

UNIQUE SOAKAGE DESIGN FOR THE THREE KINGS QUARRY

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ABSTRACT

Fletcher Residential Ltd own the former Three Kings scoria quarry in central Auckland and are turning the quarry into a large scale residential development – a place of 1200 homes. The development is directed by a comprehensive masterplan which includes a range of different housing typologies, cultural recognition, creation of new sports fields, retaining elements of the quarrying and geological heritage and the filling the quarry pit by about 70% of its former depth.

The Three Kings quarry sits within a unique environment. The geology is complex, with a 1km diameter surrounding tuff ring (with a breach to the north), a series of scoria cones and basalt pushing up through the scoria in dykes and forming lakes. Much of the geology is disturbed and overlain by subsequent eruptions. The quarry sits at the top of the Meola Catchment where there is little separated stormwater infrastructure and only an overloaded combined sewer nearby. The planned development retains part of the former quarry pit, which means the development floor sits at about 15m below Mt Eden Road at RL62m to RL65m - with no way of providing piped gravity drainage or overland flow paths. Groundwater pumping is also to cease and the groundwater levels will return to the pre-pumping levels of RL56.5m.

Approximately 39% of the area of Auckland City is underlain by volcanic lava flows and associated scoria which has been used for soakage and stormwater disposal on the Auckland Isthmus. What differentiates the Three Kings development from others in the Auckland region is the discarding of the capture and pump stormwater system in favour of the design and construction of a unique large scale stormwater disposal system to soakage via the aquifer within the Three Kings basalt lava flow.

A companion paper by Messrs. Brunton & Seyb describes the development of the overall stormwater management approach and how the challenges were addressed related to management of stormwater in relation to the proposed dwelling floor levels, storage and soakage of stormwater, the local mounding of groundwater, protection of soakage systems and the overall operation of the system.

This paper focusses on the soakage and groundwater aspects of the design. The approach adopted for the conceptual design is discussed and the practicalities of implementation and construction utilizing materials available are covered. The assessment of the soakage capacity of the volcanic aquifer around the Three Kings quarry was done by modelling using the insitu test results

The implementation of the design objectives and the insitu testing carried out to achieve and confirm the required design criteria are described together with the approaches and methodologies adopted. Challenges associated with the construction of the soakage systems as part of the quarry filling are described and the solutions presented.

KEYWORDS

Soakage, Stormwater, Groundwater, Basalt Aquifer

Water New Zealand's 2018 Stormwater Conference

1 INTRODUCTION

The Three Kings quarry site is located within a unique and complex geological environment. The site has been quarried since approximately the 1920's-1930 by the Winstone brothers who purchased the site in 1922. Quarry operations have now since ceased and the quarry is currently being backfilled and rehabilitated in preparation for the development of the area into a large scale residential development.

Broadly speaking Three Kings (Te Tātua a Riukiuta) comprised five main scoria and tuff cones with, Big King (Koheraunui), East King and Highest King. Quarrying has removed two of the three main cones with only Big King surviving. A Painting by John Kinder of the Three Kings Volcanic Crater is held by the Auckland Art Gallery and is shown on Photograph 1. This painting provides a view of the cluster of cones prior to any quarrying.



Photograph 1: *Three Kings Volcanic Crater (Auckland Art Gallery Toi o Tāmaki, gift of Harry Kinder, 1937)*

Photograph 2 shows views taken in 1905 from Mount Eden looking south towards Three Kings and over Mount Eden Road in the foreground (formally Three Kings Road) looking west showing the volcanic cones taken in 1920.



1905



1920

Photograph 3: *Three Kings Volcanic Centre (1905 By Henry Winkelmann and 1920 By James D Richardson <http://www.aucklandcity.govt.nz/>)*

What differentiates the Three Kings development from others in the Auckland region is the discarding of the capture and pump stormwater system in favour of the design and

construction of a unique large scale stormwater disposal system to soakage via the aquifer within the Three Kings basalt lava flow.

2 GEOLOGY

Three Kings is located on the Waitemata Series dividing ridge which separates the paleo-Waitemata and paleo-Manukau River valleys. It is located on the ridge at the head of three paleo-valleys, namely Oakley and Meola to the north and west, (tributaries of the paleo-Waitemata River) and a tributary to the paleo-Manukau River to the south east (Searle E.J., 1981).

According to Searle (1981) activity from the centre is thought to be complex and diffused through a large number of vents spread over a wide area. The first stages formed a large tuff crater. Lava rising from multiple vents formed coalescing scoria cones and a small lava flow from a vent located on the western side of the scoria cones ponded within the tuff ring. An explosive eruption breached a northern portion of the tuff ring and lava from these new vents flowed down the paleo-Meola valley, making contact with the older Mt Albert lava flow.

Fine scoria (lapilli tuff) was also erupted at this time and built on an earlier tuff ring located at Landscape Road. The lava may have ponded behind the Mt Albert flow and eventually may have over-topped the earlier lava, flowing northwards into the Meola-Motions valley. A flow extends into the present day Waitemata Harbour from this paleo-valley system. It is unclear if this portion of the flow originated from Three Kings or Mt Eden. Investigation drilling carried out in the area has indicated the Three Kings flow is very thick at the head of the Meola paleo-valley.

Volcanic activity outside the central tuff crater to the south produced large amounts of tuff mantling the area, including the Mt Cecilia tuff mound and very thick beds of ash at the intersection of Mt Eden and Mt Albert Roads. Large extents of tuff also cover the Epsom area to the north and east overlying both the East Coast Bays Formation (comprising sandstone and mudstone) and the basalt lava flows from the One Tree Hill eruption. No lava producing vents have been identified in this area. Activity at the centre is thought to have been relatively short-lived (Searle E.J., 1981). The geology of the Three Kings area as mapped is shown in Figure 1.

These volcanic lava flows and associated scoria has been used for soakage and stormwater disposal within the Three Kings area and elsewhere on the Auckland Isthmus. Due to the nature of the deposition of the basalt and its subsequent cooling, the rock is highly fissured and fractured with lava tubes in places. This creates a base rock of high permeability.

Stormwater can be disposed of into this zone of permeable rock via boreholes and tunnels. The stormwater becomes part of the groundwater system and flows toward the Waitemata harbour flanking the northern edge of the isthmus. Groundwater flow is through fractures, joints, cavities and rubble or scoriaceous zones in the volcanic rocks and the aquifer behaves as a fractured rock aquifer as opposed to a porous media (Smaill, 1993).

