

Stage 1 Feasibility

Geotechnical Drilling Investigation

Summary Report

Report Prepared for:
Water Wairarapa

Report prepared by:
Water Wairarapa

June 2016

Table of contents

Executive Summary

1.	Purpose.....	6
2.	Background	6
3.	Aspects affected by geotechnical conditions	6
4.	Investigation Foci.....	7
5.	Drilling Sites	7
6.	Downhole Testing	8
7.	Inclined Directional Drilling	8
8.	Geophysical Surveying	9
9.	Instrumentation	10
10.	Laboratory testing	10
11.	Core Samples	10
12.	Summary of Findings.....	13
13.	Construction Element Uncertainties.....	16
14.	Cost Implications	18
15.	Future Geotechnical Investigations.....	19
16.	Acknowledgement.....	20
	Appendix 1: Published geology.....	21
	Appendix 2: Location plans.....	22

Executive Summary

This report summarises Water Wairarapa's Stage 1 Feasibility geotechnical investigation programme conducted between late February and late April 2016 for the Black Creek and Tivdale Scheme storage areas. The aim of the investigations and their outputs is to enhance the project's understanding of the geotechnical features which in turn influence the schemes' technical integrity and financial viability.

A total of 11 boreholes were drilled, at 5 different locations; namely:

- Wakamoekau stream dam site (3 holes)
- Black Creek saddle site (1 hole)
- Black Creek stream dam site (3 holes)
- A landslide southwest of Black Creek reservoir (1 hole)
- Tivdale dam site (3 holes)

In addition to the recovery of core samples retrieved from boreholes, a suite of other tests measured other subsurface characteristics such as groundwater levels, permeability, chemical composition, etc.

The drilling works were designed to increase the project's understanding of:

- The strength of foundation materials
- Abutment stability
- Permeability of foundation materials & presence of paleo channels
- Vulnerability of foundation materials to liquefaction
- Settlement potential of foundation materials
- Dispersity of foundation materials
- Groundwater regime, including the presence of artesian water pressures
- Potential for structural features such as faults, persistent zones of weakness, low angle jointing, bedding planes shears with low strength.

The following table summarises both the favourable findings, as well as the risks and issues identified from the Stage 1 Feasibility Geotechnical Investigations – the detailed version of the equivalent table should be referenced for interpretation purposes; this table is an abridged version

Site	Identified Favourable Findings	Identified Risks & Issues
Wakamoekau site, sometimes described as Black Creek (North) site	a) Minimal sub-excavation required b) Good foundation materials & characteristics c) Defects such as faulting, deep stress relief or bedding plane shears unlikely d) Potential borrow material for a seepage control promising	a) Greywacke rock may not be suitable for use as bulk rockfill and armour - alternative sources expected to be found b) Possible increase in cost for limited grouting of foundation

