COLLABORATION DRIVEN INNOVATION FOR DEEP CONCRETE CULVERT DESIGN AND INSTALLATION – AN EXAMPLE OF SAFETY IN DESIGN

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ABSTRACT (300 WORDS MAXIMUM)

The design and installation of culverts under high fill road embankments is a common challenge for roading projects in New Zealand's undulating landscape. Soil loading from these high fills requires high load capacity pipes that may be outside the manufacturing capabilities of concrete pipe suppliers in New Zealand.

The design consortium for the Waikato Expressway, Huntly Section addressed this challenge using a collaborative approach involving the Constructor, Designer and Supplier. Our consideration of design, manufacturing process, construction and health and safety measures gave us a workable, safe and cost-effective solution using commonly manufactured concrete pipes.

Our design and construction methodology involved designing the deep culverts assuming a negative projection installation while using a layer of expanded polystyrene (EPS) and subsequently constructing the trench in the same manner as an induced trench installation. This design was adopted to increase the negative projection design factor of safety; accounting for any non-conformances during construction. The pipe structural design by the pipe supplier was also optimised to utilise the available manufacturing resources, to achieve the design pipe classes using the thinnest possible wall thickness and reduce pipe mass, and therefore craneage. The construction methodology thus formulated provided a safer and cost effective solution as it removed the need for trench shields and risks associated with working at heights.

The paper will conclude with a review of the lessons drawn from the approach, the actual construction of the culverts and recommendations for future research to better understand the pipe-soil structure interaction in an induced trench installation.

KEYWORDS

Collaboration, Innovation, Concrete Culvert, Safety in Design, Induced Trench

PRESENTER PROFILE

Amanda, until recently an Environmental Engineer for Opus International Consultants, holds BEng (Civil/Environmental) qualifications from the University of Technology, Sydney. She was a drainage designer on the Waikato Expressway Huntly Design team from Tender through to Construction.

Husham holds, BSc and MSc (Civil Eng.) qualifications from the University of Baghdad, Iraq, and holds New Zealand CPEng, Int.PE, and MIPENZ certifications. Since 2009 Husham has been working as a senior civil engineer with Humes Pipeline Systems, where he is involved in research and development, management of technical projects, sales training and technical support.

1 INTRODUCTION

In New Zealand, concrete culverts are designed, supplied and constructed in accordance with a number of industry standards and guidance design software. These peer-reviewed industry design guidelines are prepared from empirical and experimental sources and are widely used for construction of concrete culverts with relatively low fill heights.

However, for increasing fill heights, supply chain limitations and challenging site terrain, the industry design guidelines become challenging to follow.

The primary limitation for using the industry design guidelines is their relevance to deep concrete culvert design and installation. This paper describes the collaborative effort that produced an innovative solution to this industry-wide problem in a New Zealand context.

2 CASE STUDY: WAIKATO EXPRESSWAY HUNTLY SECTION

2.1 BACKGROUND

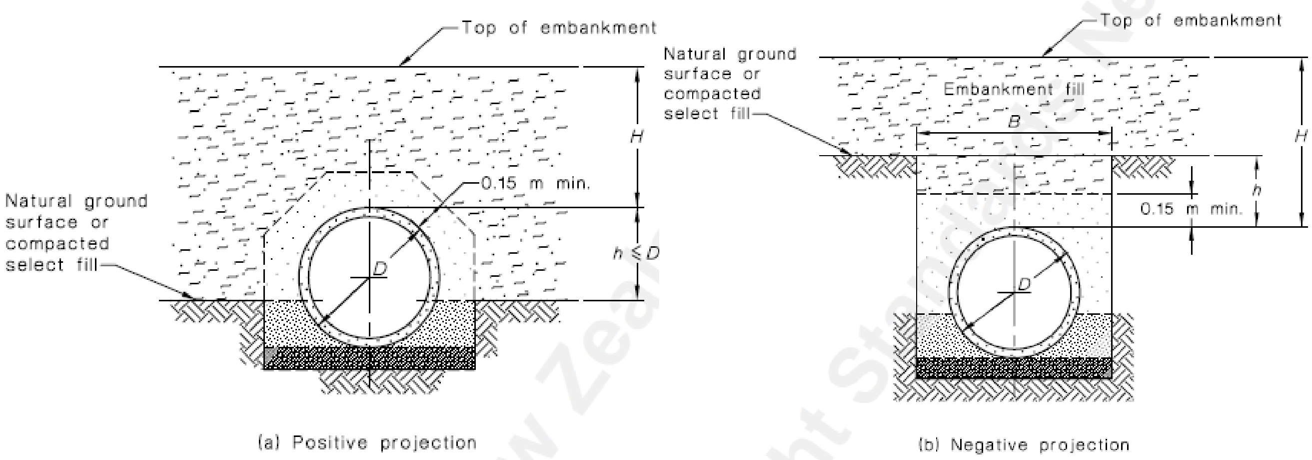
The 'Waikato Expressway Huntly Section' Project will provide an alternative State Highway 1 (SH1) route around Huntly township in New Zealand's North Island. The project is one of the seven sections classified as Roads of National Significance (RONS) comprising the overall 'Waikato Expressway Project' portfolio, from the Bombay Hills to south of Cambridge. The Huntly Section comprises of a 15.5 km section of the Waikato Expressway that will provide a four-lane expressway with nine bridges and two interchanges, tying into the completed Ohinewai and Ngaruawahia sections. Passing through the undulating areas near Taupiri Scientific Reserve, the Expressway alignment requires high fill embankments under which culverts need to be placed to maintain cross-catchment surface flows.

