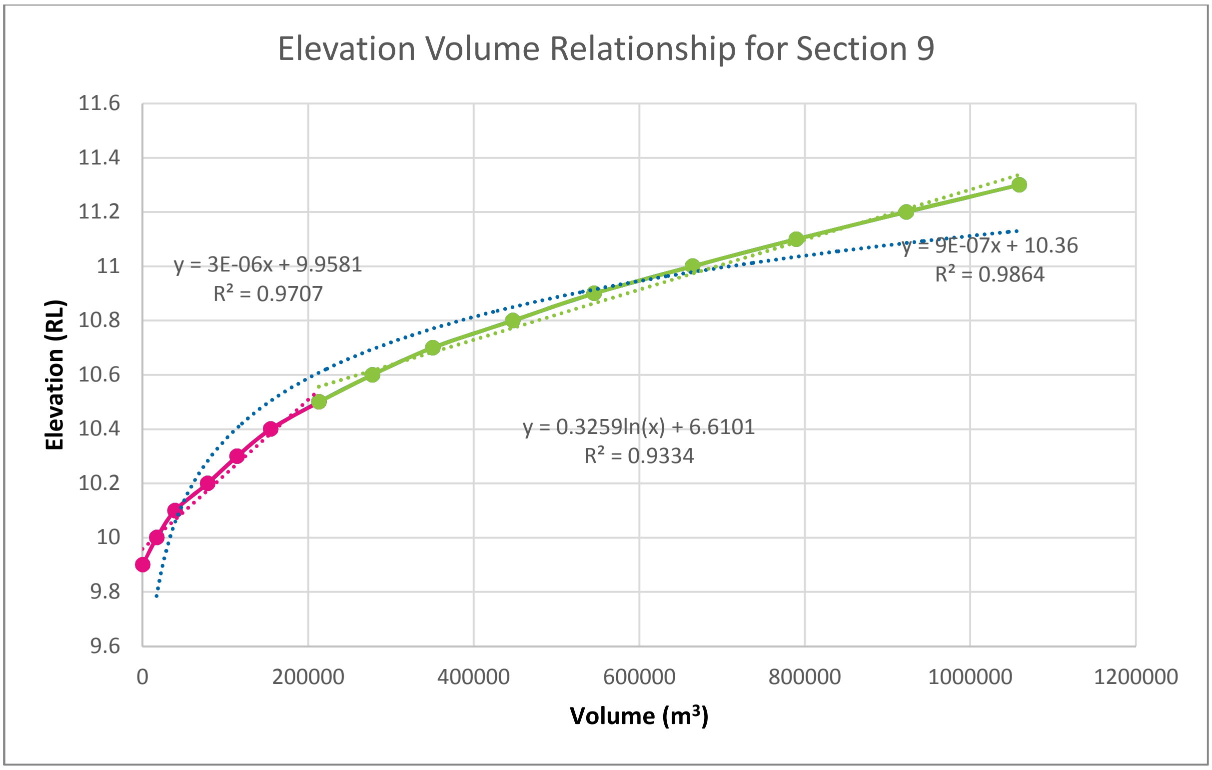


Figure 20: Breach elevation to volume relationship for Section 8

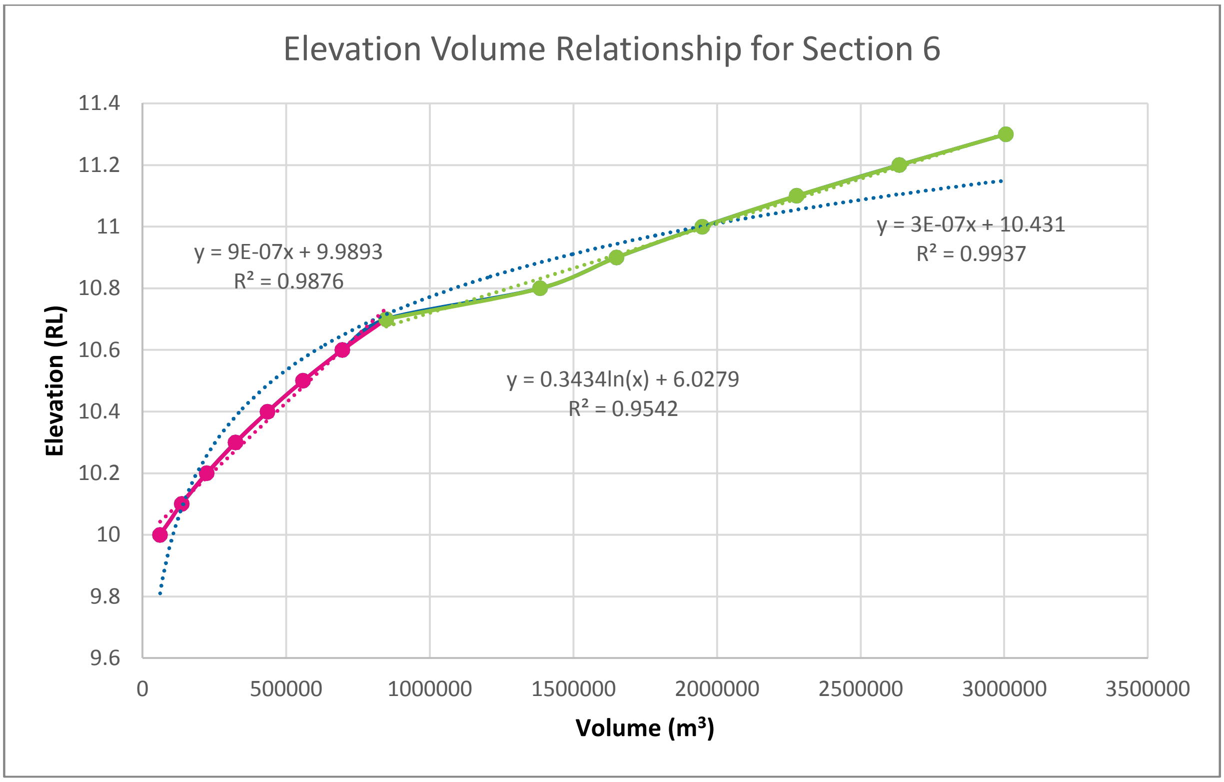


Figure 21: Breach elevation to volume relationship for Section 6

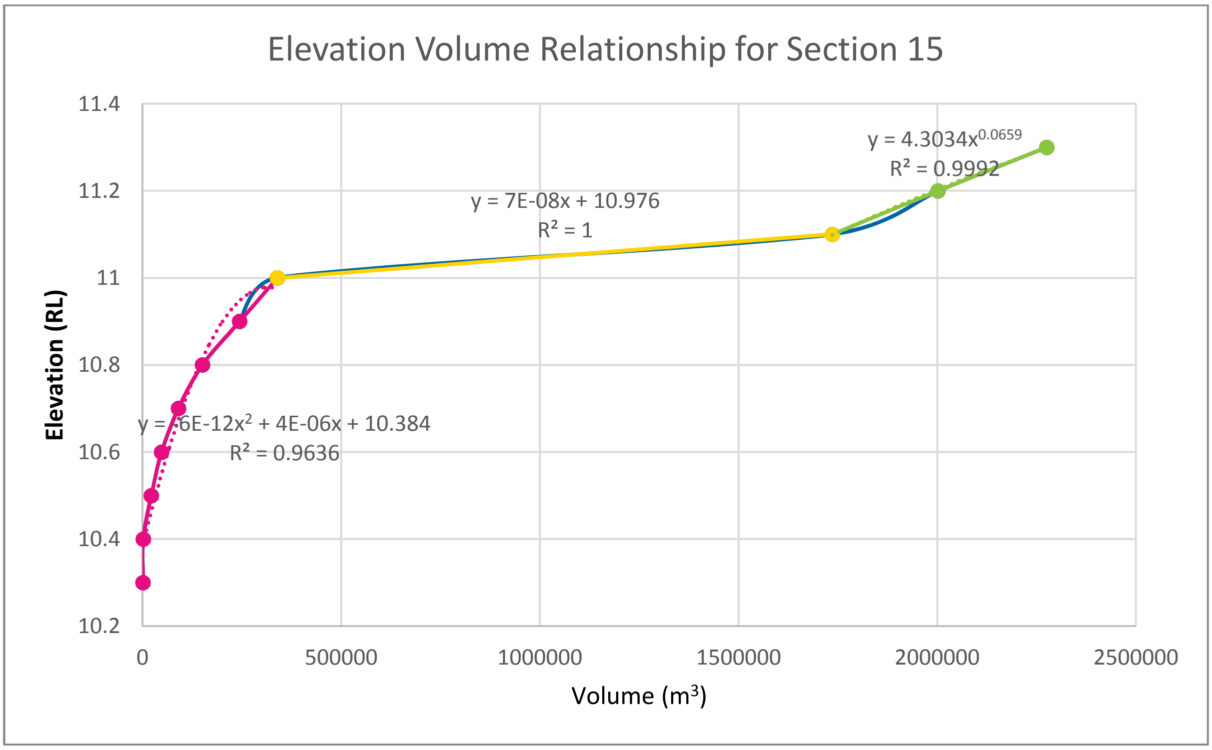


Figure 22: Breach elevation to volume relationship for Section 15

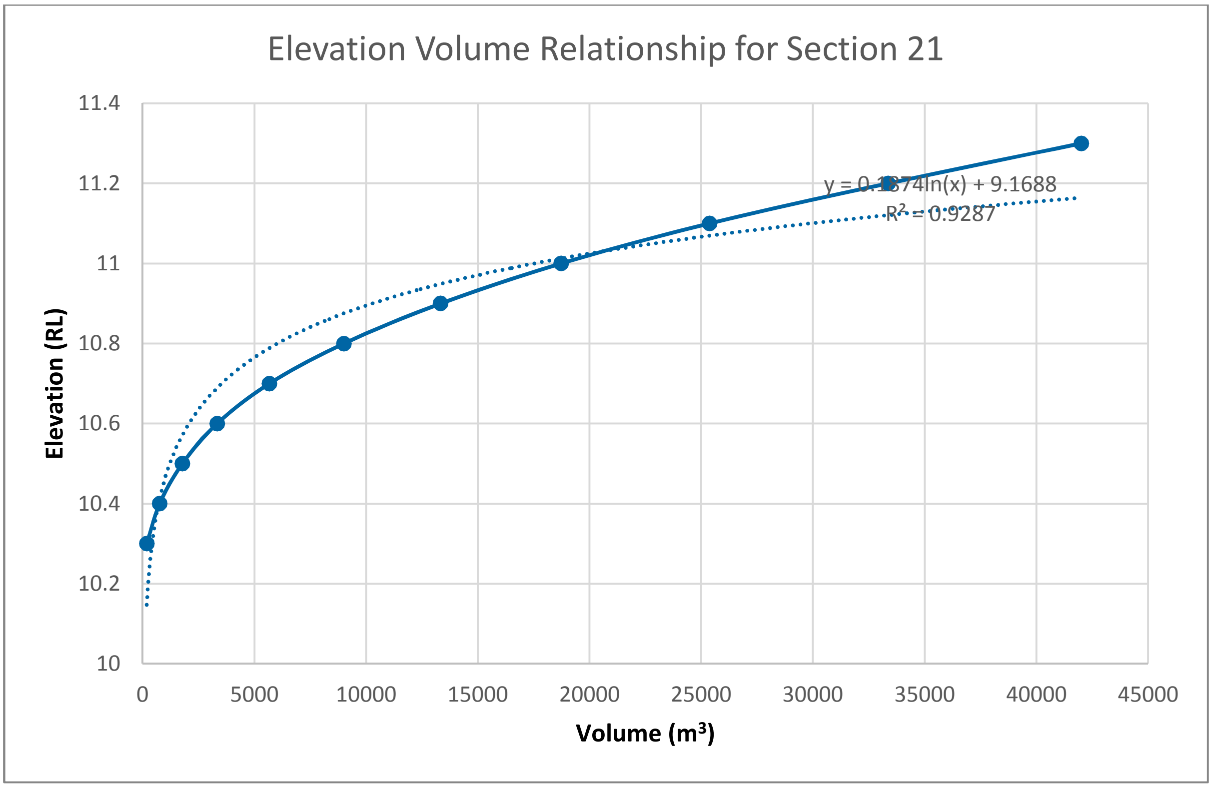


Figure 23: Breach elevation to volume relationship for Section 21

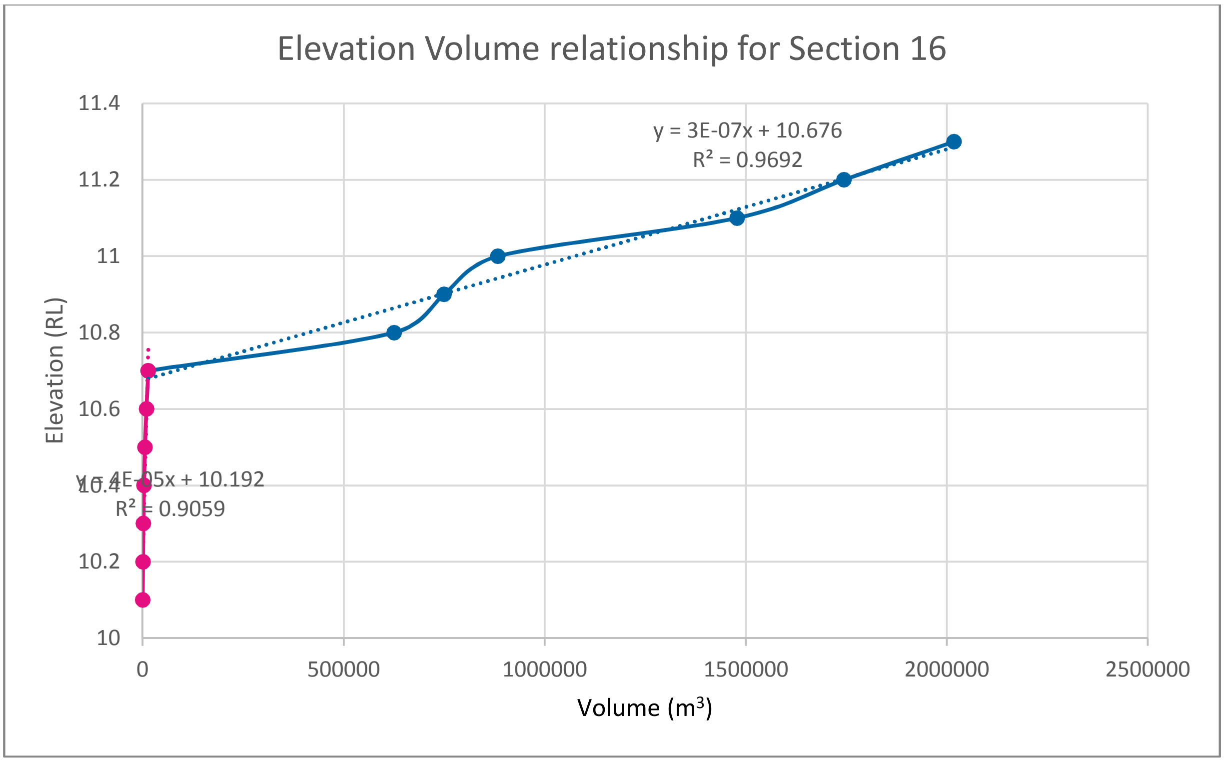
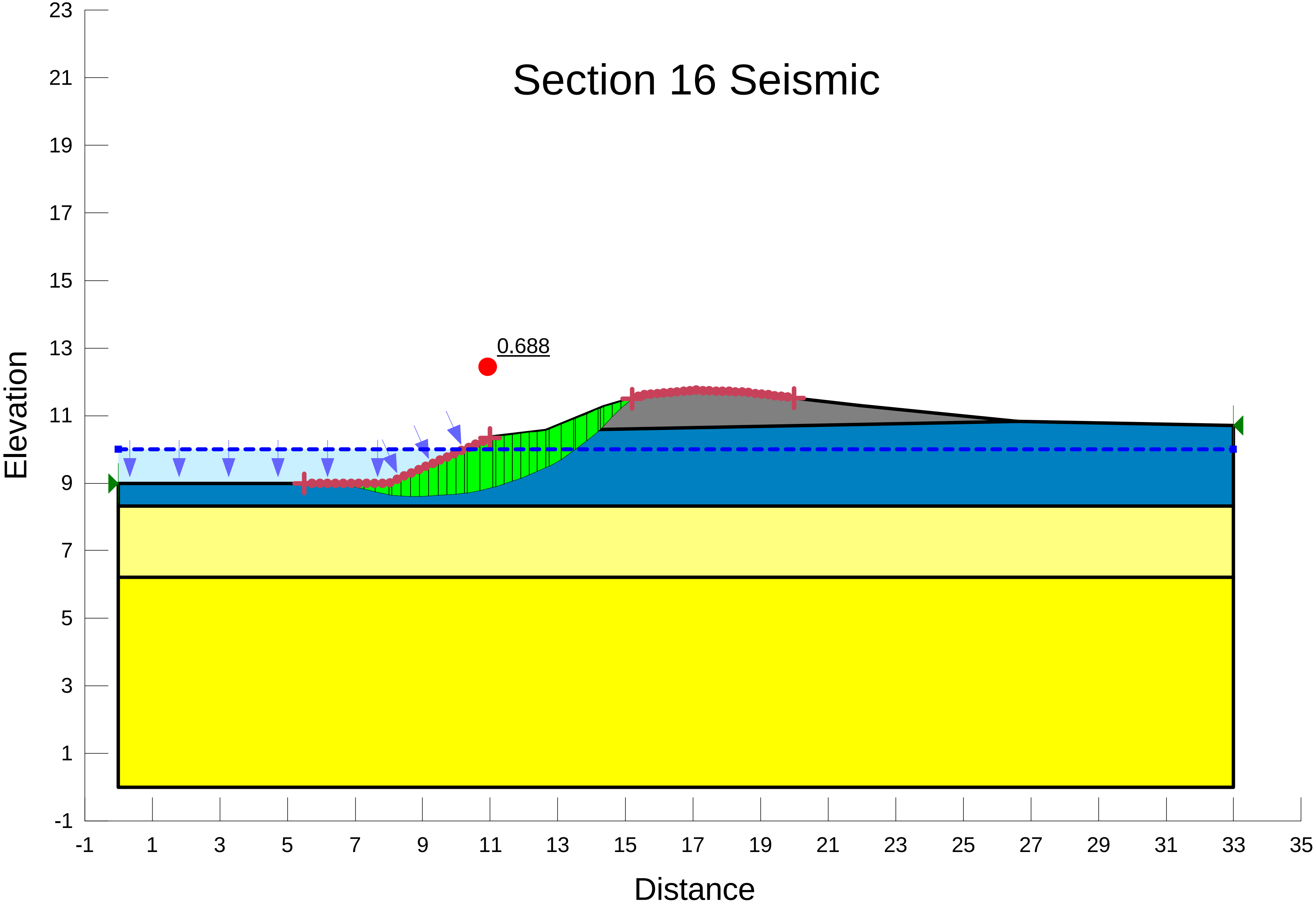