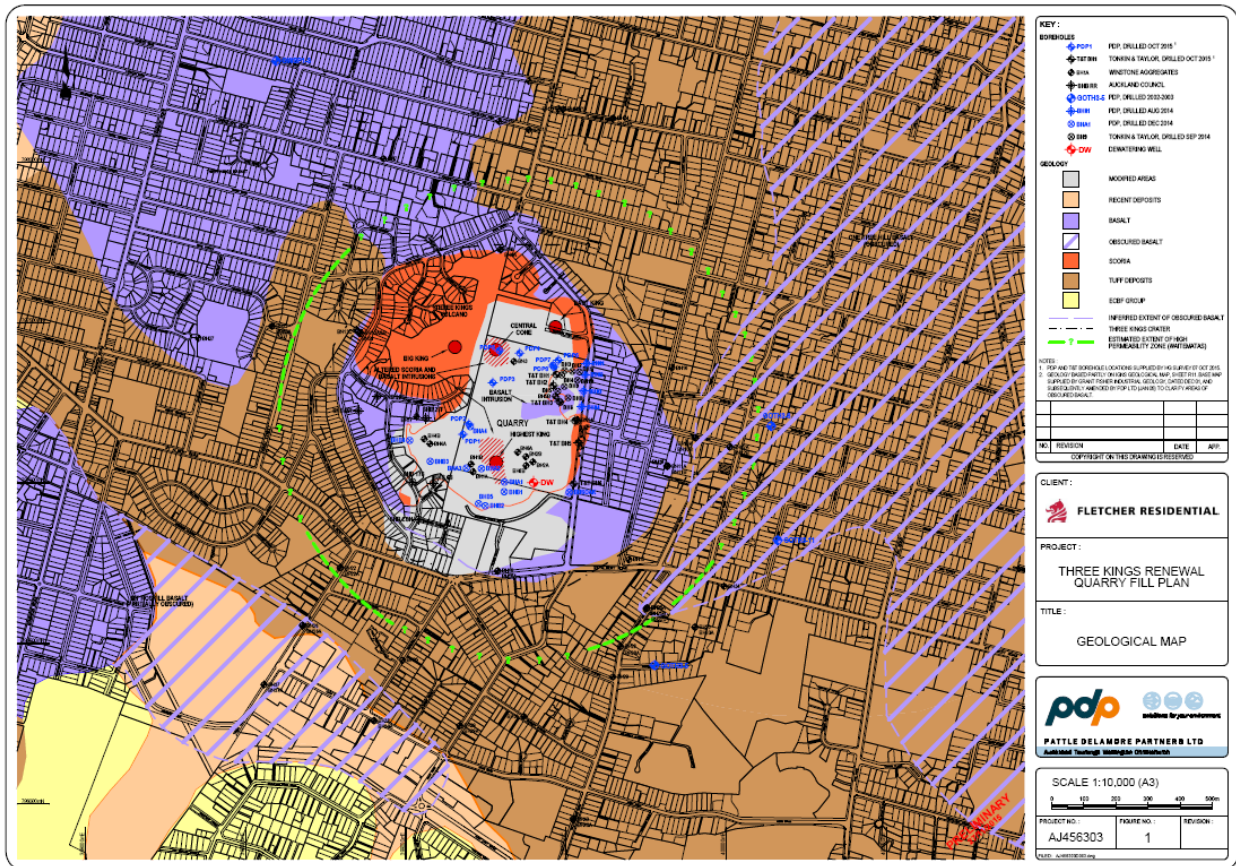


Figure 1: Geology of Three Kings Area

3 GROUNDWATER MODELLING

3.1 MODELLING OBJECTIVES

As part of the design of the storage and soakage zones, it is necessary to define the freeboard available for soakage above the original water level (RL56.5m) that is required to host the groundwater level rise associated with the design storm.

A modelling study was undertaken to estimate the rise in the reinstated original groundwater level as a result of the following rainfall events:

- 10-year ARI, 24 hour rainfall event;
- 100-year ARI, 24 hour rainfall event; and
- Sequential 2 x 100-year ARI, 24 hour rainfall events.

3.2 CONCEPTUAL GROUNDWATER MODEL

A generalised conceptual hydrogeological model for the site is shown in Figure 2 and the main elements of the conceptual model discussed below.

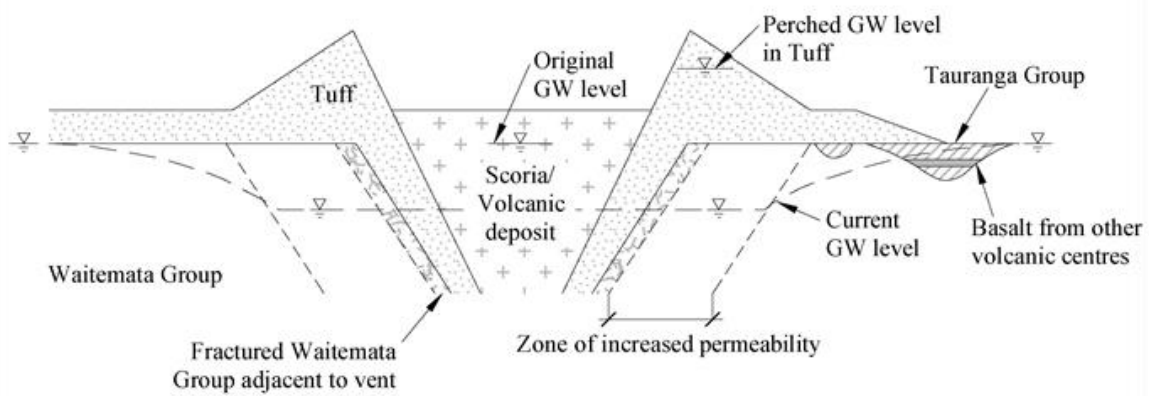


Figure 2: Generalised Conceptual Groundwater Model

3.2.1 GEOLOGY

The geology in and around the Three Kings quarry is shown in Figure 1 and can be divided into four main soil and rock types: basalt, scoria, tuff, and non-extrusive sediments (Waitemata Group). Basalt, scoria and some tuff dominate the quarry area and form a roughly circular outcrop defined by the volcanic crater. Basaltic feeder pipes might reasonably be expected at the centre of four identified volcanic cones with scoria surrounding them. A basaltic feeder pipe is currently visible toward the south east corner of the quarry at the former location of the Highest King. Based on the existing information, a breach of the northern boundary of the crater has occurred where a lava flow exited the crater and continued down to Meola and Western Springs (there is no evidence of any lava flow breach toward the Onehunga Aquifer). A detailed geological model of the quarry and surrounding crater was constructed in Leapfrog Geo which is a 3-dimensional software package used for geological modelling (Figure 3).