Highway culverts are typically installed under fills or embankments. Embankment installations are subdivided into three groups (ACPA 1998)

- **Positive projection** pipe is installed with the top of the pipe projecting above the surface of the natural ground, or compacted fill, and then covered with earth fill.
- **Negative projection** pipe is installed in relatively shallow trenches of such depth that the top of the pipe is below the level of natural ground surface or compacted fill, and then covered with earth fill to a height appreciably greater than the distance from the natural ground surface or original compacted surface to the top of the pipe.
- **Induced trench** pipe is initially installed as positive projection. When the embankment fill has been placed to an elevation of at least one pipe diameter over the proposed top of the pipe, a trench is excavated over the pipe and backfilled with a more compressible material, simulating a negative projection installation.

The current industry standards for the design of concrete culverts in New Zealand are AS/NZS 3725:2007 and AS/NZS 3725 Supplement 1:2007 (Standard New Zealand 2007). These two industry standards cover the three main embankment condition culvert installation methods, as given in Figure 1 and 2 below.

Selection of these embankment installation methods is primarily determined by the imposed soil loads experienced by the pipe relative to the combination of pipe strength and bedding strength of the installed culvert. For a culvert with relatively low soil loads in comparison to combined pipe and bedding strength, the dominant culvert installation method is positive projection. As the soil loading increases, installing the culvert using the negative projection method can be advantageous instead of increasing the pipe and/or bedding strength in positive projection installation.



(a) Positive projection (b) Negative projection

Figure 1: Embankment condition concrete culvert installation methods as per AS/NZS 3725:2007

In a case where positive and negative projection installation yields an impracticable pipe and bedding strength, AS/NZS 3725 Supplement 1:2007 offers some guidance on an alternative installation method to account for high imposed soil loading conditions. By utilising a layer of compressive material to induce soil arching, imposed loads on the concrete culvert are reduced.

Negative projection installation design is well documented in AS/NZS 3725:2007, however clear, up to date guidance relating to design and construction of the induced trench installation has only been partially provided by industry bodies.

Analysis of loads on pipe culverts in the project indicates that off-the-shelf, locally available pipes could be safely used with traditional positive projection installation and either HS2 or HS3 pipe support; however a few culverts under high fill embankments were found to require high pipe classes that were beyond New Zealand manufacturers' conventional capabilities. Upgrading the pipe bedding to the higher support, type HS3, reduced the pipe class required for the deep culverts marginally and therefore all the deep culverts were installed with type HS3 bedding.

Out of the 41 major culverts on the Waikato Expressway Huntly Section, three required an alternative design approach due to high imposed loading from high fill embankments. These three concrete culverts ranged from DN 1350 mm to DN 1950 mm in diameter, 120 to 130 metres in length and 18 to 29 metres of structural embankment fill above the pipe.

