Evolving an Australian Design Procedure for Structure Blockages

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Abstract

Recent growth in media coverage of flooding has reinforced the observation that large quantities of debris can be conveyed by floodwaters, which may lead to partial or complete blockage of structures designed to pass those floodwaters. In 2008 the committee responsible for upgrading Australian Rainfall and Runoff (ARR) formed a project subcommittee to investigate and report on structure blockages. This Project 11 committee was tasked with the development of Design Blockage Guidelines for Australian Conditions. Local and international literature reviews confirmed that little documented material was available on this subject, the most relevant being associated with the impact of blockages during flooding in Wollongong and Newcastle. Despite broad enquiry, only one local government body was found to have recorded blockage information during a major flood event and this information was largely based on debris levels observed after the event. There were however many photographs provided of blockages that provided additional information on blockage mechanisms and extents in most states. There were generic comments on blockage in a number of guidelines, but these varied and were inconsistent and not based on observations or data. Together with inputs from committee members, these materials were used to develop guidelines for the assessment of likely blockage levels at culverts or small bridges in a design event and their impacts on flood hydraulics. These guidelines considered the type and quantum of debris available in the source area, the ability of floodwater to mobilise the debris into a stream and the transportability of that debris in the stream, to establish the debris potential at the target structure. This debris potential was then combined with details of the structure to establish a most likely design blockage level at that structure. These draft guidelines were initially tested by a select group of consultants and after incorporating feedback, a second version was released for testing by a wider group. While testing confirmed some variations can arise between users, the guideline was found to provide logical consideration of most factors influencing blockage and was submitted to the ARR committee in January 2015. Further research is however needed to support on-going refinements of this initial procedure.

1. INTRODUCTION

1.1. Background

While blockage has long been considered a matter to be considered in the design of new culverts and bridges, it has largely been accommodated by the incorporation of an appropriate freeboard to minimize the likelihood of a blockage in the design event, with analysis of design flood behavior then being based on a clear waterway or by the application of an assumed blockage factor. This might be a reasonable approach up to a flood of the design magnitude, but clearly could lead to increased risk of blockage at higher discharges such as those now often included in analysis for risk assessment. At the same time as analysis was incorporating consideration of these higher discharges, a major increase in the use of the internet and number of phones with cameras, created a corresponding increase in the availability of photos of major flood events. These images made clear that blockages were developing and that some means of assessing likely design blockages seemed to be needed. Following major flooding in Wollongong in 1998 a significant body of information on debris collected at and in structures was analysed and formed the basis of an initial blockage policy for that LGA, Rigby and Silveri (2001) and Wollongong City Council (2009). Major flooding in Newcastle in 2012 raised similar concerns as to the potential for blockages to adversely impact flooding in that LGA.

As a major revision of Australian Rainfall and Runoff was also commencing at this time, a review of possible procedures for assessing design blockages was considered both timely and appropriate. An initial step in the revision of ARR was the preparation of research reports covering a number of major topics of concern. One such topic was structure blockages, referred to as Project 11. At the direction of the ARR revision committee, a panel of sixteen experts was assembled under the chairmanship of Dr Bill Weeks to investigate and report on possible means of quantifying likely design blockage levels in small bridge and culvert structures across Australia. This committee met on several occasions to consider available data and discuss views as to how best to progress the development of such a procedure. This led to the release of an initial Stage 1 Report in November 2009.

Following release of the Stage 1 report, efforts were directed toward the development of outline procedures for blockage assessment. This led to the release of a Stage 2 report in February 2013 in which two schemes for assessment of likely blockage levels were presented for discussion.

1.2. Project 11 Stage 1

This first stage of Project 11 concentrated on the collection and review of available data and policies associated with blockage of drainage structures. Since little published information was found to exist on the subject, an important part of this initial process was the collection and collation of the experiences of people and organisations responsible for drainage systems and the management of blockages in those systems. The resulting Stage 1 report described the various sources of information investigated and based on those investigations provided an overview of the Committee's findings in respect to factors influencing blockage. In conclusion, this report recommended that more data be sought, further policies be reviewed and efforts be made to develop procedures based on available knowledge. This report was made available for comment by the profession on the project website.

1.3. Project 11 Stage 2

This second report documented the committee's updated knowledge of factors influencing the blockage of structures generally and presented two possible schemes for the assessment of likely design blockage levels of culverts and small bridges for further consideration by the committee and drainage professionals. This report concluded that "*While the report has gathered relevant data and drawn conclusions from this data, there are still considerable uncertainties and further research will be needed to improve these recommendations".*

1.4. ARR Guidelines

While the limited data available for calibration or validation of either procedure was of concern, the procedure developed by Rigby, Barthelmess and others (2001, 2002, 2004, 2009 and 2011) was considered to be more physically based and open to logical adjustment as more data becomes available. This procedure, referred to as Scheme A in the Stage 2 report, was then developed further, tested and released on the Project website (Weeks (Ed) (2015)). A companion document was released shortly thereafter on the website providing users with a simple form to facilitate design blockage assessment in accordance with this procedure (Rigby and Weeks (2015)). This guideline has been adopted for incorporation in the new edition of ARR when released.

