CITY RAIL LINK STORMWATER DROP STRUCTURES

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ABSTRACT

The Auckland City Rail Link is a 3.45 kilometre twin-tunnel underground rail link up to 42 metres below the Auckland city centre. It will transform the downtown Britomart Transport Centre into a two-way through-station that connects the Auckland rail network and allows the network to double its capacity.

The North Auckland Line intercepts several overland flow paths that could, without appropriate assessment and design, flood the tunnels. Thus, an important aspect has been to divert or redirect stormwater away from the stations and tunnel portals. These diversions often required deep drop shafts (from 4 to 14 m deep, with flows ranging between 100 ℓ/s and 3000 ℓ/s) to convey water from surface stormwater systems to deep transmission stormwater pipes under the stations. The stormwater drop shafts' primary objectives were to convey the required flows while preventing erosion, managing air entrainment and utilizing existing stormwater structures that were often too small to permit a conventional approach.

This paper highlights how, through a collaborative approach, the designers developed several innovative solutions that did not fit within normal design guidelines or standards. The innovations included re-purposing existing shafts not designed for such flows, counter-current energy dissipation, using baffles to control fall velocity, and using methods like computational fluid dynamics (CFD) and finite element analysis (FEA) to confirm designs.

The design innovations were not always straightforward, and limitations included:

- Limited information and technical resources covering the combination of flow magnitude and drop height to base designs upon;
- Published research is often based on scale models; however air behaviour isn't readily scalable from model studies;
- Working in congested sites, with minimal space inside and outside the shaft;
- Working within tight construction schedules on a just-in-time approach
- Institutional pressures to follow a conventional approach.

This paper provides some critical learnings along our journey, which included the following:

- How a design cannot always follow a textbook solution, and solutions need to be found elsewhere while recognizing the extra cost associated with non-conventional approaches;
- Importance of a healthy balance between informed engineering judgement/experience versus analysis (the need to avoid "paralysis by analysis"); and
- How regular client and contractor engagement can be highly beneficial.

The solutions finally adopted are a great example of innovation born of necessity. They deliver the required hydraulic performance while often utilizing existing shafts, thus ticking boxes for cost-effectiveness and sustainability; they also meet the future asset owner's requirements for safety, accessibility and low-maintenance.

KEYWORDS

City Rail Link, Stormwater, Drop shafts, Shaft erosion, Air entrainment, Collaboration, Innovation

PRESENTER PROFILE

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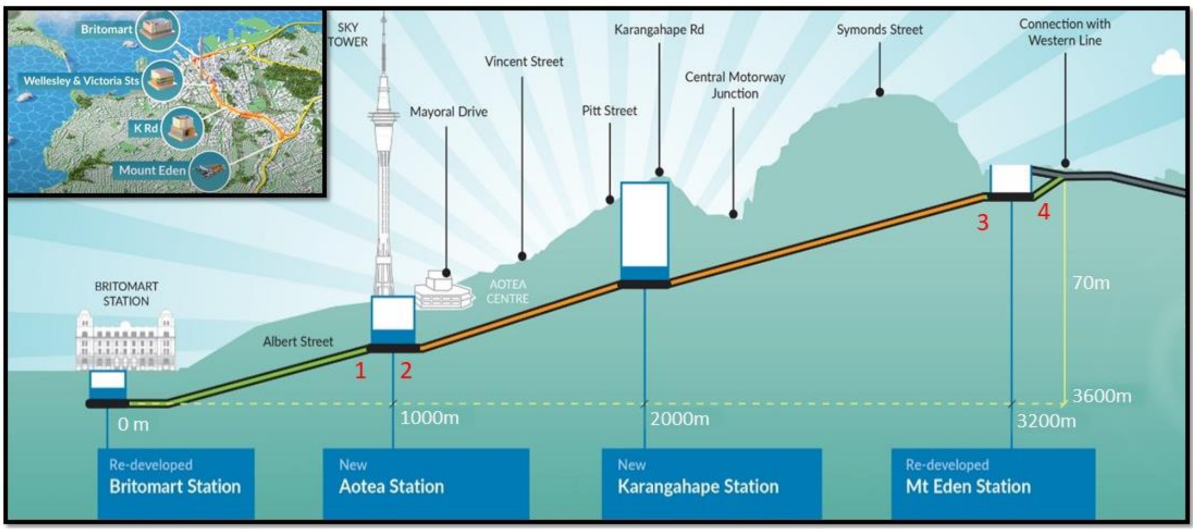
The Link Alliance is an alliance between City Rail Link Ltd and six NZ and international construction companies and design consultancies.

1 INTRODUCTION

The Auckland City Rail Link (CRL) is a 3.45 km twin-tunnel underground rail link up to 42 metres below the Auckland city centre. It will transform the downtown Britomart Transport Centre into a two-way through-station that connects the Auckland rail network and allows the network to double its capacity (Figure 1).

Figure 1: CRL Alignment and Station Location Plan (1.Victoria Street Shaft, 2. Wellesley Street Shaft, 3. Mount Eden Stormwater Diversion Shafts, 4. Enfield Street Shaft



2 DEFINITION OF THE PROBLEM

The existing North Auckland railway line (NAL) cuts across the slopes of Mt Eden in a shallow cutting and a consequence of this is that it intercepts several gully overland flow paths. This hasn't been a huge problem historically, as the overland flows would simply flow westwards along the rail corridor before spilling back into their original path further downstream. Construction of CRL will change all that. If not addressed, overland flows would be captured by tracks falling towards the tunnels and would eventually flood Britomart Station – an unacceptable outcome. The obvious solution would be to construct flood walls, to keep floodwater out of the railway, but the resulting "dams" would flood private properties immediately upstream – again unacceptable. Instead, a large new pipe was constructed to capture and convey overland flows to the lower catchment. Even here, delivering flood flows to the lower catchment faster could have unacceptable flood effects, but that solution is a story for another day.

Two new trunk stormwater pipelines were constructed as early CRL enabling works. One trunk main – known as "C2" after Contract 2 was a DN1950 micro-tunnelled concrete pipe. The C2 pipe is constructed along the eastern side of Albert Street, between Swanson and Wellesley Street, 500 m long with depths ranging from 14 to 16 m. The second new trunk pipeline – known as "C6" after Contract 6 that was responsible for it – was a DN2000 diameter concrete pipe that was directionally drilled from Boston Rd, Mt Eden to Nikau St, 450 m away, at depths ranging from 11 to 20 m. The challenge (and the subject of this paper) was to deliver surface flows into those deep pipelines.

Across the project in total there were 10 locations where near-surface flows ranging from 100 to 3,000 ℓ/s had to be delivered to trunk stormwater pipelines up to 14 m deep.

Deep drop shafts introduce several extra design considerations compared to normal shallow systems. Free-falling water has the power to seriously erode manhole bases unless consideration is given to energy dissipation. Less immediately obvious is the management of air entrainment. Free-falling water entrains a considerable volume of air, which "bulks up" the water and affects its behaviour in the shaft and in the receiving pipeline. Some of this air is carried through into the downstream pipe system where it can reduce pipe capacity and/or create unstable air pockets, which can "belch" upstream against the flow of water with considerable force. This can cause structural damage but also be a significant safety risk due to dislodged covers.

One final and very significant challenge (although it was just as much an opportunity, from a sustainability viewpoint) was that in both the central city and along the North Auckland Line there are several existing access chambers. These were built for maintenance access to the deep pipelines, but mostly without any special consideration of them being used as drop shafts.