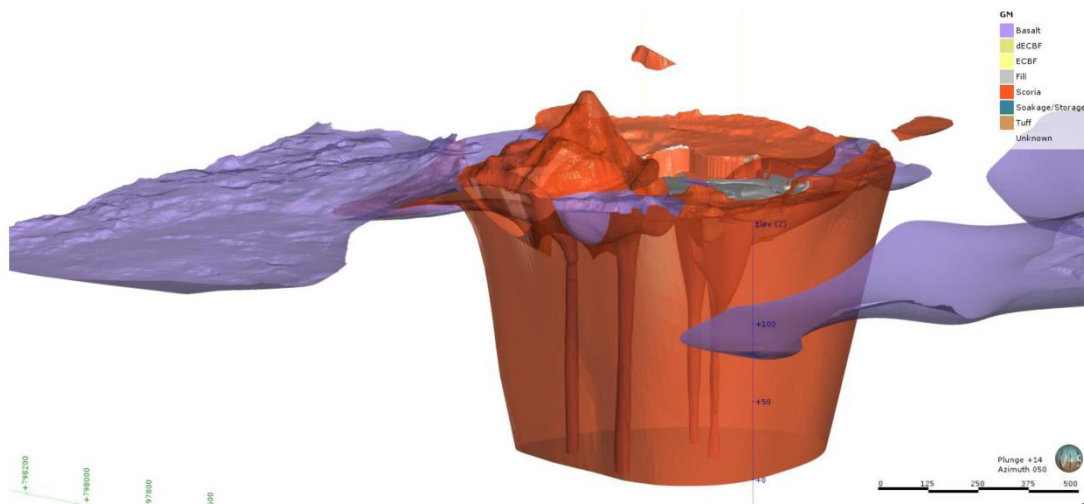


Figure 3: Leapfrog Geological Model

3.2.2 HYDROGEOLOGY

Following the dewatering by the quarry operations the groundwater has been drawn down by about 23m (RL34m) and now predominately flows towards the quarry dewatering pumping well (which is referred to as DW in Figure 1). Cessation of the groundwater abstraction within the Three Kings volcanic crater will cause the groundwater level to recover to the pre-dewatering levels of around RL56.5m. This will result in resumption of groundwater through-flow from the crater along the Three Kings lava flows and towards Western Springs.

The groundwater level hydrographs shows that most bores have reached their maximum response to the dewatering and are currently close to steady-state. Groundwater levels in the crater (basalt and scoria) have behaved similarly suggesting that there are no significant hydraulic barriers within the crater. The nature of the tuff ring breach has been defined using the groundwater level monitoring data inside and outside the crater. Based on the available data, the tuff ring breach invert is about 8.5m below the pre-dewatering groundwater level at RL48.0m. As the groundwater level in the quarry dropped below the invert of the tuff ring breach, the connection between the groundwater inside and outside the crater ceased.

Under current steady-state dewatering conditions, the rainfall recharge has been balanced by outflow through dewatering abstraction. The total long-term groundwater inflow to the pit under the current dewatering conditions is about 2,500m³/day. This includes some groundwater contribution from the surrounding Waitemata Group (disturbed zone) which is diverted to the pit. Using the above pump out rate, the recharge over the scoria and basalt is estimated to be about 83% of rainfall falling on the crater catchment (which is considered to be within previous recharge estimates and modelling). The groundwater catchment for the above abstraction is limited to the crater (basalt and scoria) and the disturbed Waitemata Group.

3.3 GROUNDWATER NUMERICAL MODEL

The performance of the proposed underground storage and soakage zones during the design rainfall events has been confirmed using the 3-dimensional groundwater model. The modelling code used was the 3D finite difference program MODFLOW (Harbaugh, 2005). The geological input into the model was built with the Leapfrog Geo geology model that was created for the crater.

The model area covers the Three Kings crater and a 400m zone of Waitemata Group outside the crater. A 200m ring of disturbed Waitemata Group with a higher permeability occurs around the edge of the crater. The proposed soakage zone to be constructed to service the quarry development was included within the model. The model grid spacing ranges between 10m (inside the crater) to 25m, vertically discretized into 17 model layers. The bottom of the model is set at RL-100m. The model domain and grid structure is shown in Figures 4 to 6.



Figure 4: Model Domain

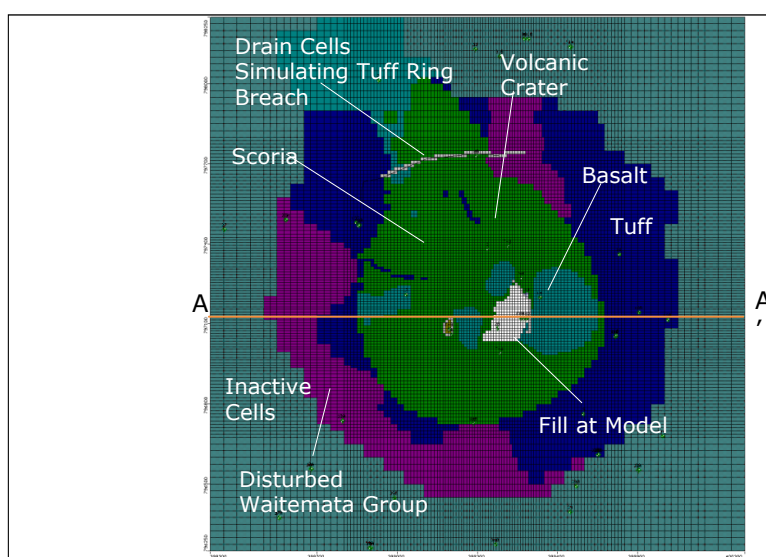


Figure 5: Model Grid and Boundary Conditions (model layer 4)

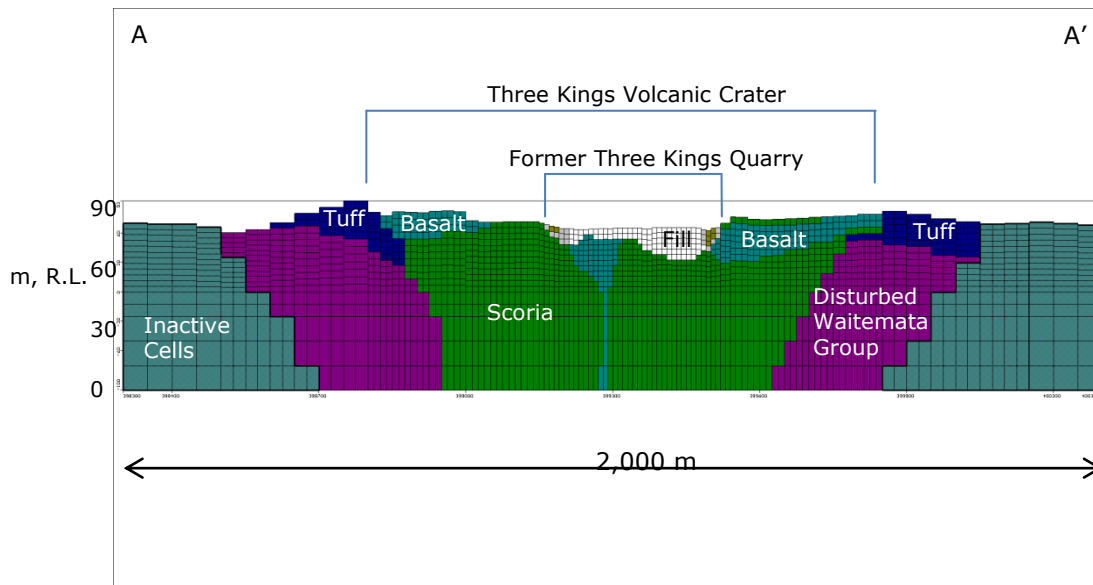


Figure 6: Model Grid (Section AA')

The drain boundary was assigned to nodes located along the tuff ring breach between RL56.5m and RL48.0m. The head along the drain cells were set at pre-dewatering groundwater level (RL56.5m). The quarry pumping was simulated in the model using abstraction cells with specified pumping rates.