2. DATA COLLECTION

A major objective for ARR is to ensure that all techniques included are based on observed data and published methodology but this is difficult for blockage because there are very few published documents on the methodology for assessment of blockage and also data suitable for assessment of the issue is very limited. Blockage is also highly variable across the country and even between individual catchments or events.

The collection of data on blockage of drainage structures is often conducted by observing the condition of the structure after the flood has receded and noting the extent of apparent blockage. Observations of actual blockage during events are difficult and hence rarely are undertaken so the most common method of observing blockage is the evidence remaining after the flood has receded.

Blockage can also be assessed by measuring the maximum flood levels upstream and downstream of the culvert, which are the flood levels for the peak of the flood. These measurements can then be compared with the theoretical water level difference assuming no blockage and the effect of the blockage can then be estimated. This was the procedure used in some of the Wollongong catchments to assess blockages in 1998, when flood level data was available but debris observations were not.

3. THE ARR BLOCKAGE GUIDELINES

3.1. Guideline Overview

Following discussion on the relative merits of the two blockage assessment schemes outlined in the Stage 2 report, Scheme A was adopted for further development. The guideline's scope being then specific to blockage of small bridges and culverts.

The guideline is divided into sections describing;

- The background and scope of the guideline and procedure
- The limitations of the procedure
- The types of structures and drainage systems considered
- The factors influencing blockage
- The assessment of design blockage levels
- The hydraulic analysis of blocked structures
- The management of blockage

All are important factors in the consideration of blockage and potential users are encouraged to download and read the whole guideline. Of key relevance however, are the procedures for the assessment of likely design blockage levels and their analysis. These procedures are discussed further in the following section.

3.2. Design Blockage Assessment

Assessment of the most likely design blockage levels are based on the type and size of debris likely to reach the structure, the potential quantum of that debris likely to reach the structure and the likely interaction between that debris and the structure. This procedure uses a simple sequential series of assessments of the likelihood (High-Medium-Low) of each factor's significance in the context of blockage of a particular structure in a particular catchment, with the most likely design blockage level as the procedures output. These sequential steps are set out in the following tables.

Tables 1, 2 and 3 qualify the likely availability and mobility of debris in the source area and the transportability of that debris in the stream, down to the target structure.

Table 1. Debris Availability - in the source area of a particular type/size of debris

Availability	Typical Source Area Characteristics (1% AEP Event)
High	*Natural forested areas with thick vegetation and extensive canopy cover, difficult to walk through with considerable fallen limbs, leaves and high levels of floor litter. Streams with boulder/cobble beds and steep bed slopes and steep banks showing signs of substantial past bed/bank movements.*

	Arid areas, where loose vegetation and exposed loose soils occur and vegetation is sparse. *Urban areas that are not well maintained and/or where old paling fences, sheds, cars and/or stored loose material etc., are present on the floodplain close to the water course.*
Medium	*State forest areas with clear understory, grazing land with stands of trees.* *Source areas generally falling between the High and Low categories.*
Low	*Well maintained rural lands and paddocks with minimal outbuildings or stored materials in the source area.* *Streams with moderate to flat slopes and stable bed and banks.* *Arid areas where vegetation is deep rooted and soils are resistant to scour.* *Well maintained urban areas with limited debris present in the source area*

In considering the quantum of debris available in Table 1, it should also be assessed in relation to the volume of storage available at and on the floodplain upstream of the structure under consideration. High availability meaning a great deal more available debris than could be accommodated in these storage areas and low meaning significantly less.

Table 2. Debris Mobility – Ability of a particular type/size of debris to be moved into streams

Mobility	Typical Source Area Characteristics (1% AEP Event)
High	*Steep source areas with fast response times and high annual rainfall and/or storm intensities and/or source areas subject to high rainfall intensities with sparse vegetation cover.* *Receiving streams that frequently overtop their banks.* *Main debris source areas close to streams*
Medium	*Source areas generally falling between the High and Low mobility categories.*
Low	*Low rainfall intensities and large, flat source areas.* *Receiving streams infrequently overtops their banks* *Main debris source areas well away from streams*

Table 3. Debris Transportability - Ability of a stream to transport debris down to the structure