Constructing deep new shafts would involve significant expense, consumption of materials and energy with associated carbon footprints, so it was desirable to re-purpose the existing shafts to serve as combined access and drop-shafts. Unfortunately, the shafts were almost all less than 3 m in diameter, which was not enough to fit a conventionally-designed plunge drop shaft while still meeting Council's access requirements.

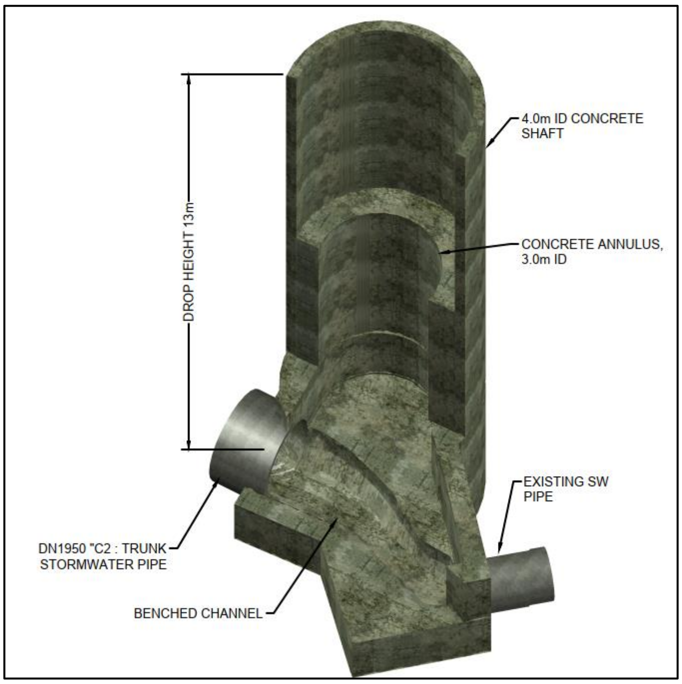
3 DROP-SHAFT SPECIFIC DESIGNS

This section outlines the selection of an optimal drop shaft configuration at each of several locations.

3.1 WELLESLEY STREET STORMWATER SHAFT RETROFIT.

The existing Wellesley Street shaft has a 4.0 m internal diameter for the top 6.5 m height and 3.0 m diameter for the lower 6.5 m. The reduction in diameter is a result of a thick concrete annulus (Refer Figure 2 below). This shaft was originally used as a receiving pit for the C2 jacking pipe installation.

Figure 2: Existing ("New") CRL C2 Wellesley Street Shaft



The approach pipe is a DN450 concrete pipe with a design flow of 375 ℓ/s in the 10% annual exceedance probability (AEP) storm. The drop height is 13 m from the invert of the proposed incoming high-level pipe to the floor of the shaft.

3.1.1 MAIN DESIGN CONSIDERATIONS, CRITERIA AND CONSTRAINTS

1. The drop shaft is designed to match the 10% AEP capacity of the upstream pipe system. Excess flows from larger storm events will continue flowing over-land down Wellesley Street away from the station.
2. The drop height exceeds the range where a straight drop shaft is appropriate, due to excessive velocity (abrasive and cavitation wear), excessive air

entrainment and noise/vibration considerations. Therefore, some form of energy dissipation is required within the shaft (e.g. vortex, helical ramp etc.) (Hager, 2010).

3. The shaft is located near a busy intersection where maintenance access needs to be minimized. An Auckland Council requirement for a 900 mm diameter opening to allow for man-cage access applied.
4. Also, a direct line of sight was required from the surface to the base of the shaft where work is being conducted for safety reasons.

3.1.2 OPTIONS CONSIDERED

1. A standard internal drop pipe structure from Watercare's Wastewater Standard was investigated. The total drop within this pipe would have been 12 m, which is considered too high for a straight plunge.
2. A two-stage cascade was initially attractive, using a slab at around the mid-depth of the shaft. The slab would contain an orifice to allow water to collect and discharge at a controlled rate. At both the shaft base and mid-depth slab a plunge pool would form, dissipating energy and thus minimizing erosion. This option was viable hydraulically but was discarded as a line-of-sight was not possible. Refer Figure 3 below.
3. A subcritical vortex is a commonly used device where the drop height exceeds about 7 m. A vortex is suitable for the Wellesley St height and configuration, with sufficient space for air re-circulation. Refer Figure 4a below. A supercritical vortex head was also considered as it is more compact, but more complex. Refer Figure 4b below.

A subcritical vortex was preferred, provided subcritical flow inlet conditions could be provided.

Figure 3: Wellesley Street Shaft Option 2 showing mid-height plunge pool

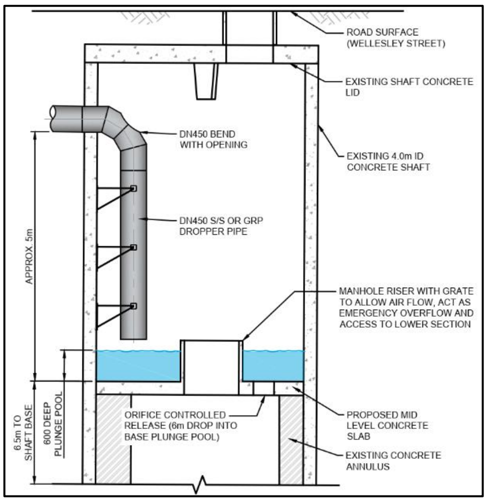


Figure 4: Geometry of vortex drop for (a) subcritical and (b) supercritical approach flow with plan (top) and section (bottom) (Hager, 2010) .

