PROPOSED KOTUKU FLOOD DETENTION DAM – GEOLOGY AND GEOTECHNICAL DESIGN FEATURES

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ABSTRACT – In the North Island of New Zealand, volcanic soil and rock pose seepage issues for water retaining structures, and very careful investigation and design is necessary. The proposed Kotuku Flood Detention Dam has been designed to reduce flooding within Whangarei City, and is expected to commence construction in the 2014/2015 earthworks season. The proposed dam is classified a high potential impact classification (PIC) dam, and hence the geotechnical issues have been rigorously analysed. The proposed dam and catchment are located within a complex geological environment, where a basalt flow and flow margin, firm alluvial soils, and massive sandstone rock are present in the proposed dam foundation. This paper describes the geotechnical issues posed by site geology in preparing a detailed design of the 18m earth embankment dam. Investigation and testing has been undertaken to assess the site geology, including founding conditions, seepage potential and materials for dam construction. Permeability testing, including packer, falling and constant head tests, provided input to forming a geological model of the subsurface conditions. Transient groundwater analysis on the geological model was undertaken for a 36 hour, 1% annual exceedance probability (AEP) flood event. This analysis led to the development of a detailed design for the proposed dam, which comprises a clay liner, undercuts of alluvial and selected residual and flow margin materials, toe drains and internal drainage.

1. Introduction and Project Background

The Northland region of New Zealand, in which Whangarei is situated, has been subject to significant flood events over the past 10 years. In many cases, these events have highlighted the vulnerability of certain land areas to flooding and a requirement to improve/upgrade flood protection.

The proposed Kotuku flood detention dam is one such flood protection measure identified by Northland Regional Council (NRC). The concept for a dam at the proposed site, however, is not new, with studies dating as far back as 1966. Riley Consultants Ltd has been providing geotechnical and water resources engineering services for the proposed dam since undertaking feasibility studies in 2011.

The proposed embankment-type dam is located on the Nihotetea Stream to the south-west of the Whangarei Central Business District (CBD), as shown on Figure 1. The dam has a high potential impact classification (PIC) by NZSOLD Guidelines (2000).

The dam will be approximately 18m high and contain approximately 1.3 million m^3 of water during the design 1% Annual Exceedence Probability (AEP, which includes climate change) flood event. The 9.1km^2 catchment area shown in Figure 2 is predominantly covered in pasture, with some areas of scrub and bush. A predicted 1% AEP flood event currently results in a flood depth of 0.75m in the CBD, affecting approximately 620 buildings.

Three sites were initially considered, and the proposed dam site was selected after a feasibility study, cost comparison, and a reservoir stability investigation.

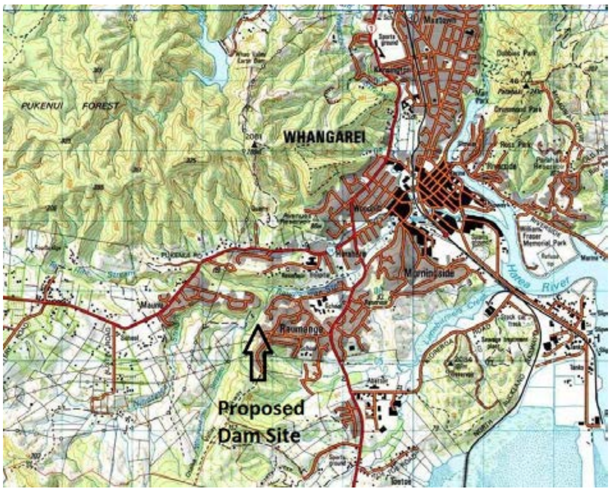


Figure 1. Map of proposed dam site

At the time of preparing this paper, August 2014, resource consent for construction of the dam has been obtained, and a contractor has been selected to undertake the construction works. Earthworks will be undertaken in the 2014/2015 earthworks season starting October 2014, and preliminary works to relocate services at the dam site were completed in July 2014.