Transportability	Typical Transporting Stream Characteristics (1%AEP Event)
High	*Steep bed slopes (> 3%) and/or high stream velocity (V>2.5m/sec)* *Deep stream relative to vertical debris dimension ($D > 0.5L_{10}$)* *Wide stream relative to horizontal debris dimension.($W>L_{10}$)* *Stream relatively straight and free of major constrictions or snag points.* *High temporal variability in maximum stream flows.*
Medium	*Stream generally falling between High and Low categories.*
Low	*Flat bed slopes (< 1%).and/or low stream velocity (V<1m/sec)* *Shallow depth relative to vertical debris dimension ($D < 0.5L_{10}$)* *Narrow stream relative to horizontal debris dimension ($W<L_{10}$)* *Stream meanders with frequent constrictions/snag points.* *Low temporal variability in maximum stream flows.*

The assessments from Tables 1 - 3 (HML) are then combined in Table 4 to establish the "Debris Potential" at the structure.

Table 4. 1% AEP Debris Potential at Structure

Classification	Combinations of the Above (any order)
High	HHH or HHM
Medium	MMM or HHL or HML or HMM or HLL
Low	LLL or MML or MLL

As the assessments in Tables 1 - 3 are based on debris availability, mobility and transportability in a 1% AEP event, adjustment needs to be made to the associated debris potential at the structure in more frequent and rarer events. In general, lesser events will mobilise and transport lesser volumes of debris to the structure and rarer events more. Table 5 provides adjustment for the debris potential in greater and lesser design events.

Table 5. AEP Adjusted Debris Potential at Structure

Event AEP	(1% AEP) Debris Potential at Structure		
	High	**Medium**	**Low**
AEP > 5% (Frequent)	Medium	Low	Low
AEP 5% - AEP 0.5%	High	Medium	Low
AEP < 0.5% (Rare)	High	High	Medium

Based on the AEP adjusted debris potential (High, Medium or Low) at the structure, the most likely design blockage levels are tabulated in Tables 6 and 7b. Table 6 tabulates the most likely inlet design blockage level for floating debris assuming a floating (top down) blockage scenario, where the width of the structure's opening relative to the length of the longer debris is key to the free passage of debris. In this table, L_{10} is the assessed average length (m) of the longest debris (upper 10% of sample) likely to reach the structure.

Tables 7a and 7b provide similar advice on most likely design blockage levels when the dominant debris is sediment. Typically the deposition of sediment is velocity and grain size dependent and results in a bottom up blockage of the barrel of the structure Table 7a establishes the likelihood of deposition occurring and Table 7b relates the most likely design blockage level to both the likelihood of deposition and debris potential at the structure.

Table 6. Most Likely Inlet Blockage Levels at Structure - BDES%

Control Dimension Inlet Clear Width W m	AEP Adjusted Debris Potential At Structure		
	High	**Medium**	**Low**
$W < L_{10}$	100%	50%	25%
$W \geq L_{10} \leq 3^*L_{10}$	20%	10%	0%
$W > 3^*L_{10}$	10%	0%	0%

TABLE 7a. Likelihood of Sediment Being Deposited in Barrel/Waterway (HML)

Peak Velocity Through Structure (m/s)	Mean Sediment Size Present				
	Clay/Silt 0.001 to 0.04 mm	**Sand 0.04 to 2 mm**	**Gravel 2 to 63 mm**	**Cobbles 63 to 200 mm**	**Boulders >200 mm**
>= 3	L	L	L	L	M
1.0 to < 3.0	L	L	L	M	M
0.5 to < 1.0	L	L	L	M	H
0.1 to < 0.5	L	L	M	H	H
< 0.1	L	M	H	H	H

Based on Hjulstrom's diagram as modified by Sundborg

TABLE 7b. Most Likely Depositional Blockage Levels – B_{DES}%

Likelihood that Deposition will Occur (Table 7a)	AEP Adjusted Non Floating Debris Potential (Sediment) at Structure		
	High	**Medium**	**Low**
High	100%	60%	25%
Medium	60%	40%	15%
Low	25%	15%	0%

3.3. Design Blockage Analysis

Using the prior assessment of the dominant material type (floating or non-floating) and an assessment of the most likely form of debris delivery and blockage type, Table 8 provides an estimate of the most likely timing, location and level of a design blockage. While few hydraulic models include the ability to simulate blockage at this level of detail at this time, testing confirms (Rigby and Barthelmess (2011)) that failure to recognise the temporal pattern of blockages can significantly alter peak flood behaviour.