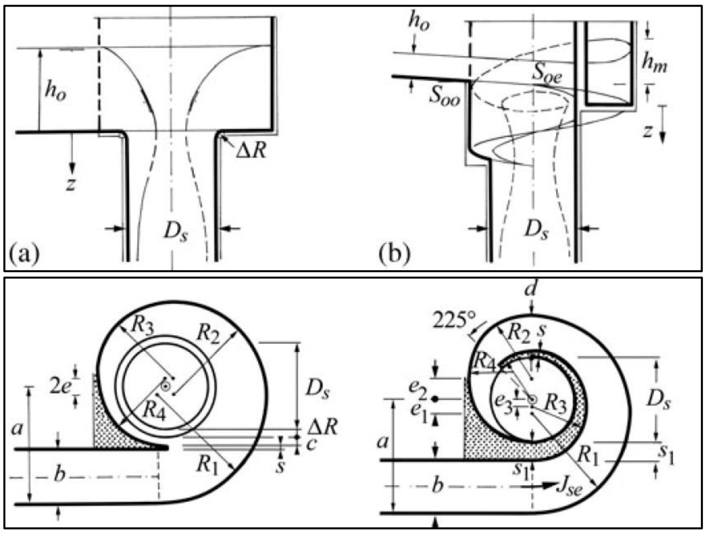
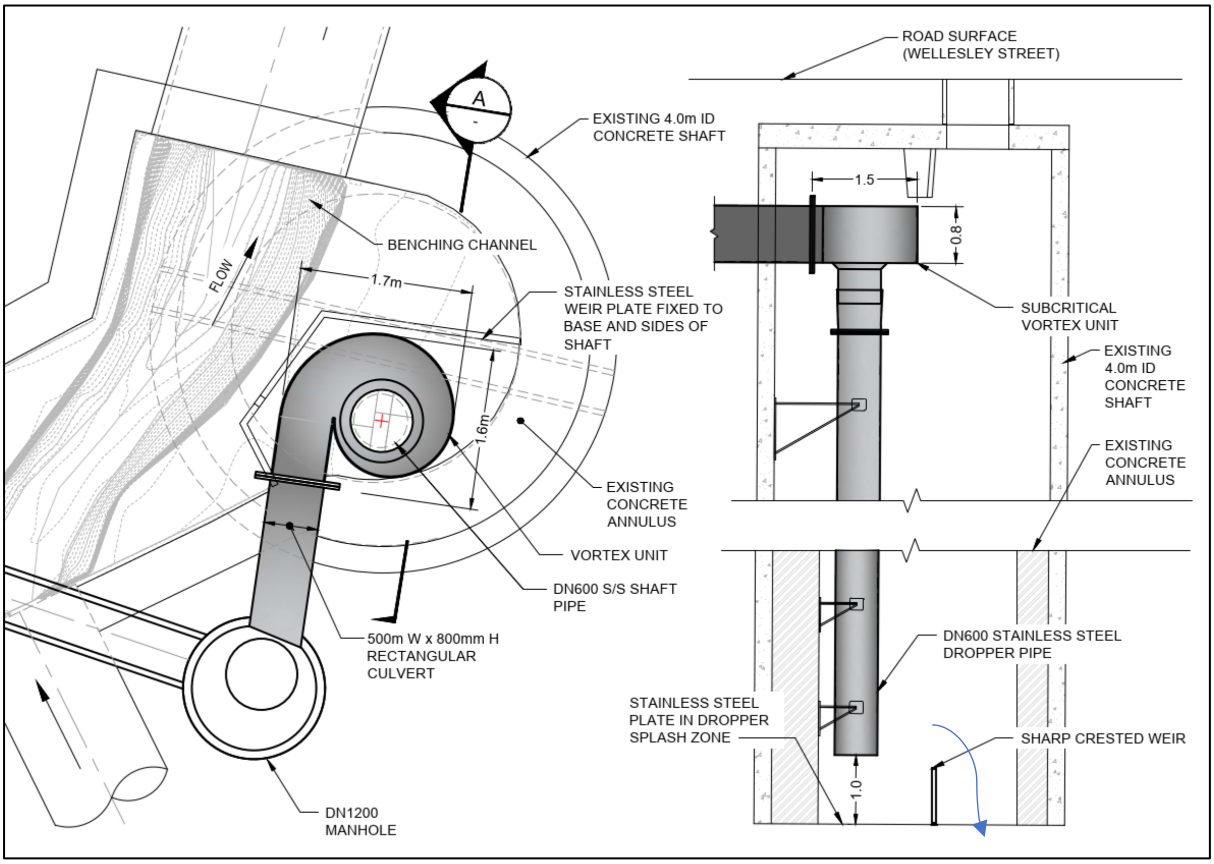


Figure 5: Wellesley Street Subcritical Vortex Shaft General Arrangement



3.1.3 HYDRAULIC DESIGN

A vortex hydraulic design was undertaken using principles developed through physical modelling by W. Hager (Hager, 2010). Refer Figure 4a above.

The inlet pipe was increased to DN600 and reduced in grade to 0.2% to provide subcritical inlet conditions. The vortex has a choking flow of about 1.0 m^3/s (the flow at which the central air core in the drop pipe reduces to zero) however should inflows exceed the capacity of the vortex, the water will rise and spill over the rim, plunging to the floor outside the drop pipe but inside the shaft. This is unlikely to occur as the choking flow is more than double the 10% AEP flow (Q_{10}), and so overland flow will already be occurring elsewhere.

Air was not considered critical as the HGL in the trunk drain is below the obvert for all likely design events and sufficient space exists in the shaft to allow air to recirculate. For smaller flow events where a vortex may not form, erosion will be prevented by the use of a stainless-steel plate.

3.1.4 MATERIAL SELECTION AND MECHANICAL DESIGN

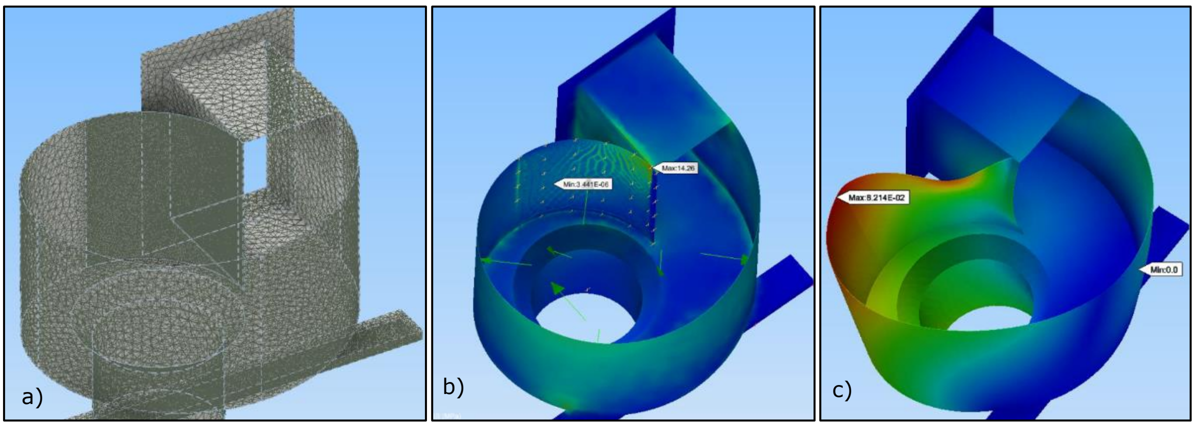
The Vortex installation was modelled and assessed using Autodesk Inventor (2018) software, utilizing the sheet metal component of the package and performing a finite element analysis on the hydraulic performance. Refer Figure 6.

Main design features included:

- Making unit as light as practicable to allow easier installation and maintenance.
- Having a friction fit between the vortex head and drop pipe to allow for removal and installation without the need for bolting or welding at height underneath the unit.
- Keeping within acceptable stress, strain and deformation limits.

The material selected was a 3 mm SA-240 316L (stainless steel) sheet. Stresses were shown to be relatively low compared to allowable material stresses. Deflection would be minimal in a major storm event. Stainless steel was selected over polyethylene to avoid creep due to temperature expansion and contraction.

Figure 6: a) FEA Analysis Mesh, b) Max. Principal stress results (Max. 14 MPa shown in red), c) Maximum displacement (8mm shown in red)



3.2 VICTORIA STREET SHAFT RETROFIT

The Victoria Street shaft was initially a launch pit for the DN1950 C2 ("Contract 2") pipe installation and also serves as a trunk stormwater junction chamber. The existing circular shaft is 2.05 m internal diameter with a reduced 1.2 m diameter riser for the top 6.5 m of the shaft. At the base of the circular shaft is a "tee" shaped chamber with approximately 2 m headroom from the benching to the underside of the roof. The shaft was constructed inside a secant pile shaft and the annulus backfilled with low strength concrete.

The incoming high-level pipe is a new DN710 PE100 SDR13.6 (ID 606 mm) pipe, designed for 1088 ℓ/s in the 10% AEP storm with a drop height of 14.3 m.