Site	Identified Favourable Findings	Identified Risks & Issues
Saddle site between Wakamoekau Creek and Black Creek catchment areas	<ul style="list-style-type: none"> a) Good ground conditions for a connecting channel / pipe b) Risk re excavation costs can be dismissed c) Minimal subexcavation required for a saddle dam e) Good foundation materials & characteristics f) Defects such as faulting, deep stress relief or bedding plane shears unlikely g) Tests on potential borrow material for bulk fill promising 	<ul style="list-style-type: none"> a) Greywacke rock may not be suitable for use as bulk rockfill and armour - alternative sources expected to be found b) Internal erosion of foundation possible - measures expected to mitigate this
Black Creek (South) site - possible dam site on Black Creek	<ul style="list-style-type: none"> a) Less cost for valley floor subexcavation b) Right abutment terrace materials are not expected liquefaction prone c) Defects such as faulting, deep stress relief or bedding plane shears unlikely d) Potential borrow material for a seepage control promising e) Alignment of fault aligned with river is now unlikely 	<ul style="list-style-type: none"> a) Greywacke rock may not be suitable for use as bulk rockfill and armour b) Possible increase in cost for limited foundation grouting c) Control measures required to limit seepage into high permeability materials underlying the right abutment
Landslide site - landslide into Waingawa valley	<ul style="list-style-type: none"> a) Improved understanding of landslide depth b) Reservoir seepage unlikely to affect landslide c) Unlikely that the landslide would regress sufficiently to compromise the integrity of the reservoir rim 	<ul style="list-style-type: none"> a) To improve understanding, although considered unlikely, further investigation recommended into potential for: <ul style="list-style-type: none"> - reservoir seepage into the landslide - ongoing movement of landslide (unrelated to the dam) to compromise the integrity of the reservoir rim
Tivdale site - possible dam site on Tauweru River	<ul style="list-style-type: none"> a) Very consistent foundation materials b) Foundations relatively incompressible, sufficiently strong, low permeability (not requiring grouting), and not vulnerable to liquefaction c) Defects such as faulting, deep stress relief or bedding plane shears unlikely d) Potential borrow material for a seepage control promising 	<ul style="list-style-type: none"> a) Internal erosion of foundation possible - measures expected to mitigate this b) Potentially vulnerable to internal erosion of foundation, but a lesser risk due to low rock mass permeability and limited defects -measures expected to mitigate this c) Potential sandstone erodibility and need for lining the spillway confirmed - already allowed for in Prefeasibility cost estimates d) Sandstone may be unsuitable as a foundation for very large scale structures such as concrete operational intake tower.

Overall, the geotechnical investigations revealed:

- a) No unexpected findings with only relatively minor potential cost increases or decreases resulting at most. Generally, the investigations confirmed what was previously suspected in areas where there was previous uncertainty;
- b) Both schemes will continue to be investigated; and
- c) Two areas require further investigation, namely the use to which the greywacke rock can be best put and the need to build an improved understanding of the landslide relative to the Black Creek Schemes

1. Purpose

This report describes in brief¹ the drilling works, findings, implications and next steps for the geotechnical programme that was conducted between late February and late April 2016 for the Black Creek and Tivdale Schemes for Water Wairarapa. The laboratory tests followed in May.

2. Background

Water Wairarapa's purpose is to secure a sustainable future for the Wairarapa region's people, land and water by storing, managing and using water in ways that boost regional prosperity, care for the environment and support community use. The investigations conducted support this by establishing an improved understanding of the geotechnical aspects which feed into the financial viability.

Following the June 2015 Prefeasibility investigation decisions to proceed with Black Creek and Tivdale schemes, it was determined that more information was needed on the subsurface conditions for the dam² sites and other critical parts of the schemes. The subsurface conditions can have a significant influence on construction costs and the schemes' design, but as they can only be inferred from surface features until drilling has been conducted, a greater degree of uncertainty has to be assumed.

An associated purpose of the drilling was to provide the project with an enhanced understanding of the subsurface conditions to establish whether they would either preclude a site from being considered further or sufficiently question its viability to proceed further. Equally, the drilling was to help identify unreasonably technical challenges, so that landowners potentially affected by the drilling investigations and within possible reservoir induction areas had certainty with respect to a scheme's progress as early as possible.

During the Prefeasibility investigations an inspection of the surface features provided a certain amount of information – this was supported by published information on the areas geology. **Appendix 1** summarises this information.

3. Aspects affected by geotechnical conditions

Due to the significance on the project's viability, the potential geotechnical cost implications, together with the associated uncertainty, need to be narrowed as early as possible in the investigations. The subsurface conditions affect matters such as:

- The dam foundations in terms of the amount of material that needs to be removed to get a good founding and achieve minimal seepage, and the nature of the excavated materials – can it be used elsewhere on the project?