2. Geology

The Institute of Geological Nuclear Sciences Ltd (GNS) 1:25,000 geological map of the Whangarei Urban Area (GNS geological map 26) indicates the site is underlain by several different geological units. The basement rock in the area is Waipapa

Terrane greywacke, which is overlain by Ruatangata sandstone, and is located near the ground surface on the southern and eastern slopes.

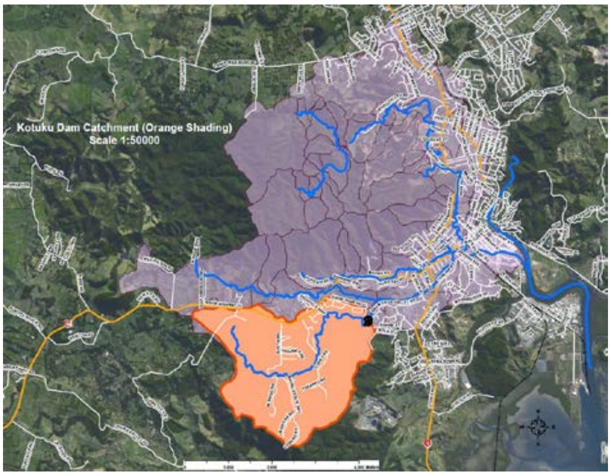


Figure 2. Kotuku Dam catchment

The northern and western slopes of the valley are underlain by basaltic lava of the Kerikeri Volcanic Group. The basaltic lava sourced from the Maunu Mountain volcano and associated scoria cone to the west of the site has flowed down and infilled a paleochannel of the Raumanga Stream and dammed associated tributaries. The basalt lava outcrops as cobbles and boulders at the ground surface and in the stream bed, and is exposed in a waterfall downstream of the dam site. The rocks are generally fine-grained and vesicular.

The lower-lying central portions near the watercourse are underlain by alluvium. The alluvium on the site is fluvial and lacustrine deposits consisting of clays, silts and gravels with generally minor organics. These are likely to have accumulated with the partial damming of streams by lava flows.

Site inspection, mapping, machine boreholes, test pits, and hand auger boreholes were undertaken at the dam site, in the borrow area, and reservoir to investigate the geology at the site. Three phases of investigation work were undertaken: feasibility study, preliminary design and detailed design.

2.1. Dam Site Geology

2.1.1. General

A plan layout of the dam site is shown in Figure 3. The proposed dam footprint extends over variable soil and rock types on both the left and right abutments and upstream to downstream. The right abutment is underlain by competent sandstone with a relatively shallow depth of overlying residual soil. The left abutment consists of a lava flow with mixed flow margin materials surrounding the basalt lava. The lava flow, which sits on the alluvium that overlies sandstone at depth, has filled a paleovalley. The firm alluvium varies in thickness from 2m to 5m in the valley floor at the dam centerline, increasing in thickness upstream into the old basin. Figure 4 presents a geological long section along the centre line of the embankment.

Investigations at the dam site were undertaken to develop and refine a geological model of the subsurface conditions. Testing was challenging due to access constraints from private properties, dense bush, steep slopes and large boulders at the ground surface. During drilling of the machine boreholes, falling head, constant head, and packer testing was undertaken in the Kerikeri Volcanic Group and Ruatangata Sandstone formation materials to assess soil and rock mass permeability. Angled machine boreholes were undertaken at the proposed dam abutments to maximise the likelihood of intercepting steeply dipping and vertical rock joints to provide a better understanding of defects and the rock mass permeability.