3.2.1 MAIN DESIGN CONSIDERATIONS, CRITERIA AND CONSTRAINTS

1. The shaft will ultimately pass through a section of the future Aotea Station. For this reason, reducing odour, noise and vibration were important design considerations.
2. With the shaft being located within the station, space for installation and future maintenance was very limited. Auckland Council require a minimum 900 mm maintenance opening and a direct line of sight from surface level to the base of the shaft.
3. Entrainment, movement and release of air bubbles/pockets in the downstream pipe.
4. It was assumed that timing of inflows was independent of the downstream hydraulic grade line (HGL). Catchment modelling showed an air space will be available in the trunk pipe for all design events.
5. It was critical that the dropper have negligible effect on the upstream pipe capacity because the upstream pipework was already surcharged.

3.2.2 OPTIONS CONSIDERED

There are two critical locations to consider in the design of energy dissipation in drop structures: the header (top) and the base. The header controls how water enters the dropper (e.g. a straight plunge or a vortex transition). The base is designed to reduce high velocities and remove entrained air.

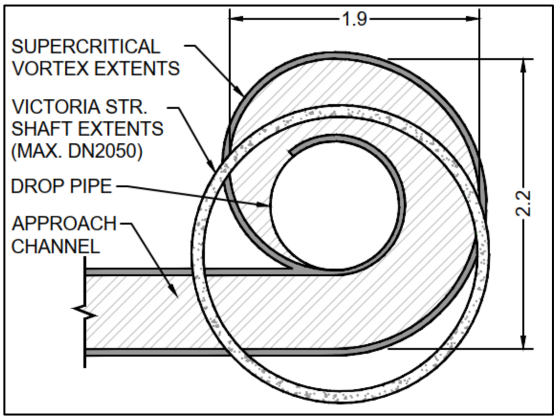
The following two header options were considered:

1. Subcritical and Supercritical Vortex Head Unit

Vortex head units induce a spiral action in the falling water, and energy dissipation is achieved by friction against the pipe wall (Hager, 2010). A vortex-type drop was initially considered as a safe method of conveying the flow, given the 14.3 m drop height to the floor of the chamber and the spare shaft area allowing air recirculation. The arrangement would require the upper section of the shaft to be increased to at least 2.05 m diameter to provide sufficient space for maintenance access.

Both a subcritical and a supercritical vortex were investigated due to the space constraints. The subcritical vortex head was 2.2 m diameter and a supercritical vortex head 2.05 m. However, cover to road level would be less than 0.5 m, and station design was too far advanced to permit the re-configuration required for either vortex so regrettably, vortex options had to be abandoned. See Figure 7 below showing the area required for a supercritical vortex unit.

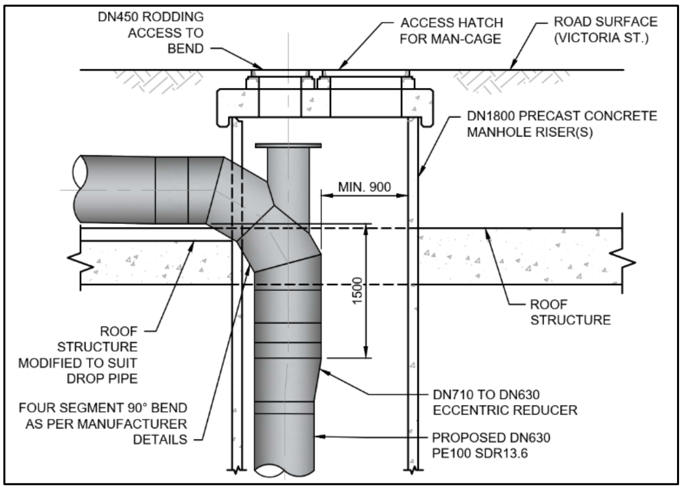
Figure 7: Initial sizing estimate, showing the footprint of a supercritical vortex head entering the Victoria Street drop shaft.



2. Vertical Bend (Preferred option)

The incoming pipe was turned through a vertical 90° bend and extended a further 1.5 m downwards to reduce head loss in the drop pipe and avoid impacting on the capacity of the upstream network. A reducer was then installed to transition to a DN630 PE100 SDR13.6 drop pipe. This header option resulted in larger pipe velocities in the pipe below but fitted in the available space while still allowing maintenance access to the base of the shaft. A rodding point was installed on the bend to allow future flushing and camera access.

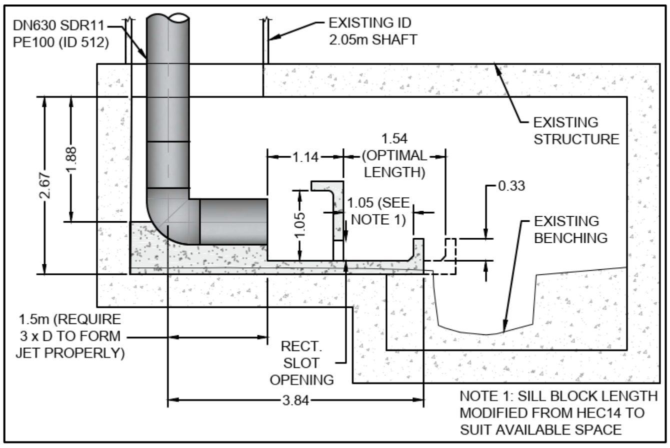
Figure 8:Vertical Bend (Elevation view)



The following energy dissipation options were considered at the base:

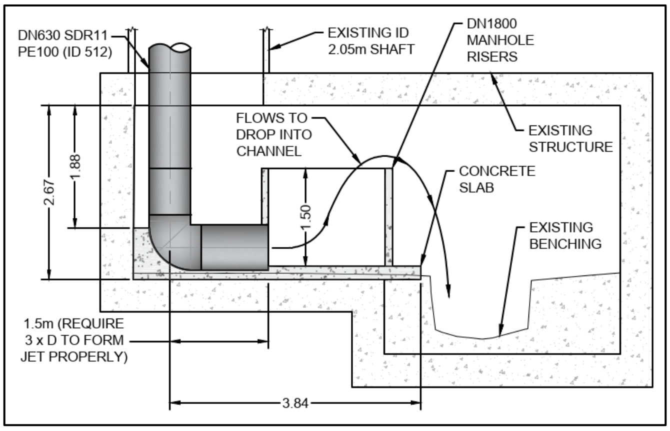
1. An impact-beam energy dissipater option was developed based on HEC 14 14 (Hydraulic Engineering Circular No. 14 Third Edition) (USBR Type Vl) (Thompson & Kilgore, 2006). This option was hydraulically viable but had restricted maintenance access due to the height of the impact wall.

Figure 9: Option 2 Impact Energy Dissipator adopted and modified from HEC14, USBR Type VI Impact Basin.



2. A HEC- stilling well was also considered (refer Figure 10). This type of energy dissipator was attractive in terms of its simplicity. The diameter was feasible, but the required height meant there was insufficient clearance between the top of the well and the chamber roof, so this option was also discounted.

Figure 10: Option 3 Stilling Well Energy Dissipator adopted and modified from HEC14, Chapter 12.



