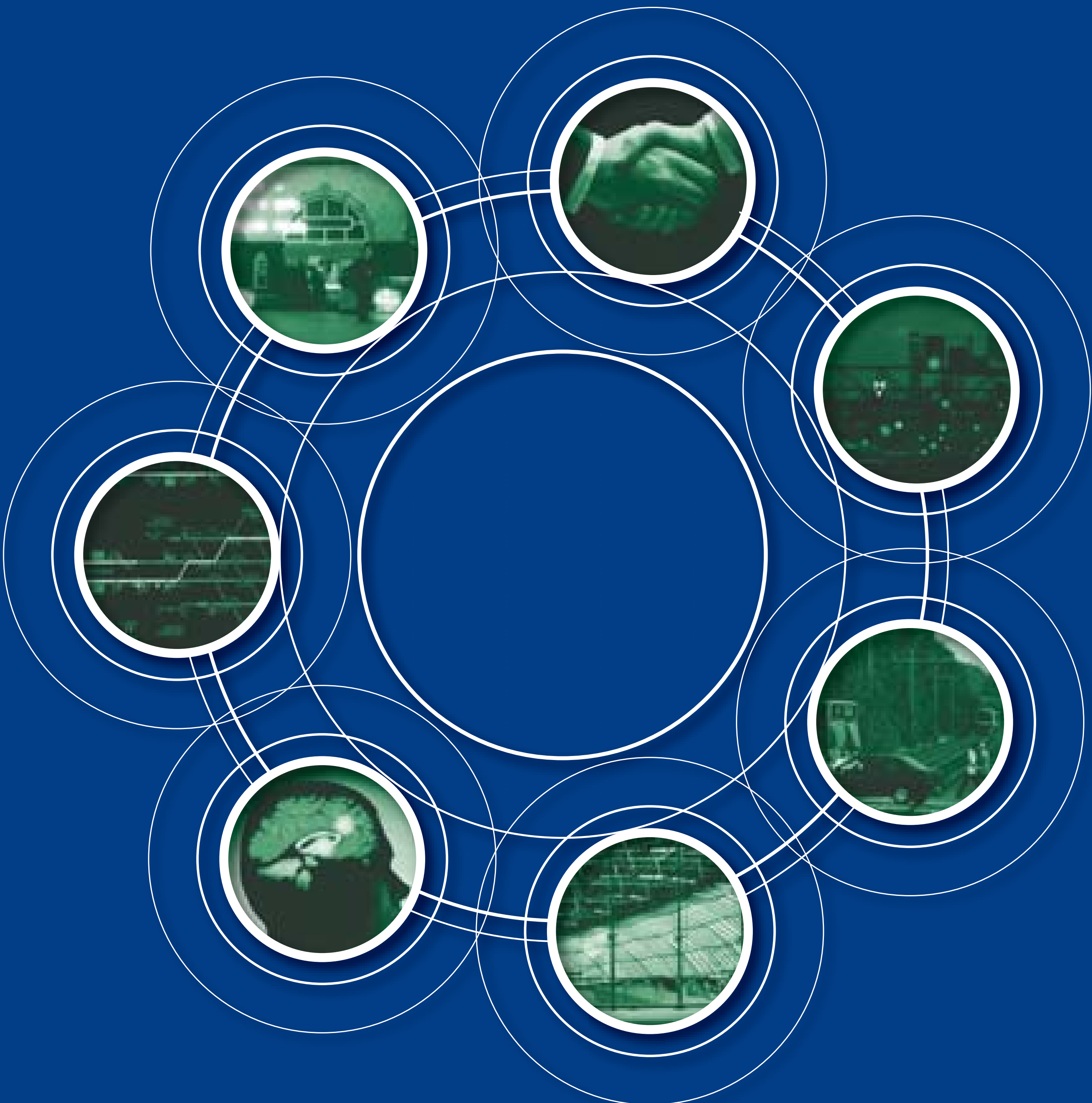
Rail Safety & Standards Board

Research Programme

Engineering

Impact of scour and flood risk on railway structures



Impact of scour and flood risk on railway structures

Research aims

The purpose of this paper is to outline the Rail Safety and Standards Board's (RSSB's) response to the attached report.

The report was commissioned under the Railway Safety Research Programme, and prepared by JBA Consulting. Railway Safety changed to RSSB in April 2003.

The objective of this report was to review the current guidance that stated for a structure with a priority rating greater than 16.0, urgent action should be taken. This threshold was an initial estimate made in the 1980s based on a small number of assessments.

The experience of industry experts, through undertaking many scour risk assessments, suggests that a priority score of 16.0 is too conservative, because there have been relatively few failures compared to the number of bridges with a risk priority score of 16.0 or more.

An additional aim was to establish if this priority rating equation and threshold value should be reviewed, in light of the large number of assessments that have been carried out and the known scour failures. If possible, this would help to reduce the catastrophic risk profile of the railway and allow the more effective distribution of resources according to the magnitude of the risk and the mitigation potential.

Research findings

The research concluded that the existing assessment procedures were not conservative, as the risk priority score of 16.0 is only appropriate for a 30-year return period and there are other scour and flood risk issues, which are not included within the method as it stands.

A risk priority score of 15.0 would be appropriate for a 250-year flood event, and in view of the age profile of railway structures, this is highly relevant. The risk assessment method could be improved at little additional cost. Also the collection and recording of information on damage incurred and water levels reached after a flood will be valuable in developing effective management procedures.

JBA Consulting also recommend that enhancements to the existing EX2502 scour assessment procedure should be considered, if it is to cover the full range of flood-related risks (eg build up of debris within the watercourse and impounding of water behind embankments) and all the types of structure maintained by railway operators.

Next steps

RSSB are now in the process of scoping further research and follow on work, based on this project's findings. This work is planned to commence July 2004.

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Rail Safety & Standards Board

Infrastructure Integrity (4)
Research Theme:

Project Number T112

Scour & Flood Risk at Railway Structures

Final Report

March 2004

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REVISION HISTORY

Revision Ref./ Date Issued	Amendments	Issued to
Final Report – 2nd Issue *Mar 2004*	Amendments to paragraphs 6.2.8, 7.5, 7.7.4, 8.2. 9.1.1.	Huw Parry-Jones RSSB, Evergreen House (4 copies)
Final Report *Feb 2004*	Typographical corrections & amendments as discussed at meeting of 22 Jan 2004	Huw Parry-Jones RSSB, Evergreen House (4 copies)
WBS Work Package 4 *Jan 2004*	Draft	John Lane RSSB, Evergreen House (by post and e-mail)
WBS Work Package 3 *Oct 2003*		Margaret Adams, RSSB, Evergreen House (by post and e-mail)
WBS Work Package 2 *July 2003*		Aqeel Janjua, RSSB, Evergreen House (by post and e-mail)
WBS Work Package 1 *January 2003*		Aqeel Janjua, Railway Safety, Evergreen House (by post and e-mail)

REPORT PURPOSE

This report describes the results of the research work commissioned by the Rail Safety & Standards Board (RSSB) into the Scour and Flood Risk at Railway Structures - Project Number T112 under the Infrastructure Integrity (4) Research Theme.

Railway Safety's representative for the contract was Aqueel Janjua and the work was carried out by Jeremy Benn, Dr Peter Mantz, Andrew Mountain, Tony Green, Ross Bryant and Andrew Gubbin of JBA and Dr Duncan Reed of DWR Consult.

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Date : January 2004

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ACKNOWLEDGEMENTS

The considerable help provided by Network Rail staff in providing information and assisting in the project is gratefully acknowledged. Thanks are also due to local libraries, the British Newspaper Library in Colindale, Public Record Office in Kew and the National Library for Scotland.

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EXECUTIVE SUMMARY

Summary of Findings

Incidence of Failure

- 15 fatalities and perhaps 4-5 times that number of injuries can be attributed to scour/flood structure failure on the UK railway system since the 1840's.
- 6 fatalities due to drowning and rest due to injury resulting from derailment. Two of these were due to inadequate culvert flow capacity and impoundment of water behind a disused railway embankment.
- Highly localised storms more likely than large scale flooding to lead to fatalities. Such events are almost impossible to predict/ provide advance warning.
- Statistical average is one bridge failure every 2.5 years but multiple structure failures have resulted from several incidents.
- Although not formally considered as part of this study, the incident of embankment slippage/ erosion, pipe and drain collapse and track flooding is significantly greater than scour or flood related failures of bridges and culverts.

Causes of Failure

- Bridge/culvert failure due to flooding most commonly associated with 'extreme' but not necessarily 'very rare' floods; average event rarity 160 years but 200 to 250 year return period includes most flood related failures.
- The high incidence of summer/early autumn flood events leading to failure mainly as localised high intensity rainfall on small catchments is of particular note. These events are likely to be at time of reduced vigilance for flood management and a particular risk must be for the washout of a relatively small bridge/ culvert just before a train arrives as a result of a localised thunderstorm on a small steep catchment.
- Bridge protection measures unlikely to be adequate for very rare floods so necessary to ensure bridge opening wide enough in future designs.
- Undermining of abutments and piers by scour is the most common form of failure of bridges and these would be adequately predicted by Network Rail assessment procedures (EX2502); remaining failures attributable to 6 other failure types and these are not adequately addressed using existing procedures.
- Structure damage dependent on many local factors in addition to flood. The most important being build up of debris of bridge piers and at culverts and modification to the river within the immediate vicinity of the bridge.
- Land use changes within the contributing catchment likely to have a minor effect except for the smallest catchments (less than 25 km^2).
- Accommodation bridges accounted for 10% of total bridge failures; these structures are not currently assessed for scour and flood risk unless known to be on floodplain.
- Existing default foundation depth of 1.0m used for preliminary scour assessments when foundation depth unknown is close to median of observed values; uncertainty of ± 1 exists for priority rating.
- Current priority rating threshold of 16 for 'high risk structures' is associated with a flood return period of 30 years. For a more reasonable 'assessment' or 'design' event a 200 year return period event is suggested which would require a reduced priority rating threshold of 15.1.
- Monitoring movement of bridge piers and abutments at or near deck level could be an effective parameter to provide warning of actual failure.
- Climate change may be expected to increase risk of structural failure due to scour and flood events but there is currently no evidence of a change in the frequency of flood related failures. However, great climatic variability with the 'bunching of flood events' can be expected as shown by the historical record.

Predicting Floods

- Flood forecasting inexact and has large degree of uncertainty. Flow forecasting more promising than rainfall forecasting.
- Rainfall forecasting unlikely to provide sufficient information to forewarn of possible failure owing to large spatial scale of this information compared to the local scale of the events likely to cause failure and also associated factors such as debris build up.
- Monitoring of water level promising but requires installation of suitable equipment at vulnerable structures and within the upstream catchments. Such instrumentation is best operated and maintained by flood defence/ land drainage authorities. However installation of simple gauge boards and recording of past flood levels will provide useful data for flood management plans.
- Many potentially vulnerable structures located in small upland catchments where flood prediction in sufficient time to allow line closure is extremely difficult.
- Scour and flood protection measures should be given priority for small catchments (25 km^2 or less) or where time to peak of flooding less than 4-6 hours.
- Flood prediction and action planning more reliable in larger river catchments where service provided by Environment Agency or Scottish Environmental Protection Agency.

Design Floods/Acceptable Risk

- Based on the results of this research and practice elsewhere (e.g. in planning guidance) it is recommended that the design flood for scour assessment and scour protection design should be based on a uniform and consistent 200-year return period flood event. A higher value (of 1,000-years) may be appropriate for structures with a particular high impact of failure such as high speed lines where no adequate warning can be provided, or where flood waters could impound behind embankments and be released suddenly.
- Design life of structures commonly 30-150 years; design flood based on probability of occurring or being exceeded at least once within return period 'N' years; practice of using structure design life potentially unsafe as probability of equalling/exceeding design flood too great e.g. 63% for 100 year design life and return period.
- CIRIA guide ('Manual on Scour at Bridges and other Hydraulic Structures, 2002) recommends rigorous approach to deciding probability of design flood being exceeded over design life using following formula:-

$$P_r = 1 – [1 – (1/N)]^{L_y}$$

Where: P_r = Probability of exceedance, L_y = Design Life (years), N = Return Period (years)

- Indicative values of return period as multiples of design life are given for different structure types and probabilities of exceedance within the CIRIA guide.
- A 250 year design flood is recommended for scour assessment and scour protection design for simplicity, although different design or acceptable risk levels should not be precluded where sufficient data exists for a formal risk analysis.

Recommendations

Scour & Flood Risk Assessments

- Enhancements to EX2502 necessary if it is to cover the full range of flood related risks and all types of railway structure.
- Overall priority score should reflect priority for pro-active management measures; a scale of 10-20 is suggested to maintain consistency with existing procedures with a threshold of 15.0 for structures requiring additional action.
- Where foundation depth unknown a default depth of 1.0m recommended for scour risk assessment; this is justified from assessment of average depth for wide range of railway structures; it is recommended that 1.0 be added to priority ratings where depth assumed.
- Where foundation depth known, important to re-check depth relative to river bed level in future scour assessments.