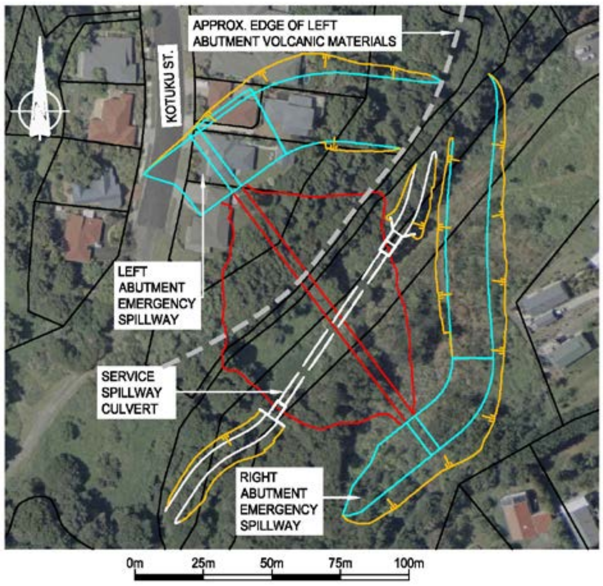


Figure 3. Plan layout of dam site

2.1.2. Subsurface Conditions

The central stream area has been infilled with alluvial material transported from the catchment upstream. The alluvial material is generally firm to stiff silty material with fractions of organics and a maximum thickness of 5m at the upstream end of the dam footprint.

The right abutment comprises a steep slope of typically fine-grained and massive Ruatangata Sandstone of the Te Kuiti Group. The sandstone is generally completely weathered near the surface grading to unweathered at approximately 7.5m depth. Localised areas of colluvium and alluvium were encountered at the ground surface. Artesian pressures were encountered near the base of the slope, inferred to be from groundwater originating in the area upslope of the proposed dam site.

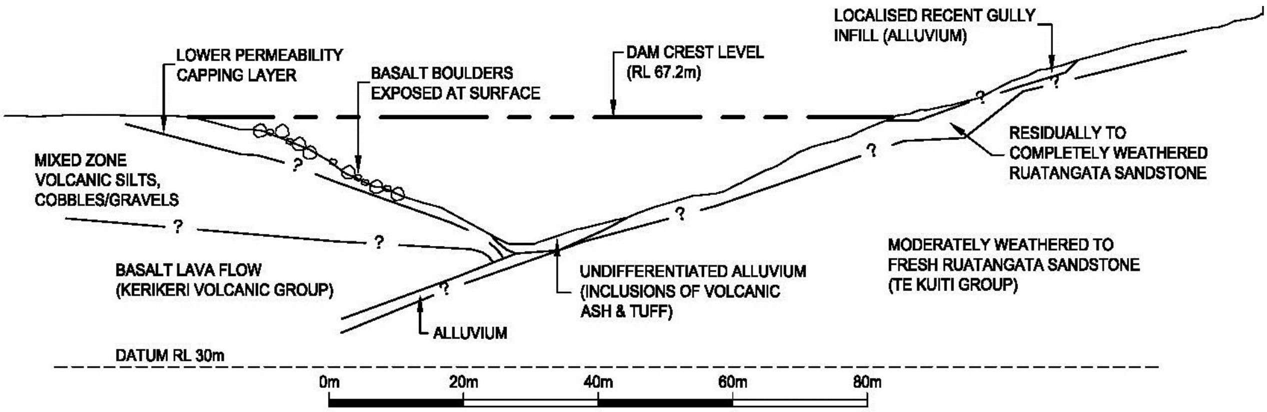


Figure 4. Geological cross section

The left abutment is located on the southern lateral margin of a large basalt lava flow of Kerikeri Volcanic Group material from the Maunu Mountain volcano and associated scoria cone to the west of the dam site. The lava flow margin generally comprises a mixed zone of materials including volcanic silts, gravels, and cobbles overlying the strong basalt lava flow at between 9m and 15m depth in the mid-slope to dam crest area. The basalt lava flow comprises strong fractured basalt rock. Defects in the basalt have a very narrow aperture with clay infill, and are vertical with moderately widely spaced sub-horizontal defects. A capping layer of lower permeability material overlies the mixed zone materials. The lava flow and flow margin are underlain by slightly weathered Ruatangata sandstone and, near the toe of the slope, with a firm to hard alluvial layer.

