PRACTICAL CULVERT DESIGN OBSERVATIONS IN QUEENSLAND

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ABSTRACT

Buried underground drainage structures are used to satisfy the hydraulic requirements of a given site/environment and are typically manufactured of reinforced concrete. With the improvement of culvert inspection technology incorporating robotic camera inspection post installation, discovery of cracked culverts has been an increasing issue. Reinforced concrete pipe culverts are known to crack for various reasons including transport, handling, placement, backfill, foundation quality and vehicle over-loading during construction. A culvert's vulnerability to be adversely affected by these conditions can be a function of its design, particularly associated with installation conditions and strength class. This review focuses on these aspects from a geotechnical and structural perspective, for reinforced concrete culverts of rubber ring joint or flush joint type, with outside dimension greater than 375mm. The review highlights how the current culvert design process occurs and provides geotechnical and structural insight around the importance for designers to have a good working understanding of AS 5100.2:2017 and AS/NZS 3725:2007. Reference is also made to Queensland Road authority 'Transport and Main Roads' (TMR) Technical Specifications where modification to the Australian Standards has been made. The review also assesses, using finite element analyses, the accuracy of published methods used to determine vertical load from vehicle loading and soil overburden, and demonstrates how these findings may be relevant to the broader Australian and New Zealand region. Practical insights and suggestions on how analysis, selection of appropriate culvert class and detailed design information can be improved are also discussed.

Keywords: RCP, Culvert Cracking, Culvert Design Loading

1 INTRODUCTION

Common industry practice for calculation of concrete pipe culvert class in Queensland (QLD) continues to involve the use of design software 'Pipeclass' developed by the Concrete Pipe Association of Australasia (CPAA). On 19th August 2019, the State Road Authority for QLD, the Department of Transport and Main Roads (TMR) distributed a letter to detailing that CPAA Pipeclass software was not suitable for use on TMR projects based on the following information:

- The Road Drainage Manual (RDM) requires pipes to be designed in accordance with AS/NZS 3725, using the load distribution through fill from AS 5100.2.

Main Roads Technical Specification (MRTS) MRTS25 concurs with the RDM and specifies certain construction loads.
There are three Australian / New Zealand standards that designers need to have a working knowledge of for the design of reinforced concrete pipes:

- AS/NZS 3725 (2007) [Design for installation of buried concrete pipes].
- AS/NZS 4058 (2007) [Precast concrete pipes (pressure and non pressure)].
- AS 5100.2 (2017) [Bridge design loading standard, design load].

Additionally, for Transport and Main Roads (TMR) projects in Queensland, Technical Specification MRTS25 (January 2018) [Steel Reinforced Precast Concrete Pipes] provides further criteria over and above that outlined in the standards that designers are required to consider and design for.

The aim of this paper is to provide commentary on design for culvert class in Queensland, and highlight issues when navigating commonly used software and the Australian Standards that are applicable.

2 LIVE LOAD DISTRIBUTION THROUGH FILL

2.1 AS/NZS 3725 as augmented by AS 5100.2

Reinforced Concrete Pipes (RCP) are designed in accordance with AS/NZS 3725 with the exception that, in QLD on State Road projects, the method to calculate live load through fill is to be deleted (Clause 6.5) and replaced with the relevant AS 5100.2 method. There is a significant difference between the magnitude of the live loads calculated using the two methods. AS 5100.2 tends to result in the live loads being the governing load case for low cover scenario. To highlight this, Table 1 presents a comparison between the two methods with a first principles comparison using the Boussinesq Equation for live load distribution.