- Where railway embankments could impound significant volumes of water to significant depths, consideration should be made of the risk they pose to downstream property.
- The suggested revised scour and flood assessment techniques should be 'piloted' on 50 or so representative railway structures to refine the methodology; the procedure should then be incorporated in to Network Rail's new 'Flood Risk Management Best Practice Guidelines', with EX2502 included as an appendix to the guidance.

Acceptable Risk

- A 250 year return period or 0.4% annual probability of exceedance of the design flood should be basis for assessment of structures for scour and flood risk and for design of new structures.

Underwater Examinations

- Current railway standards provide no guidance on how to carry out underwater examinations; all supports should be examined including those not normally within the watercourse; examination should cover the condition of supports located 4.0m or less above normal river level.
- Bed levels should be recorded on grid basis for at least 10m upstream and downstream of support faces or invert (0.5m circumferential spacing at 0.3m and then 2.0m spacing from the structure face for spans greater than 6m and 1.0m spacing for spans less than 6m).
- Presence of soft bed material may be compared with hard bed material by applying pressure to a ranging pole.
- Bed levels should be established to a common datum to allow comparison with future examinations; ideally Ordnance Datum should be used but a fixed and clearly identifiable mark on the structure may be used; x, y and z coordinates should be recorded.
- Plots comparing difference in levels between current and past surveys should be provided.

Coring to establish foundation depth

- Diamond coring still the most reliable technique for brick/masonry structures.
- Minimum of one 75mm diameter core extending 0.5m below underside of each foundation is required.
- Location of core should be at position of lowest bed level from recent underwater examination; where survey not available it should be within 2.0m of upstream face of structure.
- For each support being cored, river bed/ground levels should be recorded every 0.5m around circumference of supports at a distance of 0.3m from structure.
- As for underwater examinations, core log should be related to consistent reproducible datum and ideally the same one.

Public relations

- Review of historical flood-induced railway bridge failures helps to put recent flood related damage in context.
- Accounts of flood disruption during an earlier era might be used to convey the message that the railway system has always had to cope with natural conditions that are occasionally overwhelming.
- It would be unwise to attribute recent flood related damage as being caused by climate change.
- Rapid replacement of failed structures was evident at Apperley (Bradford, 1866), Scottish Borders (1948) and Surrey (1968).

Future Work

- Pilot study to verify and fine tune the suggested new assessment procedure for scour and flood risk.
- Further research into improved methods for determining foundation depth of structures and range and type of foundations that can be expected.
- Further research into instrumentation that may reliably detect movement of supports at deck level as an indicator of possible undermining.

- Additional work to identify appropriate risk management measures for structures found to be of high priority; range of measures likely as risk will vary for structures of similar priority due to factors such as impact of failure and its predictability.
- Additional work to produce simple means of identifying risk from ponding of water behind embankments and the impact of a sudden breach.
- Production of 'time to peak' maps and flood warning provision maps to identify those parts of the railway network where adequate flood warnings and lead in time (at least 2 hours) is possible. These maps will allow resources for additional scour protection measures to be targeted on those structures where sufficient warning time cannot be provided with current technology.
- Development of software to reduce the time needed for scour and flood risk assessments.
- Incorporation of the conclusions and recommendations from this report, where appropriate, in to the Network Rail Best Practice Guidance for Flood Risk Management.

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CONTENTS

CONTENTS

1 INTRODUCTION

1.1 Summary

1.1.1 This research project originated from an external proposal by Jeremy Benn of JBA Consulting – Engineers & Scientists submitted to Railway Safety in March 2002. The theme of relevance to the research is infrastructure integrity. The work relates to Railway Group Safety Plan (2002/2003) objective 2a, that is to:

'Work towards eliminating catastrophic accidents by application of existing control measures and new initiatives.'

1.1.2 In view of the Glanrhyd fatal accident in 1987, recent widespread flooding and the presence of other structures-related risks, the results of this research may help reduce the catastrophic risk profile of the railway by enabling a more effective distribution of resources according to the magnitude of the risk and the mitigation potential. A method of rating bridges for risk priority from scour was developed following the Glanrhyd incident ('Handbook 47'[1]) and this research provides an opportunity to appraise its effectiveness after 15 years of use.

1.1.3 This research has arisen from an identified need to review the current 'Priority Rating' formulae and the threshold value of 16.0 for high priority structures. The latter was set in the late 1980s when 'Handbook 47' was first developed for the then British Rail as a preliminary method for assessing the risk to structures from scour. Due to the lack of data at the time the threshold was set on the basis of 'judgement' and a very limited sample (around 12) of bridge scour assessments. Although Handbook 47 was revised in 1992[2] and is colloquially known as 'EX2502', the basic scoring system remained unaltered.

1.1.4 The Priority Score provides Network Rail with a means of prioritising risks, and aiding budgeting for the management of risk from scour. It is believed that the current threshold value is too conservative, based on the number of bridges already assessed compared with the number of failures. It also does not adequately account for associated risks such as flooding and water pressure on the bridge deck and supports.

1.1.5 The current 'Priority Score' formula is as follows:

Priority Score = 15 + ln [(d_t-d_f) / d_f +1]

Where:

d_f=foundation depth
d_t=total scour depth

(Note - the formula can also be written more simply as 15+ln (d_t / d_f)).

Both depths are taken from a common reference point – usually the lowest river bed level beneath the structure.

1.1.6 Current guidance is that if a structure has a Priority Score greater than 16.0, then urgent action should be taken. This normally includes further study, implementation of line closures during flood, or installation of scour prevention/protection measures. A Priority Score of 16.0 implies that a potential scour depth of 2.7 times the proven foundation depth is required before the structure becomes of undue concern. Typically some 20-30% of all the structures assessed score above 16.0. Experience, however, suggests that the 16.0 Priority Score 'threshold' is too conservative because the number of

[1] Precautions Against Scour Action On Structures (Handbook 47). British Railways Board. 1989.

[2] Hydraulic Aspects of Bridges: Assessment of the Risk of Scour. Hydraulics Research Limited. Report EX2502. April 1992.

structures which score higher than 16.0 greatly exceeds the number of known failures. The possible reasons for this are threefold:

- The foundation depth for railway structures is rarely known accurately. The most commonly used method of coring tends to confirm only the position of the pile cap or raft foundation. If the structure is founded on piles then this method can substantially underestimate the true depth.
- The scour equations (largely based on laboratory experiments using unconsolidated sand) tend to substantially overestimate the potential for scour in British rivers. The latter often have a gravel or cobble component, and flood events are of a relatively short duration.
- The resistance of the bed material to erosion is greater than laboratory studies suggest, due to consolidation under the weight of the structure.

1.1.7 It should be noted that additional work related to the research into the best methods for determining foundation depth is recommended as a follow on from this research project.

1.2 Objectives

1.2.1 The aim of this research is to establish if this Priority Score equation and threshold value needs to be revised in light of the large number of assessments that have been carried out, and the known number of failures.

1.2.2 A further objective of this research is to determine whether a revised equation for assessing flood and scour risk to railway structure foundations located in or over watercourses would be more appropriate.

1.2.3 The benefits of the project were expected to be (a) increased confidence in the definition of acceptable levels of scour and (b) provision of enhanced scour risk assessment procedures for the Railway Industry.

1.2.4 The success of the project has been measured in terms of providing better tools for scour and flood risk management. 'Better' is defined as tools that reduce the uncertainty in the risk estimation. Key questions to be answered are:

- What is the historical incidence of the failure of railway structures as a consequence of scour and flooding? Note that in this context, the term "failure" includes total or partial destruction of a structure that is sufficient to cause line closure.
- What are the mechanisms of past failure and can these can be categorised in a manner which helps in identifying and managing hazards?
- Are there any previously unidentified pre-cursors or indicators that can be used to readily identify structures most prone to flood or scour damage?
- Where are the uncertainties in scour and flood risk identification and how can they be quantified?
- What is an acceptable estimated scour depth versus estimated foundation depth ratio?

1.3 Scope

1.3.1 In order to achieve the objectives, the following staged work items have been carried out:

1. A review of the information in the JBA/Network Rail database of bridges/culverts at risk from scour and flood damage. This is reported in Chapter 2, where a total of 2,924 structures have been analysed using the EX2502/Handbook 47 bridge scour method.
2. An assessment of the uncertainty in the foundation depth and scour depth estimations. This is reported in Chapter 2, and the uncertainty for each is found to be about ± unity for the EX2502 priority rating.
3. An update and review of the information in the existing JBA database of historical scour failures. This is reported in Chapters 3, 4 and 5, where 63 bridge failures from a total of 129 failures in England, Scotland and Wales have been analysed using the EX2502 bridge scour method.
4. Based on the review of information and assessment, confirmation of the appropriateness of the Priority Rating equation and/or the Priority Rating threshold in the current scour and flood risk

assessment procedures. This is reported in Chapter 6, where the use of the priority rating equation has been maintained, and a new series of high priority thresholds have been derived which vary with the return period or flood rarity.

5. An assessment of appropriate safety factors from an analysis of the modes of structural failure during flood/ scour events – based on typical scenarios from the known failures. This is reported in Chapter 7, where new safety factors in the form of added priority ratings for newly identified modes of structural failure are proposed.

2 ANALYSIS OF THE DATABASE OF SCOUR ASSESSMENTS

2.1 Data Sources

2.1.1 The data used for the JBA/Network Rail database has been taken from the Bridge Scour Information System (BSIS) records containing the results of past scour assessments undertaken by Network Rail and its predecessors using Handbook 47/EX2502. Digital copies of the BSIS databases were obtained from each of the Network Rail Regions (Southern, London North Eastern, Great Western, Midland, North West and Scotland). These were then merged into one 'unified' database using Microsoft SQL-Server. After 'cleaning' of spurious and duplicate data, a total of 8,438 bridges and culverts were included in the database. Of these, complete BSIS records for 2,924 structures were available. For the remainder only the BSIS score, bridge number, mileage and ELR existed.

2.1.2 As a further check for the completeness of the database, a query was made on a Geographical Information System database assembled by JBA for this project using data provided by Network Rail and other sources. The query identified all the points where the existing rail network crossed a watercourse. This was taken as a reasonably accurate indicator of the number of bridges and large culverts on the network crossing a river or stream. The query did not of course identify bridges that span water in flood but which are normally 'dry' – such as flood arches and 'cattle creeps' nor does it include structures with a span of less than 1.8 m (6 feet). The watercourse dataset used was a digital map of all the watercourses shown on the Ordnance Survey 1:50,000 maps. The results are shown in Table 2.1 below.

Table 2.1: Estimate of the Number of Major Railway Structures Over Water

Network Rail Region	Number
Southern	1,171
Great Western	1,820
London North Eastern	1,366
Midland	1,152
Scotland	2,144
North West	830
Anglia	545
Total	**9,028**

2.1.3 These figures indicate that the assembled database contains references of some 8,438 out of 9,028 or 93.5% of the major watercourse (bridge/culvert) crossings on the operational UK rail network, and 'complete' information for a scour risk assessment on about 32.4% of these recorded structures. To infill the 'missing' information would require either a repeat scour assessment or a search of the individual bridge structure files for any paper records of the scour assessment. However, for the purposes of this research, the database of 2,924 structures was considered sufficient. This new database containing complete BSIS records is referred to in the remainder of this report as "NRStructures".

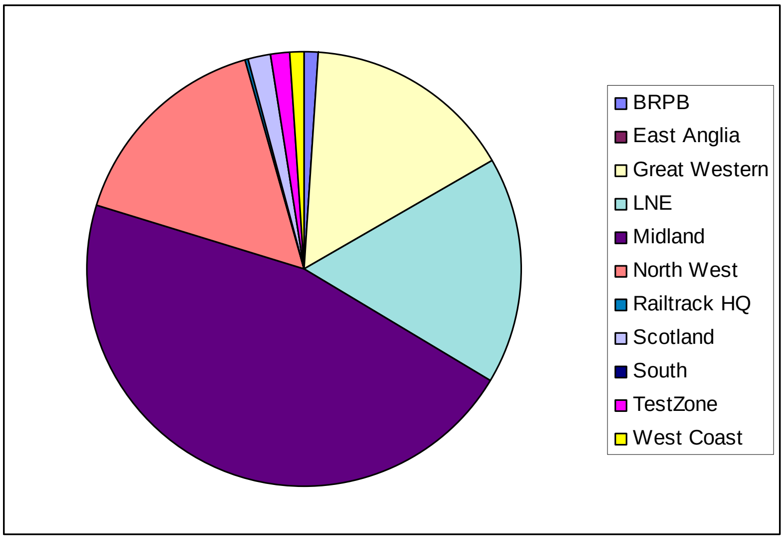
2.2 Preliminary Analysis of BSIS Assessment Data

2.2.1 The database consisting of the records for 2,924 railway bridge structures in the UK has been analysed to provide a first interpretation of the data. The regional distribution for these structures is shown in Figure 2.1 overleaf. The records have been modified to enable the rapid calculation by computer of the EX2502 "Priority Rating" (PR) that indicates the degree of risk associated with bridge failure due to scour.

