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Glenorchy Rees Floodbank

Floodbank Assessment

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Disclaimers and Limitations

This report ('**Report**') has been prepared by WSP exclusively for Otago Regional Council (ORC) ('**Client**') in relation to the floodbank to the Lagoon Stream and Rees River at Glenorchy ('**Purpose**') and in accordance with the Offer of Service dated 0.707.2020. The findings in this Report are based on and are subject to the assumptions specified in the Report. WSP accepts no liability whatsoever for any reliance on or use of this Report, in whole or in part, for any use or purpose other than the Purpose or any use or reliance on the Report by any third party.

1 Introduction

This report builds on a previous inspection and assessment undertaken of the existing floodbank at Glenorchy Rees completed in June 2020.

The findings of the previous inspection works are detailed in the report issued by WSP on 19th June 2020. The previous inspection identified potential erosional risks with the floodbank and proposed mitigation measures at some key locations.

Since the initial inspection there was has been a further significant rainfall which resulted in flooding of the Lagoon Creek bridge around the 21st July. This was detailed in an email from Ulrich Glasner (QLDC) showing photographs of the flooding taken by Ingrid Temple.

Remedial works were then undertaken by Otago Regional Council (ORC) at the end of July 2020 which involved clearance of the vegetation in the Lagoon stream and dredging of the riverbed to relocate the main Rees channel towards the true right bank.

ORC provided an update to the community in August 2020, and have since applied to the Department of Conservation (DoC) to install a water level monitoring station in the Lagoon with the aim of providing a better understanding of the behaviour of the Lagoon during rain events and to assist with community flood response.

Hydraulic modelling of the Rees River in this area was carried out by ORC to determine flood flow water velocities to inform the design of erosion protection.

This report provides additional site-specific detail and preliminary failure mode analysis assessment findings to address specific queries raised by ORC in order to assist with an assessment of the behaviour of the floodbank during future events and in developing likely erosion protection measures (or other options) that may be required to address the increasing risk presented to the area of the site.

Figure 1 - Lagoon Bridge 21st June. Photograph Ingrid Temple to Ulrich Glaser

2 Preliminary Slope Stability Assessment

As part of the overall condition and performance analysis a preliminary assessment of slope stability has been undertaken.

The construction of the existing flood bank has not been determined from intrusive geotechnical investigation, however, it is understood from the Resource Consent application[1] that the material used for construction was alluvium sourced from the Buckler Burn alluvial fan, end tipped, shaped and compacted in layers not exceeding 300mm. The maximum aggregate diameter was 150mm.

The side slopes of the embankment were to be a minimum of a 1 vertical to 2 horizontal (26°).

Between Butement and Argyle Streets the flood bank coincides with the location of the road, and at this point the maximum width is identified as 7.4m.

The previous June 2020 WSP report identified some areas of over steepness of the bank, where the slope angle is potentially 45° or steeper. There are also some areas where headscarps are visible on the top of the slope, suggesting that some localised slope instability has occurred.

2.1 Slope Instability

Slope instability typically occurs when the strength of the bonds between the soil particles forming the stopbank are exceeded, causing them to move, slide or slump and ultimately fail.

Soil slopes or embankments typically fail when they lose strength, such as through increased water content, or through additional loading, or through scour and loss of support of the toe of the embankment.

Important factors in the stability of the stopbanks are therefore the angle of the slope face to the bank, the typical water content of the stopbank materials and the general geotechnical material properties of the soil used in the construction of the banks. Understanding the river environment and loading of the bank are also a key consideration.

2.1.1 Methodology

To assess the stability of a slope, those forces driving the instability of the slope (the weight of the soil, water and additional weight of any additional loadings on top of the slope, such as vehicles) are compared to those forces resisting the instability, such as the internal friction between the soil particles or cohesion.

The ratio of the driving force versus the resisting forces is referred to as the Factor of Safety. The slope will not fail if the resisting force is larger than the driving force, and the factor of safety is greater than 1.0. If the factor of safety is less than 1.0, then the slope will become unstable and may begin to fail. To account for uncertainties in soil properties and assessment of the driving and resisting forces, the factors of safety given in Table 1 are typically adopted for stopbank design, these are taken from The International Levee Handbook (CIRIA C731)[2].