¹ Two reports detailing the investigation findings and implications will be provided on the project web site: <http://www.wairarapawater.org.nz/>

² Dam – the structure that impounds the water body (reservoir)

- The dam abutments (the sides of the dams) – are the materials likely to seep and therefore need to be moved or lined etc?
- The use to which materials within or close to the inundation area can be applied for armouring the dam faces or as bulk fill for the dam
- The potential vulnerability to seismic movement and the design levels required
- The possibility of materials sliding into the reservoir³ water body upstream of the dam
- The ease of excavation and the associated removal costs
- The ability or otherwise to use rock materials based on their crushability and propensity to absorb moisture

4. Investigation Foci

Specifically, the drilling works were designed to provide an enhanced understanding of:

- The strength of foundation materials
- Abutment stability
- Permeability of foundation materials & presence of paleo channels
- Vulnerability of foundation materials to liquefaction
- Settlement potential of foundation materials
- Dispersivity of foundation materials
- Groundwater regime, including the presence of artesian water pressures
- Potential for structural features such as faults, persistent zones of weakness, low angle jointing, bedding planes shears with low strength.

5. Drilling Sites

The investigations focused on each of the dam foundations, plus the landslide near Black Creek. The following investigation sites were therefore relevant to each scheme:

- a) **Black Creek scheme** comprising:
 - i. Wakamoekau site, sometimes described as Black Creek North site – a possible dam site on Wakamoekau Creek
 - ii. Saddle site between Wakamoekau Creek and Black Creek catchment areas – possible dam site or connecting channel/ pipe depending on the alternative scheme arrangements
 - iii. Black Creek (South) site – possible dam site on Black Creek

³ **Reservoir** – the body of water (lake) retained by the dam structure

- iv. Landslide site – a landslide in the Waingawa valley (not Black Creek) to the southwest of the potential Black Creek scheme reservoir.

b) **Tividale scheme** comprising:

- i. Tividale site – possible dam site on the Tauweru River

A total of 11 boreholes were drilled, so the findings provided only a representative⁴, not a complete, sample of the subsurface conditions at 5 different locations; namely:

- Wakamoekau stream dam site (3 holes)
- Black Creek saddle site (1 hole)
- Black Creek stream dam site (3 holes)
- A landslide southwest of Black Creek reservoir (1 hole)
- Tividale dam site (3 holes)

Maps of the site locations and the drill holes are shown in Appendix 2.

6. Downhole Testing

The downhole testing completed differed between the vertical and inclined boreholes. The downhole testing in the vertical boreholes generally comprised:

- Groundwater measurements
- Lugeon tests
- Standard penetration tests
- Downhole imagery
- Downhole shear wave velocity testing

The downhole testing in the inclined boreholes generally comprised:

- Groundwater measurements;
- Lugeon tests
- Core orientation

7. Inclined Directional Drilling

Most holes were driven vertically, while some were incline drilled at about 50°. The purpose of the inclined holes was to detect fault lines or structure weaknesses running parallel with the valley floor, as a stream course will sometimes follow a crush zone created by a fault line. **Figure 1** below depicts how the inclined directional drilling tries to detect the presence a fault line.

⁴ Refer to the section 15, 'Future Geotechnical Investigations' in this report for a description of future stages of the geotechnical investigations required.

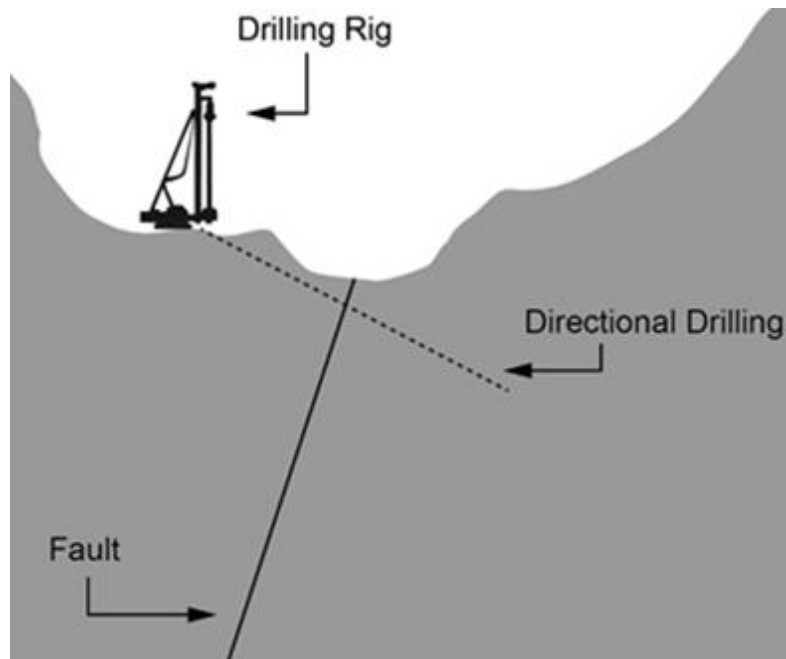


Figure 2 below shows drilling at the Tivdale site with the rig set at an incline of 50°.