2.2.2 All of the bridges have been inspected and assessed using Handbook 47/EX2502 at least once, whilst 459 have been assessed twice and 16 have been assessed three times. Out of the 2,924 structures, a total of 9,305 bridge supports or elements (an element is either an abutment or bridge pier) have been rated. A Priority Score above 16.0 is an indication that the structure is vulnerable to scour and a value of 10.0 represents a structure of least concern (i.e. either founded on bedrock or with adequate scour protection). A total of 1,336 elements have a known foundation depth (FD) and are designated as 'FD elements'. The remaining 7,969 elements are designated as 'NonFD elements'. Of these NonFD elements, 7,120 were assumed by the original assessor to have a foundation depth of 1.0 m. The remainder were assumed to have a foundation depth of zero or greater.

Figure 2.1: Regional Distribution for Railway Bridge Structures Over Water

(Note - BRPB – British Rail Property Board)



2.3 BSIS/EX2502 Priority Rating

2.3.1 In the current Network Rail EX2502 scour assessment procedure, the change of bed depth (total scour) at a bridge structure is assumed to be composed of 3 components. The first component is the River Type (TR) and is an estimate of the overall changeability of the river course. It is often called the Regime change (or natural scour), since most rivers are assumed to vary about a steady state called the Regime. The second component is the general reduction of the watercourse dimensions by the structure, and is referred to in some text books as contraction scour. The third component is caused by flow discontinuities at the structure itself, and is named local scour. Since long term regime change is the most difficult to assess, it is treated as a separate variable. The summation of contraction scour and local scour is named total scour (TS), and is divided by the Foundation Depth (FD) to give a Preliminary Priority (PP), thus:

$$PP = f(TS/FD) = 15 + \ln(TS/FD)$$

2.3.2 The PP range for most bridges is between 10 and 20. The Preliminary Priority is adjusted for regime (or river type, TR) and the Foundation Material (FM) to give a Final Priority Rating (PR), thus:

$$PR = f(TS/FD,TR,FM) = 15 + \ln(TS/FD) + TR + FM$$

2.3.3 A mountainous catchment with high flood severity is considered "flashy" and TR = 0. A lowland catchment with low flood severity is considered "non-flashy" and TR = -1. Foundation materials are classified as unknown for which FM = 0, as clay for which FM = -1, and rock for which the whole Priority Rating, PR = 10. The Priority Rating is then classified as in Table 2.2:

Table 2.2: Definition of Priority ratings

Priority rating	Category	Priority
> 17	1	High
16 - <17	2	High
15 - <16	3	Medium
14 - <15	4	Medium
13 - <14	5	Low
<13	6	Low

2.4 Summary of the Analysis

2.4.1 The initial analysis of the 9,305 bridge elements indicated that the uncertainty in the scour Priority Rating for a NonFD element (i.e. where foundation depth is unknown and assumed as 1.0 m) is ± 1.0, and the probability associated with this range of uncertainty is 67%. That is, 67 of a survey of 100 NonFD elements would have a priority rating within the computed value plus 1.0, and the computed value minus 1.0.

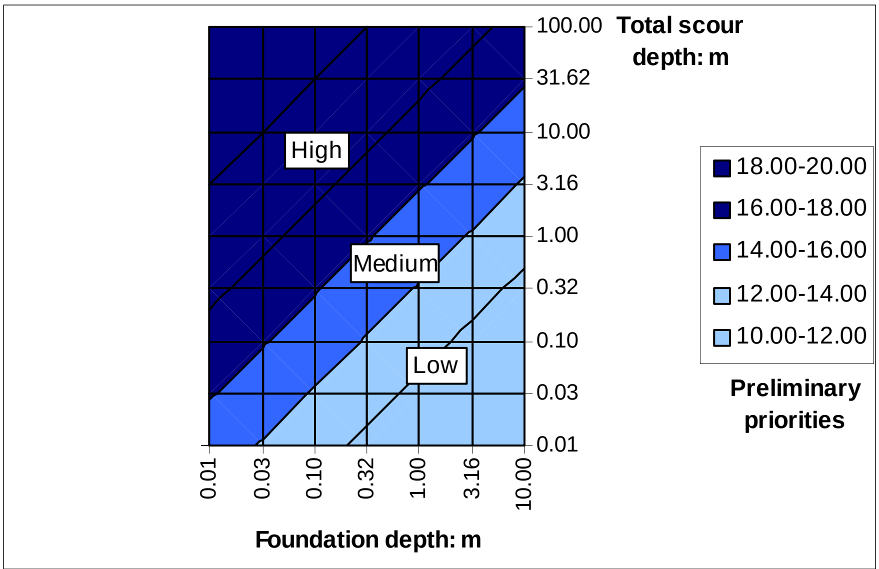
2.4.2 The priority rating is computed as a function of the ratio of total scour depth (TS) and foundation depth (FD). It is generally considered that TS is overestimated for UK structures, and the effect of reduced TS on PR was therefore investigated. An analysis for the FD elements showed, for example, that the percentage of structures with high priority elements (PR > 16.0) was reduced from 55% to 27% when the estimate for TS was halved.

2.4.3 As noted above, the NonFD element Priority rating has a 67% uncertainty range of ± 1.0. An analysis for the NonFD elements showed, for example, that the percentage of structures with high priority elements (PR > 16) changed from 59% to 4% when the FD was varied within this range of uncertainty.

2.5 Uncertainty in the Estimation of Foundation Depth

2.5.1 Since the preliminary Priority Rating is a logarithmic function of two variables (total scour depth and foundation depth), it can be illustrated as a contour chart as in Figure 2.2.

Figure 2.2: 'Contour' chart of Priority ratings for preliminary priorities



2.5.2 Figure 2.2 illustrates the range of foundation depths and total scour depths occurring in the NRStructures database, and the associated zones of preliminary priority ratings enumerated in Table 2.2. This representation will now be used to illustrate the uncertainty in estimating the Priority Rating, PR for unknown or uncertain foundation depth. Since the ratings are derived from the Preliminary Priority, PP, they may be considered as relevant for TR = 0 and FM = 0, that is flashy streams with unknown foundations.

2.5.3 The distributions of the foundation depths measured for the 1,336 elements where foundation depths were known (FD elements) are illustrated in Figure 2.3. These distributions are skewed. When the FDs are plotted as linear values, the distribution is skewed towards the positive values, and when plotted as logarithmic values the distribution is skewed towards the negative values. The following estimates (Table 2.3) were therefore obtained for the mean values and their values at the limits of one standard deviation (SD).

Note:

There are very few 'as-built' drawings available for railway structures. Most foundation depths are therefore established by coring. Coring, however, can only establish the depth of the pile cap or strip/pad foundation and will therefore provide a conservative estimate if the structure is founded on piles or is protected by timber coffer dam. Coring cannot be used on structures supported by steel/iron caissons.

Figure 2.3: Distributions of structure foundation depths (in metres) from scour assessment records

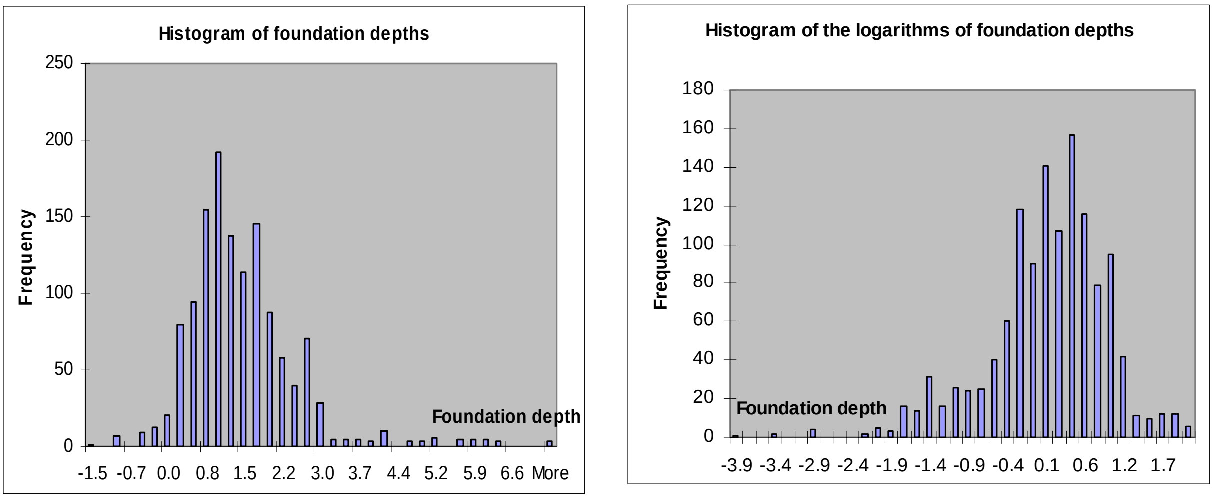
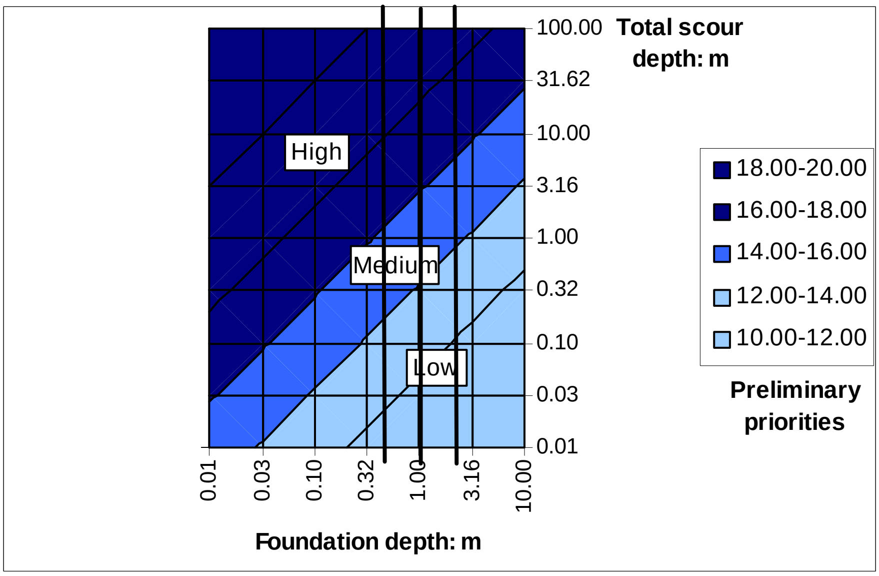


Table 2.3: Known foundation depth statistics

	Mean value	Upper SD limit	Lower SD limit
	m	m	m
Linear	1.3	2.4	0.3
Logarithmic	1.1	2.4	0.5
Mean	1.2	2.4	0.4

2.5.4 The mean value can thus be estimated as 1.2 m with 2.4 m and 0.4 m as the upper and lower SD limits. This is remarkably close to the 1m 'default' foundation depth currently used in assessments when the foundation depth is not known.

Figure 2.4: 'Contour' chart illustrating the uncertainty of priority rating with foundation depth



2.5.5 Since the majority of NonFD elements in the NRStructures database assume a foundation depth of 1 m, their range of priority ratings can be represented by a black vertical line at FD = 1 on Figure 2.4. Similarly, the upper and lower SD limits can be represented by the vertical lines at FD = 2.4 m and FD = 0.4 m. It is then seen that for any total scour depth (TS), the preliminary priority score varies about the mean value at FD = 1 by about ± 1.0.

2.5.6 Thus the uncertainty in the priority rating for a NonFD element (with FD assumed as 1.0 m) is ± 1.0, and the probability associated with this range of uncertainty is 67%. That is, 67 of a survey of 100 NonFD elements would have a priority rating within the computed value + 1.0, and the computed value – 1.0.

2.6 The Effect of Reducing Estimated Scour Depths

2.6.1 The total scour depth estimated in EX2502 is a function of at least 11 variables that represent stream and structure dimensions. Since the influence of each variable is complex to analyse, a general reduction factor (k) was applied to the total scour depth, and its effect on priority ratings investigated. This reduction in TS was applied to both the preliminary priority (PP) and the final priority (PR) for the 1,336 supports with known foundation depths (FD elements).