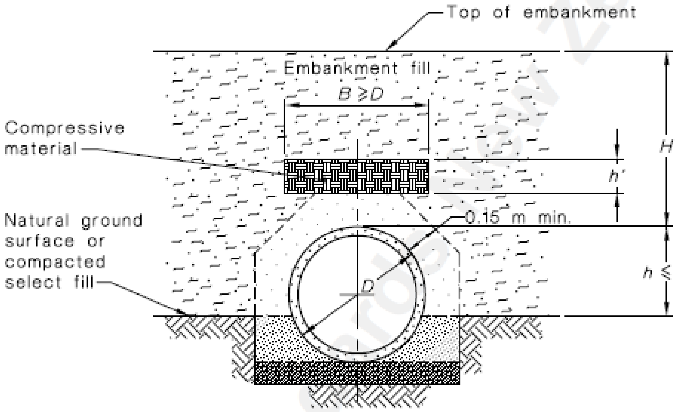


FIGURE C2 INDUCED TRENCH CONDITION

Figure 2: Induced trench concrete culvert installation methods as per AS/NZS 3725 Supplement 1:2007

Special high class pipes are more expensive and usually heavier than lower class pipes, and installation methods other than the traditional positive projection may need special construction resources (e.g. cranes) that are not feasible to bring to site. For these reasons a practicable alternative installation method was sought to reduce the loading on the deep concrete culvert and therefore reduce pipe class, as well as address other project construction constraints.

2.2 SAFETY IN DESIGN

At the core of safety in design is risk management throughout the value chain, for the life of the asset. A preliminary assessment of the project constraints related to the construction of deep concrete culverts highlighted elevated hazards/risks.

For this Project, the key to addressing these hazards/risks through the value chain was early consultation and collaboration between the value chain representatives, including the Designer, the Supplier and the Constructor. The Principal (NZTA), Principal's Representative and Design Checker were kept informed on the design process and assisted in the review and necessary approvals. Explicitly outlining each party's limitations and flexibility fostered a shared understanding and increased the opportunity for determining a safe and practicable solution that is viable for the life of the asset. For example, once the Designer understood the complexities of constructing in steep terrain, allowances were made for tolerances due to imperfect construction, which significantly reduced the risk to culvert serviceability and structural integrity post construction.

Details of the design, supply and construction approaches are presented in this paper in isolation for the sake of clarity. However, in reality, it was the continuous collaboration between all parties, and resulting adaptation that undoubtedly led to the innovative solution that is currently being implemented on site at Huntly.

2.3 DESIGN APPROACH

2.3.1 DESIGN CONSTRAINTS

In addition to the construction and supply constraints presented later in this paper, the following design-specific constraints needed to be addressed:

1. Limited industry standard guidance relating to deep concrete culvert design; and

2. Limited local industry design and construction experience with induced trench installation.

The induced trench methodology, which was included as a mainstream design technique in the now-superseded AS3725:1989, was relegated to the Supplement in 2007, with the comment that:

> This installation condition can be used for pipes under high embankment fills. As it is less commonly used, it has not been referred to in the Standard.

Anecdotal evidence suggests that the dominant reason for this relegation from the 2007 standard was due to failures due to lack of understanding of the sensitivity of key parameters during the construction phase. AS/NZS 3725 Supp. 1:2007 appears to support this, with the following note:

> Although the benefits of this method are well proven elsewhere (notably in California), the induced trench construction has not been used to any great extent in Australia and New Zealand. This is probably due to some subsidence failures, caused by inadequate construction procedures, experienced in the early history of the method.

Due to the potential for the design solution to lead to a design that is outside accepted industry standards, and therefore considered high risk, the decision was made to keep the design, as far as possible, aligned with current industry standards. In this way, the final core design would be in accordance with the industry standard, but utilise recommended methods from relevant research to increase the factor of safety of the deep concrete culvert design.

2.3.2 DESIGN METHODOLOGY

In order to address the above design constraints, the following methodology was followed:

1. Determine the nature and extent of current industry knowledge, case studies and examples of deep concrete culvert design;

2. Undertake a desktop assessment of local and international deep concrete culvert design and construction research and case studies;

3. Use any existing guidance and research to formulate an alternative installation method that meets the design requirements of the deep concrete culverts on Waikato Expressway Huntly Section; and

4. Ensure the project drainage specification document was clear and prescriptive regarding the construction methodology, quality assurance and designer involvement during the installation process.