8. Geophysical Surveying

A seismic refraction survey was also undertaken comprising three lines for the Black Creek scheme and one line for the Tivdale scheme. A further line was previously surveyed in 2014 and is relevant to the possible dam site on Black Creek.

9. Instrumentation

Standpipe piezometers were installed in all boreholes to monitor groundwater levels. Rising and falling head tests to estimate in-situ rock mass permeability were completed in installed standpipe piezometers for two boreholes.

10. Laboratory testing

Laboratory testing was undertaken on selected samples from test pits, surface samples, and boreholes. The test pit samples were obtained during previous investigations in 2014, and proved more suitable for laboratory testing in some cases than the core samples from the 2016 boreholes.

11. Core Samples

One of the aims of the drilling was to recover quality core samples – a segment of the ground beneath the rig is retrieved to test conditions for the dam foundations and the permeability of the ground to the body of stored water - would it leak too much? The results will not only help determine whether a dam could be built on that site, but also the associated cost implications, for example how much unsuitable material has to be removed.

The quality of the core samples was important, so the subsurface materials could be assessed. **Figure 3** below is at one of the Black Creek sites next to Falloon Settlement Road - the pipes on the table are ready for drilling to greater depths and to help retrieve the core samples.

Figure 3



Every 1.5m metres, the drilling pipe is drawn out of the borehole and the core (rock sample) carefully removed as depicted in the **Figure 4** below.

Figure 4



The core materials retrieved from the boreholes are then boxed ready for storage before going to a laboratory for testing to assess their chemical and physical properties (**Figure 5** below).

Figure 5



As **Figure 6** below shows, once drilling, testing and measurements in the boreholes were completed, a standpipe (the yellow marker) was concreted into place and surrounded by a permanent fence (not shown). The standpipe provides an access point for ongoing monitoring of groundwater levels to be taken.

Figure 6



12. Summary of Findings

The following table summarises both the favourable findings, as well as the risks and issues identified from the Stage 1 Feasibility Geotechnical Investigations.

Site	Favourable Findings	Identified Risks & Issues
Wakamoekau site, sometimes described as Black Creek (North) site - possible dam site on Wakamoekau Creek	<ul style="list-style-type: none"> h) Minimal sub-excavation required i) Foundations appear relatively incompressible, sufficiently strong, not vulnerable to liquefaction during earthquakes, and not vulnerable to internal erosion j) No identified unfavourable defects such as faulting, deep stress relief or bedding plane shears k) Lab test results on potential borrow material for a seepage control zone appear promising 	<ul style="list-style-type: none"> c) Greywacke rock may not be suitable for use as bulk rockfill and armour due to the presence of laumontite in veins within the rock (further investigation recommended to better understand this risk) d) Possible increase in cost for limited grouting of foundation
Saddle site between Wakamoekau Creek and Black Creek catchment areas - possible saddle dam site, or connecting channel / pipe depending on alternative scheme arrangements	<ul style="list-style-type: none"> d) Ground conditions appear promising for a connecting channel / pipe e) Previous risk that the cost of excavation for a connecting channel could increase due to strength of material can be dismissed based on latest findings f) Minimal subexcavation required for a saddle dam l) Foundations for a saddle dam appear relatively incompressible, sufficiently strong, low permeability (not requiring grouting), and not vulnerable to liquefaction during earthquakes m) No identified unfavourable defects such as faulting, deep stress relief or bedding plane shears n) Lab test results on potential borrow material for bulk fill appear promising 	<ul style="list-style-type: none"> e) Greywacke rock may not be suitable for use as armour due to the presence of laumontite in veins within the rock, but expected that an alternative source could be found for the limited quantity required f) Potentially vulnerable to internal erosion of foundation, expected to be able to be mitigated by defensive design and construction practice