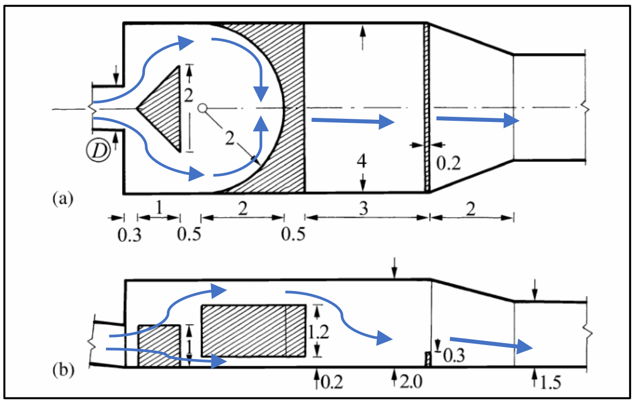
3. A counter-current arrangement (preferred) as described in 3.2.3 below, promised a lower structure height and easier maintenance access.

3.2.3 COUNTER-CURRENT FLOW DISSIPATOR HYDRAULIC DESIGN

The counter current flow dissipator (Vollmer, 1972) consists of a triangular flow-splitter directing flow into a semi-circular baffle. Energy is dissipated as the two opposing flows collide. For low flows, a small gap is provided below the semi-circular baffle to the end sill. For the design discharge, the water flows can flow both under and over the semi-circular baffle into a pool, created by an end sill (Hager, 2010).

Hydraulic design for the counter-current arrangement indicated the pipe exit velocity would be around 6 m/s, so abrasive wear of a concrete splitter block and curved baffle may occur. Stainless steel was selected to provide appropriate wear resistance in this location. Given the inherent wear resistance of PE, rapid abrasive wear was considered unlikely; however, the bend at the base of the chamber was increased to SDR11 for added risk mitigation.

Figure 11: Reverse flow basin of Vollmer (1972) (a) plan, (b) longitudinal section. Numerical quantities correspond to multiples of the approach flow diameter D (Hager, 2010). Flow arrows shown in blue.



3.2.4 MAINTENANCE-LED DESIGN

A strong Project-wide Safety in Design (SID) culture encouraged the design team to consider both constructability and future maintenance. This aspect was particularly important on this shaft as individual elements had to be man-handled into place in a confined space, through a 900 mm surface opening, to a depth of 14 m and then around a corner, putting them beyond the reach of lifting equipment. In response, all elements were designed in small segments capable of being fitted through the restricted space and man-handled into place. This approach will also assist future maintenance

3.3 ENFIELD STREET SHAFT RETROFIT

The Enfield Street shaft is an existing DN2050 diameter circular access shaft in Mt Eden. The shaft was built inside a ring of secant piles (which still remain), with the annulus filled with low-strength concrete. This chamber was built above the C6 pipe with a 975 x 990 orifice/opening through the shaft's concrete base.

Photographs 1 and 2: Construction photos of the existing Enfield Street shaft prior to the requirement to connect a large stormwater network. Visible in the photos is the 975 X 990mm orifice opening, the secant pile temporary works, a DN2100 SRJRC access chamber and a preliminary dropper pipe (which proved inadequate for the required flow).

3.3.1 MAIN DESIGN CONSIDERATIONS, CRITERIA AND CONSTRAINTS

The Enfield street shaft has been redesigned to pass the 1% AEP design storm flow with no impact on upstream flood levels and to accommodate the 0.04% AEP (2500-year ARI) storm without causing flooding to the CRL tracks or stations, as a requirement of the station design.

The design inflow and drop are summarised in the following table.

	Diameter (mm)	$Q_{10\%}$ (ℓ/s)	$Q_{1\%}$ (ℓ/s)	$Q_{0.04\%}$ (ℓ/s)	Drop height* (m)
New Pipe	900 RCP	868	1592	2322	9.1

*Drop is from incoming pipe invert to trunk drain invert

3.3.2 OPTIONS CONSIDERED

1 Vortex drop. A supercritical vortex was initially considered as it has a smaller head diameter than a subcritical vortex. However, the vortex could not be made small enough to meet Council's access requirements. Enlarging the shaft at the top was considered but due to the unknown fill behind the secant pile wall, a constructability review concluded that a vortex drop inside the existing shaft was not workable. Construction of a completely new, parallel vortex drop shaft with a tunnelled connection was also rejected as too expensive. Refer Figure 4 for illustrations of vortex drops.

2 A straight plunge drop. Due to the restricted space inside the DN2050 diameter shaft and the difficulty of enlarging it, a straight plunging drop was considered. The initial concept for a straight drop shaft is shown in Figure 12a. At 6.35 m from incoming pipe invert to shaft floor, and 9.07 m from incoming pipe invert to invert of the trunk drain, this arrangement exceeded the general limit of drop height for plunging flows. Also, having the discharge through a port in the shaft floor rather than a horizontal discharge pipe through the wall meant that it was not a "standard" drop manhole, for which design methods are available. The large drop and high flows (for the diameter of the shaft) meant that entrainment of large

quantities of air would occur. Initial estimates for a standard drop structure with an unrestricted outlet indicated a relative air demand of 3 or higher (i.e. for every 1000 ℓ/s of water, 3000 ℓ/s of air will be entrained). This volume of air would significantly affect performance of the trunk drain, so more sophisticated modelling of the structure was required. The alternative was to either enlarge the shaft or construct a new shaft adjacent to the existing, either of which would be complex and costly.

3.3.3 CFD MODELLING-LED HYDRAULIC DESIGN

To overcome these technical challenges and provide confidence in an acceptable hydraulic solution a numerical 3D model was built, and its hydraulic/pneumatic performance was assessed using computational fluid dynamics (CFD) modelling. Over 20 different configurations were trialled.

Inflows assessed were the $Q_{10\%}$ and $Q_{1\%}$ flows under various tailwater conditions.

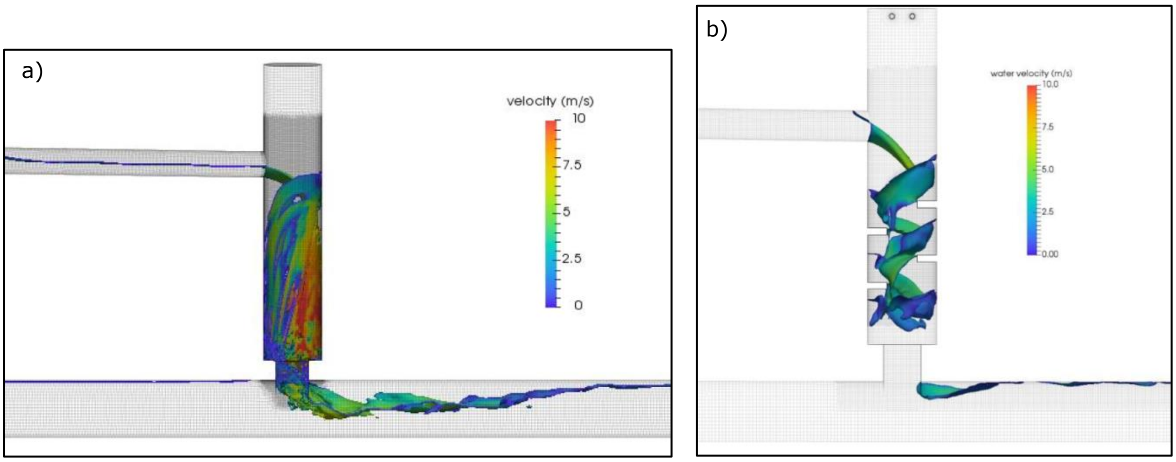
Through CFD modelling it became apparent that the HGL in the trunk stormwater pipe had a dramatic influence on the amount of air entrained if the port in the shaft base was not constricted. At low flows, the trunk drain will flow part-full, so air movement along the system won't be constricted. The modelling showed that the critical flow regime is when the trunk drain is just full but not pressurized, as this restricts free air passage in the trunk drain and also has the greatest air entrainment from the drop.