Figure 24: Breach elevation to volume relationship for Section 16

Appendix I – Embankment Stability Input Data

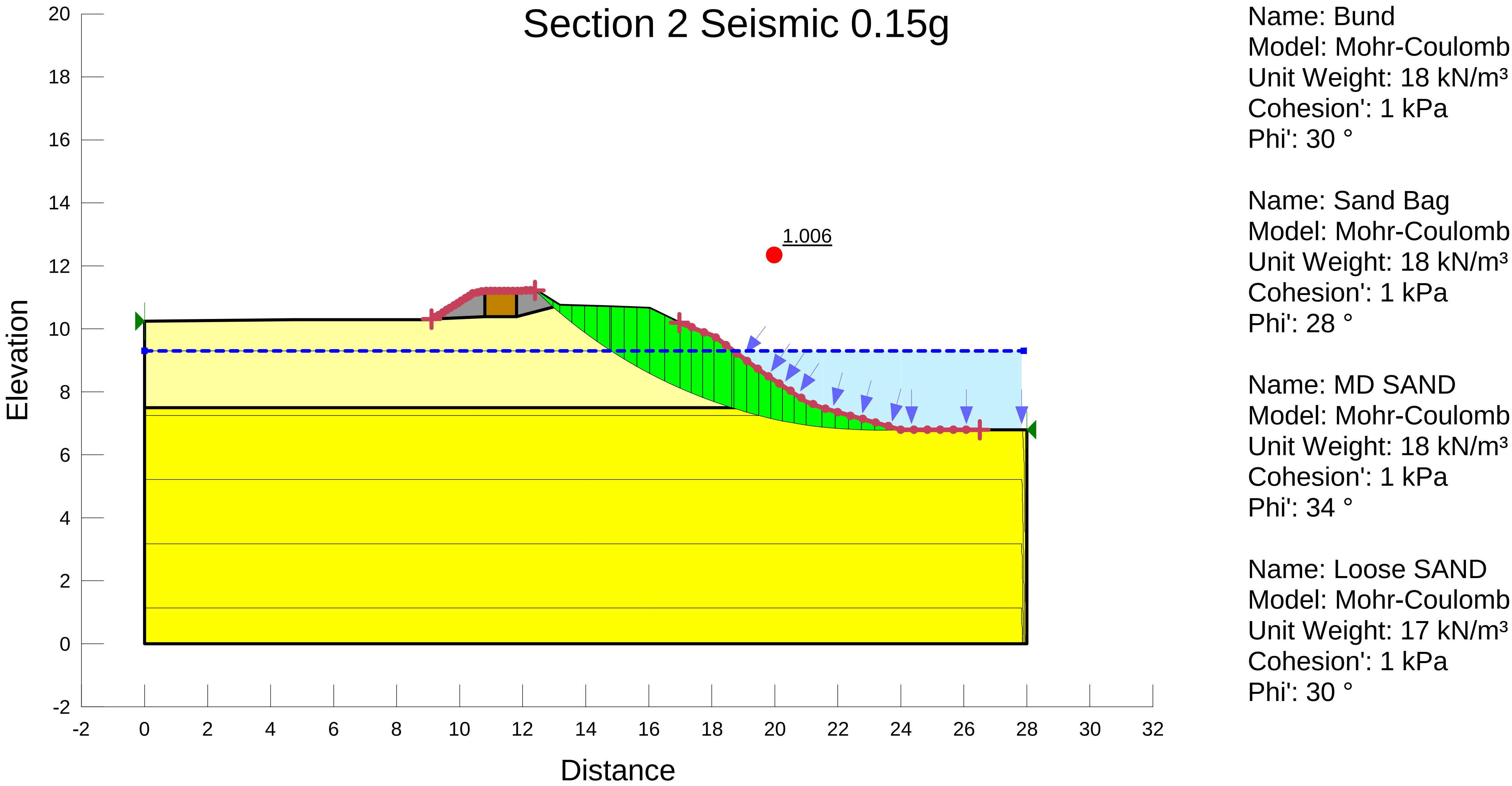


Name: Bund
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 36 °

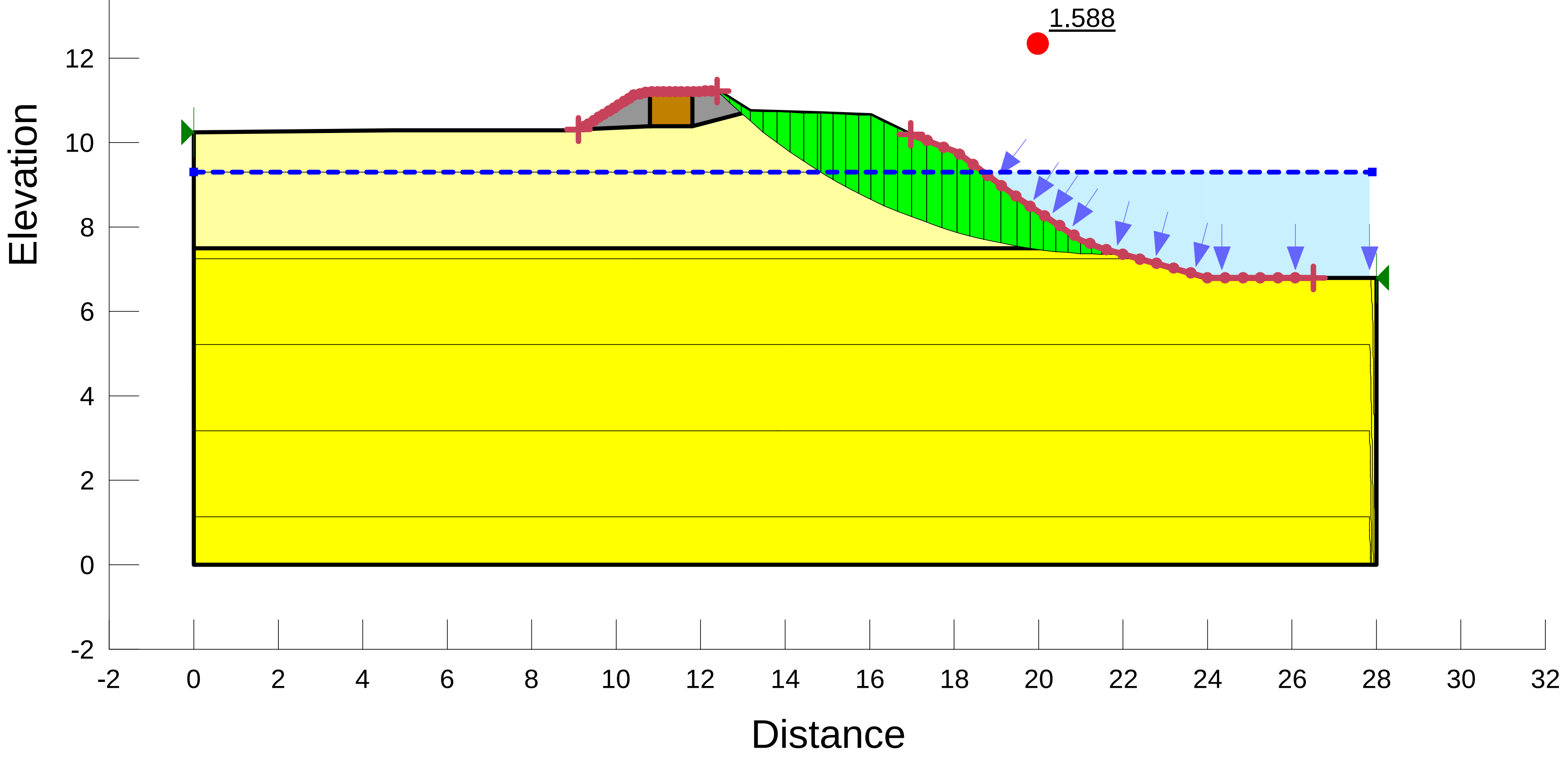
Name: SILT minor sand
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 0 kPa
Phi': 22 °

Name: Loose SAND
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 31 °

Name: MD SAND
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 34 °


Section 2 Seismic 0.15g
1.006
Elevation
Distance
20
18
16
14
12
10
8
6
4
2
0
-2
-2
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
Name: Bund
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 30 °
Name: Sand Bag
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 28 °
Name: MD SAND
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 34 °
Name: Loose SAND
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 30 °

Section 2 Static



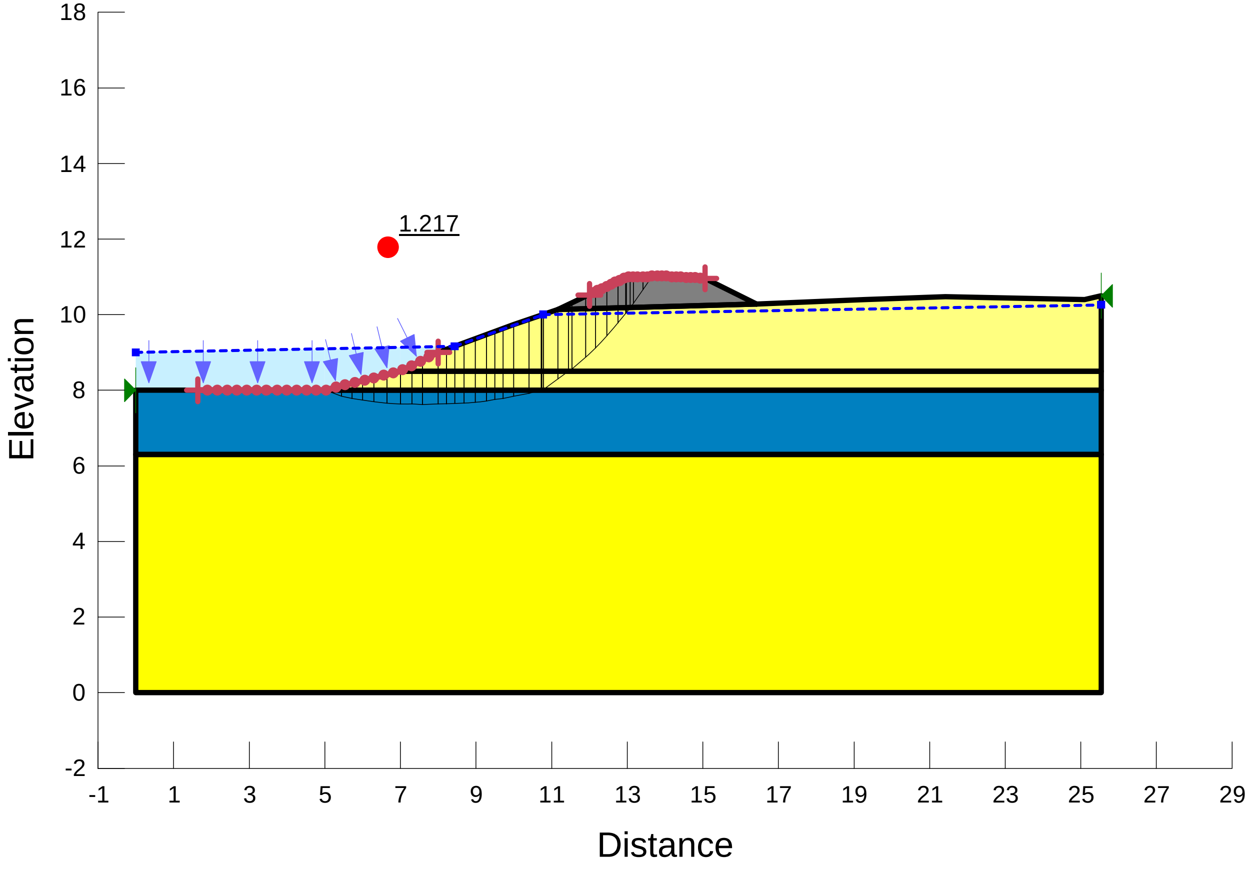
Name: Bund
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 30 °