Table 1: Live load distribution through fill comparison (Truck and Dog)

	AS/NZS 3725 method	AS 5100.2 method	Boussinesq Eq.
Wheel contact area at surface	0.08 m^2	0.08 m^2	0.08 m^2
Pressure[a] at surface	750 kPa	750 kPa	750 kPa
Calculated distribution area at 500 mm depth	1.04 m^2	0.57 m^2	N/A
Calculated pressure at 500 mm depth	57.7 kPa	105.3 kPa	93.5 kPa

[a] Dynamic load allowance not considered

As illustrated in Table 1, for this scenario the pressure calculated using AS 5100.2 is approximately 83% greater than that using AS/NZS 3725. Hand calculation checks using the Boussinesq equation were completed for comparative purposes with the pressure at 500 mm depth shown to be 93.5 kPa. Therefore, AS 5100.2 remains the governing method.

Notably, the difference between methods reduce as cover is increased and dead load becomes the critical load component. On this basis, designing in accordance with MRTS25, under shallow cover scenarios (during construction and shallow pavement subgrades), will likely be the most critical case.

3 DESIGN CONSIDERATIONS

3.1 Haunch And Bedding Zone

Correct design selection and site installation of the haunch and bedding material are critical to the performance of a buried RCP. The bedding layer serves to evenly distribute vertical pressure with the ground's reaction at the base of the pipe. A properly performing bedding layer will improve the functional life of the RCP by evenly distributing stresses in the pipe wall that could otherwise become concentrated, leading to increased risks of a variety of concrete cracking phenomena to occur (e.g. radial shear).

The importance of appropriate selection of the bedding material type on the culvert's structural performance is recognised under AS/NZS 3725. For calculation of load on a RCP at a given depth, determining the appropriate bedding factor to apply during design is critical. By virtue of the soil/structure interaction, RCPs can carry a greater vertical load buried in-situ than they could above ground. The distribution of load that occurs through the haunch zone most significantly impacts the load carrying capacity of the pipe. However, in determining a culvert's structural capacity (defined as 'class'), an above ground/unsupported three-edge bearing test is used to calculate the proof and ultimate load values. To account for the improvement in capacity of a buried RCP, the bedding factor serves to bridge analytically the relationship between the two different service conditions.

AS/NZS 3725 standard drawings include an uncompacted middle third bedding detail whereas TMR standard drawings (e.g. Standard Drawing 1359) do not. Loosely placed, uncompacted bedding directly under the invert of the pipe significantly reduces pipe stress concentrations. The intent is to allow a small amount of displacement to create a cradling effect that achieves an even load distribution along the longitudinal component of the culvert in the supportive spring zone, increasing the effectiveness of the haunch support. Incorrect compaction of the middle third or use of certain unsuitable material types in this zone can increase a risk of uneven load distribution, increasing likelihood of asymmetrical loading with circumferential or longitudinal cracking or other failure mechanism.

MRTS04 permits the following material types for bedding and haunch zones:

- well graded sand (in accordance with grading limits set by MRTS).
- 20 mm nominal free draining granular material.
- 10 mm nominal free draining granular material.

Success achieving a uniform and evenly distributed support using these materials is variable. There are constructability issues placing a well graded sand in a confined excavation and achieving compaction in the side zones while leaving a loose middle third that is level enough to provide even support across each cell. Commonly, contractors will use a single sized stone that is faster to place and eliminates compaction testing. Care must be taken when using 10mm stone to ensure it is a true screened high quality quarry product, free of fines (for example – decomposed granite) that can wash during high water table episodes, resulting in inadequate support.

3.2 Bedding Factor

In accordance with AS/NZS 3725, there are two Bedding Factors used in the calculation of the proof load (T_c):

- F, for fill and superimposed dead loads.
- Fq, for live loads.

The live loading Bedding Factor (F_q) is limited to 1.5 on the basis that it has been proven to be almost independent of the support type in a shallow cover live load scenario. The dead load Bedding Factor (F), ranges between 1 and 4 depending on the type of support selected.

Bedding Factor selection has significant bearing on the combined actions to be assessed against a culvert's proof load. AS/NZS 3725 allows for a denominator for Bedding Factor of up to 4 depending on the designer's assessment of the reliability of the bedding material and installation of the culvert. The authors' note that caution should be applied in the consideration of the appropriate Bedding Factor to utilise given the magnitude of the impact to loading it can have.