3.3.1 MODEL CALIBRATION

As part of the quarry dewatering monitoring conditions, the groundwater levels, rainfall and dewatering pumping rates are being monitored and have used for the calibration. The steady state calibrated model parameters are shown in Table 1.

Parameters	Basalt/Scoria	Disturbed Waitemata Group
Hydraulic Conductivity (m/s)	0.0015	9.4×10^{-7} (1)
Recharge (mm/year)	1,000mm/y (83% of rainfall)	120mm/y (10% of rainfall)

The average difference between measured and calculated groundwater level in bores within the crater is less than 0.3 m with root mean squared error of 0.25 m. The model input and output was 2469.79 and 2469.94 m³/d respectively with less than 0.05% error.

The data from two pressure transducers installed within quarry pit bores BH17 and BH5B, between 9 July 2016 and 21 December 2016 (Figure 7) was used to define the model storage parameters under transient conditions.

The best calibration, was achieved using the specific yield (storage) of 0.08 (or 8%) for basalt and 0.2 (20%) for scoria. The basalt storage is in agreement with the upper range of storage identified as part of the GAS study (0.01 to 0.08) (PDP, 2005). The model predicted groundwater level rise in BH5B for the above storage parameters of about 0.27m is shown in Figure 8. The observed rise at this monitoring bore is 0.25m.

The sensitivity and uncertainty modelling results indicate that calibrated parameters are reasonably conservative and suitable for assessing the effects of rainfall events on groundwater levels.

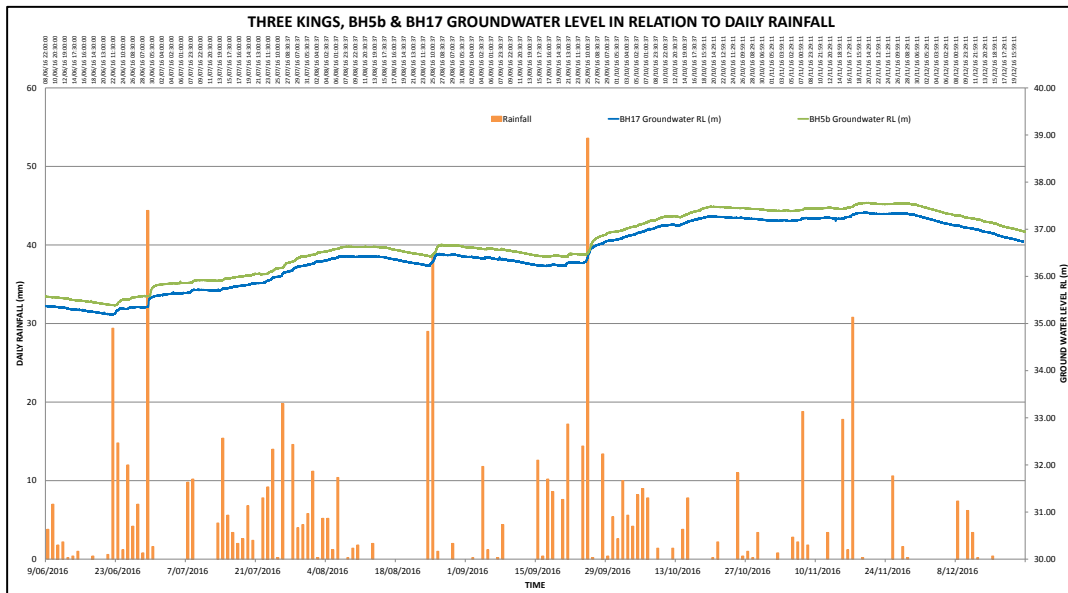


Figure 7: Groundwater Level Hydrographs (BH17 and BH5B)

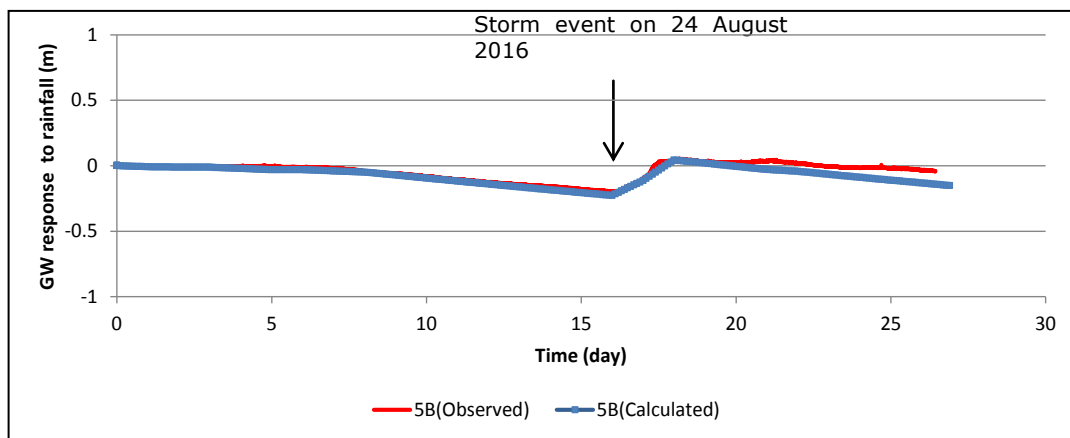


Figure 8: BH5B head response to a 44.4 mm (over 24 hours) rainfall event on 24 August 2016

3.4 PREDICTIVE SIMULATIONS

The calibrated model parameters were used to simulate effects of rainfall induced infiltration from peak flows on the groundwater levels in the crater as a result of the rainfall events. In order to estimate the appropriate recharge that occurs during storms, the infiltration volumes for the various sub-catchments in the crater were taken from the HEC-HMS surface water model during the design events given in Section 2.1.

3.4.1 SCENARIO PARAMETERS

The hydrogeological input parameters are provided in Table 2.

A factor of safety of 3 has been applied to permeability of the soakage zone walls to allow for future degradation in soakage capacity through clogging/siltation.

A detailed HEC-HMS rainfall-runoff model was created for the crater. Infiltration was taken from the HEC-HMS model which calculates infiltration based on the SCS Curve Number rainfall-runoff method. All stormwater which did not contribute to runoff was assumed to enter the groundwater system (no allowance for evapotranspiration has been made).

Table 2: Summary of Hydrogeological Properties

Lithological Unit	Kh (m/s)	Kv/Kh	Storage Coefficient ¹
Scoria	0.0015	1.0	0.20
Basalt	0.0015	1.0	0.08
Soakage Zone Connection to Quarry Wall ²	0.0005	1.0	0.20
Soakage Zone Material	0.010	1.0	0.25
Fill	1.0×10^{-7}	1.0	0.20
Disturbed Waitemata Group	9.4×10^{-7}	0.1	0.10
Waitemata Group	5.0×10^{-7}	0.1	0.10

Notes:
 1. Specific Storage (Ss) is assumed to be $1 \times 10^{-5} \text{ m}^{-1}$
 2. Includes factor of safety of 3 for Kh

The modelled infiltration zones are shown in Figure 9.