Site	Favourable Findings	Identified Risks & Issues
<p>Black Creek (South) site -possible dam site on Black Creek</p> <p><i>Not relevant for Wakamoekau (Scheme 206)</i></p>	<p>f) Possible decrease in cost for subexcavation in the valley floor since the sandy gravels likely can be left in place under the shoulders of the dam, since expected to be sufficiently strong and incompressible, and not vulnerable to liquefaction during earthquakes</p> <p>g) Materials underlying the right abutment terrace are not expected to be vulnerable to liquefaction during an earthquake</p> <p>h) No identified unfavourable defects such as faulting, deep stress relief or bedding plane shears</p> <p>i) Lab test results on potential borrow material for a seepage control zone appear promising</p> <p>j) Previous risk of a fault aligned with the river is now considered unlikely based on the latest findings</p>	<p>d) Greywacke rock may not be suitable for use as bulk rockfill and armour due to the presence of laumontite in veins within the rock (further investigation recommended to better understand this risk)</p> <p>e) Possible increase in cost for limited grouting of foundation</p> <p>f) Control measures required to limit seepage into high permeability materials underlying the right abutment</p>
<p>Landslide site - landslide in valley to the southwest of the potential Black Creek scheme reservoir.</p> <p>[Refer to Figure 6 below]</p> <p><i>Not relevant for Wakamoekau (Scheme 206)</i></p>	<p>d) Improved understanding of the likely depth of sliding and the materials involved</p> <p>e) Unlikely that reservoir seepage could exert a significant driving force on the landslide because the reservoir is low in elevation relative to the likely depth of sliding and groundwater levels at the landslide, and relatively distant</p> <p>f) The natural dam / ridge along the reservoir rim above the main landslide area is also approximately 400m wide (above reservoir level) so it is unlikely that the landslide would regress sufficiently to compromise the integrity of the reservoir rim</p>	<p>b) Potential reservoir seepage into the landslide, increasing driving force for the landslide (considered unlikely, but further investigation recommended to provide an improved understanding)</p> <p>c) Potential for ongoing movement of the landslide (unrelated to the dam) to compromise the integrity of the reservoir rim (considered unlikely, but further investigation recommended to provide an improved understanding)</p>

Site	Favourable Findings	Identified Risks & Issues
Tivendale site - possible dam site on Tauweru River	<ul style="list-style-type: none"> e) Very consistent foundation materials f) Foundations appear relatively incompressible, sufficiently strong, low permeability (not requiring grouting), and not vulnerable to liquefaction during earthquakes g) No identified unfavourable defects such as faulting, deep stress relief or bedding plane shears h) Lab test results on potential borrow material for a seepage control zone appear promising 	<ul style="list-style-type: none"> e) Potentially vulnerable to internal erosion of embankment bulk fill, expected to be mitigated by defensive design and construction practice f) Potentially vulnerable to internal erosion of foundation, but this is a lesser risk due to low permeability of the rock mass and limited defects. Also, expected to be mitigated by defensive design and construction practice g) The potential erodibility of the sandstone and need for lining the spillway has been confirmed (noted already allowed for in Prefeasibility cost estimates) h) Uniaxial compressive strength results indicate that the Miocene-aged sandstone may be unsuitable as a foundation for very large scale concrete structures. Possibly only a design consideration for the operational intake tower.

13. Construction Element Uncertainties

Based on current knowledge of the sites, no issues were found that would preclude either of the schemes from further investigation.