The stopbank geometry and soil profiles were modelled in the GeoStudio software Slope/W. This is a common geotechnical slope modelling software programme. A number of design scenarios were assessed, which relate to the situations to which the floodbank is considered likely to be typically subjected to. The typical conditions the stopbanks are considered to perform under are:

1. Empty – the dry static condition of the slope
2. Usual river flow conditions – with the river at its usual flow levels
3. High flood level (1% AEP) – the level of water in the stopbank under the 1%AEP flood,

[1] Glenorchy Flood Protection Resource Consent Application – Imtech, 4 October 1999.
[2] The International Levee Handbook (C731), CIRIA, Ministry of Ecology, USACE, 2013

4. Bank full conditions – water at the crest of the stopbank
5. Embankment under water - Those situations where both sides of the stopbank are inundated, such the situation if the Lagoon stream breaches the stopbank and water is present on both sides.
6. Rapid drawdown., floodbank saturated - The situation following a flood where the embankment is saturated with water and is therefore heavier and weaker but has no lateral support.

Three different slope angles have been considered against the above conditions in order to develop a slope model:

- 2:1 slope angle – the typical design for the water side embankment angle
- 1.5:1 slope angle – where the bank has become slightly over steepened.
- 1:1 slope angle – those areas where, as assessed during the site inspections, the stopbanks appear to be over steep.

No specific geotechnical testing of the stopbank construction and materials has been carried out at this stage and no seismic analysis of the stability model has been undertaken.

The design parameters for the assessment of the stop bank have therefore been assumed based on available anecdotal information, assuming likely material properties and reviewed or back analysed against existing observed conditions.

The outputs of the modelling suggest that the strata below the stopbank do not significantly affect the overall behaviour of the stopbank.

An example input to the modelling is provided below, and an example output, showing a factor of safety of FOS 0.6, is presented in Figure 3. A diagrammatic representation of slope failure is shown in Figure 4.