The selected design adopted for these deep culverts was to calculate the load on the pipes assuming a conventional negative projection installation, while also using a layer of expanded polystyrene (EPS) and subsequently constructing the trench in the same manner as an induced trench installation to achieve a further reduction in load and a simplified construction method.

The Project Designer and Supplier worked together to develop the alternative culvert installation design using the guidance for ‘negative projection’ and ‘induced trench’ given in AS/NZS 3725-2007, and its Supplement (section C6.3.3.1, C6.3.3.2, and C6.3.3.5).

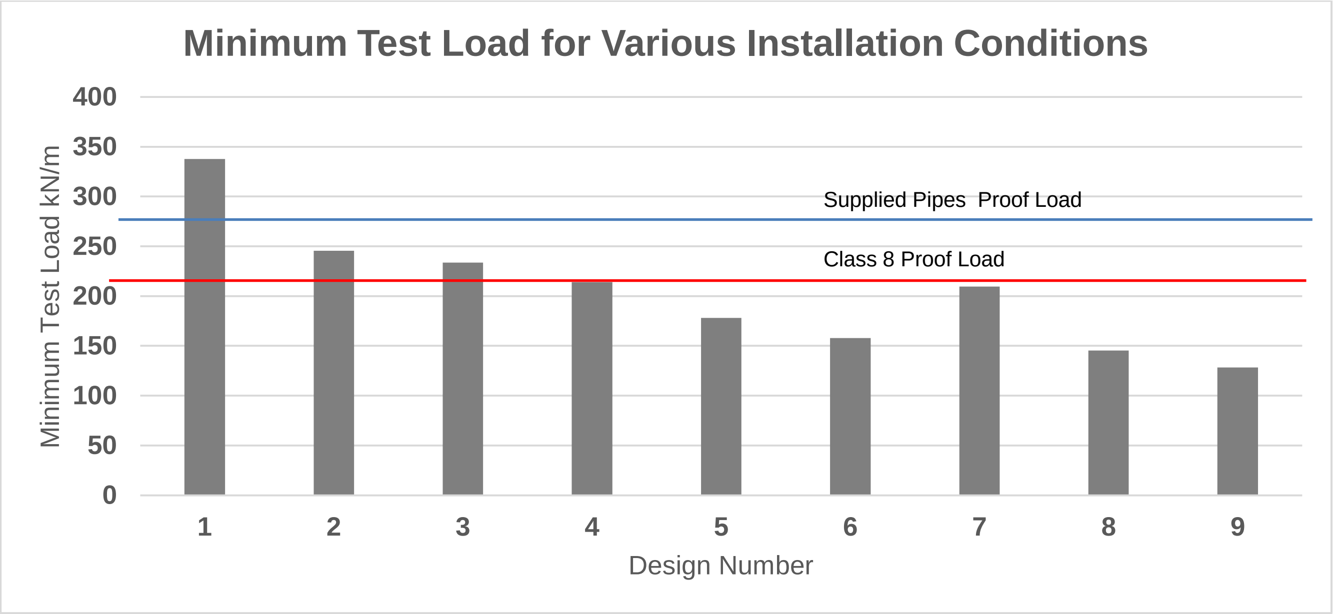
Worked examples given in the Supplement were replicated and validated using the CPAA PipeClass V2.0 software to build understanding of the design process. This was then followed up by applying the same design process to selected high fill culverts.

Table 1 and Figure 3 show the results of various design options considered during the design of one DN 1500mm culvert, calculated using CPAA PipeClass V2.0 software.

Table 1: Load –DN 1500mm pipe for Various Installation Options

Design Number	Installation Condition	Projection Type	Settlment Ratio	Trench Width m	Height of Fill m	Soil Density kN/m^3	Projection depth m	Projection Ratio	Support Type	Bedding Factor	Minimum Test Load kN/m
1	Embankment	Positive	N/A	2.453	26.15	20	0.92	0.5	HS3	4	337.6
2	Embankment	Positive	N/A	2.453	26.15	20	0	0	HS3	4	245.5
3	Embankment	Positive	N/A	2.453	26.15	19	0	0	HS3	4	233.5
4	Embankment	Negative	-0.5	2.453	26.15	19	1.227	0.5	HS3	4	213.9
5	Embankment	Negative	-0.5	2.453	26.15	19	2.453	1	HS3	4	178.1
6	Embankment	Negative	-0.5	2.453	26.15	19	3.68	1.5	HS3	4	157.9
7	Embankment	Negative	-0.5	2.453	26.15	19	2.453	1	HS3 Reduced	3.4	209.4
8	Embankment	Induced Trench	-1	1.84	26.15	19	2.453	1	HS3 Reduced	3.4	145.2
9	Embankment	Induced Trench	-1	1.84	26.15	19	3.68	1.5	HS3 Reduced	3.4	128.3