However, the two issues listed below for the Black Creek scheme, are considered the most significant areas of uncertainty in terms of feasibility:

13.1 Landslide to the southwest of the Black creek scheme reservoir

Previous reports have identified risks relating to the landslide, which are considered unlikely due to the elevation and distance of the Black Creek scheme reservoir relative to the landslide, but require due consideration as part of a rigorous investigation:

- The potential for reservoir water to seep through the reservoir rim on the true right of the possible Black Creek (South) dam into the large scale, active landslide area, and for that reservoir seepage to add a new driving force for the landslide.
- The potential for continued movement of the landslide due to rainfall/earthquake events (unrelated to the presence of the dam) to substantially reduce the width and height of the ridge forming the natural dam on the reservoir rim.

The aerial photograph (**Figure 7**) below shows the seismic refraction lines for the landslide near Black Creek. The diagram above that indicates the inferred (estimated) depth of the greywacke rock, shown by the red dashed line with the red shading underneath, relative to the ground level.

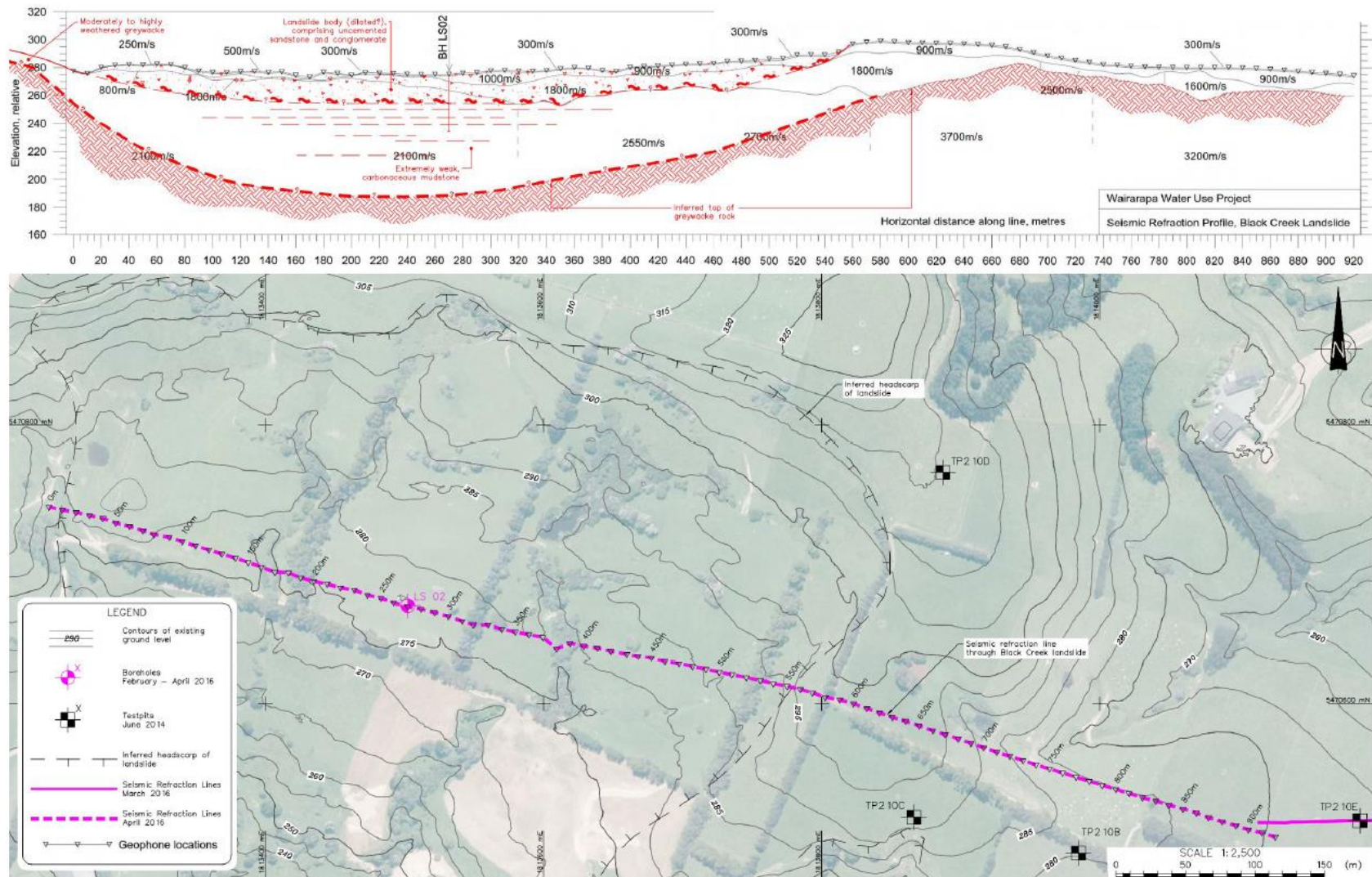
13.2 Suitability of greywacke rock as a source of bulk fill