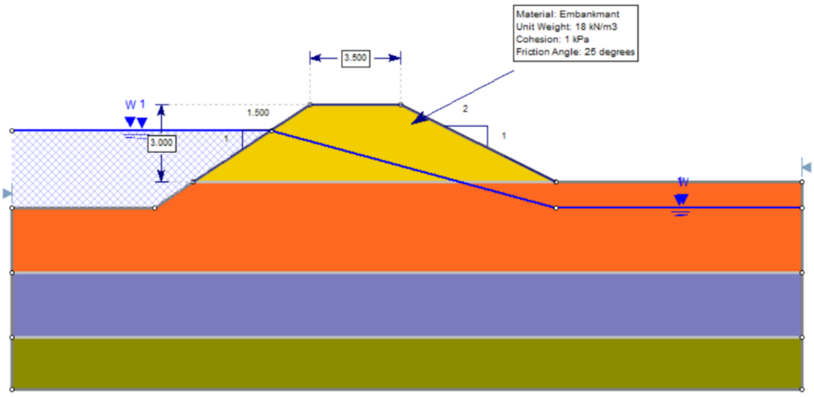


Figure 2 - Example slope stability assessment input

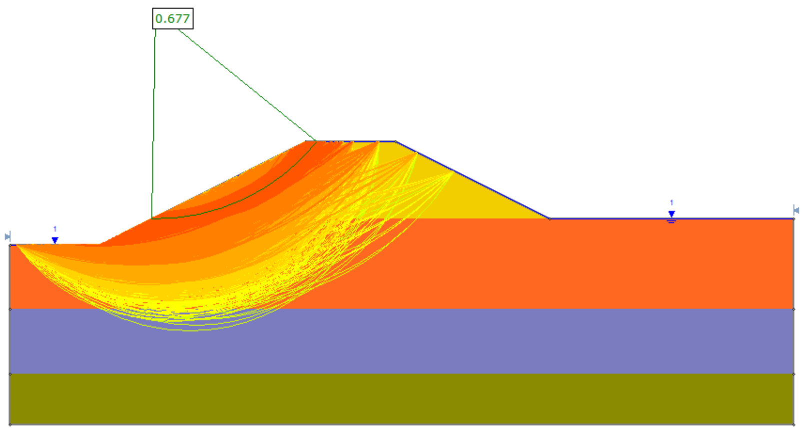


Figure 3 - Example slope stability assessment output

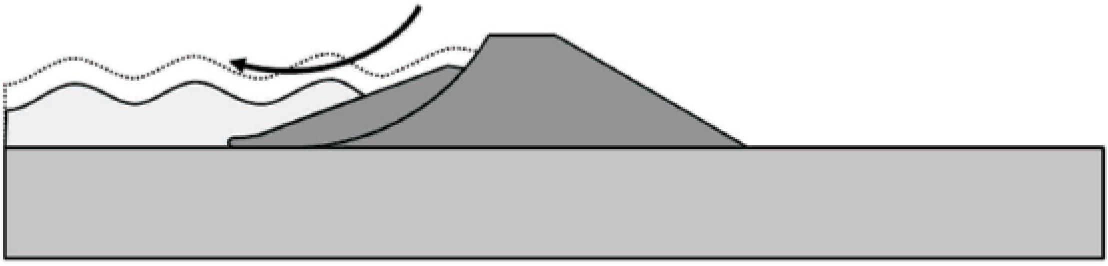


Figure 4 - Diagrammatic representation of rotational slope failure (from CIRIA C731)

2.1.2 Slope Instability Assessment Results and Discussion

The results of the slope modelling completed are provided in Table 1 for the likely material properties for the stopbank material.

Cells highlighted in green indicate where the Factor of Safety exceeds that recommended by current recognised design guides for stopbank construction[3].

Cells in red indicate those areas where the Factor of Safety is below that recommended, and indicate that a risk of failure may be present. The text in bold indicates a Factor of Safety less than 1.0, suggesting the stopbank would be unstable and prone to localised failures.

The results typically indicate that where a 2:1 slope angle exists, the stopbanks are more likely than not stable under all conditions except rapid drawdown. This is typical of earth dams and would suggest that the stopbanks may require re-assessment or inspection following a major floor event as localised effects or weakening may have occurred.

The preliminary modelling completed indicates that under typical river conditions, those stopbanks with a slope angle of 1.5:1 potentially have a factor of safety less than the required standard of FOS=1.5. These areas should therefore be investigated further to qualify and confirm the actual soil parameters and overall likely performance of the stopbanks.

Under both drained and typical river conditions stopbanks with a slope angle of 1:1 would most likely be unstable.

This is likely to manifest as localised failures such as slumping or with cracking appearing at the head of the slope. Areas where this form of failure is likely to occur should be investigated further to qualify the material properties and the form of construction of the bank in order to confirm or otherwise this preliminary assessment.

Table 1 - Assessed scenarios with the friction angle of embankment material $\Phi = 30^\circ$, Expected conditions.

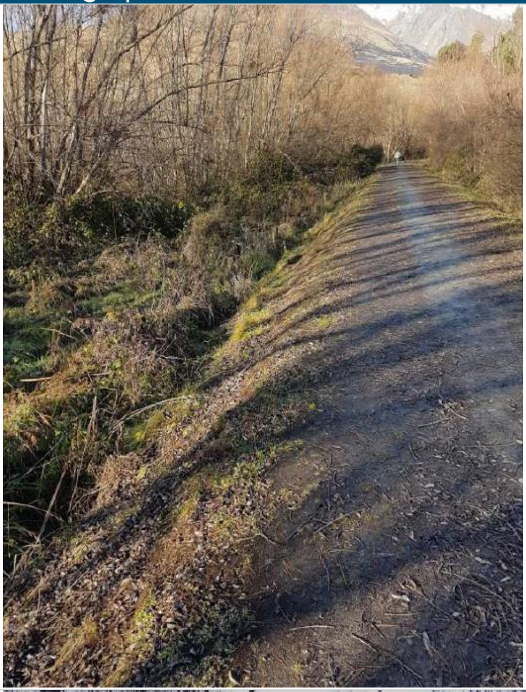
Scenario	Description	Calculated Factor of Safety			
		Required	Slope angle		
			1:1	*1.5:1*	*2:1*
1	Empty	1.2	**0.89**	1.21	1.52
2	Usual river flow conditions	1.5	**0.90**	1.17	1.52
3	High flood level (1% AEP)	1.2	1.20	1.29	1.94
4	Bank full conditions	1.2	3.66	1.38	5.36
5	Embankment under water	1.2	3.61	1.36	5.31
6	Rapid drawdown. Saturated.	1.0	**0.88**	**0.48**	**0.67**

[3] International Levee Handbook , (C731), CIRIA, Ministry of Ecology, USACE, 2013

2.2 Identified Potential Slope Instability

During the site inspection the following sites were identified as having slope angles steeper than expected.