Figure 3: Load on Culvert DN1500mm pipe for Various Installation Options



The results indicate that, when using a reduced bedding factor to allow for installation methods and materials, Class 8 pipes will be safe for the proposed culvert if installed using a Negative Projection installation with a 2.45 m in projection depth (design number 7, above). This design, if selected, would require the use of a trench shield, which adds further cost and complexity to an already complex installation.

Through a continuous collaboration between design, pipe supply, and construction teams it was found that adopting the induced trench installation will achieve the following advantages:

- The installation will comply with the AS/NZS 3725:2007 normative negative installation where the load on the pipe will be just below the proof-load capacity of the pipe, i.e. its serviceability limit, as the induced trench installation stages proposed for the construction of the culvert involve construction of trench on top of the pipe to the design depth, therefore

- Increases the negative projection design factor of safety. Accounting for any possible non-conformances during construction and/or unforeseen conditions, the use of induced trench installation will increase the design safety margin even if there is doubt that it can achieve the full load reduction shown in Table 1 and Figure 3.
- Allows for the use of bedding materials with grading outside the limits of AS/NZS 3725:2007 (Tables 5 & 6) by allow for a reduced bedding factor, without breaching the safety of the installation or requiring an increase of pipe class.
- Simplifies the construction process by eliminating the need for trench shield or construction of a wide benched trench.
- Improves construction health & safety by eliminating deep trench excavation and work required inside the trench.

Expanded Polystyrene (EPS) was selected to form the compressible layer required for induced trench installation in lieu of the traditional straw bales. The effectiveness of EPS was confirmed by reference to comprehensive studies in Europe. (Vaslestad et al 2008 and Vaslestad 1991)

The compressibility of the EPS layer is important to achieving the settlement ratio for the induced trench design. Both Vaslestad et al 2008 and Vaslestad 1991 recommend an EPS density of 20 kg/m3, though the stress-strain relationship is required to determine the compressive strength of the material. Too stiff, and the EPS may not shed load sufficiently to the trench walls; too soft, and it might squash excessively during initial backfilling. The Designer recognized this importance through the addition of an EPS testing requirement in the Project Drainage Specification document to ensure the installed EPS meets the required stress-strain relationship using testing guidance given in AS 2498.3.

The Design team also addressed the second design limitation noted above relating to the uncertainty in construction. In discussion with the constructor, this was achieved through the addition of specific hold points in the Project Drainage Specification document to ensure designer involvement and quality assurance through the installation process.

The resulting design produced a viable alternative installation method that achieved a reduction in pipe class to within the supplier's and constructor's respective manufacturing and handling ranges. The lower pipe classes meant a reduction in the amount of concrete and reinforcement that is required for pipe strength. This is a safer solution as the pipes are considerably lighter, and easier to transport, handle and place – a major consideration given the tough terrain of the project – and can be installed using conventional machinery. Pipes with lower classes are also more readily available, and cost effective.

2.4 SUPPLIER APPROACH

2.4.1 SUPPLIER CONSTRAINTS

Though the design for selected deep concrete culverts had been rationalized with an acceptable safety factor, discussions within supply team staff identified a number of supply-side optimizations that could assist with the design and construction limitations.

These included the following:

1. Investigate any scope to maximize the production pipe strength to increase the safety margin; and

2. Minimise the weight of pipes to aid supply to the site and transport and handling within the site.

3. Design, type-test, manufacture, cure, and supply super strength DN 1500 mm and DN 1350 mm concrete pipes within 8 weeks for installation;

The supplier started production using their Papakura VT pipe manufacturing facility, which supplies large diameter pipes throughout the North Island including the 1500mm VT pipes. As VT technology involves casting pipes in vertically-installed moulds using semi-dry concrete, pipe wall thicknesses are limited to the wall thickness of the available moulds.

The supplier's available VT moulds produce pipes with a 120mm wall thickness. This wall thickness was successfully utilised to produce Class 6 pipes. However, special reinforcement and concrete design was required to achieve the Class 6 standards.