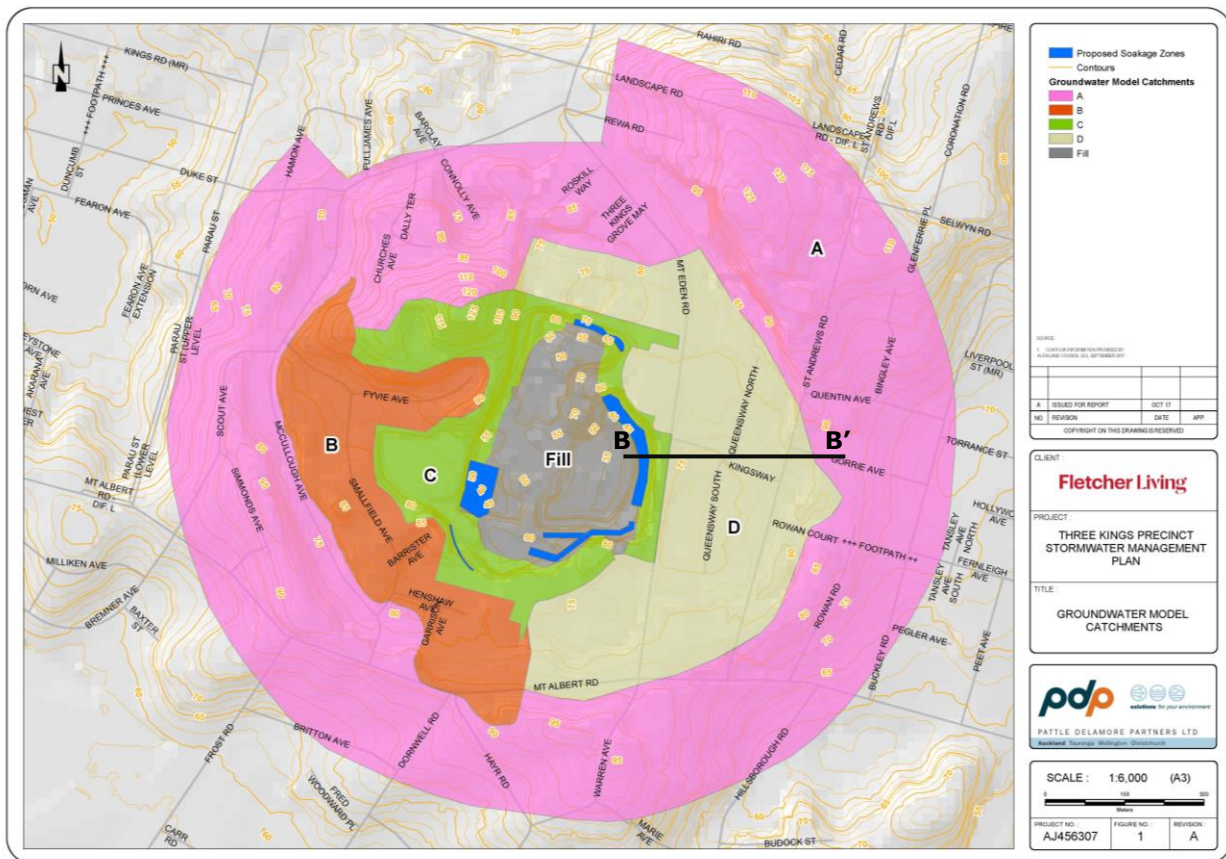


Figure 9: Modelled Infiltration Zones

The soakage zones and chimney drains are simulated in the model by high permeability cells (0.01m/s).

3.4.2 MODEL RESULTS

The groundwater model results are summarised in Table 3. The results are given for the soakage zones as they fill during the respective rainfall event. The modelling results indicate that the 10-year ARI rainfall event causes the soakage zones to fill up by around

3.1m to 3.4m above the normal original crater groundwater level (RL56.5m). These rises equate to soakage zone groundwater levels of between RL59.6m and RL59.9m.

The highest soakage zone water level elevation is well below ground level and therefore confirms that runoff caused by 10-year rainfall event can be contained below ground level without above ground ponding.

Rainfall Event ARI	Soakage Zone	Water Level Rise (m)	Soakage Zone Groundwater Level (RLm)	Required Storage Volume Above the Ground (m ³)
10-year	Northeast	3.44	59.94	0
	East	3.13	59.63	
	South	3.29	59.79	
	Southwest	3.27	59.77	
100-year	All Zones	> ground level		20,300
2 x 100-year	All Zones	> ground level		56,500

The maximum groundwater mounding caused by 10-year ARI rainfall event along the model section BB' (Figure 9) between the east soakage zone and the residential area to the east is shown in Figure 10. The general rise in the crater groundwater level caused by the 10-year ARI rainfall event is about 1m outside the influence of the soakage zone. The groundwater mound will be contained within approximately 200m of the edge of any soakage and storage zone.

The 100-year and 2 x 100-year ARI rainfall events result in 20,300m³ and 56,500m³ of above ground ponding respectively. These volumes will be used to determine the required floor levels within the Precinct.

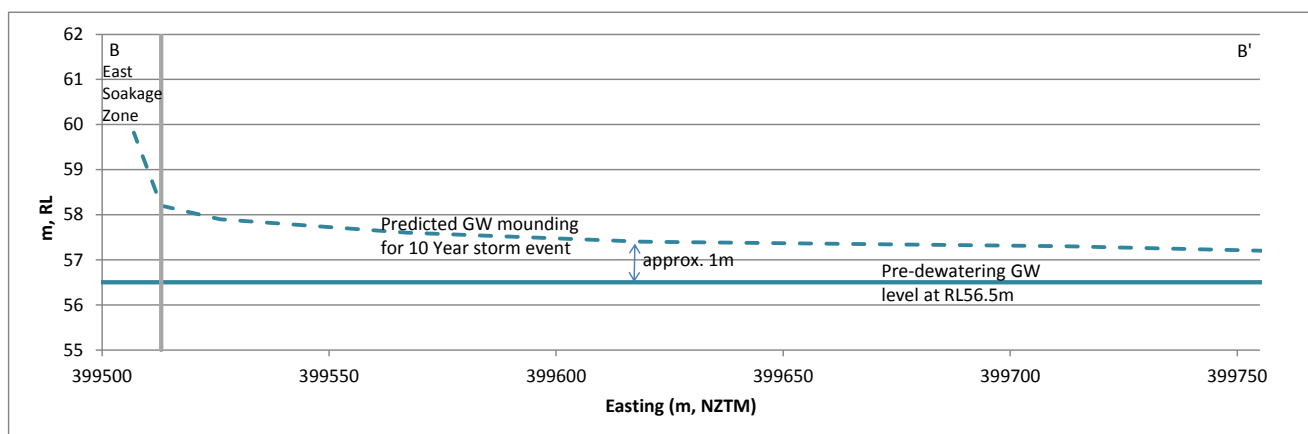


Figure 10: Groundwater Mounding along Section BB' (from Figure 9)

3.4.3 MAXIMUM GROUNDWATER TABLE DESIGN LEVELS

Maximum water table design levels (excluding local mounding) were derived from the various considerations as follows:

100-Year ARI rainfall event

Normal crater water level (no pumping)

RL56.5m

Normal seasonal maximum water table level variation	0.5m
Rainfall event water table response	1.2m
Allowance for future soakage development in surrounding area	0.3m
Minimum design water level for surface water storage	RL58.5m

For the 10-year ARI rainfall event a response of 0.8m was used giving a water table design level of RL58.0m. The development requires the quarry to be filled to above these levels for all residential areas and roads.