Table 2 - Identified areas of over steep slopes

ID	Situation	Photograph
Stab.1	Lagoon stream, some oversteep areas, slope angle estimated around (30˚) 1.7H:1V	
Stab.2	Lagoon stream walkway, some oversteep areas towards the centre of the photograph, potentially 1H:1V (45˚)	

Stab.3	Immediately downstream of the Lagoon confluence, evidence of slope failure where undercut by the Rees river, 1H:1V (45°)	
Stab.4	Downstream from the Lagoon Stream confluence, evidence of slope failure where undercut by the Rees river 1H:1V (45°)	

3 External Erosion/Toe Scour/Undermining

Undermining of the toe material occurs when the channel flow velocity increases such that the soil particles are removed by the action of flowing water. This can lead to oversteepening of the stopbank on the water side, caving or scouring which then leads to loss of support and weakening of the soil layers which may then result in larger slope instability or loss of the embankment (breach).

The critical areas of external erosion are considered to be the confluence of the Lagoon stream and the Rees River, and the length of stopbank where the Rees River runs up against the stopbank.

It is difficult to determine if this length is currently armoured, however, the resource consent viewed does not suggest that additional armouring or rock rip rap was placed on the face of the stopbank at the time of construction, with the material stripped from beneath the floodbank used for capping. Some larger stones are present at the base of the slope at the confluence, with the lagoon stream, but these do not appear consistent along its length.

The effectiveness of armouring to the stopbank typically depends on the overall velocity of the river flow, the angle of the face of the stopbank and the angle of repose of the armourstone used.

An assessment of the expected velocity of the river during flood events was undertaken by ORC[4], for varying values of mannings 'n' surface roughness coefficient. This modelling provides a good estimation of the expected water flow velocity which will be experienced by the stopbank in flood conditions.

For the purposes of design, the ORC memo recommends a water velocity of 2.3m/s be adopted.

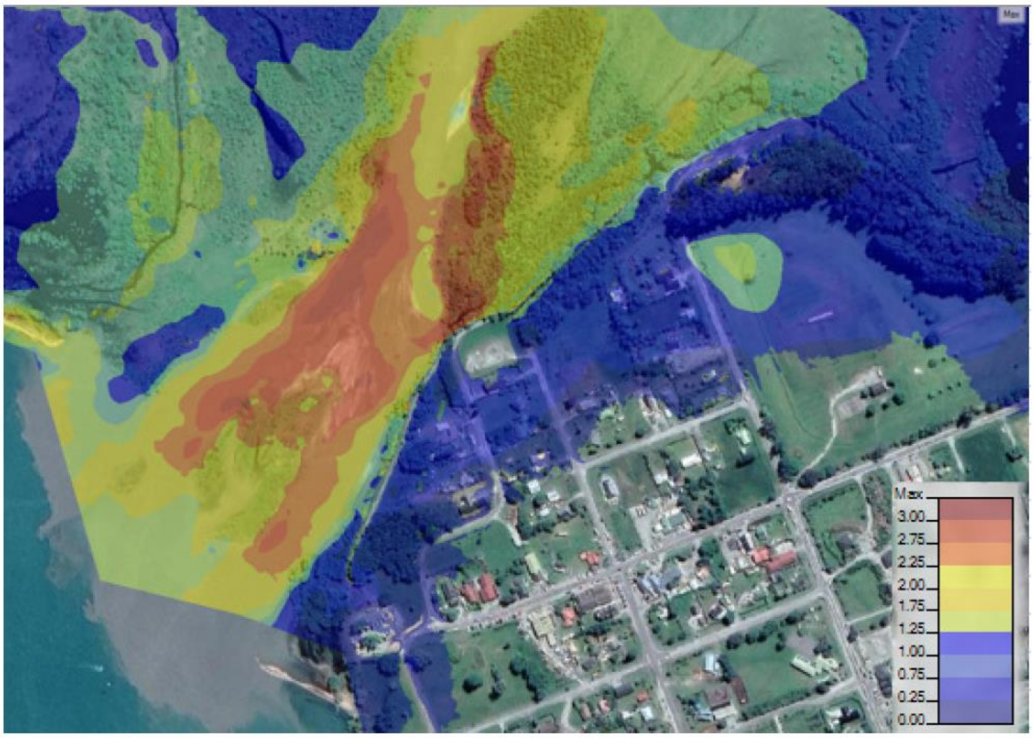


Figure 3. Velocity distribution for manning's n value of 0.025.