2.6.2 The range of reduction factor applied was k = 0.1 to 1.0, thus TS was linearly varied as:

0.1TS, 0.2TS, 0.3TS, 0.4TS, 0.5TS, 0.6TS, 0.7TS, 0.8TS, 0.9TS and 1.0TS

2.6.3 For each reduced total scour depth, the percentage of high priority values greater than 16 (PR>16) and greater than 17 (PR>17) were computed from the FD element data. The results are illustrated in Figure 2.6, and it is noted that the linear reduction in TS does not give a linear reduction in the percentage of high priority structures. For example, the original total scour estimate (k = 1) shows that 72.9% of the elements are at high priority (the PR>16 curve in Figure 2.5). If this TS estimate is halved (k = 0.5), there would then be about 50% of elements at high priority.

2.6.4 Note that the above conclusion applies to preliminary priorities, which is relevant for TR = FM = 0. The analysis may, however, be extended to include the TR variable obtained from the actual data and this is illustrated in Figure 2.6. The reduction in percentage of high priority elements is now more linear with reduction in TS. Since TR is negative ranging from 0 to -1, then only 54.9% of elements are at high priority for the original scour estimate (k=1). If this TS estimate is halved (k = 0.5), there would still be 27% of elements considered high priority.

Figure 2.5: Percentage of high priority structures calculated using preliminary priorities for the FD elements

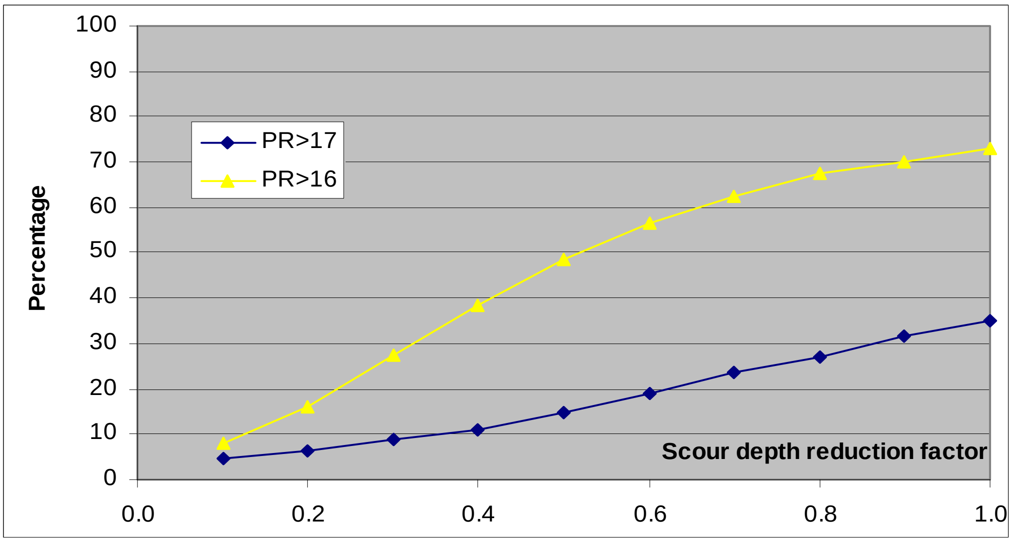
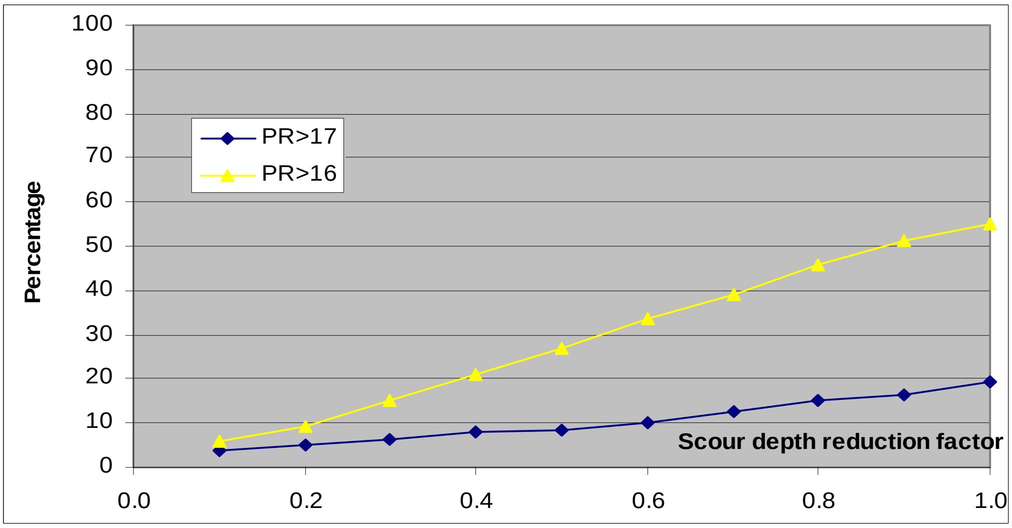


Figure 2.6: Percentage of high priority structures calculated using final priorities for the FD elements



2.7 The Effect of Changing Foundation Depths (FD)

2.7.1 A similar analysis to the above was conducted for changes in foundation depths at fixed TS. The data used were the 7,120 Non FD elements whose FD were assumed as 1.0 m. Since the assumed FD may be an under or overestimate, logarithmic factors (k) were applied to the following range of depths as follows:

0.01FD, 0.05FD, 0.1FD, 0.5FD, 1.0FD, 2.0FD, 5FD and 10FD

2.7.2 Figures 2.7 and 2.8 illustrate the percentage of high priorities (PR>16 and PR>17) for the preliminary priorities and final priorities respectively, and Tables 2.4 and 2.5 give these percentages at the assumed mean FD and the upper and lower SD limits.

2.7.3 For the PP curves, the percentage of high priority structures (PR>16) varies from 50% about the mean (estimated FD = 1m) to 81% and 12% at the SD limits. For the PR curves, the percentages are accordingly reduced to a mean of 23% with SD limits of 59% and 4%.

Figure 2.7: Percentage of high priority structures calculated using preliminary priorities for the non FD elements

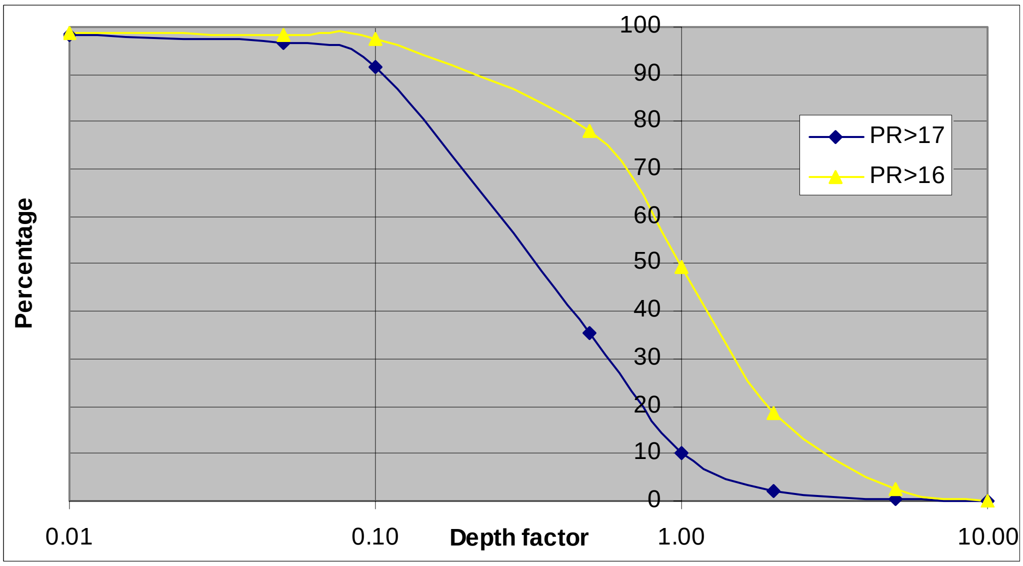


Figure 2.8: Percentage of high priority structures calculated using final priorities for the non FD elements

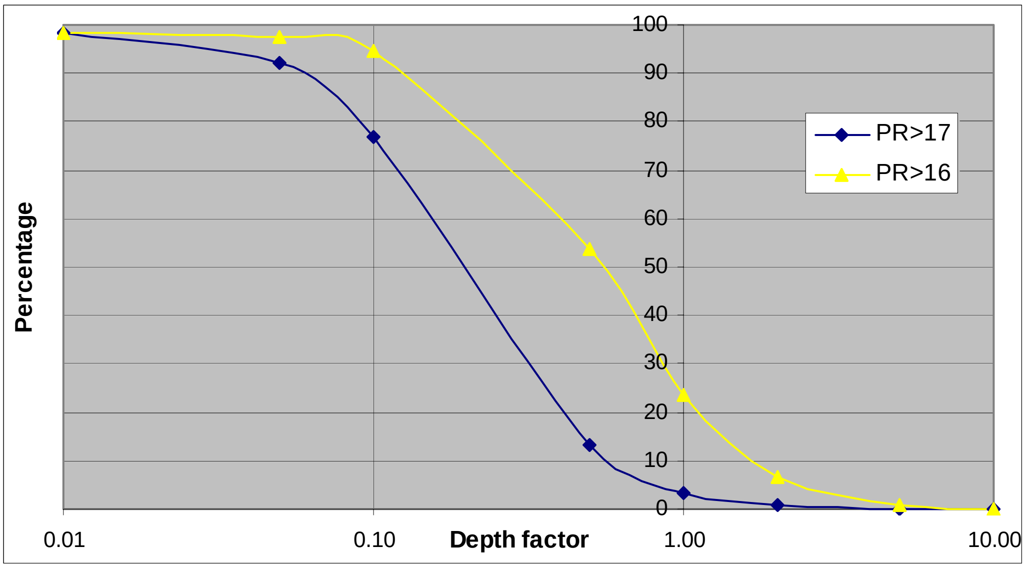


Table 2.4: Percentage of high priority structures calculated using preliminary priorities

Foundation depth : m	PR>17 (High)	PR>16 (High)
0.4	43.6%	81.4%
1.0	10.0%	49.5%
2.4	0.5%	12.5%

Table 2.5: Percentage of high priority structures calculated using final priorities

Foundation depth : m	PR>17 (High)	PR>16 (High)
0.4	20.2%	59.2%
1.0	3.2%	23.4%
2.4	0.1%	4.3%

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3 HISTORICAL INCIDENCE OF STRUCTURE FAILURE

3.1 Introduction

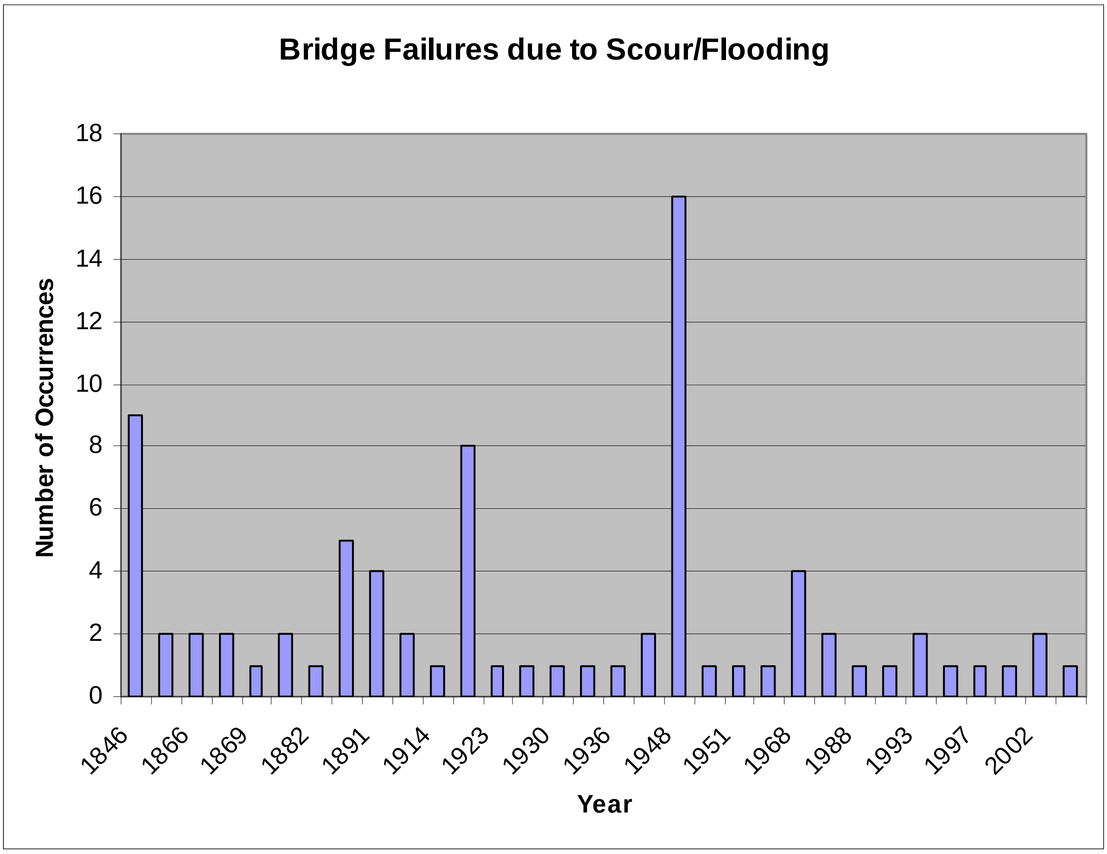
3.1.1 A major component for this research has been the assembly of a database of 131 rail structure failures in the UK and Ireland that can be attributed to scour and/or flood (129 of these are from the UK). These failures have resulted from at least 65 discrete flood events. For the purposes of the research, 'failure' has been defined as complete or partial collapse of the structure sufficient to cause derailment or closure of the line. The database has been restricted to structures (using the accepted 'railway definition' of a structure) with more than a 6 foot (1.8 metre) span. It is acknowledged that failures of smaller culverts, training walls, embankments and other small structures are as important with regard to railway safety and are more numerous. However, these failures are generally less well documented, particularly in terms of specific dates and locations (the latter information is required if an investigation for storm severity is to be attempted). Because structure failure is expensive and can lead to considerable disruption and damage, the focus on larger structures provides confidence that the number and types of recorded failure are representative of the 'overall population', even though every structure failure will not necessarily have been included in this study.