With the stormwater pipe just full, the modelling showed the 3,500-4,000 ℓ/s of air dragged in to be problematic. Also, the air inflow would be highly unstable, with large gulps of air being pushed into the stormwater pipe. This became the critical design case. Modelling of this case led to the inclusion of baffles, an orifice plate and a downstream vent pipe to allow entrained air to escape.

The situation was largely remedied by inserting D-shaped baffles onto the wall of the shaft (two each side) to create a series of splash pads and by placing a 700 mm orifice at the base of the shaft to choke the flow going into the stormwater pipe (Refer Figure 12a below). The orifice raises the water level in the shaft to create a plunge pool and the baffles reduce the plunging velocity. Both these acted to reduce the air entrainment in the 1% AEP inflow event to a manageable 900 ℓ/s. There is a 900 mm zone between the baffles to allow maintenance access and a clear line of sight to the base of the chamber. The orifice plate will be removable to allow access into the stormwater pipe through the full-sized port.

The wall baffles resulted in the peak falling water velocity not exceeding 6 m/s (Refer Figure 12b below), which is the generally accepted upper limit before abrasion will start to be significant in precast concrete pipes (Queensland Department of Primary Industries, 2013). This meant treatment of the concrete for abrasion was not required.

Figure 12: a) Flow velocity and water surface with no energy dissipation for 10% AEP flows b) Flow velocity and water surface with D-shaped baffles for 1% AEP flows.



3.3.4 DESIGN FOR AIR MOVEMENT, PRESSURE STABILIZATION AND AIR VENTING

Multiple air vents were required on the stormwater pipe and drop structure to help manage entrained air in the critical flow regime. They will release some of the entrained air but will also provide flow stabilization by preventing large air pockets from building up in the low-gradient pipe and being periodically flushed downstream. Some air will be carried downstream past the vent to the next structure, which will also have a vent installed.

Based on the CFD modelling, the optimal vent shaft diameter is 1000 mm, resulting in the greatest air capture. Further analysis was completed with smaller shaft diameters, identifying the allowable flow in the pipe that would not compromise the hydraulics. The final design was a DN450 vent pipe. The smaller size was a compromise between air capture, constructability and cost (allowing conventional drilling techniques). An upper limit air flow velocity of 25 m/s was selected, based on specialist advice.

The vent pipe construction is proposed to be a pile caisson drilled to the top of the stormwater pipe. The pipe caisson serves as a sleeve to allow for a GRP pipe with an ID of 450 mm to be installed through a penetration in the trunk drain below.

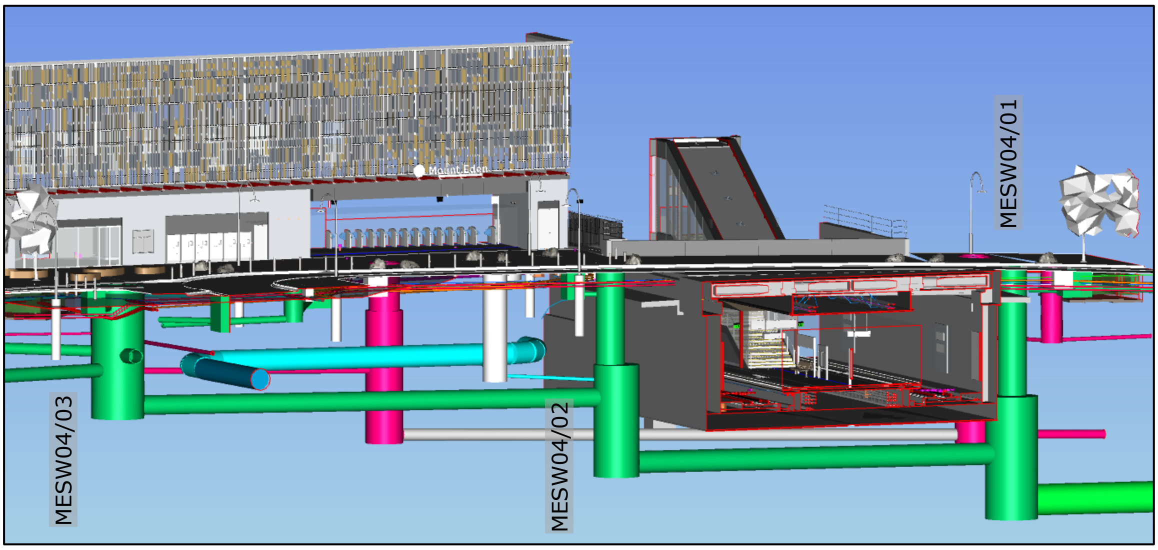
Further venting is provided at the drop shaft itself to allow air *into* the structure. To minimize noise, a DN200 vent pipe was used here rather than a grate directly over the drop.

3.4 MOUNT EDEN STORMWATER DIVERSION SHAFTS

A proposed stormwater pipeline located near the proposed Ruru St bridge over Mt Eden Station was stepped in multiple shafts instead of graded. This approach minimizes both pipe depth and excavation in hard (basalt) rock. The pipeline passes under the Mt Eden station structure before discharging stormwater into an existing DN1950 diameter tunnelled pipe. Refer Figure 13 below. The stepped pipe approach resulted in three significant drop structures.

These structures have been designed to have a drop height less than 5 m each, keeping them below the threshold where velocity and vibrations are expected to be problematic.

Figure 13: CRL BIM image showing the stepped pipe arrangement (shown in green) with large stormwater drops and passing underneath the Mt Eden station.



3.4.1 STORMWATER PIPELINE DROPS

The first (downstream) shaft (Manhole ME SW04/01) is a new stormwater manhole structure with a total depth of 15.5 m, a maximum drop of 3.4 m, conveying 1.4 m³/s in the 10% AEP storm and 2.2 m³/s in the 1% AEP storm Refer Figure 14 below.

The second (i.e. middle) shaft (Manhole MESW04/02) is also a new stormwater manhole structure with a total depth of 12.4 m, a maximum drop of 4.2 m conveying a similar flow. Refer Figure 14 below.