Class 8 pipes produced overseas have a wall thickness of either 151mm or, for pipes complying with ASTM C 76M – 08a, 169mm. However, the larger wall thicknesses would require new moulds, pushing production and delivery outside project time limitations. This option was therefore rejected.

On the other hand, moulds available in the supplier's Hastings factory produce 1540mm diameter in-wall joint (Skid Ring Joint - SRJ) jacking pipes. The wall thickness of these 1540mm jacking pipes is 150mm which, with some R&D work, could have been designed to match the ASTM C 76M – 08a wall thickness. However, given the project time and budget limitations, and after discussion with the factory engineers, it was determined that the required wall thickness of this pipe would have to increase to 170mm to achieve guaranteed high performance from reasonably short curing period.

2.4.2 SUPPLIER METHODOLOGY

To achieve the project team goals, the supplier's technical team took the following decisions:

1. Match the ASTM C 76M – 08a wall thickness by designing and producing the Class 8 DN 1500mm SRJ pipes in Hastings utilising the existing mould with modification to increase wall thickness to 170mm.

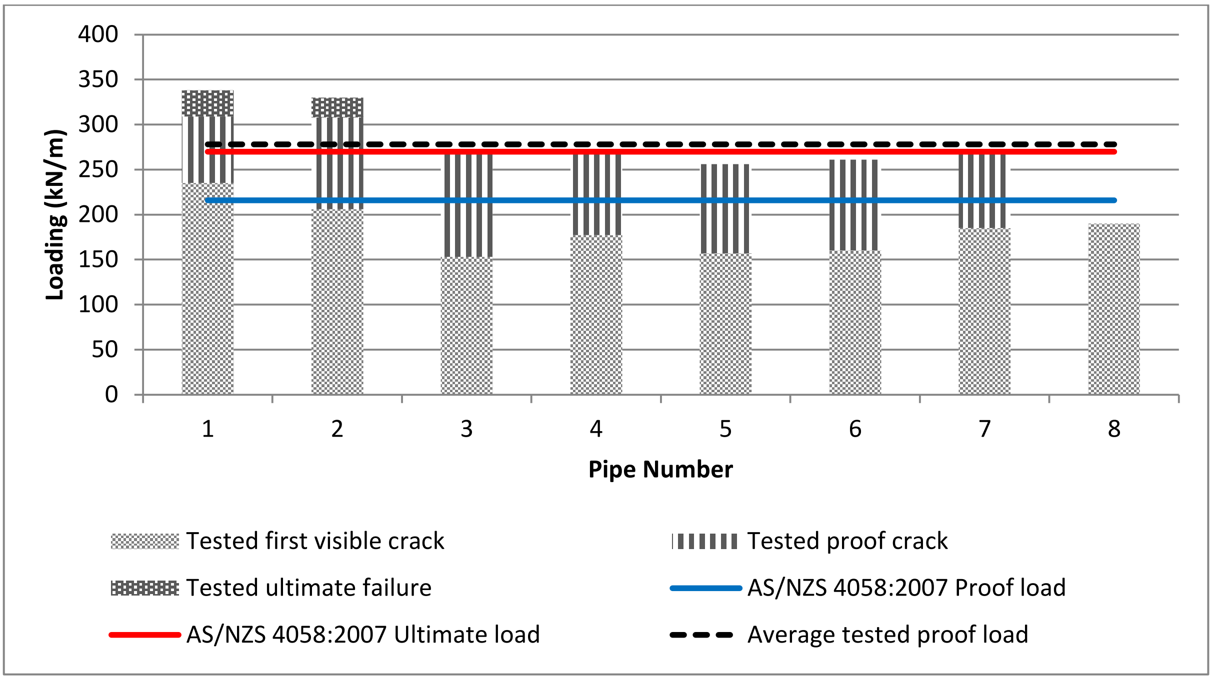
2. Select a "must pass" design so that production could be started while the first batch of pipes were still to be type-tested as per AS/NZS 4058:2007.

3. Reduce the curing period of pipes to 3 weeks instead of the standard 4 week period by "double steaming" the pipes after production. Type-testing was to be done after the same 3 week curing period to check for the effectiveness of the process.

4. Utilize a special reinforcing steel design for the pipes to achieve maximum possible strength while limiting the pipe wall thickness to that feasible using the existing moulds.