3.2 Failures

3.2.1 In total, 90 structure failure 'events' in the UK have been identified (the number of events is less than the 129 structure failures as some events resulted in multiple failures). They are listed in Appendix A, together with the known details of location, date, casualties and damage caused.

3.2.2 The earliest failure dates from 1846 and the most recent from September 2003. Figure 3.1 below shows a time series of the failures. While statistical analysis of such a relatively small dataset is problematic, Mann's test was applied and indicated no significant trend or periodicity.

Figure 3.1: Histogram showing Distribution of Rail Bridge Scour/Flood Failures with time



3.3 Casualties

3.3.1 In total 15 fatal casualties are known to have occurred as a result of structure failure in flood, as follows:

- Jan 1846, Tonbridge (England) – 1 death (driver killed while trying to jump clear).
- Feb 1868, Caersws (mid-Wales) – 2 deaths (driver and fireman – cause of death unknown).
- Jun 1914, Baddengorm Burn, Carrbridge (Scotland) – 5 deaths (all passengers – most likely crushed rather then drowned).
- Sep 1945, Llangollen Canal (Wales) – 1 death (driver – cause of death unknown).
- Dec 1979, Merthyr Tydfil (Wales) – 2 deaths (local residents drowned by flood waters when water trapped behind a culvert was released).
- Oct 1987 - River Towy, Wales (Glanrhyd) – 4 deaths (3 passengers and the driver – all drowned).

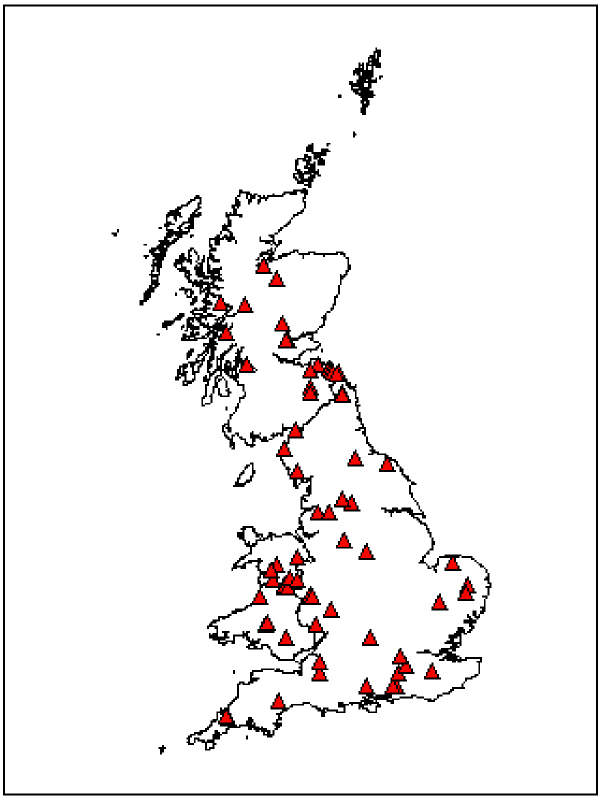
It has not been possible to establish reliable figures for non-fatal injuries.

3.3.2 Given the improvements to the construction of railway rolling stock, the risk of fatalities from derailment may be reduced compared to past incidents. However, the increased strength of carriages and locomotives is unlikely to reduce the risk of drowning (which appears to have caused 4 passenger deaths and 2 third-party deaths in the last 150 years).

3.3.3 Furthermore, 9 incidents (including the above fatal events) involved train derailment either at the time of the failure or shortly afterwards.

3.4 Geographical Location

Figure 3.2: Location of Rail Bridge Failures



3.4.1 The majority of the failures are from single incidents. Where multiple failures have occurred they have been geographically close and in the same river valley. For example, the Moray floods of September 1915 destroyed 16 rail bridges and culverts belonging to the Highland Railway in the Spey and

Findhorn valleys. The August 1948 flood event in the Scottish Borders and the Cheviots can probably be ranked as the 'worst' from the viewpoint of disruption to railway operations, with 9 bridges failing – 7 of them being on the East Coast Mainline between Grantshouse and Reston.

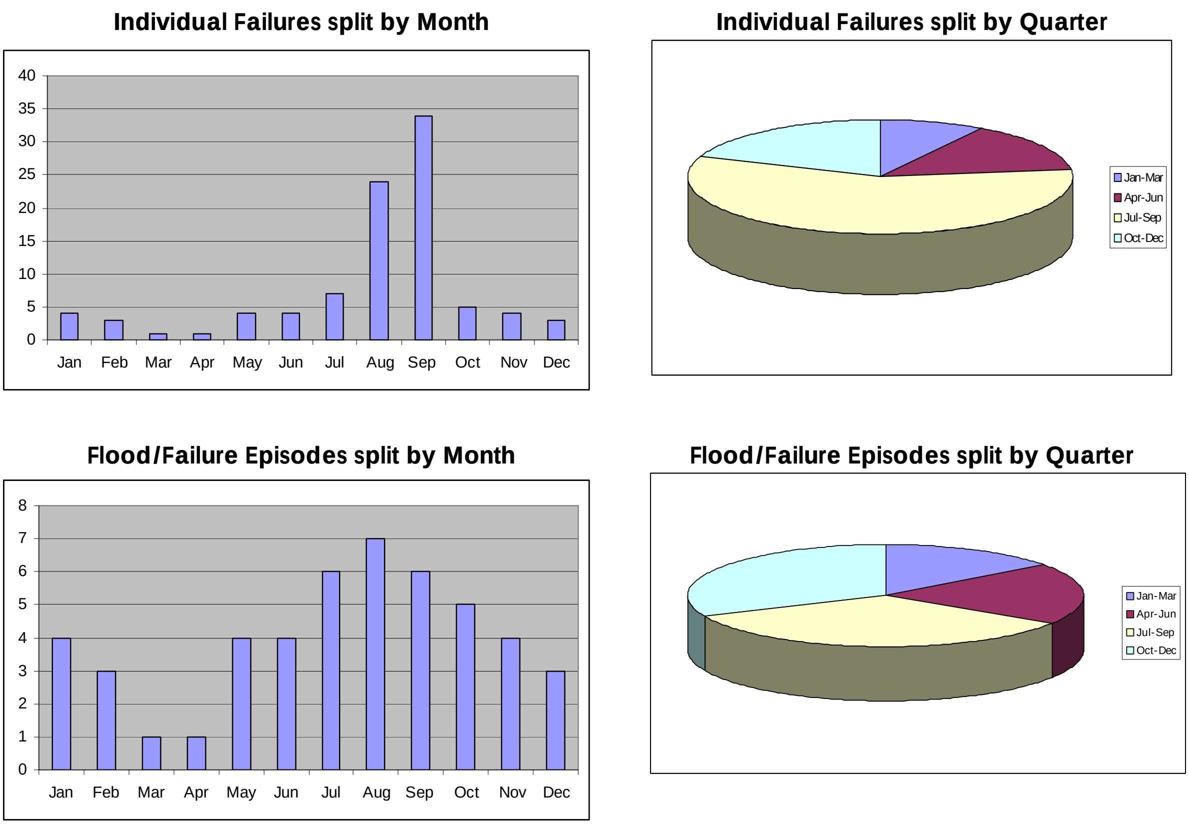
3.4.2 Figure 3.2 shows a plot of those failures for which a precise geographical location can be established. It can be seen there is no readily apparent geographical pattern. However, there are 5 identifiable 'clusters' where failures have occurred in the same river catchment for different years:

- The valley of the Eye Water between Grantshouse and Eyemouth (multiple failures in both September 1846 and August 1948).
- The Esk Valley between Glaisdale and Whitby (failures in August 1866, July 1930 and September 1931).
- The Upper Spey valley at Carrbridge (failures in June 1914 and July 1923).
- Upper Severn valley upstream of Newtown (2 failures in February 1868 and one in June 1936).
- Moray in Scotland (Spey and Findhorn valleys) – 16 bridge/culvert failures in September 1915, and previous unspecified events.

3.5 Seasonality

3.5.1 Structure failures in flood have occurred in every month of the year. The distribution of individual failures has a concentration in the summer months, especially in August and September (Figure 3.3). However, this is biased by the large number of failures that occurred in single flood events in August 1948 and September 1846. If the available data is analysed based on identifiable flood 'episodes', then the seasonal distribution is much less marked.

Figure 3.3: Seasonal Distribution of Bridge Failures



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4 RARITY OF FLOOD-INDUCED STRUCTURE FAILURES

4.1 Objective

4.1.1 Where sufficient information has been available, an attempt has been made to establish whether a flood event was associated with each bridge failure. The objective was to place the known failures into one of three categories:

- Heavy rainfall/river flooding definitely implicated.
- No particular evidence that rainfall/ river flow implicated.
- Insufficient information.

To the extent possible, the study has also provided an estimate of the severity (i.e. rarity) of the flood event. In addition, any information on failure mechanisms encountered was to be noted.

4.2 Methodology

4.2.1 Appendix B provides details of the procedures used to ascertain the rainfall and river conditions around the time of failure, and also how the bridge failure incidents have been categorised in terms of flood event severity. For most incidents, the basis of the categorisation is presented in a Bridge Incident Review Document Investigating Extremeness (BIRDIE). The details include general information about the catchment to the site of the incident, and present such historical material as has been found. For a few incidents, the data support a formal assessment of the rarity of the flood event causing failure. More typically, the rarity is inferred from a combination of rainfall data and experience in flood frequency estimation.

4.3 Findings

4.3.1 Of the 90 failure events, it has been possible to assess the rarity of flooding for 49. These can be categorised as follows (Table 4.1):

Table 4.1: Categorisation of Flood Events leading to Bridge Failure

Category	Number of Bridge Failures (%)	Exceedance probability per year (return period)
Not a flood	**1** (2.0%)	N/A
Relatively minor flood	**7** (14.3%)	50%, 20%, 10%, 5% (2, 5, 10, 20 year event)
Relatively rare flood – flooding the main cause of failure	**22** (44.9%)	2%, 1% (50, 100 year event.)
Rare flood – other contributing circumstances to failure	**19** (38.8%)	0.5%, 0.2% (200, 500 year event)
Exceptionally rare flood	**0** (0.0%)	0.1%, 0.05%, 0.02% (1000, 2000, 5000 year event)
Totals	**49** (100.0%)	

4.3.2 The annual exceedance probabilities (AEPs)/return periods are deliberately given in wide bands to reflect the uncertainty in establishing the probability of floods – especially those that pre-date river flow gauging which generally started in the 1940s.

4.3.3 Table 4.1 shows that the majority of failures (80%) have occurred as a result of significant floods but not ones that can be considered exceptionally rare. Target design standards for flood-resistance of infrastructure has steadily increased over the last 30 years and 100-year and 200-year 'design floods' are now common for river infrastructure. The above figures suggest that a 'design' flood return period of at least 200-500 years would be appropriate for major assets such as bridges.

4.4 Climate Change

4.4.1 It is prudent for the railway industry to be alert to the possibility that flood risks are increasing as a consequence of global climate change. There is much discussion that flood risks are set to increase. The true position is that the effects on river flood risk are largely unknown.

4.4.2 While it is reasonable to take a precautionary approach – i.e. to assume that river flood risks will significantly increase as a consequence of human-induced global climate change – there are ambiguities in overstating what is known about the impact of climate change on fluvial flood risk. ***When a forgotten exposure to flood risk resurfaces in a major flood, climate change provides too convenient a reason***. It encourages the view that – but for climate change – design, operation and maintenance practices are satisfactory with regard to flood-induced rail-structure failure. It is not obvious that such a view is supported by the history of rail-structure flood-failures presented here.