Name: Sand Bag
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 28 °

Name: MD SAND
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 34 °

Name: Loose SAND
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 30 °

Section15 Static RAPID Drawdown

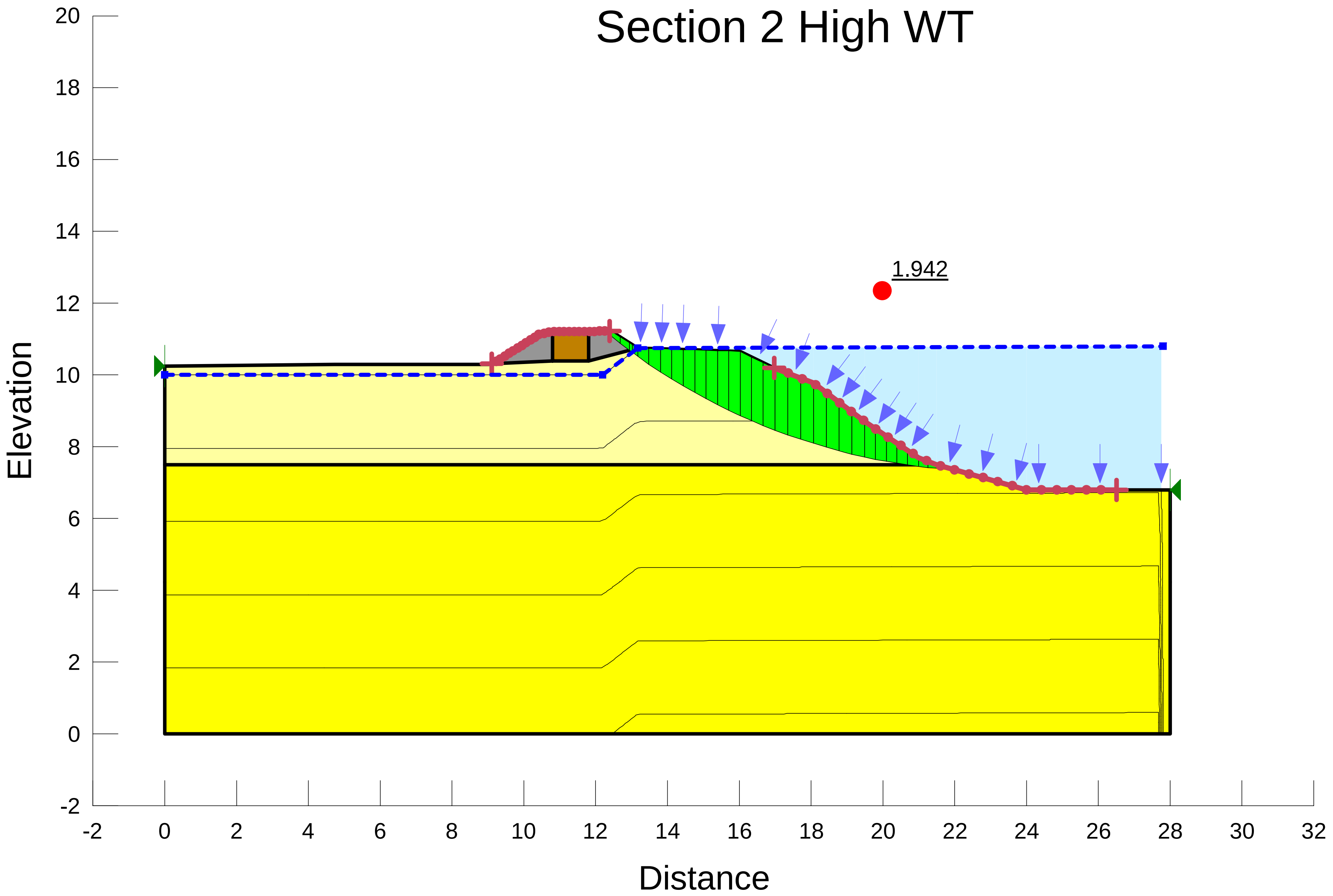


Name: Bund
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 36 °

Name: Loose SAND
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 32 °

Name: SILT
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 24 °

Name: MD SAND
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 0 kPa
Phi': 36 °



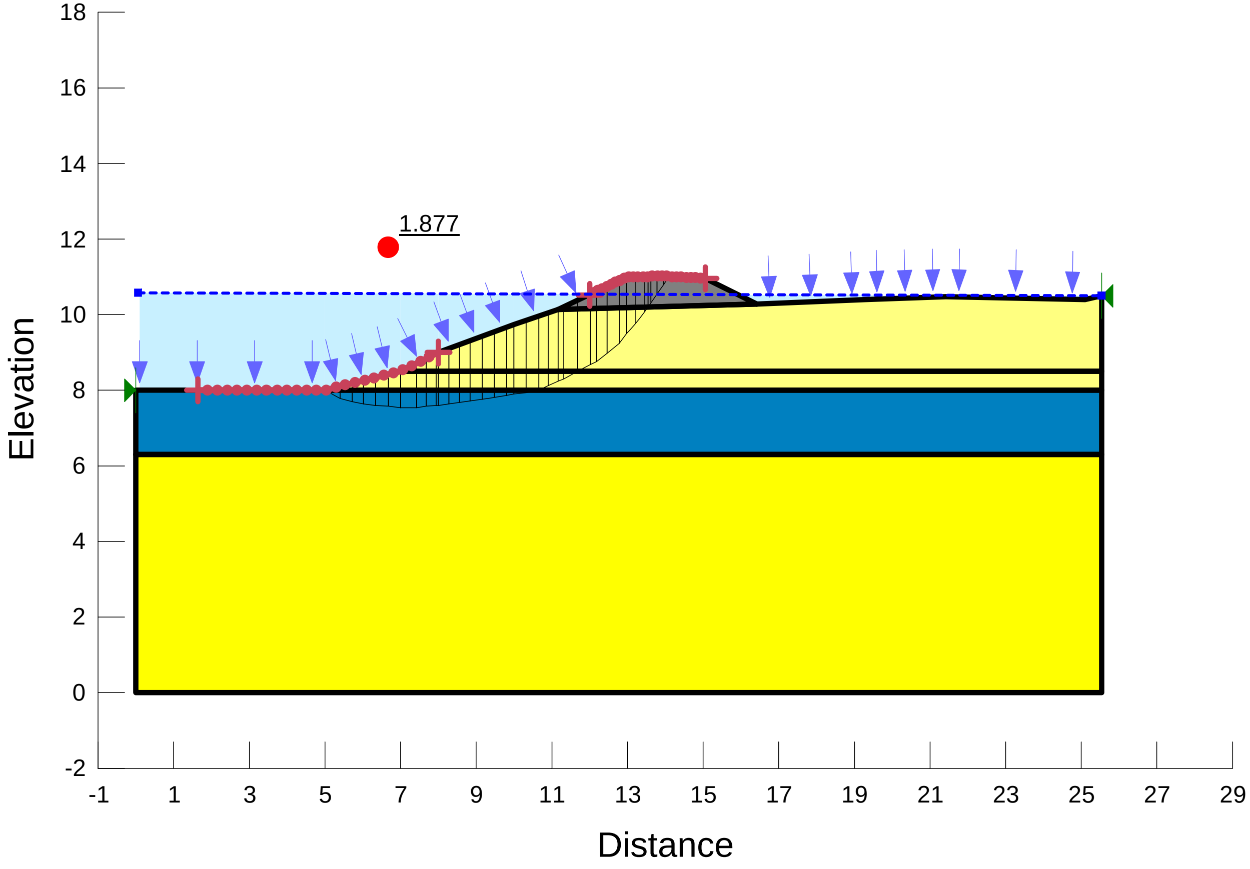
Name: Bund
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 30 °

Name: Sand Bag
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 28 °

Name: MD SAND
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 34 °

Name: Loose SAND
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 30 °

Section15 Static HWT



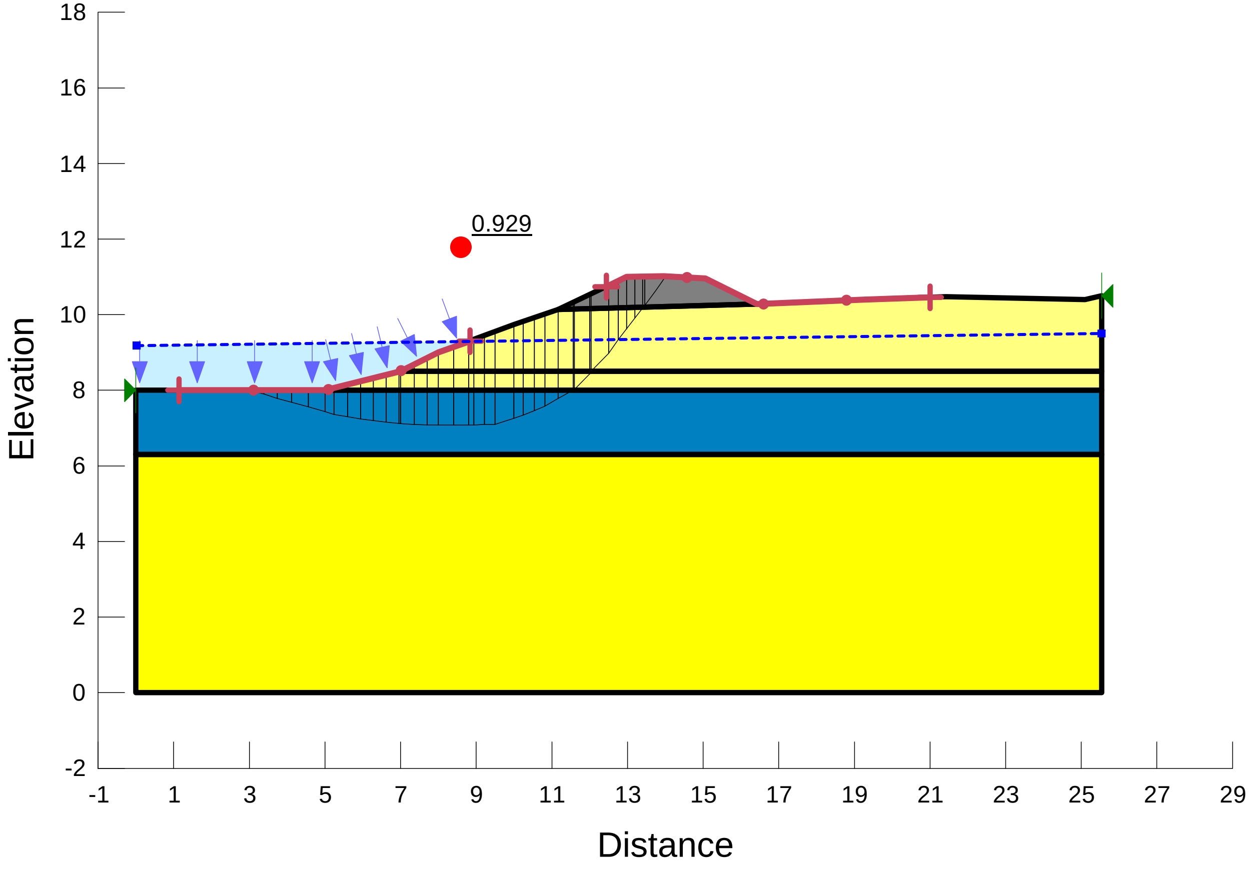
Name: Bund
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 36 °

Name: Loose SAND
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 32 °

Name: SILT
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 24 °

Name: MD SAND
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 0 kPa
Phi': 36 °

Section15 Seismic

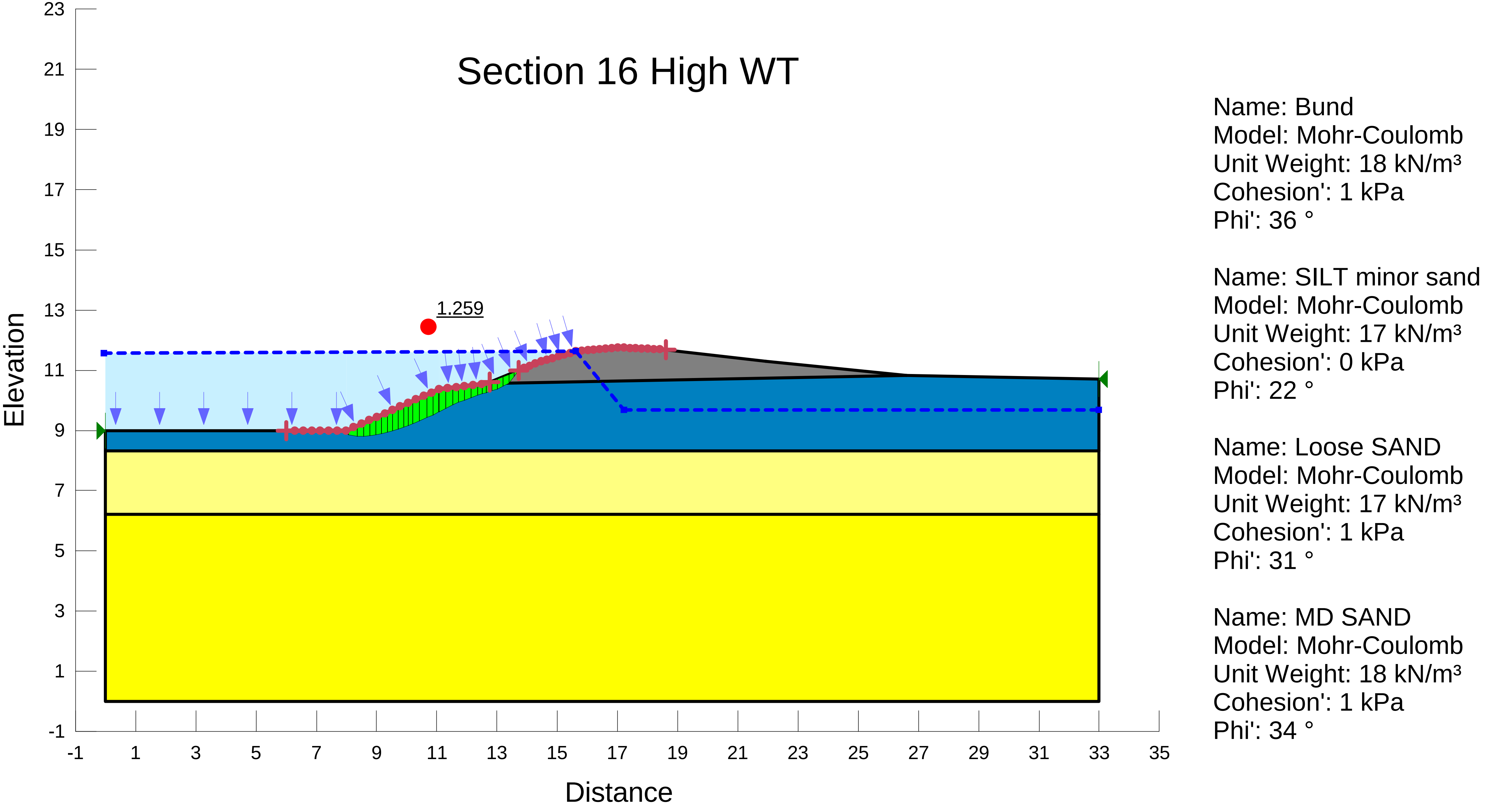


Name: Bund
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 36 °

Name: Loose SAND
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 32 °

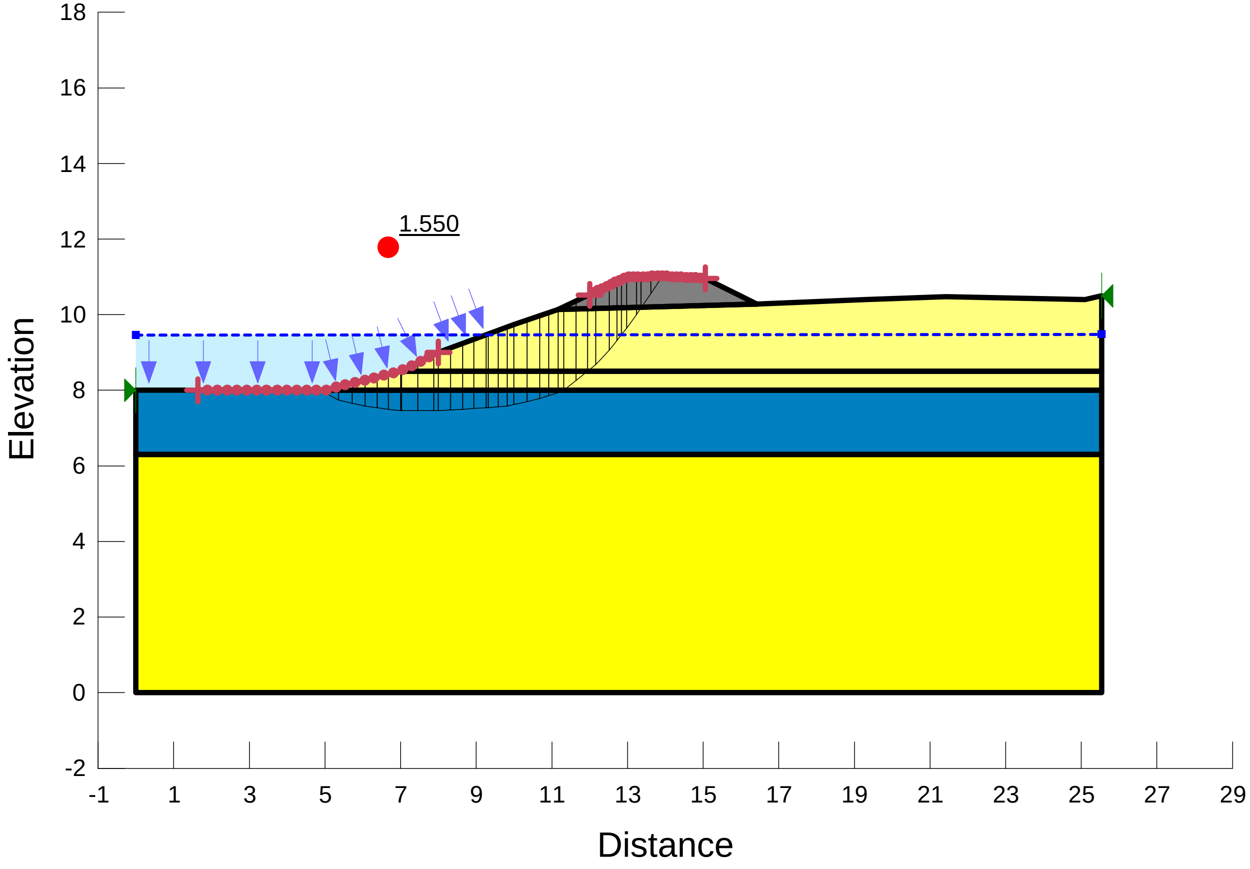
Name: SILT
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 24 °