The 0.3m groundwater level rise for future soakage development in the surrounding area represents an increase in the average infiltration rate by 24mm/day in Zone B shown on Figure 9. This area includes Fyvie, Smallfield and Henshaw Aves where the primary stormwater discharge is to the combined sewer system. The 0.3m rise allows for some stormwater to be diverted from the combined sewer to soakage. The exact amount diverted depends upon the current amount captured by the combined sewer and the extent of existing impervious area in these zones. Assuming pervious parts of these zones already drain to soakage, the 24mm/day increase in average infiltration across the zone represents a higher rate of new infiltration/soakage from existing impervious areas.

4 SOAKAGE

4.1 SOAKAGE INVESTIGATIONS

As soakage is the only method of disposal of stormwater it is critical that the soakage capacity is measured and determined to be in excess of the required soakage rates as determined from the stormwater management design system (refer to Brunton & Seyb paper for stormwater modelling). Extensive soakage testing was carried out and investigations within the Three Kings Quarry in two major phases during 2014 – 2017. The methodology to investigate the soakage potential for the development included:

- Classification of Rock Mass Units;
- Quarry wall mapping;
- Borehole investigations (downhole soakage testing);
- Surface infiltration testing;
- Assessment of hydrogeological units; and
- Field (bulk) porosity testing of proposed drainage aggregates.

The results of the investigations were used to develop and refine the conceptual hydrogeological models and to inform stormwater design.

4.2 PHASE 1 SOAKAGE INVESTIGATIONS

During preliminary investigations and mapping, eleven rock mass units (RMU) were encountered and described based primarily on primary and secondary rockmass characteristics, namely lithology and welding/jointing respectively.

The RMU encountered are summarised in Table 4 below (the RMUs were later rationalized into hydrogeological units).

Table 4: Rock Mass Units

Rock Mass Unit	Type	Rock Mass Unit	Type
RMU1	Unwelded coarse scoria	RMU7	Basalt
RMU2	Welded coarse scoria	RMU7a	Basalt with Scoria inclusions
RMU3	Coarse scoria and basalt blocks/bombs	RMU7b	Weak weathered Basalt
RMU4	Mixed basalt and welded scoria	RMU7c	Rubbly Basalt
RMU5	Welded fine scoria / Tuff	RMU7d	Fractured Basalt
RMU6	Scoria lapilli and ash		

4.2.1 QUARRY WALL MAPPING

Quarry wall mapping was undertaken at the pit floor and on benches of the proposed soakage zones. In addition, particularly due to the vegetated state of the eastern quarry wall, 10 abseil lines were conducted to further define the geology in the obscured locations. The geology was logged using the above RMU categories.

A visual assessment of the geology was also undertaken to identify the distribution of RMU in the western and northern quarry walls. This was undertaken at a less detailed scale and maps were not produced for these areas.

4.2.2 BOREHOLE INVESTIGATIONS

Eight rotary cored boreholes were drilled within the Three Kings Quarry area for the purpose of geological investigation and to examine soakage potential. Additional soakage testing was conducted in a further four geotechnical boreholes drilled along the eastern pit crest. The locations of these boreholes are shown in Figure 1.

The most recent boreholes were drilled using a rotary core (PQ) to depths between 10.5m and 42.0m below ground level (bgl). The holes were drilled at angles between 60° and 90° to provide greater coverage horizontally. The geology encountered and logged in the boreholes was indicative of the Auckland Volcanic Field and the scoria cones that erupted in the quarry area.

Soakage testing was conducted in general accordance with Auckland Council Technical Report 2013/040 (Strayton & Lillis, 2013). Water was pumped downhole to pre-soak the ground. Following pre-soaking the flow rate was adjusted to achieve a constant head. The rate at constant head was recorded and converted to permeability. If constant head was not achieved, the flow rate was increased to its maximum and the test was run for a further 10 minutes.

Soakage tests targeted specific reduced levels (RL) within proposed soakage zones and were occasionally adjusted dependent on the geology encountered. As the drill hole reached the target depth, the casing was pulled back to expose a section of open hole to undertake the soakage test. The test equipment was then removed and drilling continued. This process was repeated several times in each borehole until the borehole target depth was reached upon where the casing would be removed to test the overall soakage rate for the borehole. A total of 27 soakage tests were carried out in 12 boreholes in this manner.

4.2.3 SURFACE INFILTRATION TESTING

Rockmass permeability can vary in saturated and unsaturated conditions. The above borehole soakage tests were carried out in unsaturated conditions, due to dewatering operations of the quarry. Surface infiltration testing included test soak pits and Double Ring Infiltration Testing (DRIT). The DRIT is a soakage test at surface carried out and

designed to replicate saturated conditions. Soakage testing in test pits measures both the vertical and horizontal movement through the sidewalls. DRIT was used to estimate the local in-situ soakage capacity at the proposed soakage connections at the quarry wall.

The testing was completed following procedures developed for the project (generally in accordance with the ASTM Standard Designation: D 3385). The method was modified to account for the purpose of the testing and the field conditions. The tests were repeated several times until two or more sequential tests had the same result thus indicating the soakage rate was stable and considered saturated. The geology of the surrounding natural ground was recorded for hydrogeological classification.

DRITs were undertaken at 8 locations, along the eastern and southern bench of the quarry at RL60m. The tests were carried out above the future ground water table RL56.5m, where the highest soakage is expected to occur, although soakage will also occur below the ground water table. Tests were carried out at 25 m intervals at locations selected to obtain a good coverage of the proposed soakage zones that were also accessible.

Test pits are a preferred method used in scoria soakage testing and frequently used where conditions are not suitable for drilling. The test method is described in Auckland Council Technical Report 2013/040 (Strayton & Lillis, 2013). Soakage testing in test pits was undertaken in 2014 at a number of locations within the quarry. Test pits soakage rate results are converted into permeability using a method described by Juca, de Campos, and Marinho (2002). The method is based on an empirical relationship between the dimensions of the soak pit, the rate of discharge to the ground, and permeability of the underlying soils.

4.2.4 PHASE 1 TEST RESULTS

Mapping of the quarry walls using the RMU’s was utilised to initially identify preferred soakage zones. The conceptual hydrogeology of the RMU’s was developed based on information from the test results from:

- 27 Borehole investigations;
- 13 DRIT valid results; and
- Soakage test pits.

The range of soakage rates obtained from the previous testing outlined above and the median values are shown in Table 5.