4.5 Climate Variability

4.5.1 Regrettably, citation of climate change tends to discourage the research of past flooding. A baseline period – such as 1961-90 – is drawn, and all history before that deemed irrelevant with words such as *How can we understand climate change impacts on flooding if we continue to base our assessments on floods drawn from a past climate?* But the downside is considerable. Only by exploiting rainfall and river-level records from the 19th and 20th centuries can we hope to distinguish climate change from climate variability.

4.5.2 Ignoring climate variability is misleading and potentially dangerous. The consequence of making flood risk assessments from short-term records is invariably to underestimate design floods and to overestimate the rarity of specific incidents.

4.5.3 Flood risk in the Eye Water serves as an example. A simplistic statistical analysis of 34 years' flood data for station 21016 (the Eye Water at Eyemouth) leads to the flood of 22 October 2002 being assessed as a 275-year event (Cargill, 2003). But much worse events are known to have occurred in 1846 and 1948 (see 1846 Tower Burn and 1948 Eye Water BIRDIEs in Appendix B). Taking these into account suggests that October 2002 is only of the order of a 30-50-year return period event.

4.6 Summary

4.6.1 A review of the information in Appendices A and B indicates that flood risk continues to be an important factor when maintaining, renewing and developing Britain's railway infrastructure. The historical record of rail-bridge flood-failures and this analysis of rarity provides examples of:

- Extreme highly localised flash floods (e.g. the 1914 and 1923 Carrbridge incidents), with a particular capacity to kill;
- Severe storms of moderate spatial extent (e.g. the 1930 and 1931 Esk at Glaisdale incidents);
- Events leading to multiple bridge failures on one line (e.g. the 1846 and 1948 Eye Water incidents);
- Events leading to bridge failures on many different railway lines (e.g. May 1886 in Herefordshire and Worcestershire);
- Localities that experienced bridge failures in consecutive years (e.g. Glaisdale and Wooler);
- Other localities that have experienced more than one bridge-destroying incident (e.g. Carrbridge, Midhurst, and the Eye Water);
- Incidents where temporary bridgeworks proved unsatisfactory (e.g. 1869 Tees at Cleasby incident), thus proving that even temporary works must reach a specified safety standard;
- Failures where antecedent catchment condition (extreme wetness and/or frozen ground) has played a crucial factor (e.g. the 1886 Selham and 1951 Midhurst incidents);
- Events where flooding has coincided with other causes to lead to bridge failure (e.g. failure of an upstream structure as at Carrbridge and the Llangollen Canal and due to debris as at Lower Ashenbottom);

- Failures that have resulted in deaths and injuries to third parties at some distance from the railway (e.g. Nant Rhyd-y-Car, December 1979).

5 MECHANISMS OF FAILURE

5.1 Validation of Database Entries

5.1.1 The mechanisms or causes for structural failure as a consequence of floods are analysed in this chapter. It is shown that about 25% of the failures did not result directly from scour at the structure itself, and thus alternative means to the existing Handbook 47/EX2502 bridge scour assessment procedure are necessary. These alternatives are detailed in chapter 7.

Table 5.1: Rail Structure Failures as a result of water action

Location and relevance for Scour analysis	Database Entries	Number of Structural failures	Number of flood events
United Kingdom (UK) and Ireland	90	131	65
England, Scotland & Wales (GB)	88	129	63
Excluded from EX2502 analysis (on grounds of failure not being directly from scour at the structure)	25	41	23
Considered for EX2502 analysis	63	88	40
Sufficient data available for analysis by EX2502	53	53	35

5.1.2 The database of rail structure failures referenced in chapter 3 and Appendix A contained 90 entries for structures located in the UK and Ireland. These 90 failure incidents have been further researched for any information on the causes of failure. For failures with fatal accidents, the Board of Trade/ Railway Inspectorate "Inquiry Documents" proved useful. For other failures, reliance has been placed on secondary sources such as articles in railway journals and books. Since there was minimum information for the 2 incidents in Ireland, these failures were eliminated from further analysis. This left 88 database entries for Great Britain only (Table 5.1).

5.1.3 The current method for analysing the likelihood of scour or flood failure, as recommended in GC/RT5143, is the screening method developed by HR Wallingford. It is known as 'EX2502' or 'Handbook 47', and has been adapted for computer use as a code named 'BSIS'. The method is designed to assess the risk caused by hydraulic scour at bridge abutments and piers. In view of this, the 88 database entries were first screened to see if there was evidence of pier or abutment scour as a primary cause. It was found that 25 of the entries did not fail by reason of hydraulic scour at bridge abutments or piers. Of these 25, 5 entries were due to insufficient data. Thus the EX2502 scour approach was unsuitable for assessing 20 out of 83, or about 25% of railway structural failures. For these the mechanism of failure has been determined from the available documentary sources alone.

5.1.4 There remained 63 database entries that were relevant for EX2502 analysis, and this was attempted as summarised in Section 6.2 and detailed in Appendix C. Unfortunately, the exact locations of 10 of these incidents (dating from the year 1846) could not be determined. There remained therefore 53 entries which were available for EX2502 analysis.

5.2 The Frequency of Railway Structure Failures

5.2.1 The available data researched usually consisted of the flood date and the number of structural failures, for a particular area or location. A list was compiled of the total number of structural failures relevant to the database entries, and this is summarised in Table 5.1 for the UK and GB.

5.2.2 It is seen that a total of, at least, 131 flood related failures have occurred in the UK and Ireland since the earliest database entry in 1846. Thus there is a statistical average of almost one structural failure per year during the past 157 years. This figure, however, can be misleading, since some recorded events had as many as 16 failures within a single flood event.

5.2.3 The database entries were therefore analysed for the number of flood events which have occurred since 1846, and for which there may be one or more failures associated with each flood (whether they be in the same or a nearby catchment). Table 5.2 lists these flood events, and it is seen that there are at least 65 flood events leading to structure failure for the UK during the past 157 years. This enables the following general statements to be made:

In the UK over the past 157 years, there has been an average of at least one structural rail failure in a flooded catchment every 2.5 years.

In the UK, over the last 157 years there has been a 40% chance that at least one rail structure will fail each year due to a flood event.

Table 5.2: List of flood events in the UK and Ireland during which one or more structural failures have occurred

ID	No. Structures	Day	Month	Year	OS Easting	OS Northing	Watercourse	Country
1	1		Feb	1846?	362810	143510	River Sheppey	England
2	1	20	Jan	1846	556380	146000	Near River Medway	England
3	9	29	Sep	1846			Eye Water	Scotland
4	2	8	Jul	1847	204840	067760	River Camel	England
5	1	30	Aug	1866			River Esk	England
6	1	16	Nov	1866	419090	438530	River Aire	England
7	2		Feb	1868	303130	291650	River Severn	Wales
8	1	13	Nov	1869	424590	513410	River Tees	England
9	3	17	Jul	1880	279922	321552	Afon Wnion	Wales
10	1		Mar	1881	404164	371352	Unnamed stream	England
11	1			1881	320850	563620	Solway Firth	Scotland
12	1		Nov	1882	200740	731210	Nant Burn	Scotland
13	3	14	May	1886	381330	253080	River Teme	England
14	1		Dec	1886	450700	205620	River Thames	England
15	1	26	Dec	1886	493410	120540	Near River Rother	England
16	1		Aug	1891	359990	419600	Black Brook	England
17	3	21	Sep	1891	347550	637500	Gala Water	Scotland
18	1		Aug	1912	618240	296030	River Tas	England
19	1		Aug	1912	591865	335080	River Stiffkey	England
20	1	15	Jun	1914	289170	823290	Baddengorm Burn	Scotland
21	16	26	Sep	1915			Findhorn	Scotland
22	1	08	Jul	1923	288180	824100	Bogbain Burn	Scotland
23	1	09	Jun	1924	444260	352890	River Erewash	England
24	1	23	Jul	1930	478820	505040	River Esk	England
25	1	4	Sep	1931	478820	505040	River Esk	England
26	1	21	Jun	1936	308570	290640	Mochdre Brook	Wales
27	1	7	Sep	1945	323835	342452	Llangollen Canal	Wales
28	1	12	Aug	1946			River Blackwater	N.Ireland
29	1		Mar	1947	357770	228620	River Wye	Wales
30	1	12	Apr	1947	401980	445170	Eastburn Beck	England
31	10	12	Aug	1948	381490	665520	River Eye	Scotland
32	1	12	Aug	1948	348199	665103	Birns Water	Scotland
33	1	12	Aug	1948	400430	625370	Wooler Water	England
34	1	25	Oct	1949	400260	625740	Wooler Water	England
35	1	26	Oct	1949	401760	623640	Lilburn Burn	England
36	1	19	Nov	1951	488210	120910	River Hanger	England
37	2		Oct	1954	325540	491530	Exact Location unknown	England
38	1		Oct	1954	302960	530040	River Derwent	England
39	1	8	Dec	1954			River Tolka	Ireland
40	1	30	Sep	1960	290936	095534	River Creedy	England
41	16		Feb	1962	232860	377760	Exact locations unknown	Scotland
42	1	12	Dec	1964	260310	276210	River Ystwyth	Wales
43	1	12	Dec	1964	312510	308060	River Banwy	Wales

Table 5.2: List of flood events in the UK and Ireland during which one or more structural failures have occurred

ID	No. Structures	Day	Month	Year	OS Easting	OS Northing	Watercourse	Country
44	1	9	Jul	1968	361700	163710	River Chew	England
45	1	15	Sep	1968	496900	144330	River Wey	England
46	1	15	Sep	1968	511940	158270	River Mole	England
47	1		Sep	1968	570360	267220	River Kennett	England
48	1		Sep	1968	613767	281822	Trib of River Waveney	England
49	8	10	Aug	1969	232860	377760	Exact locations unknown	Scotland
50	1	31	Aug	1973	190830	781310	Glen Finnan	Scotland
51	1	27	Dec	1979	304430	205490	Nant Rhyd-y-Car	Wales
52	2	18	Oct	1987	268760	226930	River Towy	Wales
53	1	10	May	1988	501480	174130	Colne Brook	England
54	1	07	Feb	1989	266280	846020	River Ness	Scotland
55	1	2	Jan	1991	282650	304480	Afon Twymyn	Wales
56	3	14	Jan	1993	304821	717699	River May/ River Earn	Scotland
57	1		Jan	1994	322820	304170	River Severn	Wales
58	1		Oct	1997	346200	628488	Ettrick Water	Scotland
59	1	15	Oct	1998	238703	676835	Trib of River Leven	Scotland
60	1	30	Oct	2000	291010	095520	River Exe	England
61	1	8	Dec	2000	291010	095520	River Exe	England
62	1	3?	Oct	2002			River Tay	Scotland
63	1	14	Jun	2002	379560	420590	River Irwell	England
64	1	30	Dec	2002	443813	120021	Monks Brook	England
65	1		Sep	2003	444740	38376	River Rother	England

5.3 Structure Failures not Analysed using the EX2502 Method

Table 5.3: Failure classification of 25 database entries not analysed using the EX2502 method

Failure classification	Number of incidents
Culvert blockage	5
Culvert invert scour	1
Embankment failure	8
Deck loading	4
Ice loading	1
Insufficient data	5
Probably not flood related	1

5.3.1 The EX2502 method is entitled 'Hydraulic Aspects of Bridges: Assessment of the risk of scour'. It is therefore specific to bridges, and does not include other railway structures such as culverts and embankments. Since this present study involves railway structures in general, then it was necessary to eliminate all culverts (6 entries) and embankment failures (8 entries) from EX2502 analysis (Table 5.3, as summarised from the detail of Appendix C, Table C1). Note that those bridge failures which were indeterminate between embankment scour and abutment scour, or embankment scour and pier scour were not eliminated.

5.3.2 There were 4 database entries where the failure was caused by hydraulic forces (or loading) on the flooded bridge deck. It is stated in the EX2502 report :

"These types of study (hydraulic forces on the bridge deck) are outside the scope of this report. For further information consult Farraday and Charlton (1983) or seek specialist advice."

The 4 entries classified as "Deck loading" were thus eliminated from the EX2502 analysis.

5.3.3 There was one database entry for failure due to ice loading, and this was for the famous Solway Firth Viaduct failure in the winter of 1880/1881. It is stated in the EX2502 report:

"Ice problems are unlikely to occur in most parts of the UK. If it is thought that ice problems may occur then specialist advice should be sought."

The single entry classified as "Ice loading" was thus eliminated from the EX2502 analysis.

5.3.4 Inevitably, the 5 database entries with insufficient data and the single non-flood related entry were eliminated from the EX2502 analysis.