Figure 5 – Extract from ORC memo showing velocity distribution expected.

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[4] Velocity for design bank protection work for Rees River at Glenorchy, B. Shrestha, 2020 (unpublished)

3.1 External Protection Methodology

Preliminary rock armour design was undertaken using the methods outlined in the International Levee Handbook, according to the relationships derived by Pilarczyk suggesting that for a design flow of 2.3m/s, armour stones of approximately D_{50} = 1.0m are required at the embankment.

Typically, the armourstone is placed to a thickness of 2.5 times the characteristic stone thickness, meaning an armour stone thickness of 2.5m would be recommended.

Table 3 - Erosion protection Armourstone sizing parameters

Parameter	Symbol	Value
Stability correction factor	Φ	0.75
Porosity	n	0.3
Density of rock (kg/m^3)	$\rho_{\cdot rock}$	1800
Density of water (kg/m^3)	$\rho_{\cdot water}$	1000
Relative buoyant density	Δ	0.56
Critical mobility parameter	ψ	0.035
Turbulence factor	k_t	1.5
Velocity profile factor	k_h	0.5
Side slope angle (°)	α	26
Angle of repose (°)	φ	45
Longitudinal slope angle (°)	β	5
Side slope term	k_s	0.62
Longitudinal slope term	k_l	0.64
Side slope factor	k_{sl}	0.4
Depth averaged flow velocity (m/s)	U	2.3
Characteristic armour stone protection size (m)	D50	1.03

Table 4 - Identified potential areas of external erosion

ID	Situation	Photograph
Ext.1	Section immediately downstream of Lagoon stream confluence	

4 Internal Erosion (Piping Failure)

Internal erosion of the stopbanks is known as piping failure. This occurs when water which seeps through the stopbank carries away the soil particles forming the stopbank. This erosion process typically forms a cavity within the bank and when the cavity erodes back from the landward side of the stopbank to the river it is then possible that a catastrophic breach of the stopbank could occur.

Piping failures are often associated with structural penetrations of the stopbanks, such as where outlet pipes (electricity cables and storm water outfalls) are present. It is also possible for piping failures to be initiated by animal activity, such as rabbit burrows.

Areas where it is considered that piping failure is possibly occurring are identified below:

Table 5 - Identified areas of potential piping failure

ID	Situation	Photograph
Pipe.1	Depression in the footpath	

4.1 Piping Assessment

A detailed analysis of piping failures in the stopbank has not been undertaken as part of this investigation and assessment.

While failure through piping is considered a possibility, its assessment should be undertaken through physical investigation of the area considered to be affected, at the depression identified above. The investigation should then assess and review if the ground conditions are different here than at other parts of the stopbank.

5 Floodbank Performance

The performance of the floodbank under a high flow event, (or impacts of a series of events), and the potential for a catastrophic floodbank failure has been considered as part of this assessment.

Based on this limited assessment of the bank the floodbank performance should be reviewed in two discrete sections, that section adjacent to the Lagoon stream, and the section downstream of the lagoon stream confluence with the Rees.

The water levels in the river have not been assessed as part of this assessment, but it can be seen from the modelling undertaken by ORC (Figure 5) that the extent of the flood bank should be reviewed to ensure that the floodbank is not 'outflanked' by the overflow from the Lagoons. In the scenario shown in Figure 5, the flood bank is shown to have water on each side and is therefore performing as intended.

If any part of the stopbank is breached or outflanked then it is expected that the lower lying properties would be affected. Based on the Lidar information, the buildings at 14 and 18 Butement Street and 53 Argle Street would appear to affected in such a scenario.