<i>Table 5: Summary of Soakage Rates¹ (QFP) L/s</i>			
Test Type	Lower bound	Upper bound	Median
Borehole	0.5	79.5	18.0
DRIT	0.0	0.3	0.1
Test pits	15.0	21.5	18.3
Notes:			
1. The variability in test methodologies does not allow the direct comparison of soakage rates. Soakage rate must be converted to permeability.			

The overall permeability of the volcanic rocks (scoria and basalt) in the Three Kings Crater has been previously estimated at 2×10^{-4} m/s by groundwater drawdown and Water New Zealand’s 2018 Stormwater Conference

rainfall response analysis (PDP, 2005). This assessment was determined from short term groundwater level response to rainfall while pumping was occurring – that is the permeability estimated is the response to rainfall at rock below RL34.0m rather than RL56.5m.

The variability in results (Table 5) due to the test methodology meant that the direct comparison of soakage rates was not possible. Various methods have been employed to convert the test results and statistical techniques used to quantify the range of expected range of permeability. The measured or inferred hydrogeological unit permeability varied from $< 1 \times 10^{-4}$ to 4.4×10^{-3} m/s. This permeability range, above and below inferred permeability for the overall crater, is not unexpected.

4.2.5 LEVEL OF CONFIDENCE

The permeabilities that were measured on site were variable and as such, in order to develop an appropriate and justifiable design soakage rate, the test results were considered as a statistical distribution.

The performance of the underground storage and soakage zones are critical in protecting the development from flooding. Due to several of the soakage connections being placed underground and near multistorey apartments, there are minimal options for upgrading the system in future. The amount of soakage is dependent upon the number of fractures intercepted in the basalt, the areal extent of the soakage zone and the porosity of unsaturated material. As such, it is very important that the systems are designed adequately now for long term operation and conservative assumptions are made about the amount of soakage available. The design approach uses the lower bound of the average soakage rate along with a factor of safety to allow for long term deterioration in the soakage rate.

To process the soakage test results into a lower bound soakage rate, it was important to determine a level of confidence to be used in the design. The lower bound soakage rate was used given the nature of the soakage data collected, the importance of the infrastructure performance and the limited ability to upgrade if required.

Due to the small and highly variable sample size, a Student's T distribution (or *t*-distribution) was used on the data. The assessment was carried out for the whole RMU dataset and with the data set divided into borehole and DRITs. The 90% lower bound of the confidence interval for the mean permeability was chosen as the current permeability. The probability that the true mean permeability of the quarry is below this value is 5%. This was used across all soakage connections, creating additional confidence in the design. This is because the probability that all of the soakage connection locations have a permeability of the design soakage rate or lower is considerably lower than 5%.

There is a significant difference between the RMU1 to RMU4 (scoria) results from the boreholes and those from the DRIT. The reason for this is unclear. Plots of the two sets of results have been reviewed and show a double mode peak. This could be due to a limited number of the tests in the varieties of material present – that is more testing would give a better average and tighter confidence levels, or it could indicate a physical difference within the results - such as location (the majority of borehole tests in scoria were in the western face and the majority of DRITs were on the eastern face), or test method (some blinding on the boreholes, or lack of saturation in the DRITs).

The local permeability used for assessing the performance of RMU 1 to RMU 4 was 1.3×10^{-5} m/s for western soakage zones and 5.2×10^{-4} m/s for eastern soakage zones. This was based on the lower bound of the mean using a 90% confidence interval – with borehole tests used for the western zone and DRITs used for the eastern zone. Further testing is recommended to improve the confidence around these values.

Following this assessment the RMU's were grouped into three main hydrogeological units (HU) based on similar measured or inferred permeability.

- HU1 – Variable Scoria;
- HU2 – Fractured Basalt; and
- HU3 – Basalt.

4.3 PHASE 2 SOAKAGE INVESTIGATIONS

Phase 2 investigations involved extensive testing of the proposed soakage zones using test pits to prove that design soakage rates will be achieved. As a key part of the design is transmission of stormwater from the storage zones to the soakage zones, porosity of the aggregate used in construction of these zones is critical.

Phase 2 soakage testing and investigations included:

- Test soakage rates from (84) test pits and (2) boreholes;
- Soakage fill material (drainage aggregate) porosity testing; and
- Mapping of HU within the Eastern soakage zone.

More detailed mapping and interpretation of aerial images of soakage zones was undertaken in Phase 2, as the quarry walls were cleared of vegetation during bulk filling.

4.3.1 TEST PITS

Soakage testing was undertaken either within or in the vicinity of the proposed underground soakage zones. Test pits were typically excavated in variable scoria, with the exception of 5 test pits along the R.L. 50.0 m bench of the eastern wall, which were in basalt.

Within the variable scoria, three RMU were identified based on the recent testing with different permeability characteristics. These RMU are:

- Welded fine Scoria – typically red in colour, finer grained and without structural layering;
- Black Scoria – typically black, coarse to very coarse with layering; and
- Scoria and Basalt bombs – variable scoria with very coarse basalt fragments and bombs.

Generally, lower permeability values were obtained from testing completed in areas where the red welded scoria was present, typically found in the East soakage zone. Increased permeability values are obtained for the very coarse, loose black scoria, typically found in the South soakage zone. Very high permeability values were obtained in the Northeast soakage zone where the geology predominantly comprises scoria and

basalt bombs. As in Phase 1, soakage rates were converted to permeability using the method described by Juca, de Campos, and Marinho (2002).

Five test pits on bench RL50.0m and two boreholes on bench RL60.0m provided the means to test the permeability of the basalt. The test results show reduced permeability in basalt when compared to the scoria. The permeability from all test results within the test pits ranged from 4.1×10^{-5} m/s to 1×10^{-2} m/s with median value 1.5×10^{-3} m/s. The results of recent soakage testing for the soakage zones are summarised in Table 6 below.

<i>Table 6: Summary of Soakage Test Results</i>		
Soakage Zone	Accumulated Soakage Rate (L/s)	Median Permeability (m/s)
Eastern	232	0.0019
Southern	438	0.0010
Northeast	314	0.0030
Grahame Breed Drive	52	0.0033
<i>Notes:</i>		
1. No testing was able to be completed for the Southwest soak hole.		

4.3.2 POROSITY TESTS

The proposed storage and soakage zones will consist of rubble, rock fill and drainage aggregate to transmit water into the Three Kings Aquifer. The design target porosity for the soakage fill was 25%. The primary specification is that material can convey water to the in-situ rock soakage without restriction. Storage and soakage zones will comprise of the following aggregate types of nominal particle size:

- Rubble (1000/200);
- Rock fill (1000/200);
- Drainage aggregate D65 (65/19); and
- Drainage aggregate/gabion rock GR (175/80) or similar.

Rubble comprises of very large boulders of basaltic rock, sub-rounded to angular in shape. Rock fill comprises of inert demolition material including concrete and brickwork. Rubble and rock fill is sourced from stockpiles at the Three Kings Quarry. Drainage aggregate is sourced off site from the GBC Winstone Flat Top and Hunua Quarries.