5.4 Structural failures analysed by the EX2502 method

Table 5.4: Failure classification of 63 structural failures that may be analysed using the EX2502 method

Hydraulic classification	Number of database entries
Abutment scour	11
Abutment or embankment scour	17
Pier scour *(includes one failure where scour was exacerbated by the presence of debris)*	19
Pier or embankment scour	2
Insufficient element scour data	10
Channel or Catchment modification (e.g. dredging)	4

5.4.1 Since 25 failures were eliminated from the total of 88 GB database failures due to lack of data, there remained 63 for possible analysis using EX2502. Their hydraulic classification for failure is given in Table 5.4. They reduce to 28 entries for possible bridge abutment scour, 21 entries for possible bridge pier scour, and 10 entries where the nature of the scour is indeterminate.

5.4.2 The figures in Table 5.4 can be compared to other limited studies undertaken elsewhere. In the USA, pier undermining is cited as the single most common cause of scour-related failure. In New Zealand, abutment undermining is more common than pier failure. The climate and nature of river bed materials in New Zealand is perhaps more comparable with the UK situation. The comparison is also made more difficult by the fact that many US bridges are multi-span, and extend over an entire floodplain.

5.4.3 In several cases there is evidence of other factors contributing to the mechanisms of failure. These include 4 cases of channel modification caused mainly by dredging. The relevant database entries are:

- Ness Railway Bridge (February 1989) – possibly exacerbated by navigation dredging downstream.
- Colne Brook, Wrasbury (May 1988) – exacerbated by gravel abstraction.
- Wooler Water (Haugh Head) (August 1948) – greatly exacerbated by gravel dredging in the river channel reducing river bank stability.
- River Medway at Penhurst (Jan 1846) – gravel extraction in the floodplain provided additional flow routes.

Although the EX2502 method does not explicitly include channel or catchment modification (by dredging or otherwise) in its numerical analysis, it does include an assessment value for "visible signs of bank instability". It is therefore relevant to examine these bridge failure types as an EX2502 assessment.

5.4.4 The Jun 2002 failure of a pier on the Lower Ashenbottom Viaduct on the East Lancashire Railway can also be attributed with reasonable confidence to scour exacerbated by debris accumulation on the pier (a recent investigation[3] showed that it is unlikely that the structure would have failed if there had been no debris present).

5.4.5 As noted previously, only those database entries which could be positively identified in terms of their Ordnance Survey coordinates were analysed. Thus 53 entries were identified from the 63 available, and they are listed in Appendix C, Table C3.

3 Investigation in to the failure of Pier 2 on the Lower Ashenbottom Viaduct, Rawtenstall. Report prepared for Bury Metropolitan Borough Council/ East Lancashire Railway Trust by JBA Consulting, January 2003.

6 PRIORITY SCORES

6.1 Threshold of Failure

6.1.1 The existing Network Rail procedures for assessing the risk of failure caused by pier and abutment scour, using an EX2502 analysis, are summarised in Chapters 1 & 2 and Table 6.1. A Priority Rating or Score of 16 is the current threshold for 'high priority', for which urgent action should be taken. The criteria for this threshold was based on an original analysis of about 12 bridge structures. Since there now exists data on 63 actual bridge failure events, and the exact location for 53 of these events has been identified, a better failure threshold can be estimated with this new data.

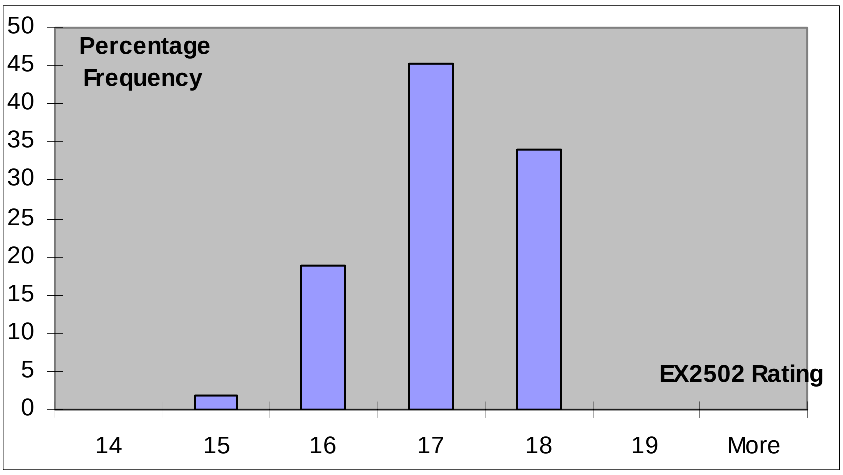
Table 6.1: Definition of EX2502 Priority ratings

Priority Rating	Category	Priority
> 17	1	High
16 - <17	2	High
15 - <16	3	Medium
14 - <15	4	Medium
13 - <14	5	Low
< 13	6	Low

6.1.2 A general threshold of failure is first estimated in this chapter. This involves an analysis of all the 53 data sets as detailed in Appendix C, and deriving the failure threshold which would encompass all the known flood related failures due to pier and abutment scour. A flood rarity/failure threshold is then derived (Section 6.2 below) for which a failure threshold is associated with a return period based on the flood severity 'BIRDIE' estimates detailed in Chapter 4 and Appendix B. This new rarity failure threshold is then extended to predict a failure threshold for any particular flood rarity.

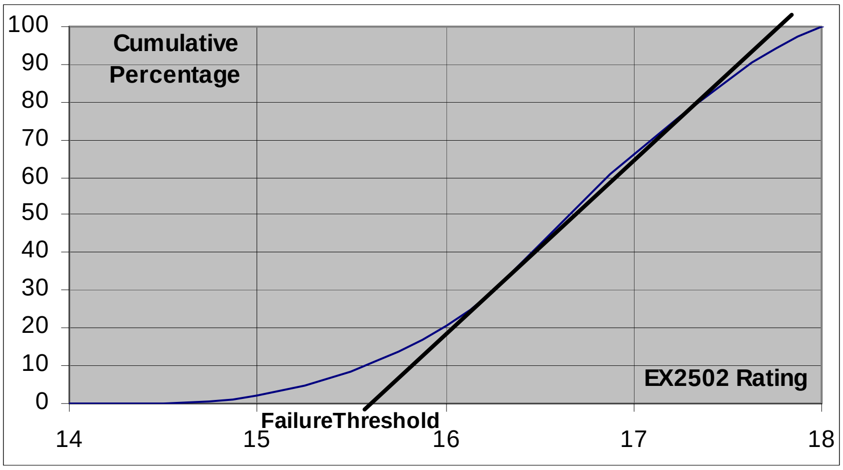
6.1.3 The EX2502 failure priority ratings for the 53 analysed structures are summarised in Table C3, and a histogram of the results are given in Figure 6.1. An average value of 16.6 was estimated, with a standard deviation of 0.7. This means that 67% of the failed structures had an EX2502 rating between 15.9 and 17.3. It is therefore found that the existing EX2502 high risk threshold rating of 16.0 is close to the 67% standard deviation limit of 15.9 for all this failure data.

Figure 6.1: Histogram of EX2502 ratings for bridge failures



6.1.4 As a further test for this new data, the cumulative percentages of the failure ratings are plotted against EX2502 ratings in Figure 6.2. In the past, engineering tradition has objectively established a 'threshold' condition by linearly extrapolating an increasing function to its zero value. Such an extrapolation is objectively maintained in Figure 6.2 for the function between the 30 and 70 cumulative percentile values, it being argued that the fewer and extreme, non-linear values are associated with very extreme flood return periods. An EX2502 general failure threshold is thus objectively estimated at about 15.7. The EX2502 high risk threshold of 16.0 is again close to this 'real' failure value.

Figure 6.2: Cumulative percentage of EX2502 ratings for bridge failures



6.2 Flood Rarity Threshold of Failure

6.2.1 The expression 'flood frequency' or 'flood rarity' refers to the same concept. It is the probability that a flood will occur, on average, in any year. Thus a flood magnitude with a 1/5 probability for occurrence in any year is designated as a 5 year flood, or that is has a 'return period' of 5 years. Such a flood is relatively frequent, and thus the term 'flood frequency' is used. In contrast, a flood whose return period is 1000 years is rare, and thus the term 'flood rarity' is used. For the purposes of this report, the 'flood rarity' term is used throughout.

6.2.2 The BIRDIE studies detailed in Chapter 4 and Appendix B enable the assignment of an approximate flood return period for the bridge failure events. The following logarithmic mean values were used for assigning a mean return period to the 53 events:

- Relatively minor flood: Return period range = 2 - 20 years; Mean value = 10 years
- Relatively rare flood: Return period range = 50 - 100 years; Mean value = 70 years
- Rare flood: Return period range = 200 - 500 years; Mean value = 300 years

Although these values are approximate, they are the only information available regarding the rarity of the past flood related failure events. A nominal uncertainty value of 75% for each mean rarity estimate was also used to represent the uncertainty from the mean value.

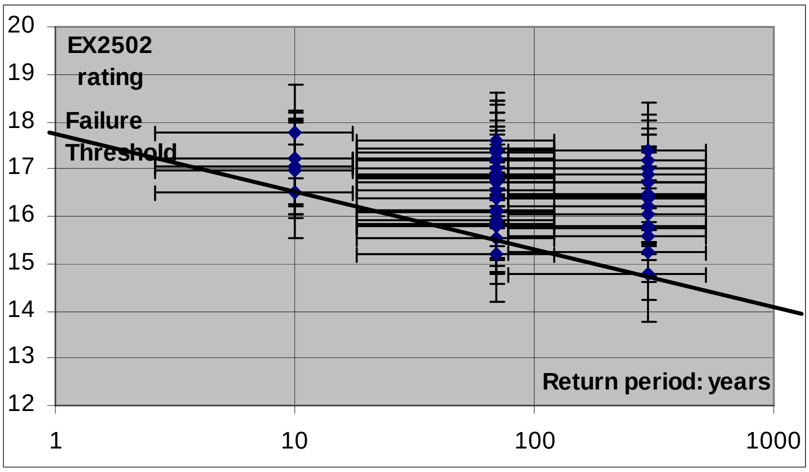
Table 6.2: Summary of EX2502 ratings and flood return periods for the 53 bridge failures

ID	Month	Year	Watercourse	Nearest town	Country	Flood severity	Return period: years	EX2502 Rating	EX2502 Priority
1	Jan	1846	River Medway Trib.	Tonbridge	England	Relatively rare flood	70	17.20	High
2	Sep	1846	River Tyne	East Linton	Scotland	Relatively rare flood	70	15.19	Medium
3	Sep	1846	Tower Burn	Cockburnspath	Scotland	Relatively rare flood	70	15.93	Medium
4	Jul	1847	River Camel	Bodmin	England	Rare flood	300	15.77	Medium
5	Nov	1866	River Aire	Apperley Bridge	England	Relatively rare flood	70	16.89	High
6	Feb	1868	River Severn	Caersws	Wales	Relatively rare flood	70	17.61	High
7	Feb	1868	Afon Carno	Pontdolgoch	Wales	Relatively rare flood	70	17.44	High
8	Nov	1869	River Tees	Darlington	England	Not a rare flood	10	16.53	High
9	Jul	1880	Afon Wnion	Dolgellau	Wales	Not a rare flood	10	16.97	High
10	Jul	1880	River Dee	Llanuwchllyn	Wales	Not a rare flood	10	17.04	High
11	Nov	1882	Nant Burn	Taynuilt	Scotland	Insufficient information		17.39	High
12	May	1886	River Teme	Bransford	England	Relatively rare flood	70	16.53	High
13	May	1886	River Oney	Ludlow	England	Relatively rare flood	70	16.37	High
14	May	1886	River Corve	Ludlow	England	Relatively rare flood	70	16.80	High
15	Aug	1891	Black Brook	Chorley	England	Insufficient information		16.35	High
16	Sep	1891	Gala Water	Galashiels	Scotland	Relatively rare flood	70	16.07	High
17	Aug	1912	River Tas	Forncett	England	Rare flood	300	16.47	High
18	Aug	1912	River Stiffkey	Fakenham	England	Rare flood	300	16.86	High
19	Jun	1914	Baddengorn Burn	Carrbridge	Scotland	Rare flood	300	15.75	Medium
20	Jun	1924	River Erewash	Ripley	England	Insufficient information		16.53	High
21	Jul	1930	River Esk	Glaisdale	England	Rare flood	300	17.03	High
22	Sep	1931	River Esk	Glaisdale	England	Rare flood	300	17.03	High
23	Mar	1947	River Wye	Fawley	Wales	Relatively rare flood	70	16.83	High
24	Apr	1947	Eastburn Beck	Keighley	England	Relatively minor flood	10	17.79	High
25	Aug	1948	River Eye	Grantshouse	Scotland	Rare flood	300	16.40	High
26	Aug	1948	River Eye	Grantshouse	Scotland	Rare flood	300	16.47	High
27	Aug	1948	River Eye	Grantshouse	Scotland	Rare flood	300	14.78	Medium
28	Aug	1948	River Eye	Grantshouse	Scotland	Rare flood	300	15.22	Medium
29	Aug	1948	River Eye	Grantshouse	Scotland	Rare flood	300	16.36	High
30	Aug	1948	River Eye	Grantshouse	Scotland	Rare flood	300	15.60	Medium
31	Aug	1948	River Eye	Grantshouse	Scotland	Rare flood	300	17.38	High
32	Aug	1948	River Eye	Eyemouth	Scotland	Rare flood	300	16.06	High
33	Aug	1948	Birns Water	Gilchriston	Scotland	Rare flood	300	16.20	High
34	Aug	1948	Wooler Water	Wooler	England	Rare flood	300	16.43	High
35	Oct	1949	Lilburn Burn	Lilburn Tower	England	Rare flood	300	16.71	High
36	Oct	1954	River Derwent	Cockermouth	England	Relatively minor flood	10	17.04	High
37	Sep	1960	River Creedy	Cowley	England	Relatively rare flood	70	17.34	High
38	Dec	1964	River Ystwyth	Llanilar	Wales	Relatively minor flood	10	17.23	High
39	Dec	1964	River Banwy	Castle Caereinion	Wales	Relatively rare flood	70	17.00	High
40	Sep	1968	Hell Ditch	Farncombe	England	Rare flood	300	17.16	High
41	Sep	1968	River Mole	Cobham	England	Rare flood	300	16.73	High
42	Sep	1968	River Waveney Trib.	Diss	England	Relatively rare flood	70	15.55	Medium
43	Aug	1973	Glen Finnan	Glenfinnan	Scotland	Insufficient information		16.67	High
44	Oct	1987	River Towy	Glanrhyd	Wales	Relatively rare flood	70	17.45	High
45	Oct	1987	River Dulais	Llanwrda	Wales	Relatively rare flood	70	15.81	Medium
46	May	1988	Colne Brook	Wraysbury	England	Insufficient information		17.35	High
47	Feb	1989	River Ness	Inverness	Scotland	Relatively rare flood	70	17.20	High
48	Jan	1993	River Tay	Dalguise (NB structure was only undermined)	Scotland	Relatively rare flood	70	16.13	High
49	Jan	1993	River Earn	Forgandenny	Scotland	Relatively rare flood	70	15.77	Medium