Three weeks after production, eight pipes from the production batch were selected and then type tested in accordance with AS/NZS 4058:2007 to determine their load capacity.

Figure 4: Type-Testing Results of SJR 1500mm Pipes Class



Note: AS/NZS 4058:2007 requirements for 1500mm Class 8: Proof Load = 216 kN/m, Ultimate Load = 270 kN/m

The results of type testing of eight pipes, given in Figure 4, indicate that the average tested proof load capacity for the pipes is greater than 278 kN/m. As shown in Figure 4, this average tested proof load is more than the AS/NZS 4058:2007 specified ultimate capacity, and 22% more than the proof load, which is traditionally used as the serviceability limit of the pipes. This extra capacity, plus the extra strength developed during normal pipe ageing, will increase the installed factor of safety of the pipe, and hence allow for safe installation even if installation field loads exceed the calculated design loads.

The extra capacity achieved during type testing is probably attributed to high quality production materials and methods that utilise full capacity of the reinforced concrete pipe wall structure, compared to the design assumptions which allow for built-in factors of safety to allow for any possible non-compliance during construction.

By following the accelerated design and production methodology the supplier was able to address all constraints, validate the product through quality assurance measures, meet and exceed the project team's expectations.

2.5 CONSTRUCTION APPROACH

2.5.1 CONSTRUCTION CONSTRAINTS

The alignment of the Waikato Expressway Huntly Section is situated in highly undulating, rocky terrain leading to the following construction constraints:

1. Requirement for specialised heavy vehicle and lifting machinery to transport and handle heavy super-strength pipes within the project site, with its challenging access;

2. Installation configurations needed for the negative projection and induced trench method required heavy trench shields, which were difficult to transport and handle to specific site locations; and

3. Where trench shields are used, extra health and safety guidelines need to be followed as workers are ‘working at height’.

2.5.2 CONSTRUCTION METHODOLOGY

Input was sought from the Constructor, the Supplier and Designer to address the above constraints. The innovative construction methodology that resulted from this collaboration addressed all the Project construction constraints in line with SID Principles.

The first constraint, related to transport and handling, was addressed by the adoption of the alternative installation method, removing the need to use the higher class and heavier super-strength pipe classes.

Trench shields were required for the traditional negative projection and induced trench installation methods for safety reasons as the design involved trenches greater than 1.5 metres deep. However, through the innovative construction methodology developed collaboratively between the Constructor, the Supplier and Designer outlined below, the need for trench shields was removed:

1. Construct cohesive structural embankment fill to culvert spring line level;

2. Excavate trench width to pipe OD + 400 mm each side of pipe to ensure enough room for proper installation and bedding compaction;

3. Install pipe and backfill haunch and side zone with approved granular fill;

4. Continue embankment from above pipe spring line with structural earthworks fill, taking care not to use heavy plant directly on top of the pipe until a safe fill depth is achieved;

5. When fill is approximately 300 mm above pipe collars, place a layer of geotextile as a marker layer. Continue filling with structural earthworks fill;

6. When fill is approximately 1.5 m above top of pipe level re-excavate trench with width equal to pipe OD through embankment fill down to the geotextile marker 300 mm above pipe collars, ensuring no damage to pipe during excavation;

7. Place 500 mm thick piece of polystyrene[1] (compressive stress-strain properties must be confirmed by testing) in the base of trench then backfill trench with excavated, loose, aerated fill material with no compaction to create induced trench; and