2.1.3. Permeability Testing

Packer testing was undertaken in the rock encountered at the dam site, with falling and constant head tests in the soils and weathered rock on the left abutment. In packer testing, pressurised water is pumped into an area of open machine borehole shut off by a packer, and the flow of water escaping through defects in the rock mass below the packer is recorded. The flow is recorded over five or more two minute intervals of water pressure being incrementally stepped-up and then down, and the pattern of the flowrate over the entire test is noted. Patterns can involve washing out of material (increasing flow during the test), filling of voids (decreasing flow during the test), higher flow when fractures are open at higher pressures (dilation), turbulent flow in fractures at higher pressures, and laminar flow where all the Lugeon values are the same for all pressures. One Lugeon unit corresponds to 1 litre/minute per metre length of test section at an effective pressure of 1 MPa. Following analysis, the most representative flowrate over the test is correlated to a Lugeon value for the rock mass.

Packer testing in the Ruatangata sandstone on the right abutment generally recorded Lugeon values of 0 to 6 (very low to moderate permeability) consistent with a massive rock with very tight to narrow defects. Packer testing in the basalt lava flow on the right abutment recorded Lugeon values of 2 to 100 (moderate to high permeability) indicating some variability between tight and many open joints.

Falling and constant head testing in the mixed zone of flow margin materials recorded permeability results of 8.3×10^{-5} m/s and 3.5×10^{-4} m/s, which are equivalent to the permeability of a silty sand to sand. A capping layer of lower permeability material was encountered between 3.7m and 6m at the left abutment, overlying the more permeable mixed zone materials.

2.2. Borrow Area Geology

The materials for constructing the dam are to be borrowed from the right abutment emergency spillway excavation and a borrow area located approximately 400m west of the dam site. The borrow area is a small hill underlain by residually weathered to unweathered weak sandstones and mudstones of Ruatangata Sandstone formation. Test pits were undertaken at the borrow area to determine the excavatability of the material and bulk samples were collected for laboratory testing.

2.3. Laboratory Testing

Laboratory testing was undertaken on samples from the left and right abutments and the borrow area. Key objectives of the laboratory testing were to assess the nature and strength of materials from the borrow area and right abutment spillway cut, and the grading of the flow margin soils on the left dam abutment to correlate to permeability and provide input for filter design. Compaction, grading and dispersivity tests were undertaken on the borrow materials to determine their suitability as dam construction materials, and strength tests were undertaken to assess the excavatability of the sandstone rock.

The borrow area and right abutment spillway materials are generally non-dispersive (ND1 and ND2), having over 65% fines (smaller than 0.063mm particle diameter, i.e. silt and clay sized