The suitability of the greywacke rock as a source of bulk fill for construction of the Wakamoekau and Black Creek dams is considered a lesser risk than the landslide (although considered ‘unlikely’).

Alternative sources of bulk fill or a change to the assumed zoning and batters of the dam embankment could be considered, though this would involve a change from the arrangements assumed for Prefeasibility cost estimates. Investigations would also be recommended to confirm that there is a suitable alternative material in sufficient quantity at an economic distance.

To provide further detail, laboratory testing has identified laumontite, which is a swelling zeolite, within the veins of greywacke rock at Black Creek and Wakamoekau Creek. Swelling zeolites reversibly swell/shrink during wetting and drying cycles resulting in rock fragmentation along the closely spaced veins and infilled joints present in the rock mass. The presence of swelling zeolites can potentially negatively affect the durability, grading and permeability of the rockfill.

Figure 7 - Seismic refraction lines for the landslide (below) & inferred profile (top)



14. Cost Implications

The investigations the individual geotechnical sites can be summarised as follows with respect to cost implications – the costs are compared with the estimates made in October 2014 following the Prefeasibility Value Engineering exercise.

These investigations did not include any re-evaluation of the prefeasibility-derived capital costs; it only reviewed the general implications of the findings – a review of the actual costs was not part of the geotechnical drilling programme.

Key to table below:

a) Blue – possible increase or decrease, or no or minimal change to cost

b) Red – possible cost or minor cost increase

c) Green – possible cost or minor cost decrease

Item	Wakamoekau or Black Creek (North)	Saddle site (between Wakamoekau Creek and Black Creek)	Black Creek (South)	Tivdale
Suitability of local borrow materials and implications for dam type, batter slopes and bulking factor	Possible change in cost (either increase or decrease) due to change in borrow source for bulk fill and armour and / or change in dam type	Possible cost increase if alternative borrow for armour proves necessary	Possible change in cost (either increase or decrease) due to change in borrow source for bulk fill and armour and / or change in dam type.	Possible minor cost increase for defensive design and construction control to mitigate risks associated with bulk fill
Subexcavation requirements for stability / leakage	Minimal change, if any.	No change	<u>Valley slopes</u> No change. <u>Valley floor</u> Possible decrease in cost due to the reduction in subexcavation under the shoulders of the dam. <u>Right abutment terrace</u> Possible change in cost (either increase or decrease) due to change in strategy to control seepage on the right abutment terrace.	Possible cost reduction due to reduction in subexcavation
Foundation treatment for seepage control i.e. cut offs, grout curtains, upstream blanketing	Possible cost increase for limited grouting	No change	Possible cost increase to provide for limited grouting	No change
Scour resistance and implications for spillway lining and terminal structures	Unlikely, but possible cost increase	No change	Unlikely, but possible cost increase.	No change

Item	Wakamoekau or Black Creek (North)	Saddle site (between Wakamoekau Creek and Black Creek)	Black Creek (South)	Tivdale
Spillway cut batters	Unlikely, but possible cost increase	No change	Unlikely, but possible cost increase.	No change
Measures to address reservoir rim stability i.e. sedimentation allowance, stabilisation measures, additional freeboard to allow for seiches	No change	No change	Possible cost increase.	No change
Measures to control leakage from reservoir area i.e. blanketing / lining	Not an issue	Not an issue	Possible cost increase, <u>may be offset</u> by cost decrease due to reduction in subexcavation at right abutment terrace	Not an issue

15. Future Geotechnical Investigations

The investigations described in this report are just the start of the investigations that needs to be conducted to fully understand the subsurface conditions.