Table 8. Likely Blockage Timing and Extents

Dominant Source Material	Debris Delivery & Type	Likely Blockage Levels and Timings			
		Inlet	**Barrel**	**Outlet**	**Handrails4**
Floating	Progressive Top Down	0 @ T_P to B_{DES} @$T_{OBV/FL}$	Unlikely	Unlikely[2]	B_{DES} @ $T_{0T/F}$ to B_{DES} @ $T_{0T/L}$
	Pulse[1] Porous Plug	B_{DES} @ $T_{OTB/SA}$	N.A.	N.A.	B_{DES} @ $T_{0T/F}$ to B_{DES} @ $T_{0T/L}$
Non Floating	Progressive Bottom Up	0 @ $T_{OTB/SA}$ to B_{DES} at T_P	$T_{OTB/SA}$ to B_{DES} at T_P	$T_{OTB/SA}$ to B_{DES} at T_P	Unlikely
	Pulse[1] Porous Plug	Unlikely[3]	N.A.	N.A.	Unlikely

1. Pulse blockages are more likely in systems subject to irregular flooding and/or streams with unstable banks

2. Unlikely - but could become likely if the inlet is open and the outlet grated.

3. Unlikely – but could become likely if upstream bed/banks are unstable and/or prone to scour

4. B_{DES} is for the handrail geometry and will normally be much higher than for the culvert/bridge waterway as L_{10} is likely to be much greater than the horizontal opening width/spacing of the balusters. In modelling Bdes can normally be assumed at t=0 as the model will not apply handrail blockages until flow reaches the level of the handrails.

The following designations are used in Table 8 to describe the timing of key trigger points in the blockage process.

$T_{OTB/SA}$ Is the time when flow that first overtops the stream's banks in the source area reaches the structure.

$T_{OT/F\ \&\ OT/L}$ Are the times when flow first and last overtops the structure.

T_P Is the time at which the upstream water level peaks at the structure.

$T_{OBV/FL}$ Is the time on the falling limb when the upstream water level drops back to the obvert level of the structure.

4. GUIDELINE TESTING

As noted in several referenced papers, the project reports and the guideline itself, the quality and quantity of data available to base and validate a nation-wide blockage procedure on, is at this time extremely limited. With respect to the guideline procedure, in the absence of data for validation, two aspects were of particular concern

- The ability of the procedure to be replicated by different users
- The ability of the procedure to produce design blockage levels that experienced users would consider sensible.

Initially a first draft guideline was presented to the committee in 2013 and various changes made to reflect the feedback from that meeting. To try and quantify the above concerns, the modified first draft was then released to a selected group of experienced drainage designers for testing on a series of catchments and structures based on an example from each testers local area. This initial testing showed that while debris potential was reasonably replicated by the testers, the assessed blockage levels were more variable and particularly influenced by the choice of debris size (L10). It was noted that outside of their own local area catchment, all testers had relied on Google Earth to assess the various inputs in the procedure relating to debris and that this was a significant factor in the variability of the assessed L10 and associated design blockage levels. The guideline was amended following this round of testing to provide additional advice on the selection of L10 and to add a recommendation that field assessment of L10 be undertaken whenever blockage could significantly modify flood behavior and put persons or property at risk. A second round of testing with different testers confirmed that the results were reasonably replicated by the testers and produced design blockage levels considered sensible. At this point, the guideline was considered ready for wider review and released on the ARR website.

5. GUIDELINE LIMITATIONS

The guideline was developed to quantify the most likely blockage level and mechanism for a small bridge or culvert when impacted by sediment or debris laden floodwater. It was not developed for and is not appropriate when considering the impact of what are known as hyperconcentrated flows, mudflows or debris flows, on blockage of a structure. At these much higher levels of suspended or fully integrated solids, blockage levels are likely to be much higher than those assessed in accordance with the guideline. Care should be taken in the review of catchment conditions where bed grades are relatively steep (say > 3%), to confirm bed and banks would remain relatively stable, such that flows would remain in the sediment or debris laden category and not become hyperconcentrated during the event under consideration.

6. CONCLUSIONS

a. The inclusion of blockage in the analysis of hydraulic structures in drainage systems is an important consideration in the realistic simulation of flood behavior. Blockage is however a complex and difficult problem to document and even more difficult to analyse. It is important to ensure that the estimate of blockage used in design is AEP neutral and not significantly over or under-estimated as this can influence the performance of the total system. The guideline presents an approach to the assessment of design blockage that has been developed in consultation with Australian experts and provides a consistent and logical approach to assist in the effective planning and design of drainage systems. A companion blockage assessment form has been developed to facilitate use of this guideline.

b. This guideline has been developed to provide an estimate of blockage that is consistent with the available observations and data and which seems reasonable to experienced practitioners and which also allows repeatable and consistent estimates to be prepared.

c. The limited data from which the guideline has been developed, particularly in regard to the temporal pattern and magnitude of design blockages, makes further research and data collection in these areas a high priority. Considerable effort has been put into the guideline to make adjustment to reflect additional research, as straightforward as possible.

7. ACKNOWLEDGEMENTS

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