Where backfill grading does not meet AS/NZS 3725 requirement, there are penalising factors that are applied to the Bedding Factor that directly increase load induced on an RCP. The Bedding Factors shall be reduced if the fill in the bed or haunch zones have a grading curve that falls outside the limits given in AS/NZS 3725, as follows:

- Where the fraction passing the 0.6 mm sieve is outside the limits, and is not cement stabilised, the Bedding Factor shall be 1.5.
- For material outside of the limits of other sieve sizes, any maximum Bedding Factor shall be reduced by 15%.

The designer should exercise caution when selecting a dead load Bedding Factor, giving due consideration for the type and availability of backfill material, what material grading is permitted in accordance with the project specification and therefore, what penalising factor may be applicable for design.

3.3 Bedding Installation

Non-uniform support of an RCP can be a function of improper bedding installation. In particular, the method of placement of spigot and socket cells (also known as rubber ring jointed culvert type) on bedding material is critical. To reduce the risk of a stress-strain concentration forming at the critical section just beyond the bell end of a RCP, the bedding material requires local modification to account for the change in pipe geometry, see **Figure 1** and **Figure 2**. This can be easily achieved via hand or shovel excavation of some bedding material local to the pipe bell such that there is an improved uniformity of support along the change in pipe geometry.

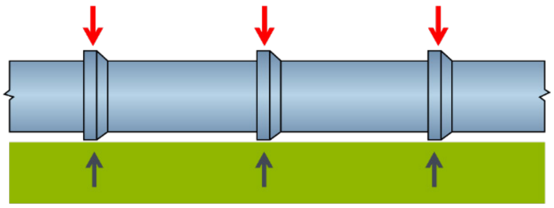

Figure 1: Incorrect bedding placement – no scuppering of material at bell end leading to stress concentration at critical zone (shear) beyond bell section

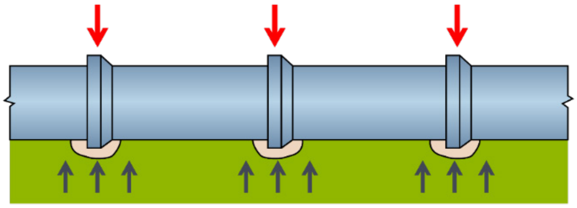

Figure 2: Correct bedding placement – scuppering of material at bell ends allowing for more even load dispersal at critical zone around bell end

It has been observed analytically that other vital considerations for installation of bedding material to yield in-field results comparable to calculated expectations include:

- (For trench installations) Careful excavation of the culvert trench line, with particular focus on not over excavating trench width, and the preparation of a smooth, homogenous base.
- Good preparation of the subgrade such that it is suitable for receiving an adjusted block load within the excavated trench zone. Typical ground preparation requirements include assessment of an influence zone, typically up to 1.5m beneath the culvert although this can be deeper depending on the ground conditions encountered and the type of culvert being installed, via dynamic cone penetrometer blow count assessment crudely converted to an estimated soil shear strength assessment, with typical acceptance ranges occurring between 50-100kPa (100-200 allowable bearing pressure at subgrade surface). Noting that it is vitally important the foundation is not 'over stiffened' (comparatively to the adjacent ground conditions) by excessive ground treatment.
- Properly confining the bedding material such that migration of bedding material away from the trench support zone does not occur. This is commonly and suitably achieved via introducing a geofabric/geotextile layer at the soil junction/excavation perimeter.