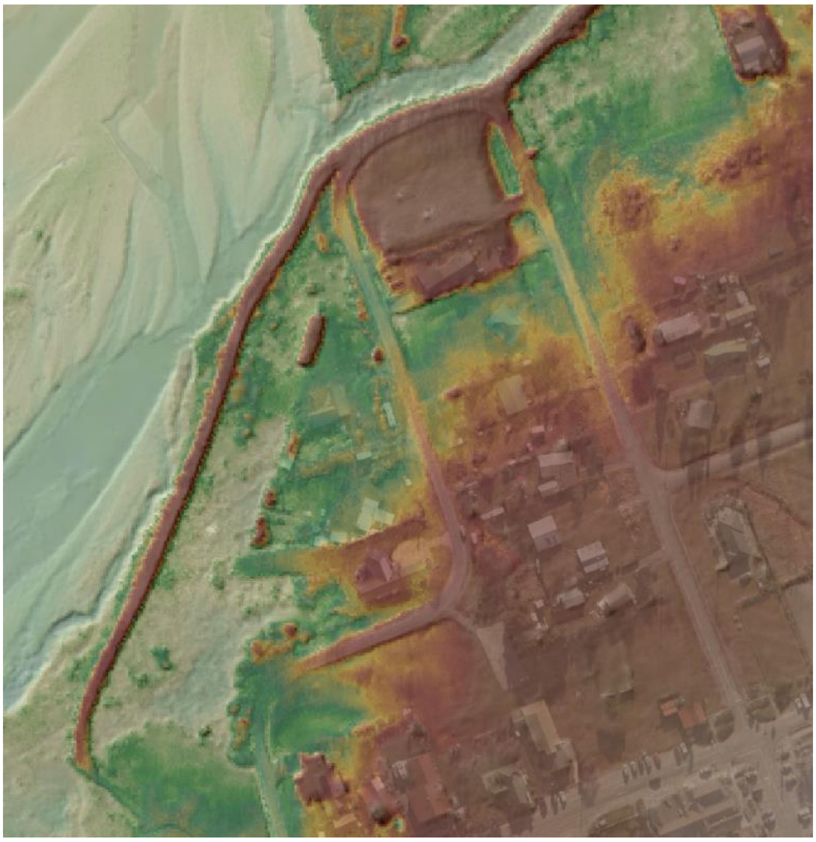

Figure 6 – Extract from Lidar, showing low lying properties

5.1 Lagoon Stream Section

The levels at the lagoon are controlled by the lagoon inflows and the lagoon outflows, with the level in the Lagoon stream derived from the level of the Rees river and the adjoining lagoons.

Excess flow into the lagoons as a result of rain events would lead to an increased water level, however further modelling of the flow and the sediment loads would be required to confirm the true water levels in this area.

This section of the floodbank is expected to not be typically subject to high velocity outflows, as the main Rees channel will not be present at this location, and the existing vegetation will provide a significant reduction in the water flow velocities. Therefore, failures here would likely be due to progressive failure, but this may not necessarily occur during high river flows. In the event of a failure of this section of the stopbank, it is possible that the lagoons could drain into the area to the south of the stopbank.

5.2 Rees Section

If the Rees main channel impacts the floodbank and continues to undermine the bank, causing an increase in the slope angle to manifest, then localised failures may begin to occur.

The main channel has recently been moved towards the True Right bank, but if it switches to the true left, then failure of the bank could initiate without additional armouring or bolstering.

Overtopping of the embankment (as a result of climate change or other environmental factors) has not been assessed as part of this review.

5.2.1 Is continued incremental/progressive erosion expected/likely to lead to a sudden failure?

Modelling of the existing floodbanks suggests that where undercutting has occurred, and the river side face angle has increased to 1:1, then there will be an increased risk of rotational failures of the embankment face. These failures typically form a slip surface, with the slipped material then quickly washing away. This can be observed at the confluence with the Lagoon Stream. Once failure is initiated, then the slipped surfaces become potentially oversteep and rapid progressive failure is then considered likely.

The effectiveness of the flood bank to act as a protection feature is a function of its width and mass, and where the expected failure surface interacts with the back face of the slope, then the floodbank becomes compromised.

5.2.2 Should there be immediate concern regarding a rapid floodbank failure, or is failure expected to slowly develop over many years?

While the condition of the floodbanks would deteriorate over time if left unchecked (the face angles becoming increasingly oversteep), it would be expected that rapid floodbank failure would be initiated either during high velocity flows or immediately following a flood event when the bank is saturated, raising the risk associated with multiple events.

Each flood event is expected to potentially induce localised failures in the floodbank, especially given the lack of armouring.

The nature and form of the floodbank would suggest that only one erosional feature location is required for a breach to occur. The nature of a breach is typically that of surface slumping leading to localised failure of the floodbank. This then widens as the side slopes of the breach progressively fail and the reminder of the bank is progressively weekend.

Failure is expected to occur during a high flow or flood event, where the flow velocities and water levels are significantly increased, or immediately following a flood event (rapid drawdown) where the stopbanks are saturated and therefore weaker.