The third (i.e. upstream) shaft (Manhole MESW04/03) is a new stormwater manhole structure with a total depth of 8.0 m. This shaft includes multiple inlets, as follows:

Table 1: MESW04/03 Drop height and flows (Refer Figure 15 below)

Drop Pipe Number	Drop (m)	$Q_{10\%}$ (ℓ/s)	$Q_{1\%}$ (ℓ/s)
1	2.47	255	559
2	3.92	149	359
3	3.33	922	1,326

Figure 14: ME SW04/01 and ME SW04/02 plan layout

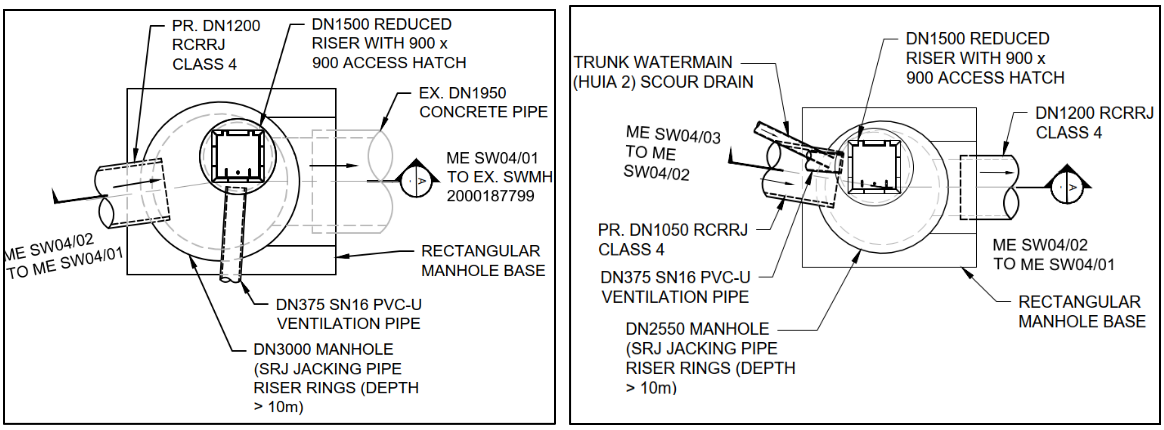
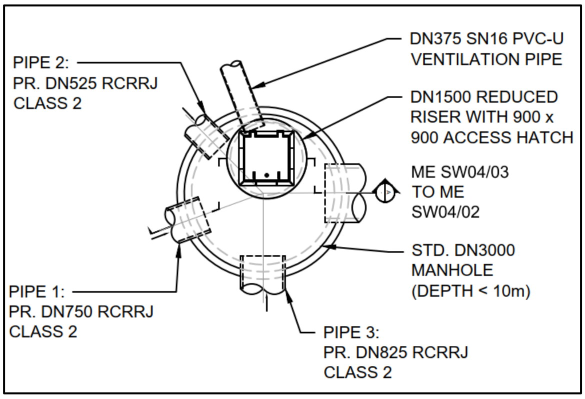


Figure 15: ME SW04/03 plan layout



3.4.2 SHAFT LAYOUT DESIGN

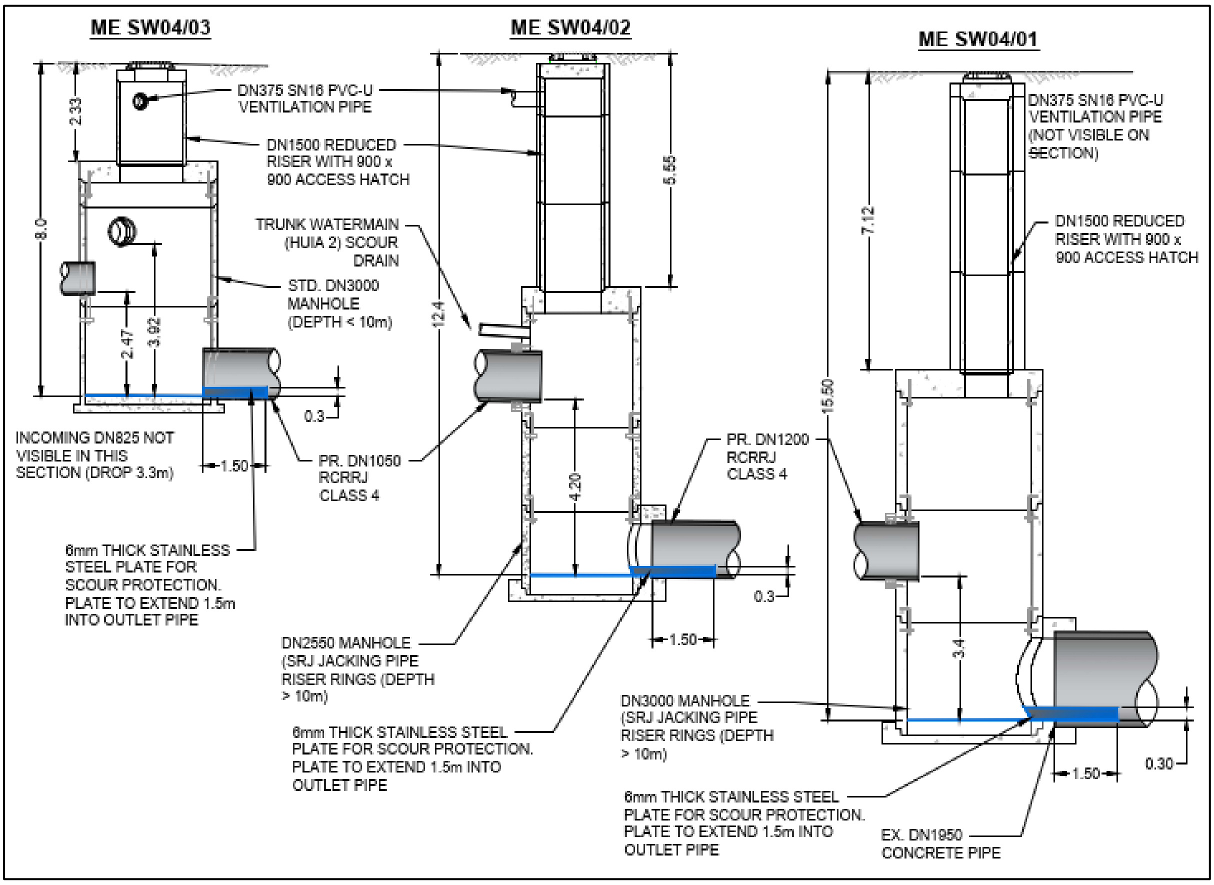
With the three shafts receiving a similar flow, being in close proximity to each other and of similar drop heights the same design approach was followed for all three.

The calculated velocity of incoming stormwater flows where they impact the far wall of the shafts is a maximum of about 7 m/s. Protection from abrasion of the wall is not required at this velocity. At the base of the chambers, the calculated velocity increases to a maximum of 13 m/s, meaning abrasion damage is likely. Larger flows will run down the opposite wall of the shafts, and low flows will strike the base of the manhole and outlet pipe. Stainless steel splash plates will be used to protect the chamber bases and the first 1.5 m along the outlet pipes (see

Figure 16). Further protection will be provided by setting the pipes back out of the path of high-energy falling water from other pipes.

The shaft diameters were based mainly on the size and number of connecting pipes. Reduced-diameter upper sections were used to prevent buoyancy without adversely impacting hydraulic performance.

Figure 16: Section A as per Figure 14 and Figure 15. In this Figure the various plunge drops are visible (<5m) with stainless steel plates (blue) extending 1.5m into the downstream pipe.