Name: MD SAND
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 0 kPa
Phi': 36 °



Section 16 High WT
1.259
Elevation
Distance
23
21
19
17
15
13
11
9
7
5
3
1
-1
-1
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
Name: Bund
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 36 °
Name: SILT minor sand
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 0 kPa
Phi': 22 °
Name: Loose SAND
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 31 °
Name: MD SAND
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 34 °

Section15 Static

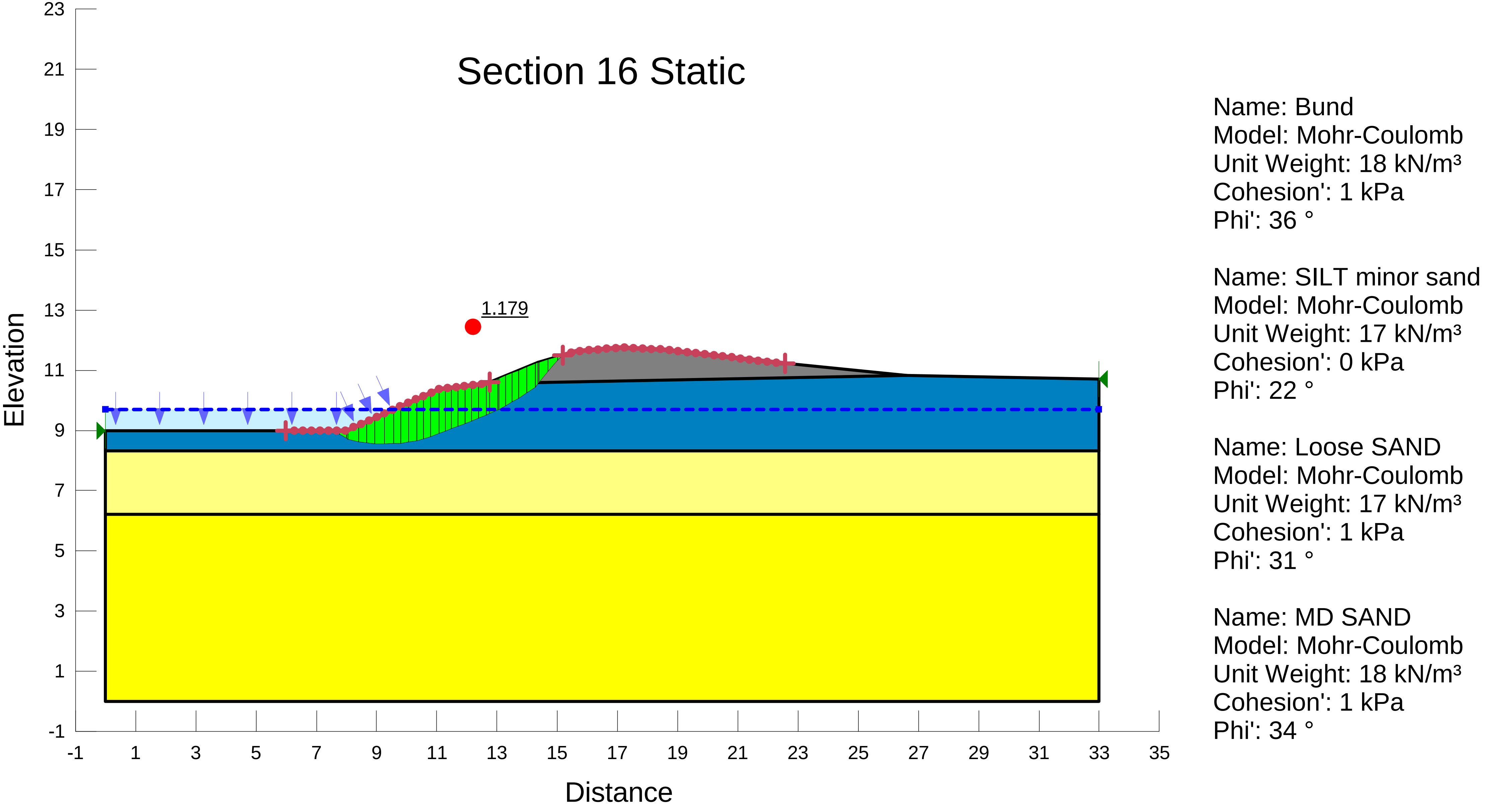


Name: Bund
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 36 °

Name: Loose SAND
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 32 °

Name: SILT
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 24 °

Name: MD SAND
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 0 kPa
Phi': 36 °


Section 16 Static
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Elevation
Distance
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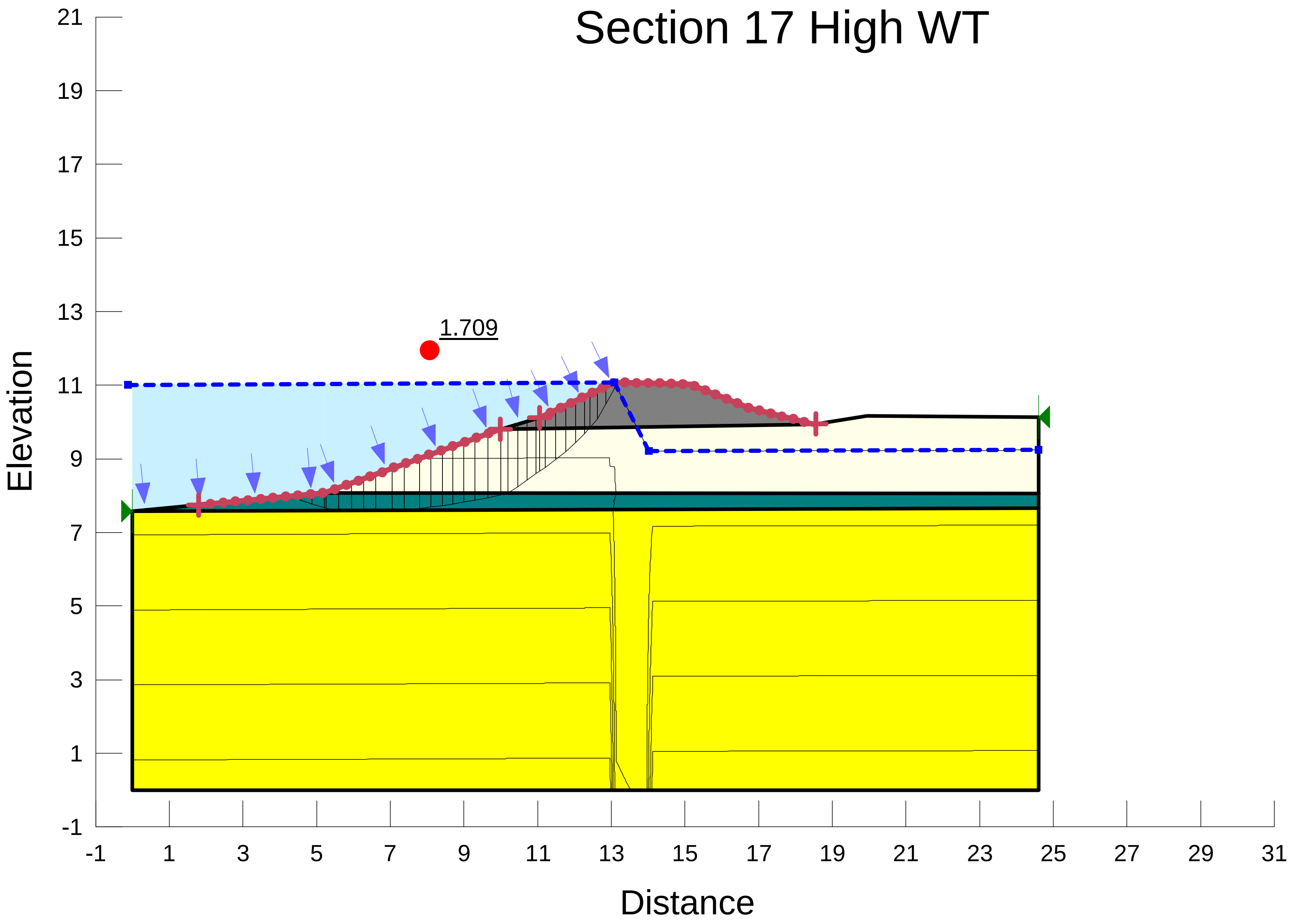
21
19
17
15
13
11
9
7
5
3
1
-1
-1
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
Name: Bund
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 36 °
Name: SILT minor sand
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 0 kPa
Phi': 22 °
Name: Loose SAND
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 31 °
Name: MD SAND
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 34 °



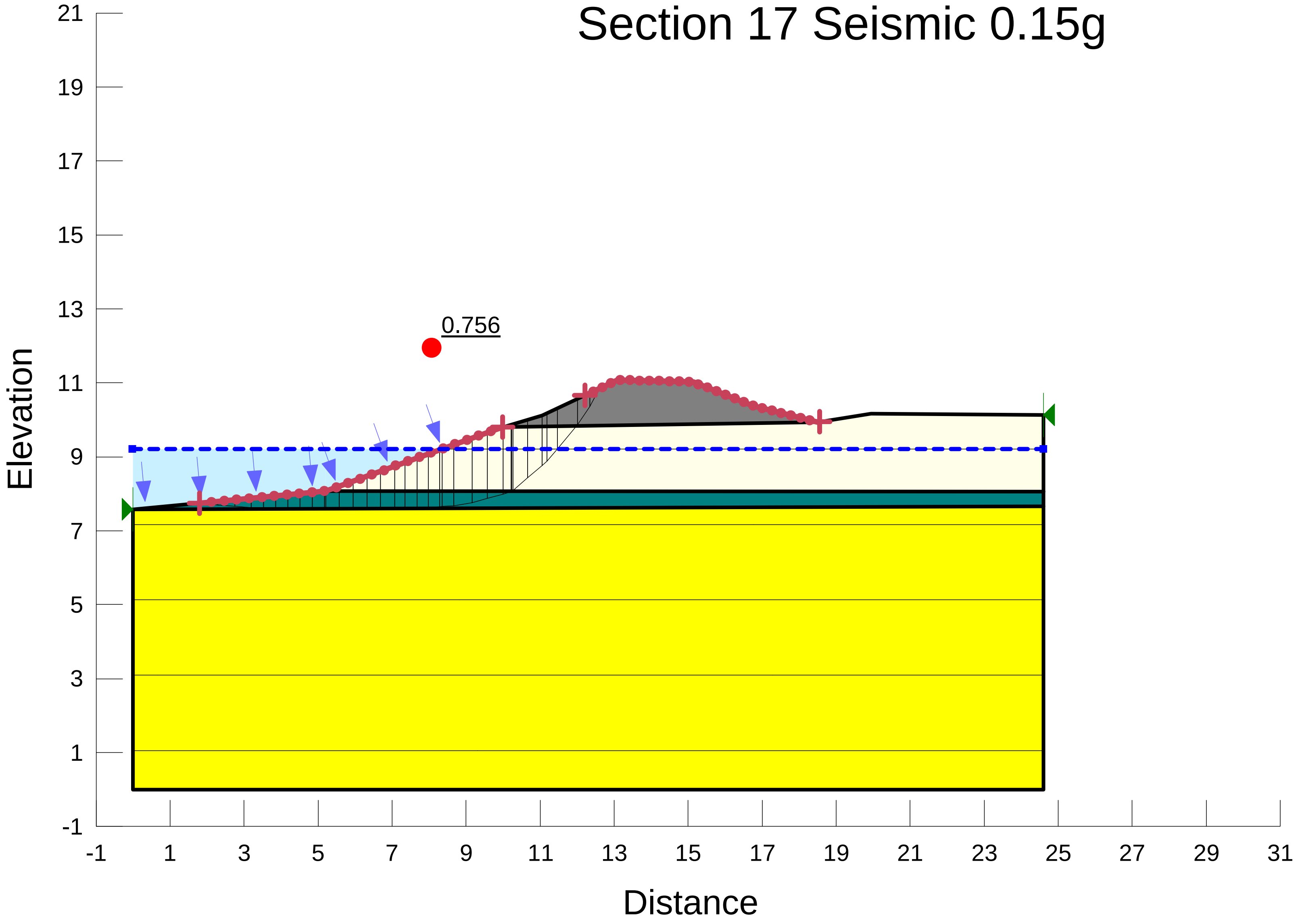
Name: Loose SAND
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 31 °

Name: Sandy SILT
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 0 kPa
Phi': 22 °

Name: Bund
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 36 °

Name: MD SAND
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 34 °

Section 17 Seismic 0.15g



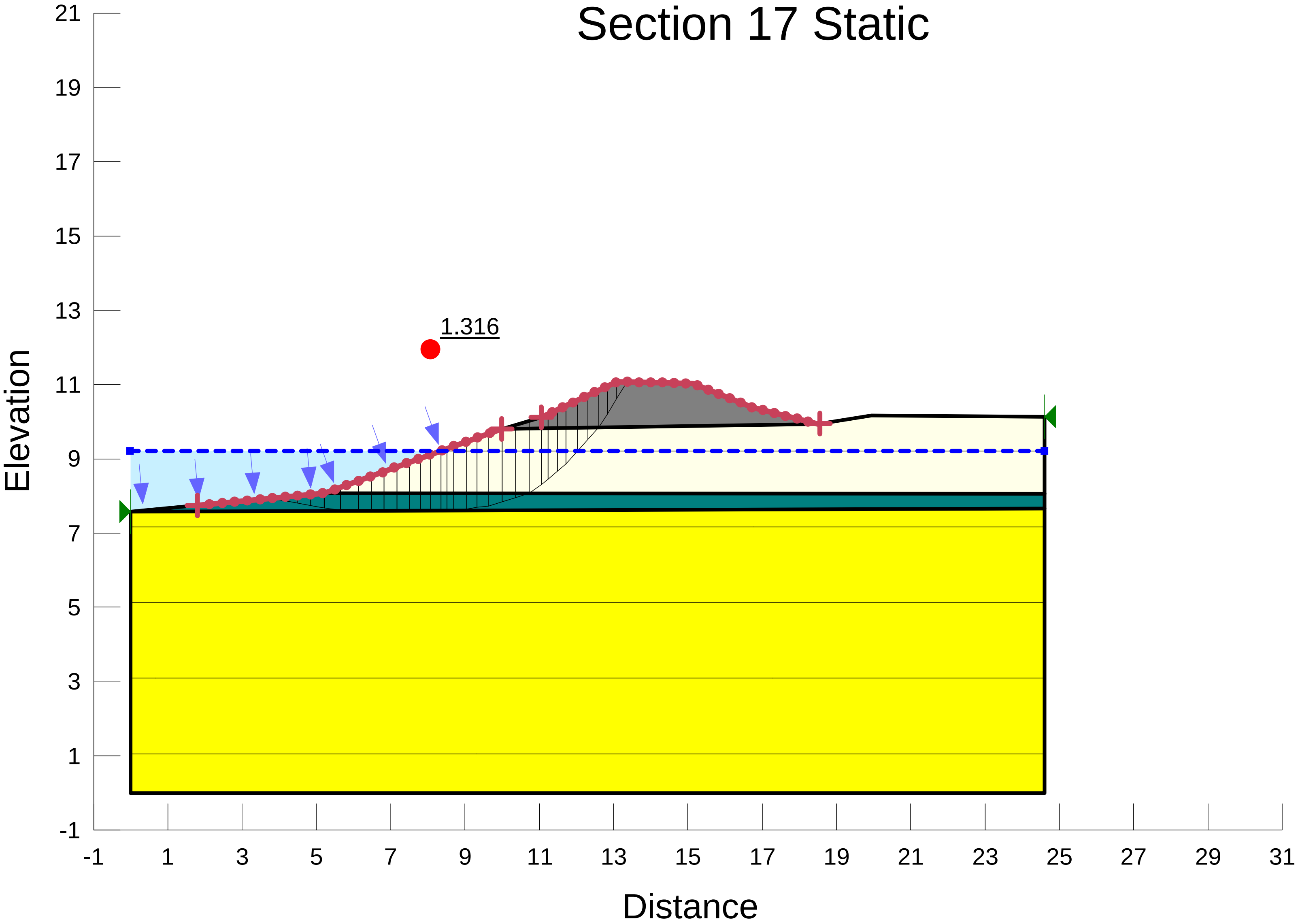
Name: Loose SAND
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 31 °