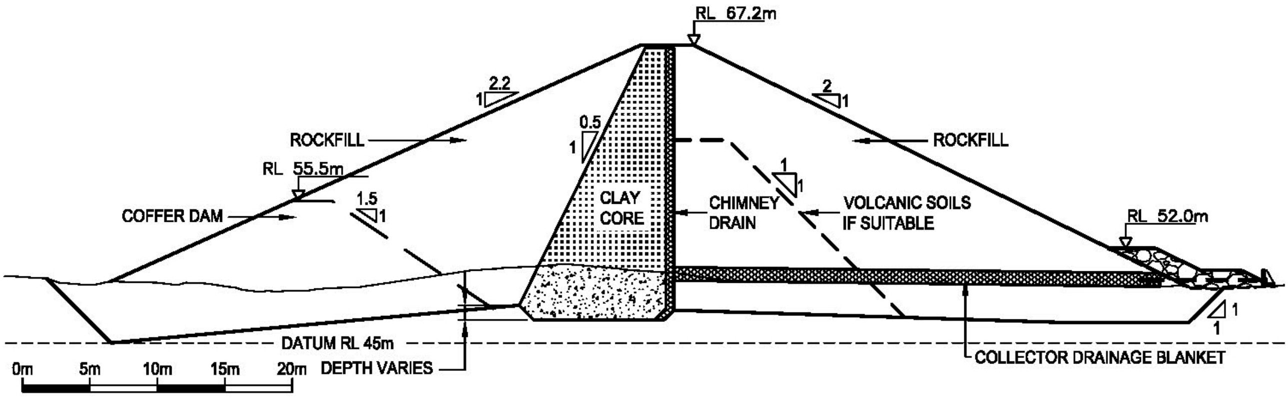


Figure 5. Typical embankment cross section

particles), and achieving maximum dry density of around 1.35t/m^3 (standard compaction) and over 1.55t/m^3 (heavy compaction). The tests in sandstone material from the borrow area recorded uniaxial compressive strength in the range of 5 to 25MPa, and will likely require ripping to excavate. The flow margin material on the left abutment has gradings ranging from silty gravel to clayey silt.

2.4. Reservoir Stability

In the preliminary stages of investigation and design, when evaluating multiple dam sites, consideration was given to geological features that could lead to instability when the reservoir is temporarily at peak levels. This stage of assessment comprised a site walkover, field testing, and analysis of results from around the proposed reservoir.

The likelihood of large-scale instability within the basin slopes due to temporarily higher reservoir levels is considered low. In an extreme rainfall event, the slopes surrounding the reservoir will likely be saturated and localised surficial slumping may occur within the lower-lying areas of the basin, which is not considered to pose an unacceptable risk to the dam.

However, as part of prudent risk management, monitoring of reservoir stability will be incorporated into a long-term dam safety assurance programme.

3. Geotechnical Design Features

3.1. Foundation Treatment

As shown in Figure 4, the geological model for the dam foundation comprises volcanic materials on the left abutment, and weathered sandstone on the right abutment, with alluvium in the central valley. The volcanic materials are variable in composition, whereas sandstone on the right abutment is relatively uniform.

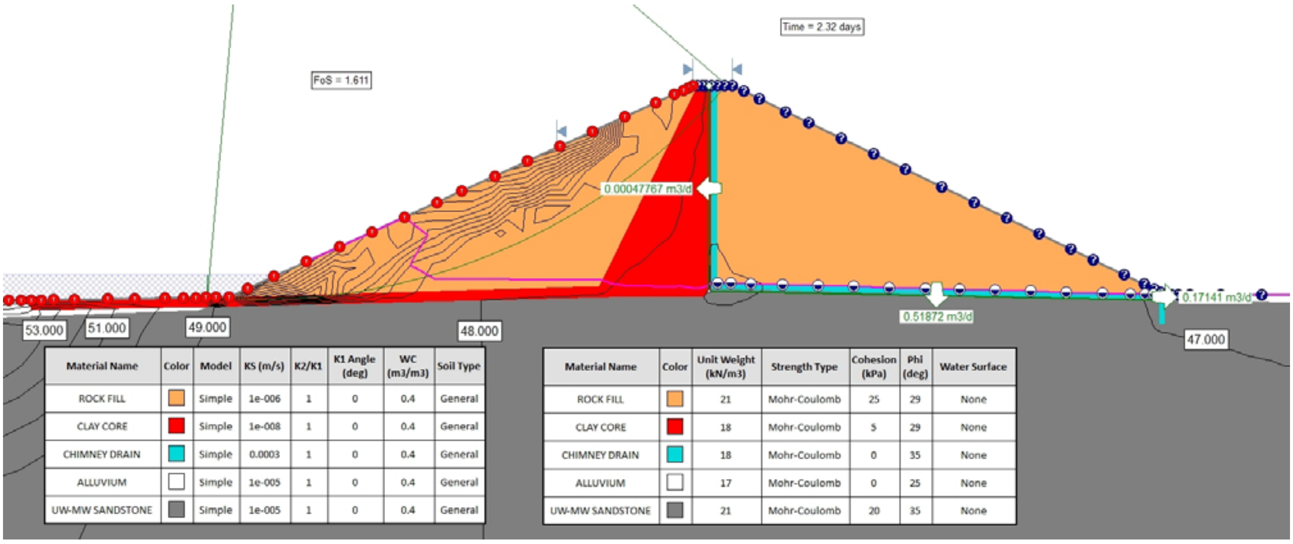
In the valley floor, the alluvium will be undercut to the stronger sandstone to minimise settlement and stability issues. At the upstream toe of the dam, the undercut may be 4m to 5m or greater, which is considered achievable. Such an earth embankment dam is typically expected to settle less than 0.7% of its height (i.e. less than 140mm), and undercutting the alluvial and completely weathered sandstone materials and compacting the dam construction materials well will ensure that the settlement is maintained in that range.