Field based porosity tests on the soakage fill materials used in construction were completed at the quarry. The porosity test is a direct measure of the void space of 'placed' (i.e. replicated conditions) soakage material by the volumetric addition of water. The samples (where possible) were saturated (up to 7 days before testing) and drained just prior to the test, to replicate the wetted surface condition of the storage fill following storm events. The results of porosity testing are summarised in Table 7 below.

<i>Table 7: Soakage Fill Material Porosity</i>	
Material	Porosity (%)
Rubble and rock fill ¹	46.3%
Drainage D65	44.6%
<i>Notes:</i>	
1. Sourced from Three Kings Quarry stockpiles.	

In addition tests were carried out to assess the porosity of the insitu scoria using Nuclear Density Meter (NDM) and Sand Replacement Test (SRT). The results indicated a range of porosities ranging from 43% to 65%. It was not clear if the voids were be formed from discrete bubbles of gas within the rock matrix and may not be connected to the other voids – this means that not all of the void space may be available for water storage.

4.3.3 CONCLUSIONS OF SOAKAGE INVESTIGATIONS

Phase 1 soakage investigations undertaken at the Three Kings Quarry as part of the original Quarry Fill Plan (QFP) included:

- 27 Borehole tests;
- 13 Infiltration tests; and
- Mapping of rock mass units within the quarry.

The measured or inferred hydrogeological unit permeability for the QFP ranged from $< 1 \times 10^{-4}$ m/s to 4.4×10^{-3} m/s.

The overall permeability of the volcanic rocks (scoria and basalt combined) in the Three Kings Crater has been previously estimated as 2×10^{-4} m/s by groundwater drawdown and rainfall response analysis undertaken by PDP.

Phase 2 soakage testing undertaken at the Three Kings Quarry has included to date:

- 84 Test pits; and
- Borehole tests

The majority of recent testing has been undertaken in variable scoria geology.

The tests described in the previous sections measured an accumulated soakage rate of 1,036L/s that is achievable in the unsaturated zone above future groundwater water level.

The testing clearly indicated the areas of the quarry perimeter to be targeted for the soakage zones for the design of the soakage system. The best soakage was found at the Northeastern corner, a portion of the Eastern wall and the Southeastern and Southern section of the quarry. The Western flank proved to be much less permeable.

4.4 DESIGN

Soakage is to be achieved by using large area connections between the flood storage and the in-situ scoria and basalt as part of the development. The connections are formed by:

- Having storage zones connected directly to the cleaned quarry face within the fill zone; and
- Excavating soakage trenches into natural rock in the cut zone.

The design component is dealt with by Brunton & Seyb (Brunton & Seyb, 2018) and the reader is referred to this paper.

4.5 CONSTRUCTION

4.5.1 EROSION AND SEDIMENT CONTROL

Sediment in runoff has the potential to clog the rock faces of the quarry walls and reduce soakage. All stormwater passing over earthworks surfaces should be treated using erosion and sediment control methods so that sediment generation is minimised and sediment is prevented from entering rock fractures or coating rock surfaces, reducing the soakage potential of the development.

The Erosion and Sediment Control Plan (ESCP) for the site during rehabilitation work requires the following control methods to be implemented as described in Auckland Council's (2016) GD005 (Leersnyder et al, 2016):

- Staged construction;
- Surface roughening and rapid stabilisation;
- Stabilised entranceways;
- Stockpiles;
- Geotextiles;
- 'Dirty water' diversion bunds;
- 'Dirty Water' diversion channels;
- Sediment retention ponds and sacrificial sumps; and
- Dust control.

Sacrificial zones to discharge stormwater are required and are generally located in the quarry floor and at quarry walls away from the target soakage zones. Controls are inspected and monitored regularly throughout construction to ensure that stormwater is adequately controlled and treated by the contractor prior to discharge. The ongoing filling of the quarry has necessitated that the erosion and sediment control measures are continually evaluated, assessed and modified to meet the changing conditions of the site (i.e. changing gradients and fill areas)

4.5.2 CHIMNEY DRAIN CONSTRUCTION

The chimney drain has been designed to provide unrestricted hydraulic connectivity from the underground storage and upper soakage zones to the lower soakage zones along the perimeter of the existing quarry. Two chimney drains are designed for the Eastern and Southern soakage zones that will access the lower soakage zones. It was intended that the construction of chimney drains would be generally concurrent with the compacted bulk fill being placed. For the Eastern Soakage zone initial delays in construction occurred due to:

- Building footprint conflict with the soakage rubble zone;
- Temporary rockfall hazard from the quarry pit crest; and
- Prioritising bulk filling operations.

To protect the soakage fill material from fines that could affect its performance, a layer of geotextile (Bidim A44) was used at the interface between the general fill compacted adjacent to the drain. Care was required during construction to ensure that rubble material does not puncture the fabric.

As the chimney drain construction advanced, the existing quarry wall was cleared of vegetation and loose material that could impact on the performance of the drainage blanket. This clearance of the face was undertaken in lifts as the height of the backfill in the base of the quarry increases (approx. 3-5 m lifts).

Sacrificial layers of geotextile (Bidim A44) and use of plywood placed over the chimney drain have been used as protection. However, blinding layers using Drainage 65 aggregate have proved more efficient at protecting the soakage zones and cleanup operations. This protection layer however needs to be removed following cleaning of the quarry wall and verified through ongoing inspections.

The width of the chimney drain was set at a minimum width of 2m. However, the width of the chimney drain can vary between 2 to 6 m to suit construction purposes. At the time of writing the Eastern Soakage zone (chimney drain) has been constructed from RL45m – RL56m.

The exposed quarry wall faces to be used for future zones will be inspected at regular intervals to confirm the extents of soakage zones and record the final interface into the aquifer.

5 CONCLUSIONS

The development of the Three Kings Quarry has and continues to provide a number of challenges as the development proceeds. The overall concept of disposing stormwater generated off the development into soakage has been proven to be viable from a conceptual, technical and construction point of view. The concept of testing the soakage capacity of the target soakage areas such that the design soakage rates are exceeded, provides a level of confidence that has satisfied all parties involved in the development.

The key aspects have been:

- The diligent and programmed soakage testing to achieve measured soakage rates in excess of the design requirements.
- The practical assessment of the porosity of the materials used in the construction.
- Ongoing surveillance and monitoring of the construction activities and a willingness of the contractors to keep all parties informed of progress and activities on site.
- Regular involvement of Fletcher Residential as the developer and overall project managers.

The last point has proven to be invaluable to ensure the soakage design has not been compromised by other aspects of the development such as building location changes, foundation requirements and the like. The willingness of Fletcher Residential to ensure that these aspects are coordinated and dealt with, provides additional confidence in the long term performance of the soakage system.

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PRESENTER PROFILE

Gerald Strayton is a Civil Engineer with over 30 years' experience. He is a graduate of the Universities of Natal and the Witwatersrand. He has been involved in a number of soakage projects within the Auckland Isthmus. He has authored and co-authored a number of papers on soakage in Auckland.