Name: Sandy SILT
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 0 kPa
Phi': 22 °

Name: Bund
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 36 °

Name: MD SAND
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 34 °

Section 17 Static

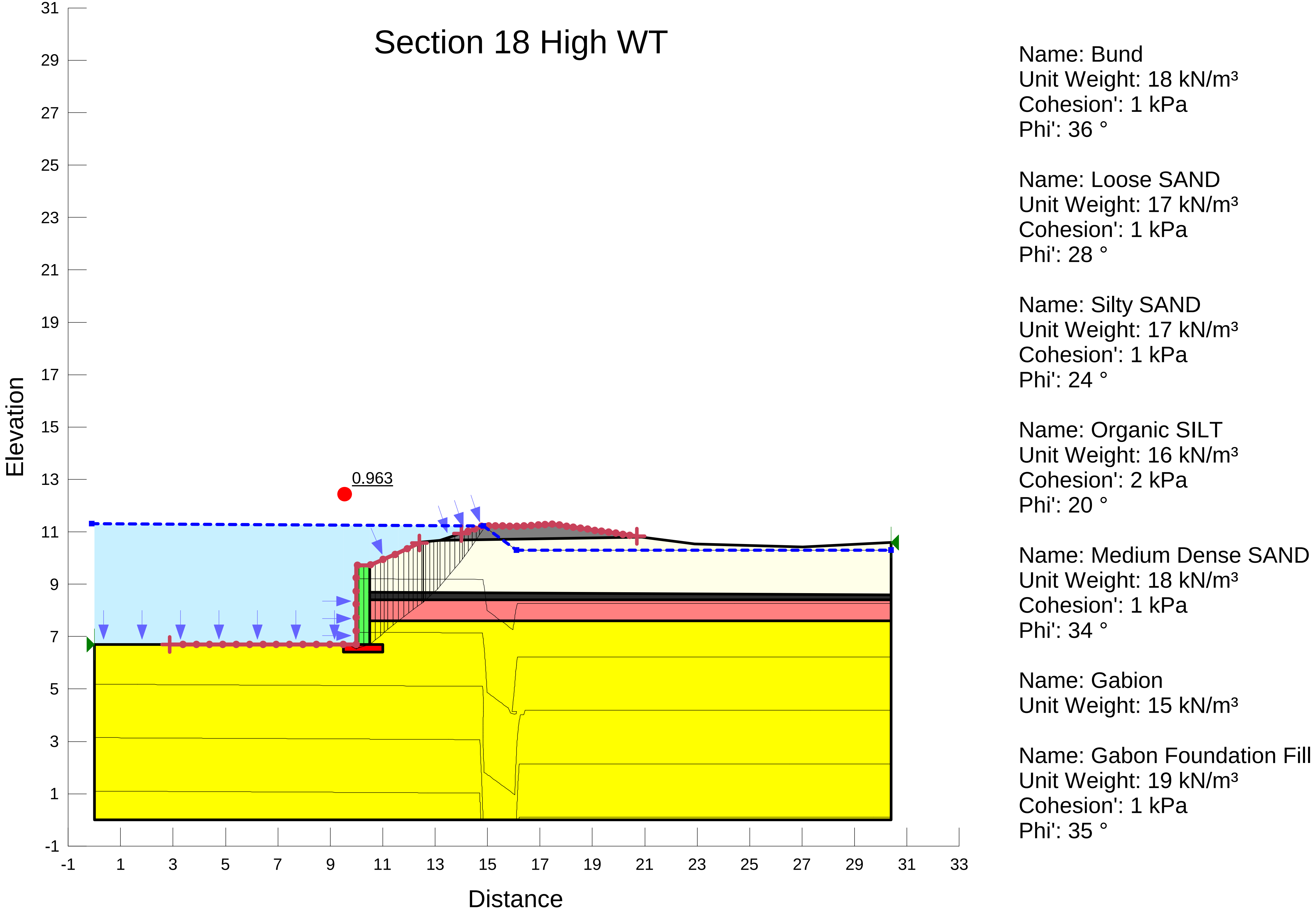


Name: Loose SAND
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 31 °

Name: Sandy SILT
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 0 kPa
Phi': 22 °

Name: Bund
Model: Mohr-Coulomb
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 36 °

Name: MD SAND
Model: Mohr-Coulomb
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 34 °



Section 18 High WT
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Elevation
Distance
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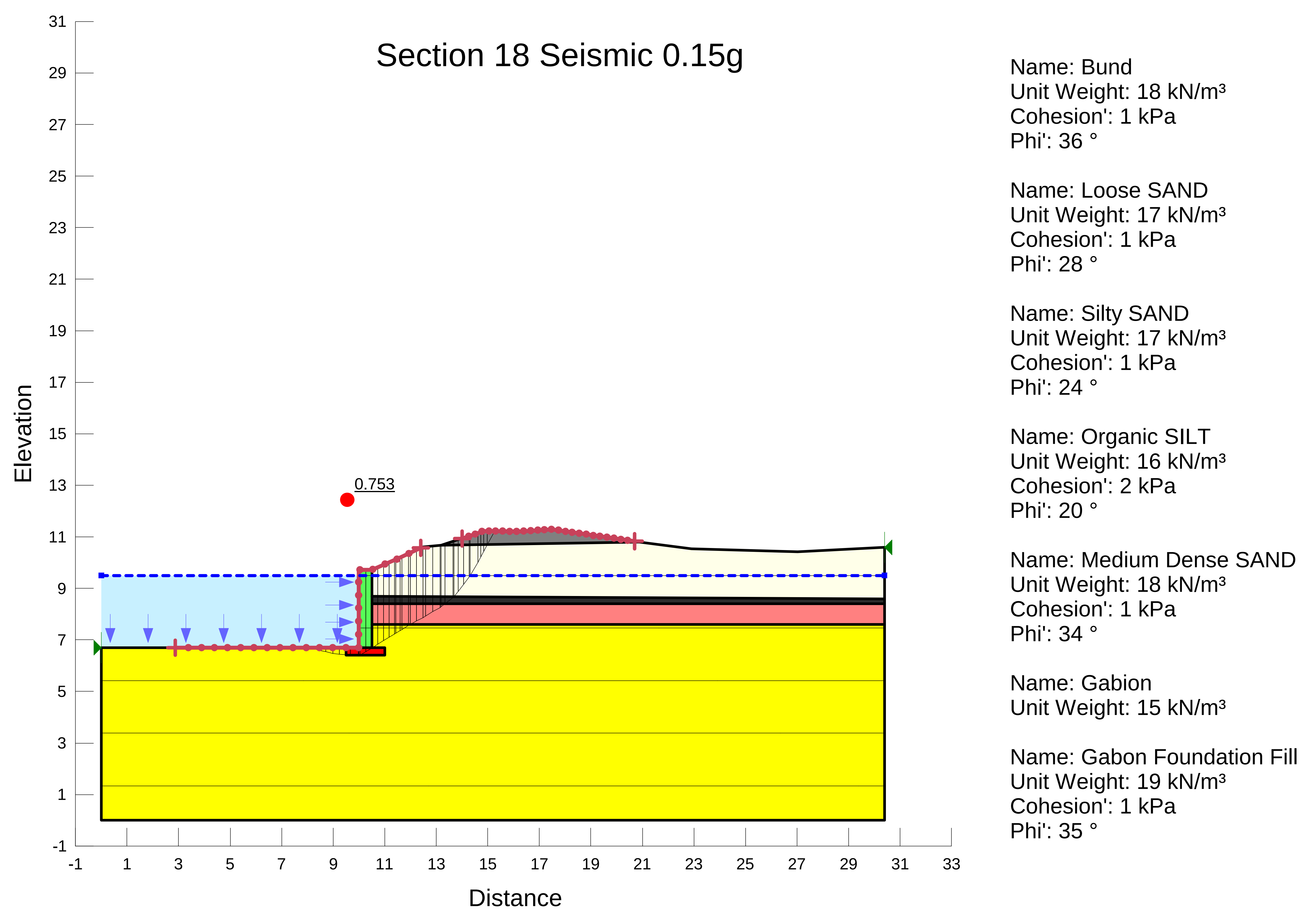
29
27
25
23
21
19
17
15
13
11
9
7
5
3
1
-1
-1
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
Name: Bund
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 36 °
Name: Loose SAND
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 28 °
Name: Silty SAND
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 24 °
Name: Organic SILT
Unit Weight: 16 kN/m³
Cohesion': 2 kPa
Phi': 20 °
Name: Medium Dense SAND
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 34 °
Name: Gabion
Unit Weight: 15 kN/m³
Name: Gabon Foundation Fill
Unit Weight: 19 kN/m³
Cohesion': 1 kPa
Phi': 35 °


Section 18 Seismic 0.15g
0.753
Elevation
Distance
31
29
27
25
23
21
19
17
15
13
11
9
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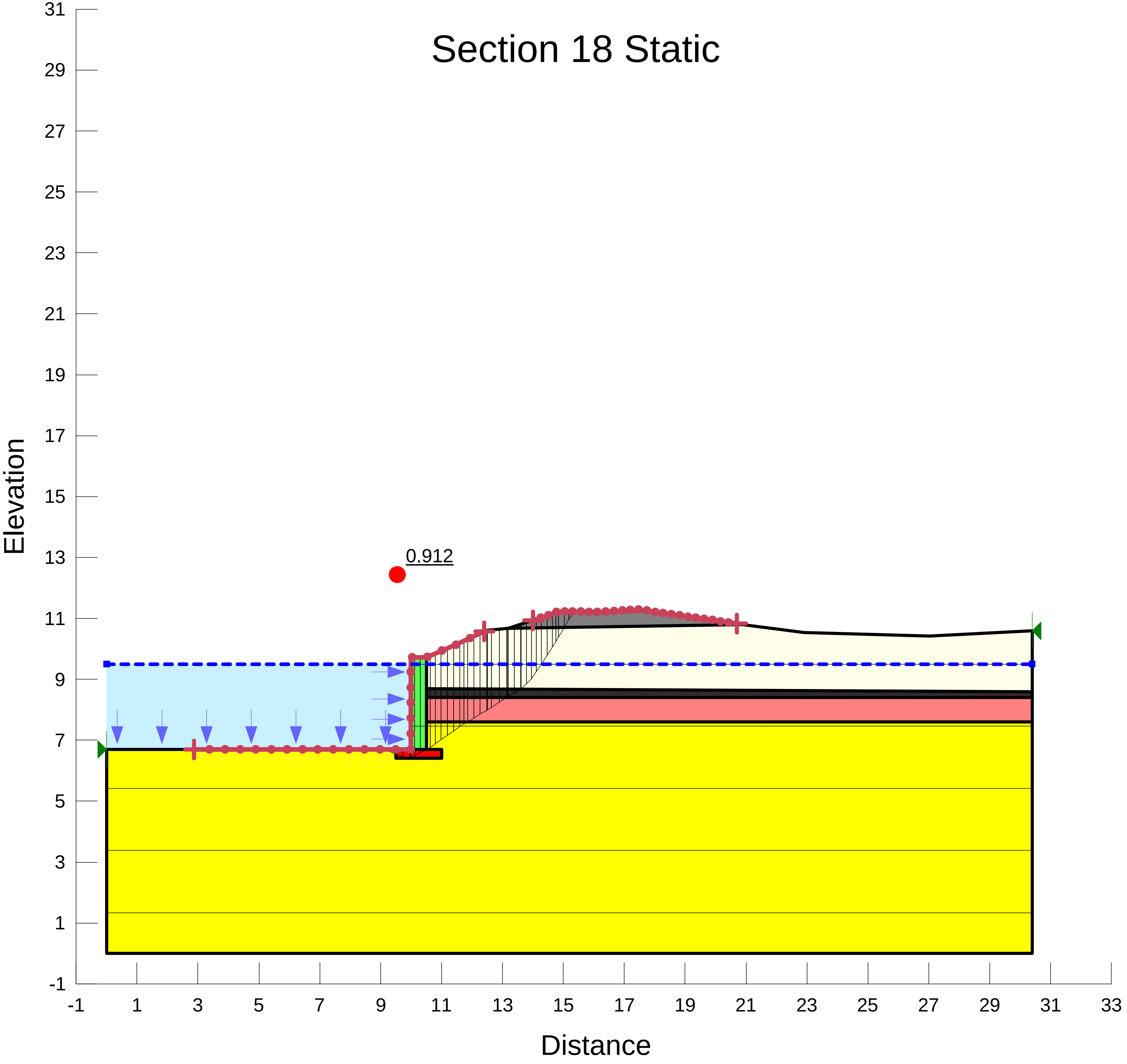
3
1
-1
-1
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
Name: Bund
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 36 °
Name: Loose SAND
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 28 °
Name: Silty SAND
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 24 °
Name: Organic SILT
Unit Weight: 16 kN/m³
Cohesion': 2 kPa
Phi': 20 °
Name: Medium Dense SAND
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 34 °
Name: Gabion
Unit Weight: 15 kN/m³
Name: Gabon Foundation Fill
Unit Weight: 19 kN/m³
Cohesion': 1 kPa
Phi': 35 °

Section 18 Static



Name: Bund
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 36 °

Name: Loose SAND
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 28 °

Name: Silty SAND
Unit Weight: 17 kN/m³
Cohesion': 1 kPa
Phi': 24 °

Name: Organic SILT
Unit Weight: 16 kN/m³
Cohesion': 2 kPa
Phi': 20 °

Name: Medium Dense SAND
Unit Weight: 18 kN/m³
Cohesion': 1 kPa
Phi': 34 °

Name: Gabion
Unit Weight: 15 kN/m³

Name: Gabon Foundation Fill
Unit Weight: 19 kN/m³
Cohesion': 1 kPa
Phi': 35 °

Appendix J – Risk Analysis Results

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180 Lonsdale Street Melbourne Vic 3000