8. Continue filling with structural fill to finished height.

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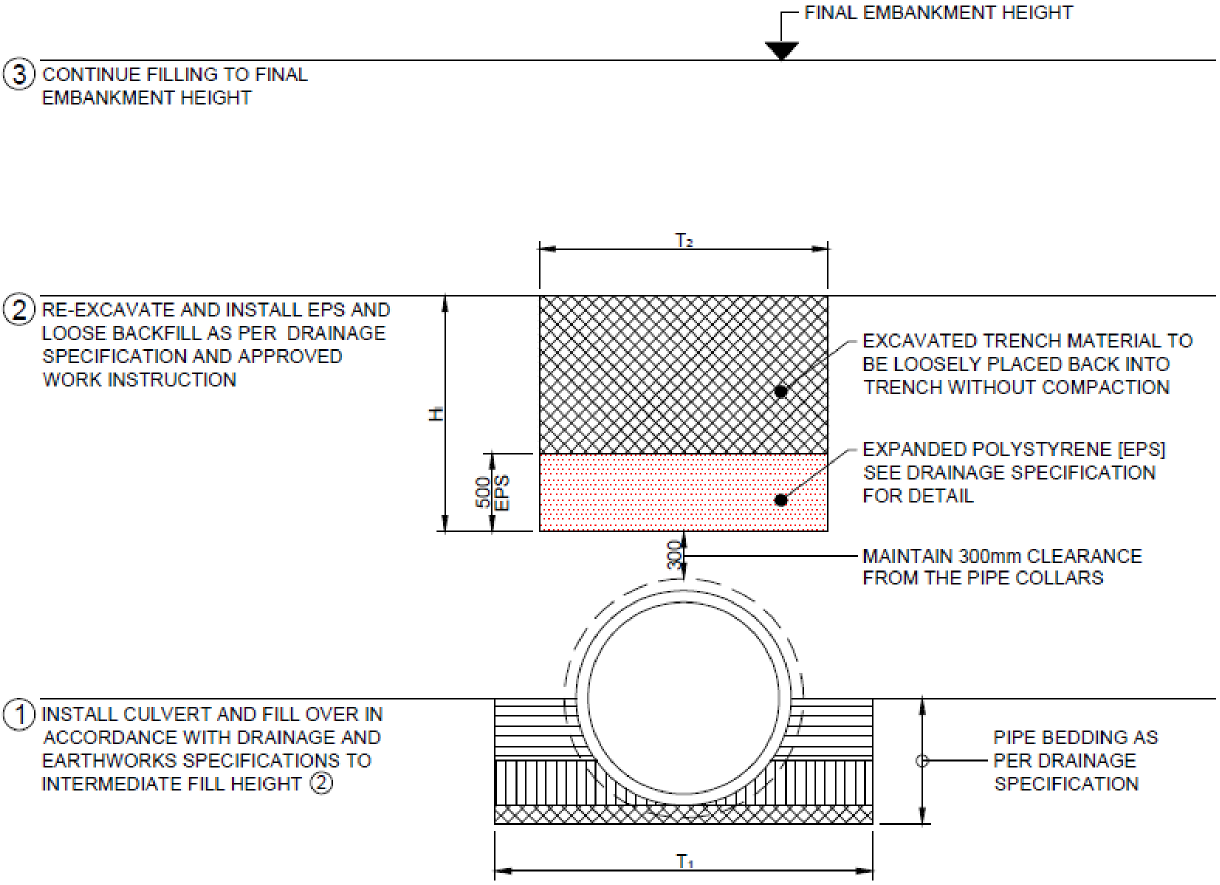
[1] Note that this polystyrene serves a different function, and has different properties to polystyrene commonly used in lightweight fill situations.

Figure 5: Alternative installation construction method as taken from Project drawings



In this way, construction was able to proceed without the requirement for trench shields, thereby removing the need to work at height, and the complexities associated with the transport, handling and hire of the trench shields.

3 CONCLUSIONS & RECOMMENDATIONS

The following conclusions may be drawn from the issues discussed in this paper:

- The collaborative approach, utilising the collective experience of the designer, supplier and constructor to address multiple project constraints was unquestionably the underlying factor that led to a successful solution.

- The formulated solution addressed the identified constraints, resulting in a much safer, cheaper and on-time solution for the Waikato Expressway Huntly Section that can act as an example for deep concrete culvert construction in New Zealand.

- Construction observation indicates that the simple design and construction methods that were developed in collaboration with the construction teams are highly effective in achieving better end results, less problems during construction, and are a better way to meet the designers' expectations.

To investigate whether actual culvert performance correlates with the design calculation in reducing the imposed soil loading on deep concrete culverts, it is recommended that one or more culverts are monitored using site-installed measuring and monitoring equipment. The results of this monitoring could be utilised in future for similar deep culvert installations and might encourage the relevant authorities to consider its wider use in future versions of the concrete pipe design standard and design software.

ACKNOWLEDGEMENTS

Fulton Hogan – Craig Brooks

Humes New Zealand – Wayne Langdon – Pipe Structural Designer

Jacobs – Philip Johnson

Opus International Consultants –Warren Bird

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