As appropriate for any project of this scale and complexity, it was recommended that the two potential (albeit unlikely) issues described in section 13 for the Black Creek scheme are investigated further to provide a suitable level of rigour, along with the general elements of a Feasibility study that are still to be completed including:

- Site specific seismic hazard assessment – development of seismic spectra and mapping of faults or persistent zones of weakness;
- Geological mapping of dam and reservoir areas;
- Investigation into geotechnical conditions for the spillway(s);
- Investigation into borrow materials for dam construction, noting that Stage 1 investigations have coincidentally provided information on some borrow materials in the course of investigating dam foundations;
- Geotechnical investigations for distribution and harvesting infrastructure; and
- Feasibility-level interpretative report covering geotechnical investigations.

In terms of these two issues for the Black Creek scheme, the risks associated with the landslide, although considered “unlikely”, are the most significant for this scheme. However, the site investigations that would normally be undertaken to address this conclusively are likely to be costly.

A more pragmatic approach therefore may be to firstly undertake a desktop sensitivity analysis based on the information currently available as a first stage to put the potential impact of the reservoir on the landslide into perspective.

16. Acknowledgement

Wairarapa Water is especially grateful to the landowners who provided access onto their farms over a number of weeks to conduct the drilling programme, and the associated testing and monitoring. The time they gave and the disruption caused to some of their farming operations activities is appreciated.

Appendix 1: Published geology

1. Black Creek scheme

Published geology for the Black Creek scheme area⁵ indicates:

- The area is underlain by Mesozoic-aged greywacke basement rocks of the Pahau Terrane
- Undifferentiated late Miocene sediments of the Palliser and Soren Groups overlies the greywacke at the Wakamoekau, Saddle and Black Creek sites
- Surficial Holocene river deposits are present in valley floors at the Wakamoekau and Black Creek south sites
- An unnamed, inactive fault is shown running through the Landslide site, trending roughly north-south
- The Black Creek scheme reservoir area is approximately 3-4 km northwest of the active Wairarapa Fault

Published geology in the wider vicinity includes studies of the Carrington⁶ and Mount Bruce⁷ areas of the Wairarapa which has relevance to the Black Creek wider area.

2. Tivdale scheme

Published geology for the Tivdale scheme site⁸ indicates:

- The Tivdale site is underlain by late Miocene sediments of the Palliser Group
- Early Cretaceous Springhill Formation of the Mangapurupuru Group sediments and Holocene river deposits are also mapped near the Tivdale site
- An inactive fault, generally trending in a northeast-southwest orientation, is approximately mapped to the west of the Tivdale site

⁵ Begg, J.G., Johnston, M.R. (compilers) 2000. Geology of the Wellington area. Institute of Geological and Nuclear Sciences 1:250 000 geological map 10. 1 sheet + 64 p. Lower Hutt, New Zealand: Institute of Geological and Nuclear Sciences Limited.

⁶ Wells, Patricia E. (1989). Late Neogene stratigraphy of the Carrington area, western Wairarapa, North Island, New Zealand. *Journal of the Royal Society of New Zealand*, 19:3, pages 283-303.

⁷ Wells, Patricia E. (1987). The stratigraphy and structure of the Mt Bruce area, northern Wairarapa, North Island, New Zealand. *Journal of the Royal Society of New Zealand*, 17:2, pages 101-113.

⁸ Lee, J.M., Begg, J.G. (compilers) 2002. Geology of the Wairarapa area. Institute of Geological and Nuclear Sciences 1:250 000 geological map 11. 1 sheet + 66 p. Lower Hutt, New Zealand: Institute of Geological and Nuclear Sciences Limited.

Appendix 2: Location plans

Figure 1 – Overall Site Locations

Figure 2 – Black Creek Scheme - North / Wakamoekau

Figure 3 – Black Creek Scheme – Saddle

Figure 4 - Black Creek Scheme - South and Landslide

Figure 5 - Tividale Scheme