Tidal Events with Seismic loading Failure Probability

Seismic	1	5	10	20	Adjusted 1	Adjusted 5	Adjusted 10	Adjusted 20
Section15	7.47E-04	3.17E-03	5.37E-03	8.37E-03	7.41E-04	2.88E-03	4.59E-03	6.71E-03
Section2	1.02E-06	3.32E-06	5.45E-06	8.75E-06	1.01E-06	3.02E-06	4.66E-06	7.01E-06
Section16	2.11E-07	7.06E-07	1.07E-06	1.49E-06	2.09E-07	6.42E-07	9.11E-07	1.19E-06
Section18	1.24E-06	3.02E-06	4.34E-06	6.12E-06	1.23E-06	2.75E-06	3.71E-06	4.90E-06
Section17	3.00E-06	8.62E-06	1.39E-05	2.23E-05	2.97E-06	7.84E-06	1.18E-05	1.78E-05
Section4	1.57E-08	7.52E-08	1.43E-07	2.61E-07	1.55E-08	6.84E-08	1.22E-07	2.09E-07
Section3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Section8	5.05E-03	6.71E-02	1.12E-01	1.56E-01	5.01E-03	6.10E-02	9.62E-02	1.25E-01
Section1	8.04E-09	3.92E-08	7.60E-08	1.43E-07	7.97E-09	3.57E-08	6.50E-08	1.15E-07
Section12	1.59E-03	2.59E-02	4.98E-02	8.10E-02	1.58E-03	2.36E-02	4.26E-02	6.49E-02
Section6	1.57E-02	1.24E-01	1.75E-01	2.19E-01	1.56E-02	1.13E-01	1.50E-01	1.75E-01
Section10	7.62E-09	3.72E-08	7.21E-08	1.36E-07	7.56E-09	3.38E-08	6.16E-08	1.09E-07
Section11	1.08E-04	5.17E-04	9.87E-04	1.81E-03	1.07E-04	4.70E-04	8.44E-04	1.45E-03
Section13	1.28E-04	6.12E-04	1.16E-03	2.09E-03	1.27E-04	5.57E-04	9.90E-04	1.67E-03
Section14	7.37E-08	3.23E-07	5.62E-07	8.97E-07	7.31E-08	2.94E-07	4.81E-07	7.19E-07
Section9	1.89E-06	6.65E-06	1.16E-05	2.02E-05	1.87E-06	6.05E-06	9.91E-06	1.62E-05
Section7	3.63E-03	5.00E-02	8.75E-02	1.28E-01	3.60E-03	4.55E-02	7.48E-02	1.02E-01
Section5	1.41E-04	6.63E-04	1.24E-03	2.21E-03	1.39E-04	6.03E-04	1.06E-03	1.77E-03
Section 21	1.89E-07	7.69E-07	1.25E-06	1.86E-06	1.88E-07	7.00E-07	1.07E-06	1.49E-06
Sum	2.71E-02	2.72E-01	4.34E-01	5.98E-01				
Common cause	2.69E-02	2.47E-01	3.71E-01	4.79E-01				
Factor	0.992	0.910	0.855	0.801				

Tidal events Failure Probability

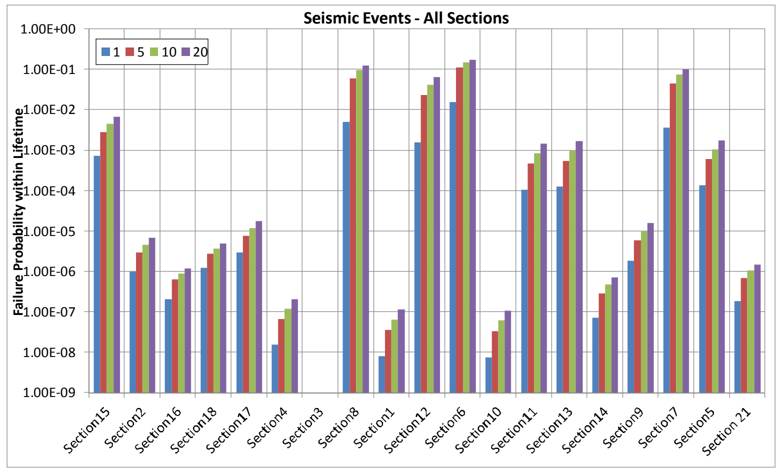
Tides	1	5	10	20	Adjusted 1	Adjusted 5	Adjusted 10	Adjusted 20
Section15	8.26E-04	1.65E-03	2.15E-03	2.73E-03	7.68E-04	7.81E-04	7.44E-04	7.77E-04
Section2	1.21E-04	2.62E-04	3.84E-04	1.54E-03	1.12E-04	1.24E-04	1.33E-04	4.38E-04
Section16	2.90E-05	6.95E-05	9.60E-05	1.26E-04	2.70E-05	3.30E-05	3.32E-05	3.59E-05
Section18	2.19E-04	4.35E-04	5.59E-04	6.93E-04	2.04E-04	2.06E-04	1.94E-04	1.97E-04
Section17	1.79E-04	3.44E-04	4.36E-04	5.34E-04	1.66E-04	1.63E-04	1.51E-04	1.52E-04
Section4	8.36E-05	1.70E-04	2.20E-04	2.75E-04	7.77E-05	8.05E-05	7.62E-05	7.83E-05
Section3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Section8	1.97E-02	2.13E-01	4.02E-01	6.99E-01	1.83E-02	1.01E-01	1.39E-01	1.99E-01
Section1	5.84E-05	1.23E-04	1.63E-04	2.07E-04	5.43E-05	5.86E-05	5.65E-05	5.88E-05
Section12	2.70E-02	2.16E-01	4.04E-01	7.06E-01	2.51E-02	1.02E-01	1.40E-01	2.01E-01
Section6	5.67E-02	7.78E-01	1.00E+00	1.00E+00	5.28E-02	3.69E-01	3.46E-01	2.85E-01
Section10	3.97E-06	1.40E-05	2.35E-05	3.72E-05	3.69E-06	6.63E-06	8.12E-06	1.06E-05
Section11	3.30E-03	6.07E-03	7.55E-03	9.19E-03	3.07E-03	2.88E-03	2.61E-03	2.61E-03
Section13	1.76E-02	3.45E-02	4.53E-02	5.95E-02	1.64E-02	1.63E-02	1.57E-02	1.69E-02
Section14	1.05E-05	3.89E-05	6.40E-05	1.61E-04	9.78E-06	1.85E-05	2.21E-05	4.58E-05
Section9	6.92E-04	1.32E-03	1.70E-03	2.31E-03	6.43E-04	6.28E-04	5.87E-04	6.56E-04
Section7	5.90E-02	7.78E-01	1.00E+00	1.00E+00	5.49E-02	3.69E-01	3.46E-01	2.85E-01
Section5	3.23E-04	1.55E-03	2.97E-03	5.60E-03	3.00E-04	7.34E-04	1.03E-03	1.59E-03
Section 21	2.43E-03	1.58E-02	2.14E-02	2.59E-02	2.26E-03	7.49E-03	7.41E-03	7.39E-03
Sum	1.88E-01	2.05E+00	2.89E+00	3.51E+00				
Common cause	1.75E-01	9.71E-01	1.00E+00	1.00E+00				
Factor	0.930	0.474	0.346	0.285				

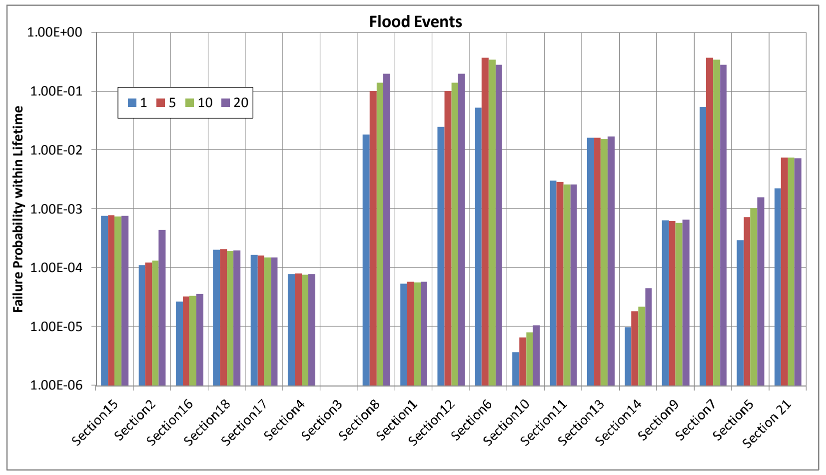
Failure Probability
Total Adjusted

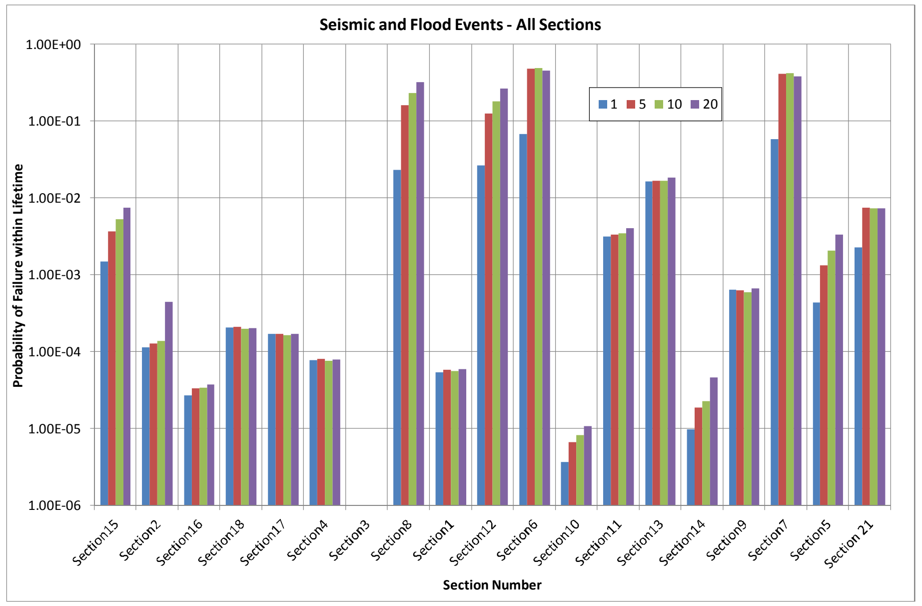
Section		1	5	10	20
15	Section 15	1.51E-03	3.66E-03	5.34E-03	7.48E-03
2	Section 2	1.13E-04	1.27E-04	1.37E-04	4.45E-04
16	Section 16	2.72E-05	3.36E-05	3.42E-05	3.71E-05
18	Section 18	2.05E-04	2.09E-04	1.97E-04	2.02E-04
17	Section 17	1.69E-04	1.71E-04	1.63E-04	1.70E-04
4	Section 4	7.78E-05	8.05E-05	7.63E-05	7.85E-05
3	Section 3	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	Section 8	2.33E-02	1.62E-01	2.35E-01	3.24E-01
1	Section 1	5.43E-05	5.86E-05	5.65E-05	5.90E-05
12	Section 12	2.67E-02	1.26E-01	1.82E-01	2.66E-01
6	Section 6	6.84E-02	4.82E-01	4.96E-01	4.60E-01
10	Section 10	3.70E-06	6.66E-06	8.18E-06	1.07E-05
11	Section 11	3.18E-03	3.35E-03	3.46E-03	4.07E-03
13	Section 13	1.65E-02	1.69E-02	1.67E-02	1.86E-02
14	Section 14	9.85E-06	1.87E-05	2.26E-05	4.65E-05
9	Section 9	6.45E-04	6.34E-04	5.97E-04	6.72E-04
7	Section 7	5.85E-02	4.15E-01	4.21E-01	3.87E-01
5	Section 5	4.39E-04	1.34E-03	2.09E-03	3.36E-03
21	Section 21	2.26E-03	7.49E-03	7.41E-03	7.39E-03

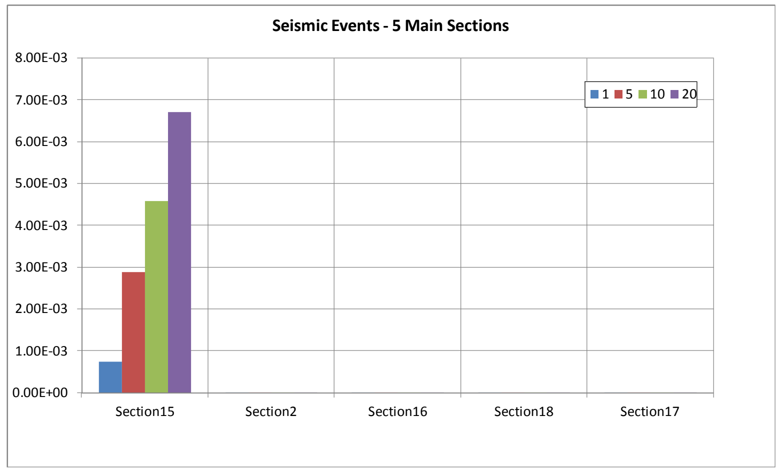
Escalation factors

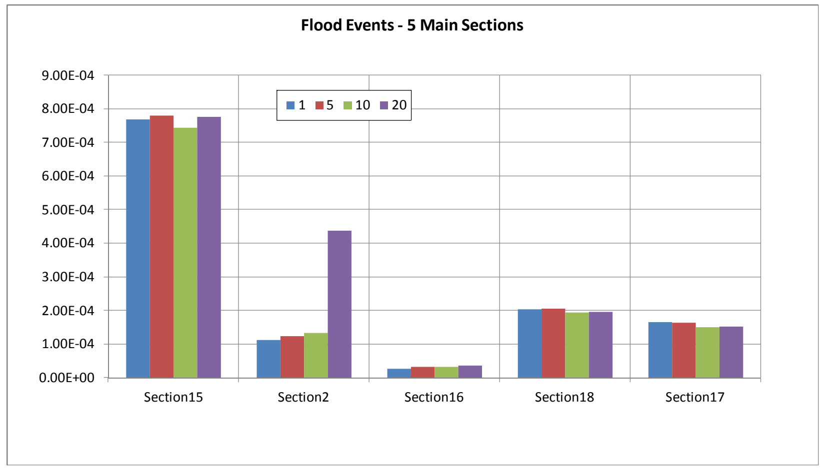
	1	5	10	20
Section 15	1.00	2.43	3.54	4.96
Section 2	1.00	1.12	1.21	3.93
Section 16	1.00	1.24	1.26	1.36
Section 18	1.00	1.02	0.96	0.98
Section 17	1.00	1.01	0.96	1.00
Section 4	1.00	1.04	0.98	1.01
Section 3				
Section 8	1.00	6.96	10.09	13.87
Section 1	1.00	1.08	1.04	1.09
Section 12	1.00	4.72	6.83	9.95
Section 6	1.00	7.04	7.25	6.73
Section 10	1.00	1.80	2.21	2.89
Section 11	1.00	1.05	1.09	1.28
Section 13	1.00	1.02	1.01	1.13
Section 14	1.00	1.90	2.30	4.72
Section 9	1.00	0.98	0.92	1.04
Section 7	1.00	7.09	7.20	6.61
Section 5	1.00	3.04	4.76	7.65
Section 21	1.00	3.31	3.27	3.26
Overall Average	1.00	2.66	3.16	4.08

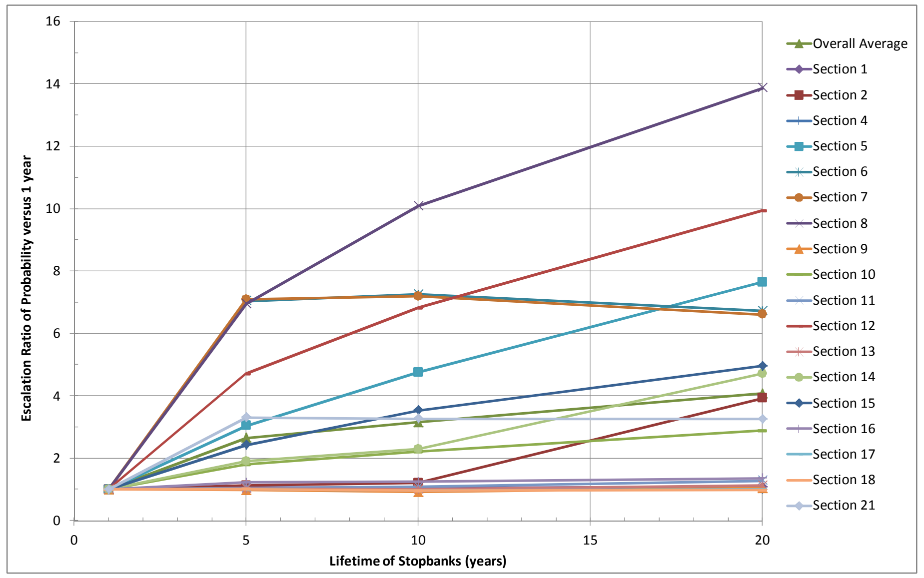


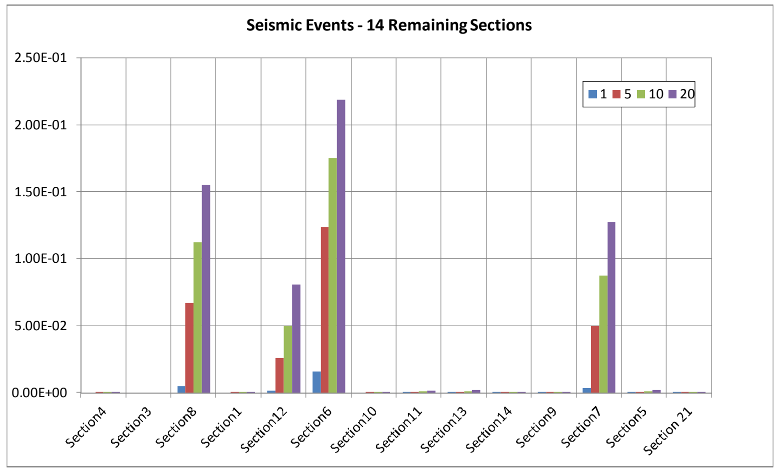


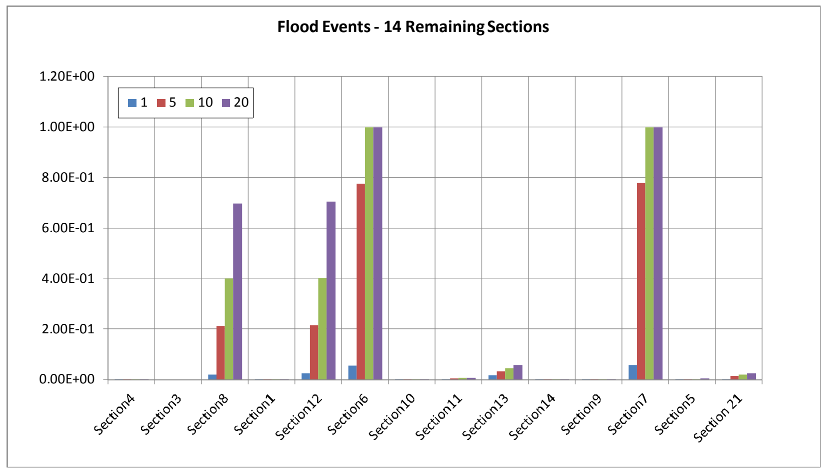












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Tidal Events with Seismic loading Failure Probability