3.4.3 DESIGN FOR AIR MOVEMENT

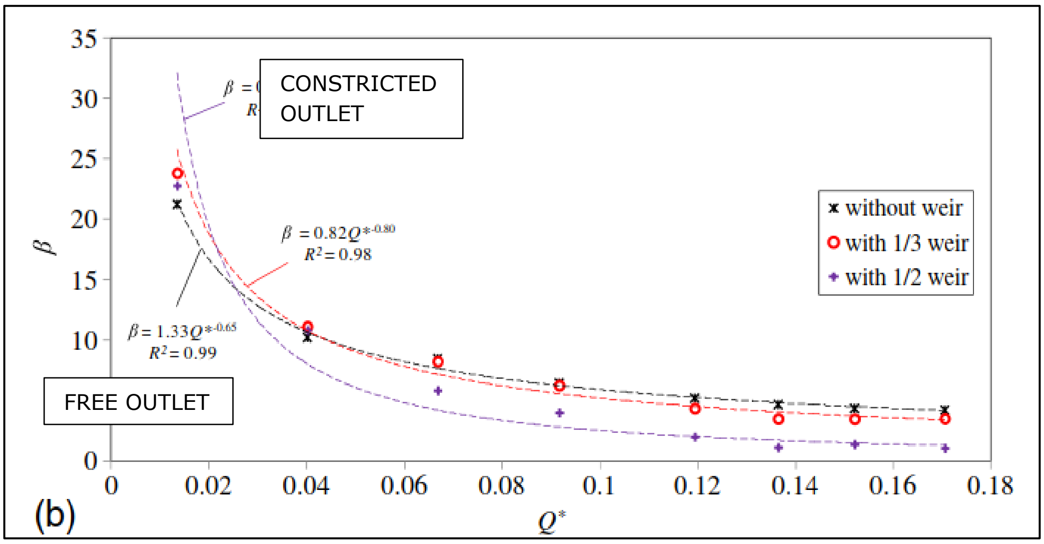
Air flow in plunge drops is a subject of debate and significant research, and there appears to be no universal agreement on how to calculate it precisely.

There are numerous equations that can be used to predict the air flow. Some are purely theoretical, and some are based on Froude-scale models. A recent study of air entrainment in real-world deep drop shafts was limited to only one model setup (Ma, et al., 2016). In this study air demands for various flow rates with and without a weir were provided (Refer Figure 17). A constricted flow was assumed to exist where the HGL (Hydraulic grade line) is at or just above the trunk pipe obvert. The design team considered this was adequately simulated by the ½ weir shown in Figure 17 while a free outfall is represented by the curve without a weir.

However, the following observations were relevant:

- The greater the water flow rate, the greater the air flow rate, but the rate of increase in air entrainment is NOT linear with increase in water flow rate. As the water flow rate increases, the water will eventually choke off the air flow, and the air flow rate will decrease dramatically. However, most plunge drops rarely, if ever, operate at the peak design flow.
- The greater the drop height, the greater the air entrainment. The rate of increase in air entrainment is NOT linear with increasing drop height.
- The higher the vertical velocity of water in a shaft, the greater the air flow rate. The rate of increase in air entrainment is NOT linear with increasing vertical velocity of the water.
- The ratio of air-to-water is sometimes used to determine maximum air flow rate. However, care is needed as the ratio of air-to-water is usually highest at the lowest water flow rates. Due to the non-linear relationship between air flow and water, the ratio of air-to-water decreases as the water flow rate increases. (Note, the actual amount of air increases with increasing water flow, but the ratio decreases.) At small water flow rates, the ratio of air-to-water has been measured in both the laboratory and in the real world to be over 20:1 air-to-water (values as high as 160:1 have been reported). That is, for every cubic metre of water dropped in a plunge, 20 cubic metres of air is conveyed. At peak water flow rates, the ratio often used is about 5:1 air-to-water.
- These ratios apply to total air conveyance. The actual amount dissolved in solution, or the amount entrained in solution might be less. Regardless of what phase the air occupies, the total amount of air conveyed must be accommodated.

Figure 17: Relative air demands (β) of the drop shafts under various water flow rates with and without a weir; $\beta = Q_a/Q_w$ versus dimensonsless flow rate, $Q^* = Q_w/(gD_s^5)^{0.5}$ with and without a weir. (Ma, et al., 2016). $Q_a = \text{air demand } (l/s);\ Q_w = \text{Design flow } (l/s);\ R = \text{Statistical confidence interval};\ D_s = \text{Shaft diameter } (m)$



In the 1% AEP event, the system flows full, so no air gap exists to allow free ventilation of the entrained air. The full receiving pipes will tend to restrict the amount of air entrained; however, there will still be large quantities of air drawn into the system. Entrained air in the receiving pipes will restrict the water flow, requiring greater head to pass the flow. This, in turn, increases the HGL in the system, reducing the drop and further constricting the outflow, which will reduce the air entrainment. So, the system will be self-limiting and adverse HGL impacts upstream of the drops are not expected. Air will still be pushed into the DN1950 trunk drain however, and it was found important to allow air to be safely released. The critical case was generally found to be when the receiving pipe is full but not pressurized.

From considering the above information the following air flow rates were calculated:

Table 2: Water and air entrainment flows (where Qw and Qa represent water and air flow respectively)

Shaft dimensions		**$Q_{10\%}$ (ℓ/s)**	**$Q_{1\%}$ (ℓ/s)**
MH SW04/03	Qw m^3/s	1.3	2.2
(Max. 3.9 m drop) x 3.0 m dia (3 inlet/drops)	Qa m^3/s	3.9 (free)	7 (constricted)
MH SW04/02	Qw m^3/s	1.3	2.2
4.2 m drop x 2.55 m dia (1 inlet/drop)	Qa m^3/s	4.5 (free)	3.9 (constricted)
MH SW04/01	Qw m^3/s	1.4	2.2
3.4 m drop x 3.0 m dia (1 inlet/drop)	Qa m^3/s	4.5 (constricted)	N/A (drowned)

4 KEY LEARNINGS AND LIMITATIONS

Having travelled the drop shaft design journey, the authors provide some critical learnings for others who travel the same path:

- When installing deep pipes, keep the final shaft diameters large as a 'future ready' approach. This is easy to do if the launch pit excavation for the deep pipes is already bigger. Consider the man-cage that will be used to access it and plan for the possible future need to convert it into a drop shaft.
- Recognize that the design can't always follow a code of practice or textbook solution. Solutions often need to be found elsewhere, while recognizing the extra cost and managing the extra risk associated with non-conventional approaches.
- Recognize institutional pressures to follow a conventional approach whereby vertical pipes are installed with a bend at the base or plunge drops are considered appropriate, which are likely to create future erosion issues. Regulators and reviewers are often more comfortable with the familiar, sometimes leading to under-engineered devices being accepted.
- Regular client and contractor engagement is highly beneficial. Bring others along on the design journey to increase their familiarity and comfort ahead of the time they are called-on to make a decision.
- Recognize the importance of a healthy balance between informed engineering judgement/experience versus analysis (the need to avoid "paralysis by analysis").
- Recognize the extra cost associated with a non-conventional design approach (design effort, peer review, possible CFD), and make sure these will be repaid

through physical works savings. The authors are grateful that CRL gave us license to innovate, albeit with an expectation of financial savings, sustainability benefits and best-for-project outcomes.

- Consider constructability. Use prefabricated man-handleable pieces. Do everything possible to simplify the effort required at-depth (both construction and maintenance).
- Consider the future asset owner's needs. How will they maintain it?

The design innovations described in this paper were not always straight-forward, and limitations included:

- Limited information and technical resources to base designs upon;
- Published research is often based on scale models; however air behaviour in particular isn't readily scalable from model studies;
- The constraints imposed by congested sites, with minimal space inside and outside the shaft; and
- Institutional pressures to follow a conventional approach.

5 CONCLUSIONS

The drop shaft solutions finally adopted are a great example of innovation born of necessity. They deliver the required hydraulic performance while sometimes utilizing existing shafts, thus ticking boxes for cost-effectiveness and sustainability; they also meet the future asset owner's requirements for accessibility and maintenance.

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