On the right abutment the moderately weathered sandstone is typically shallow (less than 2m) and is an acceptable founding material. Overlying soil, including completely weathered rock and any localised areas of alluvium and colluvium, will be stripped. There is no evidence of significant defects within the massive sandstone rock.

On the lower left abutment, where the dam height is greatest, any weaker near-surface materials and the mixed zone materials will be removed to sandstone or the basalt lava flow. Treatment of basalt defects will possibly be required when the lava is exposed in the dam foundation. As the dam section rises up the relatively steep abutment, the depth to the basalt rock increases significantly and it is not practical to sub-excavate to that depth. Consequently, rubbly flow margin materials comprising variable cohesive soils mixed with gravels and volcanic materials will be left in place in the foundation. There is no evidence of continuous highly permeable or erodible materials in the flow margin, but there are gap-graded materials that may be susceptible to piping if significant sustained seepage flow were to occur. Although peak reservoir levels are only sustained for a matter of hours, seepage control features are considered essential in the left abutment foundation, which are discuss in section 3.3 and include an upstream clay liner.

3.2. Embankment Design

The proposed dam zoning consists of a central clay core, a zone of volcanic soils immediately downstream of the core, and upstream and downstream rockfill shoulders. Figure 5 presents a typical cross section through the embankment.



Material Name	Color	Model	KS (m/s)	K2/K1	K1 Angle (deg)	WC (m3/m3)	Soil Type
ROCK FILL		Simple	1e-006	1	0	0.4	General
CLAY CORE		Simple	1e-008	1	0	0.4	General
CHIMNEY DRAIN		Simple	0.0003	1	0	0.4	General
ALLUVIUM		Simple	1e-005	1	0	0.4	General
UW-MW SANDSTONE		Simple	1e-005	1	0	0.4	General

Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Water Surface
ROCK FILL		21	Mohr-Coulomb	25	29	None
CLAY CORE		18	Mohr-Coulomb	5	29	None
CHIMNEY DRAIN		18	Mohr-Coulomb	0	35	None
ALLUVIUM		17	Mohr-Coulomb	0	25	None
UW-MW SANDSTONE		21	Mohr-Coulomb	20	35	None

Figure 6. Rapid drawdown slope stability analysis

The core materials will be obtained from the surficial soils or completely weathered rock. Completely weathered rock (especially siltstone) is likely to be an acceptable core material, as it breaks down/compacts to a fine-grained material. Sheepsfoot rollers are nominated in the construction specification so that gravel-sized particles are broken down by roller action.

The rockfill and clay materials will be obtained from the nominated borrow area and the right abutment emergency spillway excavation. As the rockfill is sourced from a weak rock, the compacted material will have a lower percentage of gravel-sized particles, and permeability is expected to be low. Selected soils from the left emergency spillway excavation are proposed to be used in the downstream shoulder. A high standard of compaction is necessary for the clay core and clay liner. It is recommended that 200mm loose layers of material with greater than 65% fines content are compacted to achieve a shear vane strength of greater than 120kPa and air voids of less than 8% (5% average). The rockfill on the upstream and downstream shoulders will be compacted to 95% of the dry density standard compaction with air voids less than 10% (8% average).