	Seismic				Adjusted			
	1	**5**	**10**	**20**	**1**	**5**	**10**	**20**
Section15	7.47E-04	3.17E-03	5.37E-03	8.37E-03	7.41E-04	2.88E-03	4.59E-03	6.71E-03
Section2	1.02E-06	3.32E-06	5.45E-06	8.75E-06	1.01E-06	3.02E-06	4.66E-06	7.01E-06
Section16	2.11E-07	7.06E-07	1.07E-06	1.49E-06	2.09E-07	6.42E-07	9.11E-07	1.19E-06
Section18	1.24E-06	3.02E-06	4.34E-06	6.12E-06	1.23E-06	2.75E-06	3.71E-06	4.90E-06
Section17	3.00E-06	8.62E-06	1.39E-05	2.23E-05	2.97E-06	7.84E-06	1.18E-05	1.78E-05
Section4	1.57E-08	7.52E-08	1.43E-07	2.61E-07	1.55E-08	6.84E-08	1.22E-07	2.09E-07
Section3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Section8	5.05E-03	6.71E-02	1.12E-01	1.56E-01	5.01E-03	6.10E-02	9.62E-02	1.25E-01
Section1	8.04E-09	3.92E-08	7.60E-08	1.43E-07	7.97E-09	3.57E-08	6.50E-08	1.15E-07
Section12	1.59E-03	2.59E-02	4.98E-02	8.10E-02	1.58E-03	2.36E-02	4.26E-02	6.49E-02
Section6	1.57E-02	1.24E-01	1.75E-01	2.19E-01	1.56E-02	1.13E-01	1.50E-01	1.75E-01
Section10	7.62E-09	3.72E-08	7.21E-08	1.36E-07	7.56E-09	3.38E-08	6.16E-08	1.09E-07
Section11	1.08E-04	5.17E-04	9.87E-04	1.81E-03	1.07E-04	4.70E-04	8.44E-04	1.45E-03
Section13	1.28E-04	6.12E-04	1.16E-03	2.09E-03	1.27E-04	5.57E-04	9.90E-04	1.67E-03
Section14	7.37E-08	3.23E-07	5.62E-07	8.97E-07	7.31E-08	2.94E-07	4.81E-07	7.19E-07
Section9	1.89E-06	6.65E-06	1.16E-05	2.02E-05	1.87E-06	6.05E-06	9.91E-06	1.62E-05
Section7	3.63E-03	5.00E-02	8.75E-02	1.28E-01	3.60E-03	4.55E-02	7.48E-02	1.02E-01
Section5	1.41E-04	6.63E-04	1.24E-03	2.21E-03	1.39E-04	6.03E-04	1.06E-03	1.77E-03
Section 21	1.89E-07	7.69E-07	1.25E-06	1.86E-06	1.88E-07	7.00E-07	1.07E-06	1.49E-06
Sum	2.71E-02	2.72E-01	4.34E-01	5.98E-01				
Common cause	2.69E-02	2.47E-01	3.71E-01	4.79E-01				
Factor	0.992	0.910	0.855	0.801				

Tidal events Failure Probability

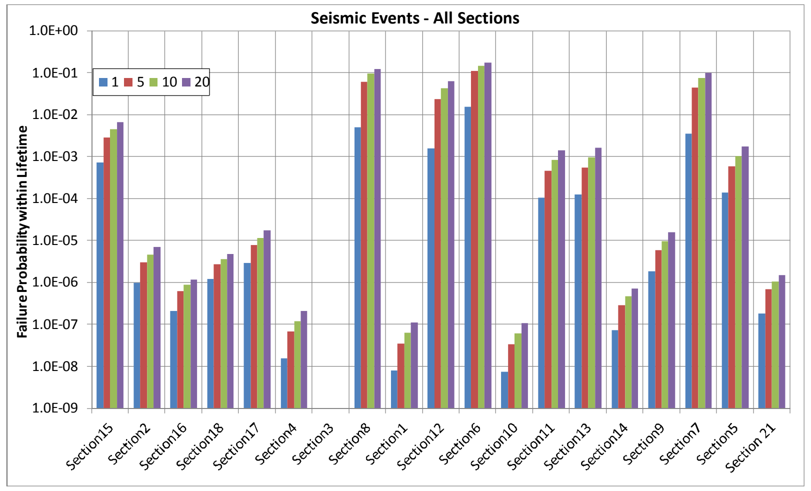
	Tides				Adjusted			
	1	**5**	**10**	**20**	**1**	**5**	**10**	**20**
Section15	1.66E-04	3.21E-04	4.08E-04	5.00E-04	1.60E-04	1.71E-04	1.53E-04	1.54E-04
Section2	1.21E-04	2.61E-04	3.83E-04	1.54E-03	1.16E-04	1.40E-04	1.44E-04	4.74E-04
Section16	2.82E-05	6.82E-05	9.46E-05	1.25E-04	2.72E-05	3.65E-05	3.55E-05	3.84E-05
Section18	2.20E-04	4.35E-04	5.59E-04	6.93E-04	2.12E-04	2.32E-04	2.10E-04	2.13E-04
Section17	1.79E-04	3.44E-04	4.36E-04	5.34E-04	1.72E-04	1.84E-04	1.64E-04	1.64E-04
Section4	8.35E-05	1.69E-04	2.20E-04	2.75E-04	8.05E-05	9.05E-05	8.26E-05	8.47E-05
Section3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Section8	8.39E-03	1.54E-01	3.24E-01	6.09E-01	8.10E-03	8.21E-02	1.22E-01	1.87E-01
Section1	5.84E-05	1.23E-04	1.63E-04	2.07E-04	5.63E-05	6.60E-05	6.13E-05	6.37E-05
Section12	8.89E-03	1.54E-01	3.25E-01	6.14E-01	8.58E-03	8.25E-02	1.22E-01	1.89E-01
Section6	4.60E-02	7.29E-01	1.00E+00	1.00E+00	4.44E-02	3.90E-01	3.76E-01	3.08E-01
Section10	2.55E-06	1.15E-05	2.05E-05	3.39E-05	2.46E-06	6.14E-06	7.71E-06	1.04E-05
Section11	1.11E-04	2.37E-04	3.20E-04	5.03E-04	1.07E-04	1.27E-04	1.20E-04	1.55E-04
Section13	7.51E-04	3.69E-03	7.24E-03	1.40E-02	7.24E-04	1.97E-03	2.72E-03	4.30E-03
Section14	8.34E-06	3.54E-05	6.00E-05	1.56E-04	8.04E-06	1.89E-05	2.25E-05	4.82E-05
Section9	1.41E-04	3.17E-04	4.48E-04	7.88E-04	1.36E-04	1.70E-04	1.68E-04	2.43E-04
Section7	4.56E-02	7.29E-01	1.00E+00	1.00E+00	4.40E-02	3.90E-01	3.76E-01	3.08E-01
Section5	2.63E-04	1.29E-03	2.52E-03	4.88E-03	2.54E-04	6.87E-04	9.47E-04	1.50E-03
Section 21	8.18E-05	1.85E-04	2.53E-04	3.95E-04	7.89E-05	9.89E-05	9.49E-05	1.21E-04
Sum	1.11E-01	1.77E+00	2.66E+00	3.25E+00				
Common cau	1.07E-01	9.48E-01	1.00E+00	1.00E+00				
Factor	0.964	0.534	0.376	0.308				

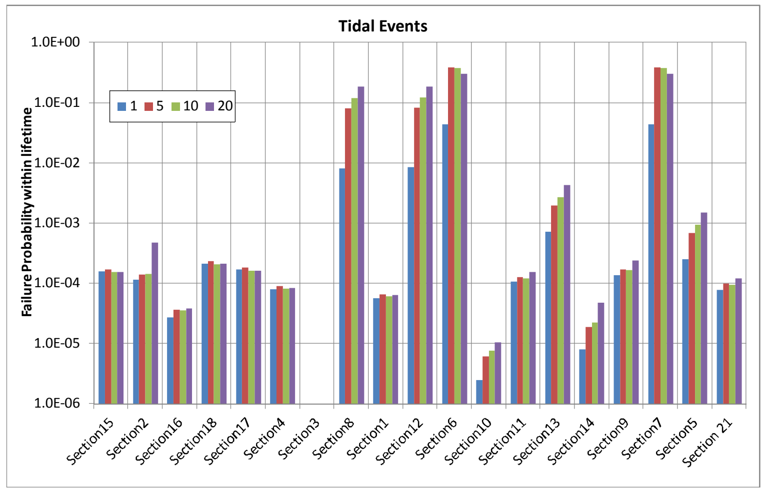
Failure Probability
Total Adjusted

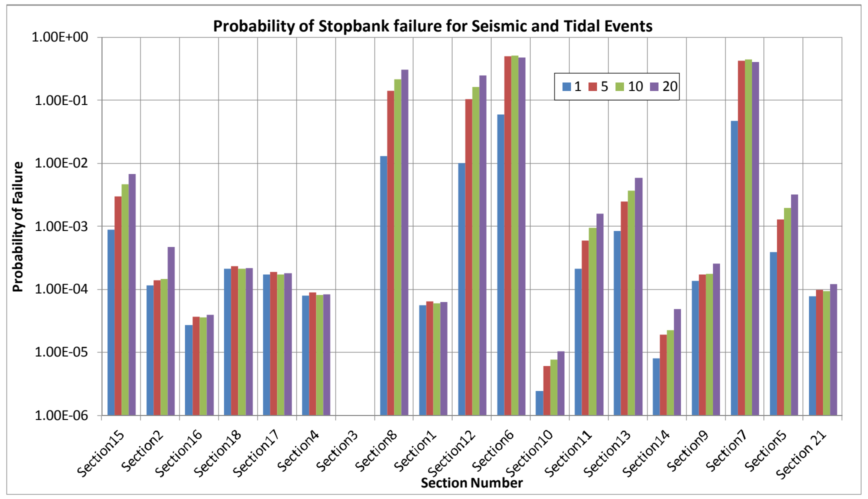
		1	**5**	**10**	**20**
15	Section15	9.01E-04	3.06E-03	4.75E-03	6.86E-03
2	Section2	1.17E-04	1.43E-04	1.49E-04	4.81E-04
16	Section16	2.74E-05	3.71E-05	3.65E-05	3.96E-05
18	Section18	2.13E-04	2.35E-04	2.14E-04	2.18E-04
17	Section17	1.75E-04	1.91E-04	1.76E-04	1.82E-04
4	Section4	8.05E-05	9.06E-05	8.28E-05	8.49E-05
3	Section3	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	Section8	1.31E-02	1.43E-01	2.18E-01	3.12E-01
1	Section1	5.63E-05	6.60E-05	6.13E-05	6.38E-05
12	Section12	1.02E-02	1.06E-01	1.65E-01	2.54E-01
6	Section6	6.00E-02	5.02E-01	5.25E-01	4.83E-01
10	Section10	2.46E-06	6.18E-06	7.77E-06	1.05E-05
11	Section11	2.14E-04	5.97E-04	9.64E-04	1.61E-03
13	Section13	8.51E-04	2.53E-03	3.71E-03	5.97E-03
14	Section14	8.12E-06	1.92E-05	2.30E-05	4.89E-05
9	Section9	1.38E-04	1.76E-04	1.78E-04	2.59E-04
7	Section7	4.76E-02	4.35E-01	4.50E-01	4.10E-01
5	Section5	3.93E-04	1.29E-03	2.01E-03	3.27E-03
2	Section 21	7.91E-05	9.96E-05	9.60E-05	1.23E-04

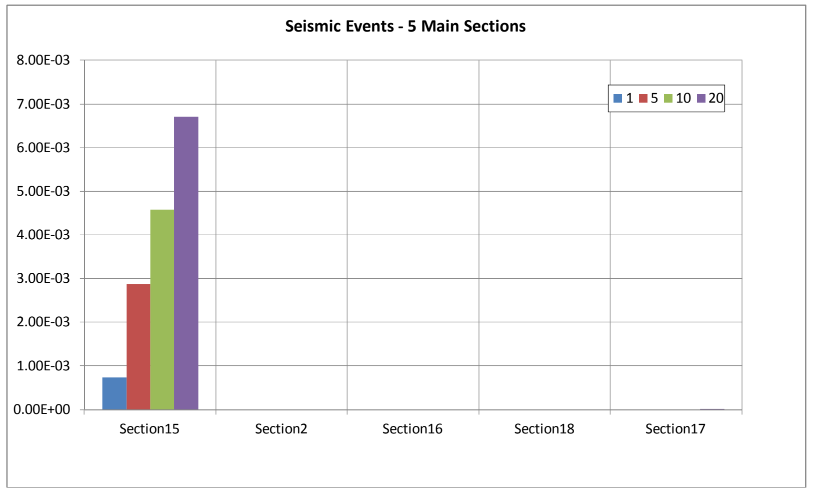
Escalation factors

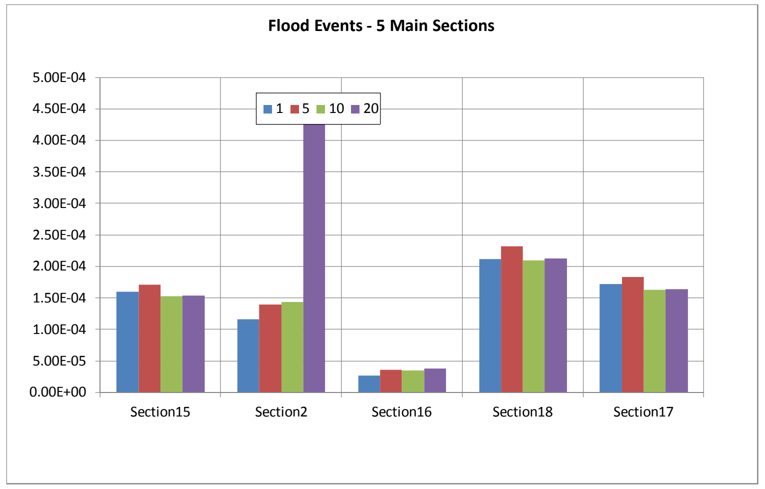
		1	**5**	**10**	**20**
1	Section15	1.00	3.39	5.27	7.61
2	Section2	1.00	1.22	1.27	4.10
3	Section16	1.00	1.36	1.33	1.45
4	Section18	1.00	1.10	1.00	1.02
5	Section17	1.00	1.09	1.00	1.04
6	Section4	1.00	1.12	1.03	1.05
7	Section3				
8	Section8	1.00	10.92	16.63	23.82
9	Section1	1.00	1.17	1.09	1.13
10	Section12	1.00	10.45	16.22	25.02
11	Section6	1.00	8.38	8.76	8.06
12	Section10	1.00	2.51	3.15	4.28
13	Section11	1.00	2.79	4.51	7.53
14	Section13	1.00	2.97	4.36	7.02
15	Section14	1.00	2.37	2.83	6.02
16	Section9	1.00	1.28	1.29	1.88
17	Section7	1.00	9.15	9.47	8.62
18	Section5	1.00	3.28	5.11	8.32
19	Section 21	1.00	1.26	1.21	1.56
	Average	1.00	3.66	4.75	6.64