4 DISCUSSION

4.1 Finite Element Analysis Assessing the Impact of Ground Support Stiffness on Pipe Bending Moment

For working dead loads, the Bedding Factor is selected using AS/NZS 3725 Table 7 that considers varying bed / haunch zone depths and degrees of compaction in the backfill material. Generally, as depth of haunch zone increases along with the material's density, the Bedding Factor increases (up to a maximum of 4). The standard contends that as the stiffness of support is increased, the bending moment in the pipe is reduced and therefore can be subjected to higher levels of vertical stress. A PLAXIS 2D model was developed to demonstrate the importance of the bedding zone and to the resultant pipe bending moment, see **Figure 3** and **Figure 4**.

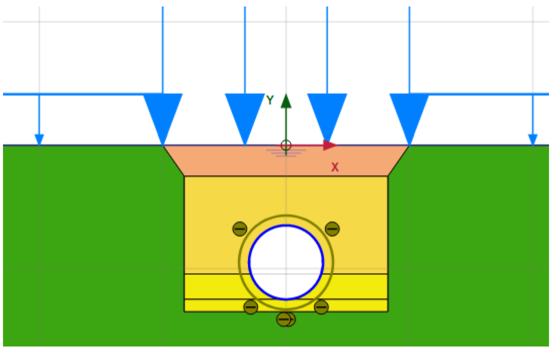

Figure 3: PLAXIS 2D Ground Model

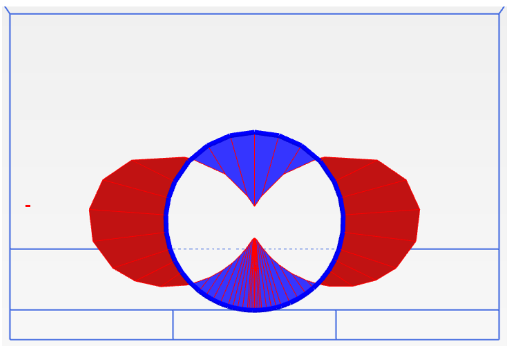

Figure 4: 600 dia. Pipe Bending Moment Diagram

Summary of findings:

- 50% reduction in bedding and haunch zone material stiffness results in a 15% and 9% increase to the bending moment and shear force, respectively.

- 50% asymmetrical material stiffness representing poor compaction on one side of the culvert and good compaction results in a 9% and 7% increase in bending moment and shear force, respectively.

Generally, there is agreement between the PLAXIS 2D assessment and AS/NZS 3725 that as density / stiffness of supporting material increases, the Bedding Factor utilised for working dead loads can be increased also, noting uniformity of support is critical.

4.2 Target Utilisation

Whilst it is structurally possible to design up to a Utilisation Factor of 1 (or 100% of proof load capacity), it is recommended designers target a lower Utilisation Factor with an appropriate risk adjusted value determined based on the consideration of a variety of factors. The authors are not aware of any publicly available design guidance for selection of an appropriate target utilisation as a percentage of proof load for RCPs. Based on anecdotal evidence collected in field, and sampling installation conformity with calculated design assumptions, it has been observed that a wide range of actual installation variables are present that would have a significant impact on a designer's assumed/calculated Utilisation Factor. **Table 2** presents a sensitivity assessment of a commonly observed as constructed variance in trench width excavation (trench installation technique) and the adverse (increased) impact this has on Utilisation Factor.

Table 2: Sensitivity assessment of an as constructed variable – trench width – and its impact on the calculated utilisation factor in design (dead load assessment)

Culvert Size	+30% over excavation	Max Permitted Trench Width
450 (Class 6) ***Impact to utilisation factor (averaged):***	1690mm *+2.50%*	1300mm *0.0*
600 (Class 6) ***Impact to utilisation factor (averaged):***	2080mm *+10.86%*	1600mm *0.0*
1050 (Class 3) ***Impact to utilisation factor (averaged):***	2730mm *+18.50%*	2100mm *0.0*
1200 (Class 3) ***Impact to utilisation factor (averaged):***	2860mm *+10.63%*	2200mm *0.0*

Increase in utilisation beyond acceptable or pre-determined and assumed limits is one variable that can lead to cracking or other damage to the installed RCP.