3.2.1. Slope Stability

Slope instability is most likely to occur during rapid drawdown conditions when the dam freeboard is much greater than at the peak flood level. The likelihood of a slope failure causing a large wave and potentially overtopping the dam is therefore much less with a detention dam compared with a permanent reservoir.

Slope stability analysis was undertaken using the Slide software package on three sections through the dam (two on the left abutment) for a variety of cases, including effective stress, total stress, seismic loading from an operating basis earthquake (OBE: 1:150 year event, 0.1g) and maximum design earthquake (MDE: 1:10,000 year event, 0.32g), and a rapid drawdown analysis on the upstream slope. Input for geotechnical material parameters came from triaxial testing on typical rockfill material from the borrow area (c' = 25kPa, φ' = 29°) and assumed parameters for other materials in the dam embankment and foundation based on in-situ strength testing. Sensitivity analyses were undertaken on all the geotechnical material parameters used. A typical Slide printout for the rapid drawdown analysis is shown in Figure 6. The required Factors of Safety (FoS) adopted from NZSOLD Guidelines (2000) are 1.5 under steady state seepage, 1.2 under OBE, a FoS of greater than 1 under MDE, and 1.2 to 1.3 during rapid drawdown conditions on the upstream slope.

A deformation analysis was also undertaken for the OBE and MDE events, which showed minor to moderate damage including 40mm crest settlement and 30mm crack width in an MDE event.

3.3. Seepage – Internal Drainage and Clay Liner

The internal drainage consists of a fully intercepting 600mm wide chimney drain that extends to peak maximum flood level and connects to a base horizontal drainage/filter blanket, as shown in Figure 5. The horizontal drain is locally thickened in the vicinity of the service spillway culvert (beneath the dam and in the current stream bed location), where there is a greater risk of cracking and concentrated leaks. A 250mm thick continuous filter layer is provided on the left abutment foundation surface with a series of 1m thick high capacity strip drains, consisting of a filter layer surrounding a coarser drainage material. A toe drain is provided on each abutment.

The filters have been designed to allow for compatibility with the embankment and foundation soils at site, with the critical surfaces being the clay core to vertical drain interface and the foundation to horizontal/toe drain interface. The filter design was undertaken according to guidelines set out in Fell et