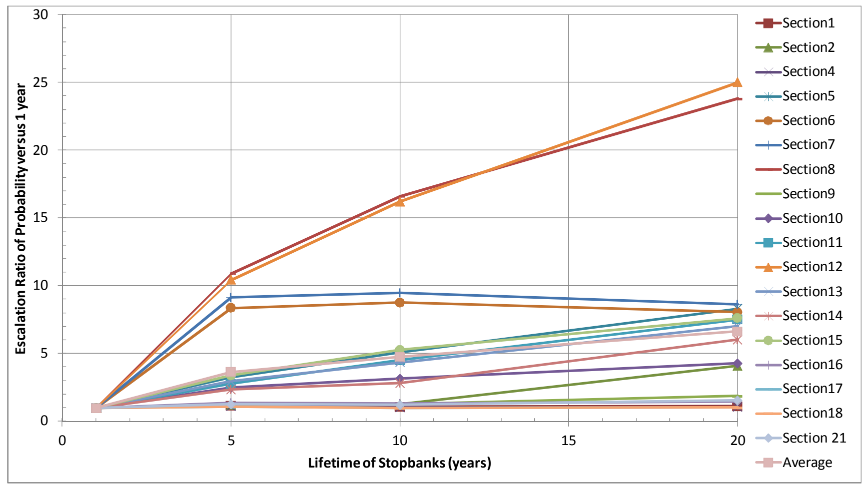


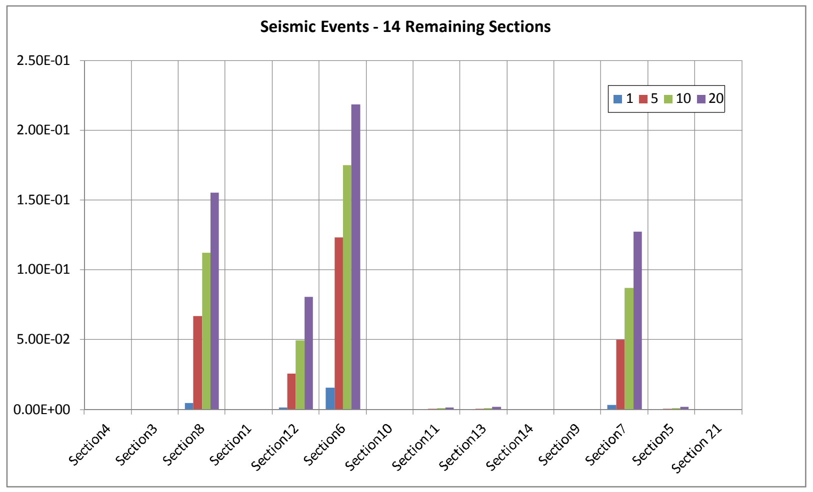


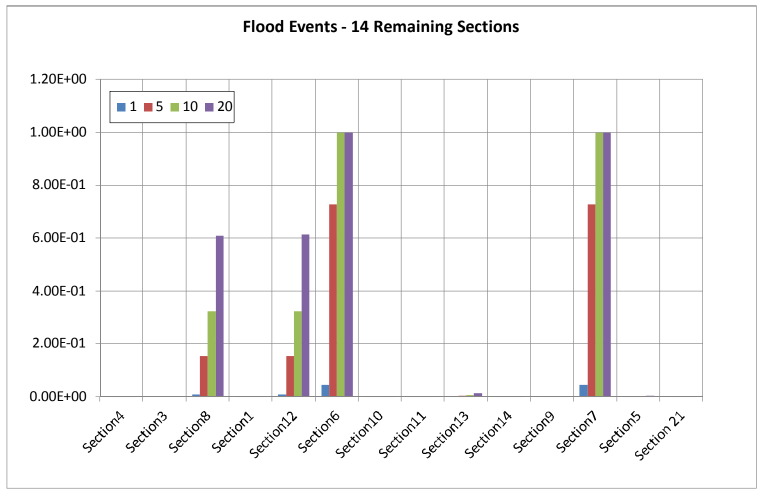












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Christchurch Stopbank
Failure Modes Effects Analysis

Sub-system	Components	Hazard	ID No.	Identification Code	Initiator	Consequence	Leading to	Leading to	Leading to	Leading to	Ultimate outcome	Consequence	Likelihood	Risk	Rejection and Reason		
Section 1	Embankment	Earthquake	1	CSF2b	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	90	1	90			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	90	1	90			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	90	2	180			
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	90	1	90			
				CSF1b	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	90	1	90			
				CSF1a	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	90	1	90		105	180
Section 2	Embankment	Earthquake	1	CSF2b	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	100	3	300			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	100	2	200			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	100	3	300			
				CSF2a	Failure of sandbags	Loss of freeboard	Overtopping if tidal level above crest				Breach	100	3	300	Only applies to Types 6, 7, 8		
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	100	2	200			
				CSF1b	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	100	3	300			
				CSF1a	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	100	2	200			
				CSF2c	Sandbag deteriorates	Overtopping during extreme floods					Breach	100	3	300	Only applies to Types 6, 7, 8		
				CSF1h	Tree roots rot	Open pipes to upstream	Pipe initiation through the embankment.	Continuation (No filter)	Progression with no intervention		Breach	100	2	200			
				CSF2f	Tree falls over	Removal of material from wall	Loss of freeboard	Overtopping			Breach	100	2	200		250	300
Section 3	Embankment	Earthquake	1	CSF2b	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	100	1	100			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	100	1	100			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	100	2	200			
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	100	1	100		125	200
Section 4	Embankment	Earthquake	1	CSF2b	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	100	2	200			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	100	2	200			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	100	2	200			
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	100	1	100			
				CSF1c	Seapage along stormwater pipes	movement of fines	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	100	3	300			
				CSF1b	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	100	3	300			
				CSF1a	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	100	2	200		214	300
Section 5	Embankment	Earthquake	1	CSF2b	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	10	1	10			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	10	1	10			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	10	1	10			
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	10	1	10			
				CSF1b	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	10	2	20			
				CSF1a	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	10	2	20		13	20
Section 6	Embankment	Earthquake	1	CSF2b	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	40	1	40			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	1	40			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	40	1	40			
				CSF2a	Failure of sandbags	Loss of freeboard	Overtopping if tidal level above crest				Breach	40	5	200	Only applies to Types 6, 7, 8		
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	40	2	80			
				CSF2c	Sandbag deteriorates	Overtopping during extreme floods					Breach	40	5	200	Only applies to Types 6, 7, 8		
				CSF1h	Tree roots rot	Open pipes to upstream	Pipe initiation through the embankment.	Continuation (No filter)	Progression with no intervention		Breach	40	2	80			
				CSF2f	Tree falls over	Removal of material from wall	Loss of freeboard	Overtopping			Breach	40	2	80	Scrubby trees - unlikely to fall over	95	200
Section 7	Embankment	Earthquake	1	CSF2b	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	10	2	20			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	10	1	10			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	10	2	20			
				CSF2a	Failure of sandbags	Loss of freeboard	Overtopping if tidal level above crest				Breach	10	5	50	Only applies to Types 6, 7, 8		
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	10	1	10			
				CSF2c	Sandbag deteriorates	Overtopping during extreme floods					Breach	10	5	50	Only applies to Types 6, 7, 8		
				CSF1h	Tree roots rot	Open pipes to upstream	Pipe initiation through the embankment.	Continuation (No filter)	Progression with no intervention		Breach	10	2	20			
				CSF2f	Tree falls over	Removal of material from wall	Loss of freeboard	Overtopping			Breach	10	1	10		24	50

Sub-system	Components	Hazard	ID No.	Identification Code	Initiator	Consequence	Leading to	Leading to	Leading to	Leading to	Ultimate outcome	Consequence	Likelihood	Risk	Rejection and Reason		
Section 8 (Low consequences all red zone but major road with media exposure)	Embankment	Earthquake	1	CSF2b	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	40	2	80			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	2	80			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	40	2	80			
				CSF2a	Failure of sandbags	Loss of freeboard	Overtopping if tidal level above crest				Breach	40	5	200	Only applies to Types 6, 7, 8		
				CSF1d	Differential movement around pipes	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	3	120	Only applies to generic services FM		
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	40	1	40			
				CSF1b	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	1	40			
				CSF1a	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	2	80			
				CSF2c	Sandbag deteriorates	Overtopping during extreme floods					Breach	40	5	200	Only applies to Types 6, 7, 8		
				CSF1h	Tree roots rot	Open pipes to upstream	Pipe initiation through the embankment.	Continuation (No filter)	Progression with no intervention		Breach	40	3	120			
				CSF2f	Tree falls over	Removal of material from wall	Loss of freeboard	Overtopping			Breach	40	4	160		109	200
Section 9 (low consequence red zone only - 1 house outside flood extent)	Embankment	Earthquake	1	CSF2b	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	10	3	30			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	10	2	20			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	10	3	30			
				CSF1d	Differential movement around pipes	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	10	3	30	Only applies to generic services FM		
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	10	1	10			
				CSF1b	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	10	3	30			
				CSF1a	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	10	2	20			
				CSF1h	Tree roots rot	Open pipes to upstream	Pipe initiation through the embankment.	Continuation (No filter)	Progression with no intervention		Breach	10	3	30			
				CSF2f	Tree falls over	Removal of material from wall	Loss of freeboard	Overtopping			Breach	10	4	40		27	40
Section 10 - dismissed - zero consequence possible flooding Lovelock street	Embankment	Earthquake	1	CSF2b	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	40	1	40			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	3	120			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	40	3	120			
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	40	2	80			
				CSF1b	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	2	80			
				CSF1a	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	1	40		80	120
Section 11 - dismissed zero consequence. Possible flooding across Gayhurst road	Embankment	Earthquake	1	CSF2b	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	40	2	80			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	3	120			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	40	3	120			
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	40	2	80			
				CSF1b	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	2	80			
				CSF1a	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	1	40			
				CSF1h	Tree roots rot	Open pipes to upstream	Pipe initiation through the embankment.	Continuation (No filter)	Progression with no intervention		Breach	40	2	80			
				CSF2f	Tree falls over	Removal of material from wall	Loss of freeboard	Overtopping			Breach	40	1	40		80	120
Section 12 - dismissed zero consequence. Possible flooding across Gayhurst road	Embankment	Earthquake	1	CSF2b	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	40	2	80			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	3	120			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	40	3	120			
				CSF2a	Failure of sandbags	Loss of freeboard	Overtopping if tidal level above crest				Breach	40	2	80			
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	40	2	80			
				CSF1b	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	2	80			
				CSF1a	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	2	80			
				CSF2c	Sandbag deteriorates	Overtopping during extreme floods					Breach	40	3	120			
				CSF1h	Tree roots rot	Open pipes to upstream	Pipe initiation through the embankment.	Continuation (No filter)	Progression with no intervention		Breach	40	2	80			
				CSF2f	Tree falls over	Removal of material from wall	Loss of freeboard	Overtopping			Breach	40	3	120		96	120
Section 13 - Low height, backflow via PVC pipes, dismissed zero consequence. River road and Dudley creek	Embankment	Earthquake	1	CSF2b	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	40	1	40			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	1	40			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	40	2	80			
				CSF1d	Differential movement around pipes	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	2	80			
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	40	1	40			
				CSF1b	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	1	40			
				CSF1a	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	1	40			
				CSF1h	Tree roots rot	Open pipes to upstream	Pipe initiation through the embankment.	Continuation (No filter)	Progression with no intervention		Breach	40	2	80			
				CSF2f	Tree falls over	Removal of material from wall	Loss of freeboard	Overtopping			Breach	40	2	80		58	80

Sub-system	Components	Hazard	ID No.	Identification Code	Initiator	Consequence	Leading to	Leading to	Leading to	Leading to	Ultimate outcome	Consequence	Likelihood	Risk	Rejection and Reason		
Section 14 - dismissed properties just outside inundation area. Porrit park access road infill. Flooding adjacent to secrion 21 Avonside road.	Embankment	Earthquake	1	CSF2d	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	40	1	40			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	1	40			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	40	1	40			
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	40	1	40			
				CSF1b	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	1	40			
				CSF1a	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	2	80			
				CSF1h	Tree roots rot	Open pipes to upstream	Pipe initiation through the	Continuation (No filter)	Progression with no intervention		Breach	40	1	40			
				CSF2f	Tree falls over	Removal of material from wall	Loss of freeboard	Overtopping			Breach	40	1	40		45	80
Section 15 (Hulverston, inundates green zone, Narrow embankment needs frequent topping up - active movement)	Embankment	Earthquake	1	CSF2d	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	100	2	200			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	100	3	300			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	100	2	200			
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	100	4	400			
				CSF1b	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	100	3	300			
				CSF1a	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	100	3	300		283	400
Section 16 (Falconwood) - riverbank slumping, inundates Anzac Drive (Life line)	Embankment	Earthquake	1	CSF2d	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	90	3	270			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	90	3	270			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	90	3	270			
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	90	2	180			
				CSF1b	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	90	3	270			
				CSF1a	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	90	2	180		240	270
Section 17 (Waitaki) - inundates greenzone	Embankment	Earthquake	1	CSF2d	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	90	3	270			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	90	2	180			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	90	3	270			
				CSF1d	Differential movement around pipes	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	90	2	180	Only applies to generic services FM		
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	90	1	90			
				CSF1b	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	90	3	270			
				CSF1a	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	90	2	180		206	270
Section 18 - Bexley - 4 properties in red zone occupied	Embankment	Earthquake	1	CSF2d	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	90	3	270			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	90	3	270			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	90	2	180			
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	90	3	270			
				CSF1b	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	90	3	270			
				CSF1a	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	90	1	90		225	270
Section 19 - small dia pipes	Embankment	Earthquake	1	CSF1d	Differential movement around pipes	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	40	2	80	Only applies to generic services FM	80	80
Section 20 - large dia pipes	Embankment	Earthquake	1	CSF1d	Differential movement around pipes	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	70	3	210	Only applies to generic services FM		
				CSF1c	Flood	Backflow through pipes	Inundation				Inundation	70	5	350	Only applies to generic services FM	280	350
Section 21 - Type 1 Levee good condition. Trees in Levee. Bob's mix. Currently floods Avonside road in Green Zone.	Embankment	Earthquake	1	CSF2d	Slumping (stopbank or foundation)	Loss of freeboard	Overtopping if tidal level above crest	Collapse of embankment			Breach	90	1	90			
				CSF1g	Slope failure through weak foundation layers	Transverse cracking of the wall	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	90	1	90			
				CSF2e	Translation (Lateral Spreading)	Longitudinal cracks	Slope failure if water enters cracks (tide / rainfall)	Loss of Freeboard	Overtopping	Collapse of embankent	Breach	90	2	180			
		Hydrological / Flood	2	CSF2d	Settlement	Overtopping during extreme floods or tide	Crest erosion downcutting				Breach	90	1	90			
				CSF1b	Seepage through foundation sands	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	90	2	180			
				CSF1a	Seepage through embankment	Excessive back erosion	Piping initiation	Continuation (No filter)	Progression with no intervention		Breach	90	1	90			
				CSF1h	Tree roots rot	Open pipes to upstream	Pipe initiation through the	Continuation (No filter)	Progression with no intervention		Breach	90	1	90			
				CSF2f	Tree falls over	Removal of material from wall	Loss of freeboard	Overtopping			Breach	90	3	270		135	270

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