Therefore, there is a concern regarding rapid floodbank failure at locations along this section.

5.2.3 Timeframe/number of flood events over which failure may develop

It is difficult to accurately assess the number of flood events which will cause failure of the floodbank to occur, without further modelling of the catchment to understand the duration, frequency and level of flood flows to the Rees or have an accurate understanding of the actual composition of the embankment. The points where the floodbank is considered to be most at risk are the high volume events which have a high velocity water flow, followed by slow recession of water contained within the lagoons. It is important to note that failure is most likely to occur at the key weak point locations identified below.

5.2.4 Most likely locations and method of any failure

Based on the inspection completed and the limited assessment presented herein, the most likely locations for failure are outlined below, and have been identified as Key locations in Section 4 above.

- Bridge

The bridge provides a constriction to the Lagoon Stream flow, and during high flows can set up a complex hydrological situation with eddies and forming around the abutments. If this leads to the floodbank being undercut then erosion and rotational failure could occur.

- 4WD crossing

Use of the 4WD crossing leads to the formation of shallower slopes on the approaches and a reduction of the crest level in this location, as well as overtopping during high flow events. The tracking of vehicles also forms rutting and reduces the integrity of the surface in this area which can lead to reduced soil strengths and increased susceptibility to rotational failure.

- Confluence of the Lagoon Stream and the Rees

The confluence provides a complex hydrological situation, where, at high flows the water from the Lagoon stream is prevented from entering the Rees. Turbulence at the confluence leads to the development of eddies and downcutting of the base of the channel. Where fast flowing river water is slowed by the turbulence, a depositional environment of mobilised river sediments forms. This can change the bed profile which could lead to the undercutting of the main floodbank and the possibility of rotational failure.

- Where the Rees channels impact the floodbank

Where sections of the bank are not armoured, and the main Rees channel is able to undercut the bank, there is the potential for over steepening of the slope resulting in potential rotational failure of the bank.

6 Recommendations

Based on the inspections completed and the limited analysis undertaken the following recommendations for measures to mitigate/remediate observed erosion and geotechnical issues at floodbank.

Preliminary slope stability modelling suggests that the face angle of the stop bank should be maintained to a minimum 2H :1V, which would provide an adequate factor of safety for the majority of the scenarios modelled.

Where slope faces are typically steeper then an increased risk of localised failure or slope instability will occur.

The analysis completed has been based on soil properties considered typical of the materials used in construction (allowing for some limited sensitivity analysis). It is recommended that the actual properties of the stopbank construction be determined to confirm or otherwise this assessment.

The stopbank is typically not rock armoured, though modelling suggests that the Rees River will continue to impact the stopbank in the medium term, and during high flow events and as such localised scour or erosion of the face of the stopbank is likely to continue or worsen over time.

Priorities for the maintenance of the floodbank are therefore to ensure that the face angle of the slope is returned and maintained at as close to the original 2:1 angle as reasonably possible, and that surface erosion or scour effects are minimised through the placement of suitably designed rock armour.

While recent works have been undertaken by ORC to move the main Rees channel towards the True right bank, it is expected that the Rees will over time move back towards the True left bank, and as such would most likely impact the floodbank.

6.1 Priority issues to be addressed by remedial measures

The priority issues for the floodbank are therefore considered to be;

- Protection of the corner at the confluence of the Lagoon stream and the Rees river,
- Armouring of the section downstream of the Lagoon confluence

It is expected that these works be undertaken in conjunction with other longer terms measures such as river training to provide an appropriate depositional environment and encourage the main Rees flow away from the Glenorchy township. Specific targetted areas related to current over steep areas, and areas where additional are

6.2 Proposed additional Geotechnical investigation

No significant geotechnical assessment is considered to be expected for this works, with the introduction of erosion protection to the face of the slope being additional to the embankment.

During the physical works it would be possible to investigate the potential piping location through the digging of a trial pit in the area and assessment of the material found.

It would also be beneficial to confirm the material properties and true make up of the embankment in order to confirm the preliminary stability analysis completed as part of this assessment.

6.3 Revetments and groynes

In addition to the armouring described above, river training in the form of channel dredging and groyne placement would encourage the main river channel to flow to the west and away from the flood bank may be considered.