4.3 Cracking in Concrete Culverts

RCPs are prone to cracking for various reasons, as a result of both design and non-design related actions including the aforementioned exceedance of utilisation for the culvert's designated loading class, transport, handling, placement, bedding (compaction, material grading, trench width), foundation quality (e.g. bearing capacity, expansive soils) and vehicle over-loading during construction. Culverts also crack when they approach proof load capacity. Per AS/NZS 4058:2007, the proof load capacity is determined by loading without developing crack width greater than the relevant test crack width (for example 0.25 mm). In other words, some types of cracking can be both expected and may be acceptable on a structural capacity and durability basis. Notwithstanding, MRTS25 mandates strict criteria for crack acceptability. Noting the various factors that cause cracking, it is not uncommon for crack widths to exceed limit criteria and require legitimate structural repair.

For determination of an appropriate utilisation percentage, designers may take a view that utilisation of 100% is acceptable given in some respects the proof load can be considered a serviceability case with the culvert having a greater ultimate capacity (ultimate capacity = 1.5 × proof load capacity). However, issues can arise when crack widths expected at 100% utilisation levels (e.g. test crack width) are classified as Type 2 defects and therefore are only acceptable after repair in accordance with MRTS25 Table 7(a). Further, there is no requirement to apply a loading Factor of Safety to AS/NZS 3725 calculations. To account for inherent variability in loading cand installation outcomes, a utilisation factor of 90% or less can offer an appropriate risk adjustment to the designer.

4.4 Culvert Inspection Technology

There is industry wide limitation with respect to the technology available that can be repeatably relied upon to provide accurate measurements of crack width. There is currently heavy reliance on operator experience, skill and judgement.

AS/NZS4058:2007 requires crack widths to be measured (and assessed) at 3 mm depth rather than at surface as is commonly undertaken from CCTV inspection. The only reliable and accepted method for achieving this is to physically insert various calibrated thickness feeler gauges into the crack to determine its width and depth. In most instances, confined space restrictions prevent this type of measurement being completed and the assessment is therefore commonly carried out via CCTV inspection with an estimate being made of crack width from photographic evidence by the CCTV robot operator. Notwithstanding, in accordance with AS/NZS 4058 Cl3.4.2.2, any crack greater than 0.10 mm (for cover ≤ 10 mm) is classified as a Type 2 defect and requires repair in accordance with MRTS25 Table 7(a). However, CCTV does not provide resolution to accurately measure width, and as such any observable crack is commonly reported discreetly as a crack less than, or greater than 1mm.

5 CONCLUSION

- Culvert supply, transport and handling, installation and construction loading are critical elements in early stage loading of a culvert.
- The authors' support TMR's requested amendments to AS/NZS 3725:2007, particularly that live load distribution is calculated in accordance with AS5100.2:2017. The authors' highlight that commonly used design software *Pipeclass* does not assess culvert loading performance in accordance with this requirement.
- The correct selection of both live and overall bedding factor (F, F_q) value is a critical factor in determining culvert suitability for applicable loading actions, and requires careful designer judgement and experience to ensure appropriate selection is made. Material selection and installation below the spring line (midpoint of culvert and below) of a buried RCP is fundamental to the loading performance in field. There is a correlation between support stiffness and loading performance, however this also relies (critically) on evenness of support.
- The sensitivity of a designer's calculation and assumptions to actual in field installation is significant. As such, designers should heed caution with utilisation factors approaching one (1).
- Current culvert CCTV inspection techniques for crack width are a crude means for designers to accurately determine structural relevance of cracking and recommend appropriate rectification methods, and risk either under or overestimating a culvert's actual structural condition. Appropriate rectification relies heavily on the designer's experience in this area.
- Improvements in CCTV inspection and reporting techniques could be made, such as higher resolution imagery, LIDAR or other higher accuracy point cloud scanning technique, and/or consideration of any correlation between surface crack width and crack depth measurement.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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