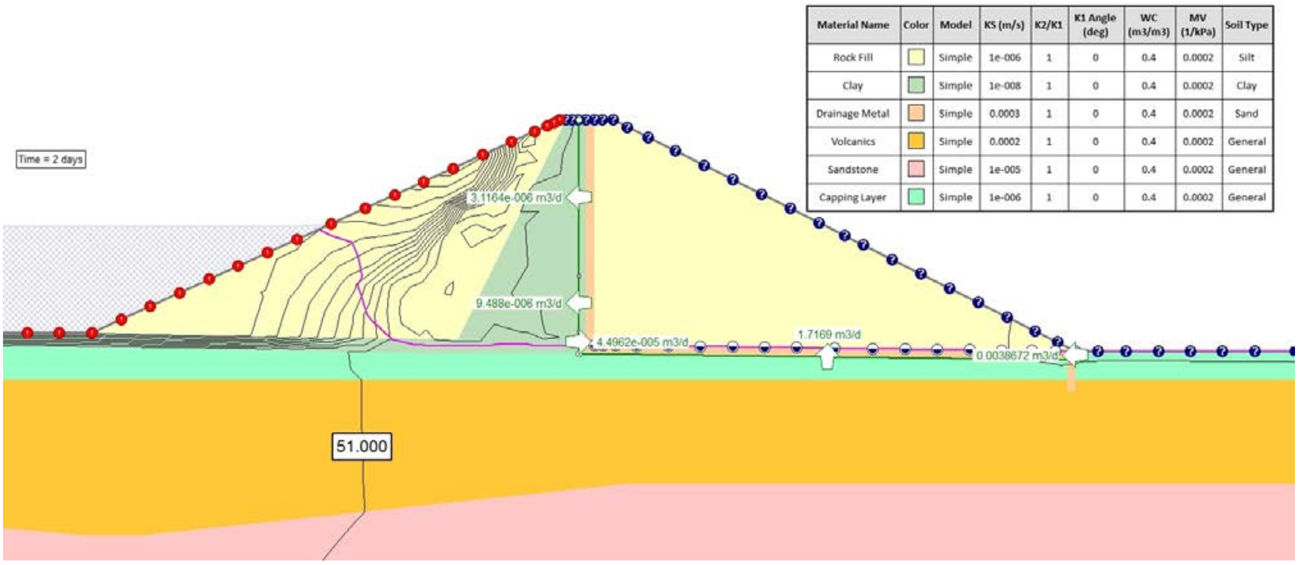


Figure 7. Transient groundwater analysis

al (2005), which has specific criteria for determining the filter design gradations for the critical filters. Two filter gradings are recommended, with the coarser (all gravel-sized, >2mm particle diameter) drainage material only to be used in the high capacity strip drains. The second filter material consists of well-graded sandy gravel with less than 2% fines. A horizontal drain thickness of 250mm, which is approximately 20 times the maximum particle diameter, has been adopted to prevent segregation of particles in the filter blanket.

An upstream clay liner on the left abutment is provided as a means to reduce seepage potential and pressures in the left abutment foundation. The clay liner is 1m thick and extends 20m from the upstream toe of the dam. This liner was modeled in the seepage analysis.

A transient groundwater analysis of flow through the dam embankment and foundation was prepared using the Slide software package groundwater function. An input hydrograph of the three day 1% AEP storm event on the upstream side of the dam was provided, which has a maximum water level after 1.32 days and no water in the basin after 2.32 days. The permeabilities for the embankment and foundation materials were inferred from the packer test and falling and constant head test results and from assumptions based on the geological model for the dam embankment and foundation materials. A key assumption in the Slide model is a pressure head of zero in the horizontal drain on the downstream shoulder, which assumes the drain is flowing in a large detention event. A printout from the Slide groundwater model is shown in Figure 7. The analysis is sensitive to input parameters and assumptions.

The highest flowrate into the horizontal drains was obtained on a mid-slope section on the left abutment, with the most likely flowrate into the drains ranging between 0.3 and 2 m^3/d/m. Assuming the most conservative parameters in the analysis, a value of 34 m^3/d/m is obtained. Lower flowrates were calculated for the lower left abutment and central dam sections. A design flowrate of 1 m^3/d/m has been used in design of the horizontal drains on the left abutment. The proposed strip drains on the left abutment achieved a FoS of 11 for this design flowrate, which is greater than a FoS of 10 that is considered acceptable for the drains.

4. Conclusions

The proposed 18m high Kotuku flood detention dam is a high PIC embankment dam to be constructed on the Nihotetea Stream to reduce flooding in Whangarei City. The dam is located within a complex geological environment with three different geological units including a moderately permeable basalt lava flow and flow margin within the dam foundation. Detailed site investigation has been undertaken to assess the subsurface conditions and prepare a geological model. Foundation treatment, embankment, seepage, and internal drainage designs have been prepared for the proposed dam, which include a clay liner, undercuts of alluvial and selected residual and flow margin materials, toe drains, and internal drainage. The dam is scheduled for construction in the 2014/2015 earthworks season.

5. References

Fell R., MacGregor P., Stapledon D., Bell G. (2005). *Geotechnical Engineering of Dams.*

Martin V., Tate D., Camuso J., Howse B. (2013). *Proposed Kotuku Flood Detention Dam.*

NZSOLD (2000). *New Zealand Dam Safety Guidelines.*