The installation of groynes in the river, upriver from the affected area of flood bank, would act to create a deposition environment between the groynes. Groynes would be placed at approximately 20m intervals, along the eastern edge of the vegetated extent of the eastern Rees River bank, above the confluence of the Glenorchy Lagoon Stream.

Groynes would be designed to have a steeper (1:5:1) upstream face, and a shallow (3:1) downstream face, with a fall of 3:1 from the bank to the river.

The installation of the groynes would need to be completed in conjunction with dredging of the original western main river channel. Removal and redistribution of the river sediment should encourage the main flow away from the flood bank, and the groyne placement would encourage future deposition of mobilised river sediments on the eastern bank of the river. The long term goal of groyne placement and river training would be to protect the flood bank from the continual erosion threat posed by the location of the main Rees River Channel against the toe of the flood bank.

The design of such groynes and river training must be undertaken in conjunction with a wider hydraulic modelling of the Rees river and Lagoon Stream to ensure that sediment bed loads, degradation and aggradation, and the lagoon levels are all taken into account.

A detailed hydraulic model and flood assessment would need to be competed in order to suitably design the location, form and orientation of such a system.

6.4 Erosion mitigation works estimated costs

Erosion mitigation are expected to comprise the following, which could be undertaken independently.:

- Installation of rock armouring to the 50m long section around of the Lagoon stream confluence. If additional funding is available, this rock armouring shout extend the full length of the stopbank downstream (approximately 300m total, additional 250m).
- Installation of groynes or river training upstream of the confluence
- Repair of oversteep areas and
- Vegetation maintenance

The cost estimate is based on the following assumptions, with the largest cost being the imported rock armour. It is expected that this could be sourced from one of the creeks near to Glenorchy. Placement rates are based on recent Queenstown projects.

Table 6 - Cost estimate for erosion mitigation works

Item	Rate	Units	Cost
Placement of rock armouring at targeted locations	$200/tonne placed*	50m x 2.5m x 6m, 850 tonnes	$170,000
Placement of rock armouring along the	$200/tonne placed*	250m x 2.5m x 6m, 4150 tonnes	$830,000

remainder of the downstream length			
Excavation of riverbed material and Groyne construction upstream	$2000/day	5 days / groyne x 5 groynes	$10,000
Rip rap facing to the Groynes	$200/tonne placed	200t/groyne x 5 groynes	$200,000
Repair of oversteep areas	$5000/location	5 locations	$25,000

*Rates are highly dependent on the source and availability of material, which is expected to be in the Glenorchy area.

7 Monitoring and Further Observations

Based on the inspections completed to date key signs of a progressing failure in the embankment are considered to be associated with a reduction in the trail width, as a result of slipping of the bank. This may be manifested as:

- A localised drop in level at the edge of the track, (as seen below)
- Trees and vegetation leaning
- Buckled surface of the vegetation, indicating surface creep of the slope

Figure 7 - Indicative surface slumping of the embankment crest

It is therefore recommended that periodic inspections are completed to assess the potential for developing failures and enable early intervention lessening the potential for a catastrophic failure.

The following inspection record presented below is therefore considered appropriate for use in this context.

Trigger	
High lagoon outflow levels. TBC following installation of the level monitor.	
High rain event.	Annual rain event
High river event	Annual river flow

Key locations to be inspected following a trigger event	
Confluence of Lagoon Stream	Assessment of the location of the Rees River in relation to the Lagoon stream, and review of any erosion to the stopbank which has occurred
Foot bridge	Review of the abutments of the bridge and erosion to the stopbank in this area,
4wd crossing point	Review of the width of the top of the bank and any additional erosion.
Where the Rees River impacts the floodbank	Review of undercutting of the bank along the Rees
Lagoon outflow stream near to the bridge	Assessment of the outflow to note any changes in the outflow width or volume

Annual assessment of the whole length of the stopbank	
Level assessment, survey of the head of the embankment	Confirmation of the level of the head of the stopbank
Track width confirmation	Confirming that any sections have a reduced width
Review of slope angle	Confirmation that all sections of the stopbank have not increased in slope angle
Assessment of track edge to determine if headscarp cracks have opened or if there have been areas which have dropped in level	Visual inspection of the track to review if any sections of the stopbank have slipped.
Rabbit holes	Review of condition of the stopbank
Assessment of the condition of the vegetation	Review of if any trees are damaged, Have become overgrown and are damaging the bank Assessment of vegetation which may be restricting the flow

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