50	Jan	1993	River May	Forteviot	Scotland	Relatively rare flood	70	16.73	High
51	Oct	1998	River Leven Trib.	Renton	Scotland	Relatively rare flood	70	16.87	High
52	Jun	2002	River Irwell	Rawtenstall	England	Relatively minor flood	10	17.21	High
53	Sep	2003	River Rother	Beighton	England	Relatively rare flood	70	15.83	Medium

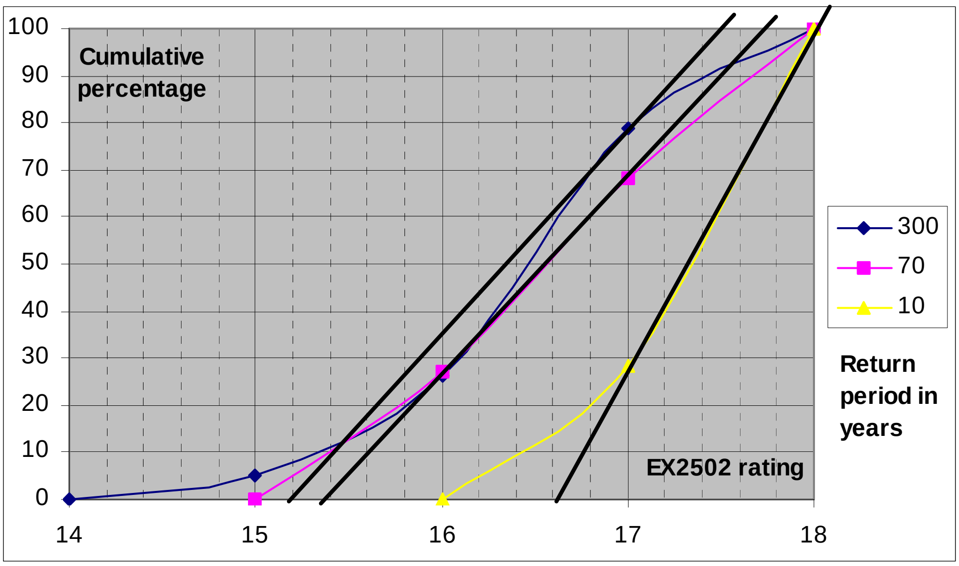
6.2.3 A summary of the flood return periods and EX2502 ratings for each of the 53 failed structures is given in Table 6.2 (above). Five of the events could not be assigned a flood return period, due to insufficient information. The data set was therefore reduced to 48 bridge failures. A "scatter" plot with associated errors is given in Figure 6.3, from which an approximate line of rarity failure threshold can be subjectively identified as the minimum rating values for each of the 3 return periods.

Figure 6.3: EX2502 ratings for bridge failures against flood rarity



6.2.4 In accord with the approach used above for the general failure threshold, this rarity failure threshold was also estimated using the cumulative percentages for the EX2502 ratings at each of the 3 indicative return periods. Figure 6.4 plots the data, and thresholds were objectively estimated using the 30 and 70 cumulative percentiles as estimates for the linear extrapolation. It is argued that these lines represent the mean return periods, although the 300 year data set shows minor uncertainty.

Figure 6.4: Cumulative percentages of EX2502 ratings for bridge failures with flood rarity



6.2.5 Both the thresholds that were estimated using a scatter plot and a cumulative plot may be averaged to estimate a mean threshold value. All these estimates are summarised in Table 6.3.

Table 6.3: Summary of failure thresholds for each estimated flood rarity

Return period: years	Scatter plot threshold	Cumulative plot threshold	Mean threshold rating
10	16.5	16.6	16.6
70	15.6	15.4	15.5
300	14.8	15.2	15

6.2.6 The mean threshold rating may thus be used to interpolate a predicted rarity failure threshold as given in Table 6.4. It is thus estimated that a high risk structure with an EX2502 rating of 16.5 will fail for a 10 year flood, and a medium risk structure with an EX2502 rating of 14.4 will fail for a 1000 year flood. Furthermore, the existing EX2502 high risk rating of 16.0 is equivalent to a failure rating for a 30 year flood. Note that the general failure threshold of 15.7 for all 53 data sets (Figure 6.2) is equivalent to a rarity failure threshold of about 70 years.

Table 6.4: Predicted EX2502 thresholds for different flood rarities

Flood return period: years	Rarity failure threshold
10	16.5
20	16.2
30	16.0
50	15.8
100	15.5
200	15.1
250	15.0
500	14.7
1000	14.4

6.2.7 There is an inevitable uncertainty in these mean values which is difficult to statistically evaluate, due to the errors involved in both the estimate of EX2502 rating (about unity from the mean value, as detailed in Chapter 7) and flood rarity (about 75% from the mean value). Nevertheless, these mean estimates have been derived from 48 actual bridge failures, as opposed to an original EX2502 appraisal of 12 structures which were not subject to actual floods or actual failure.

6.2.8 In summary of the above, it follows that:

- An EX2502 'high priority' threshold of 16.0, as currently recommended in EX2502 and in turn by railway group standards, equates to the scour depth expected from a flood return period of around 30 years using the database of past failures.
- Such a flood statistically could occur at several hundred bridge/culvert locations a year on the operational rail network. The fact that the number of actual failures is much less than this is a reflection of the imperfect (and generally conservative) nature of scour depth estimation. However, for some structures, the scour and foundation depth estimates will be accurate and therefore it would be unwise to reduce the implied factor of safety on the basis of these findings.
- If the EX2502 'high priority' threshold was reduced to 15.0, the associated flood return period for the known failures would increase to about 250 years. Ensuring that a structure can withstand a flood of this magnitude would be in accordance with current design standards.

- About 25% of structure failure events are caused by mechanisms other than bridge pier or abutment scour.

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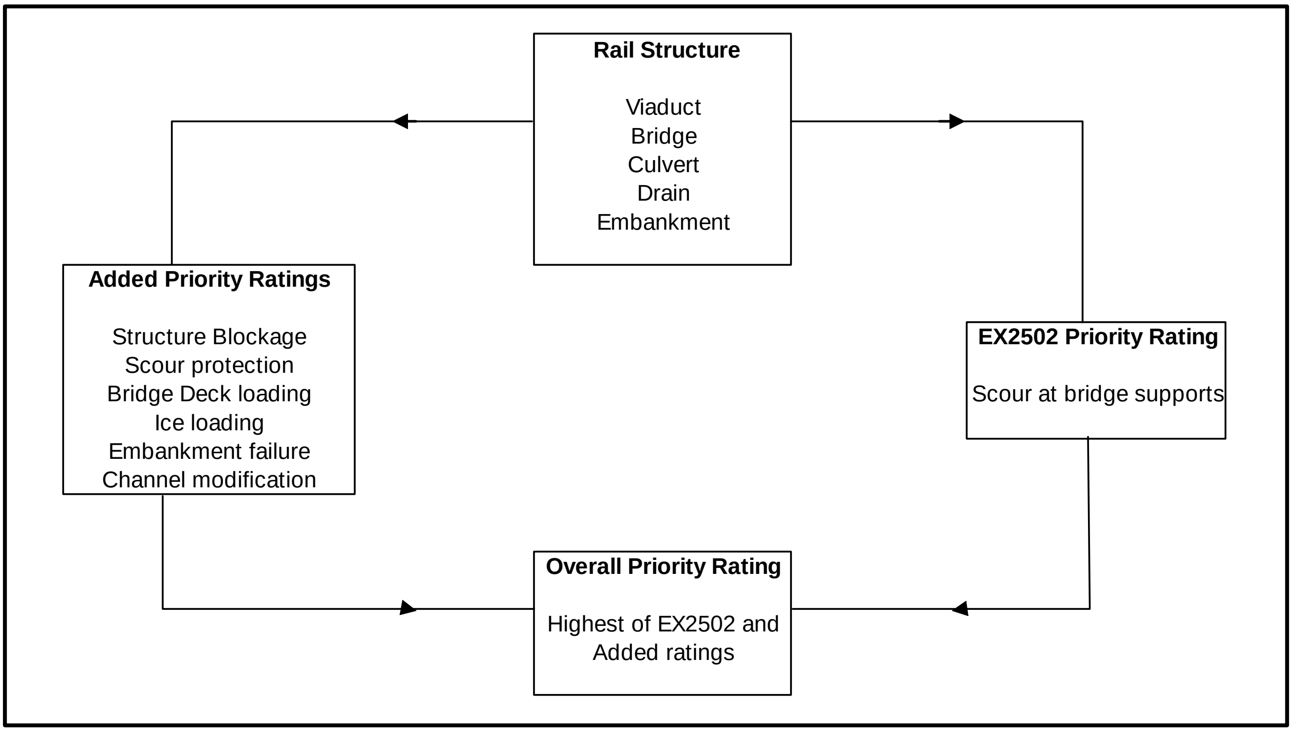
7 OVERALL PRIORITY RATING

7.1 Definition

7.1.1 In Chapter 5 and Appendix C, it was determined that about 25% of the causes for structural failure could not be predicted by the EX2502 methodology. The reason for this is that EX2502 applies to failure by bridge support scour, and does not analyse failure for culvert blockage or invert scour, embankment failure, bridge deck loading, debris loading or ice loading. It is also considered that failures caused by channel modification (such as by dredging or removal of structures from the nearby waterway) are insufficiently represented in EX2502, since such modifications may be the sole cause for structural failure. It is therefore recommended that additional assessment procedures be added to the EX2502 analysis to account for these additional failure causes. Such procedures should determine a priority rating for the added failure causes, to allow compatibility with the EX2502 rating. An "Overall Priority Rating" may then be assigned which is the highest of the EX2502 rating and the Added Ratings. This is also in keeping with the proposed revision to the RT5143 Group Standard. The suggested procedure is illustrated in Figure 7.1.

Figure 7.1: Flowchart for estimating an Overall Priority rating



7.1.2 Note first that although EX2502 can be used to analyse culvert scour, it does not explicitly give a high priority for culvert failure due to blockage or invert scour. The latter were, however, unique failure causes for 6 culverts of the failures listed in Table 5.3. Furthermore, although EX2502 can be used to assess channel modification changes by adjusting the river bank stability variable, it does not explicitly give a high priority risk to such changes. Again, channel modification (by dredging activities) was a unique failure cause for 4 of the bridge structures noted in the failures listed in Table 5.4.

7.1.3 It follows that the above failure causes due to structure blockage, scour protection and channel modification, together with the 'non undermining scour' causes of deck loading, ice loading and embankment failure should be treated additionally to an EX2502 analysis. A structure can be assessed for each of these 6 failure causes, and an added rating applied for each cause. In similarity with the EX2502 method, the added failure causes can be assigned a priority rating from 12 to 18 with associated risks as given in Table 6.1. The highest of the EX2502 and 'Added Ratings' can be used to assess the structural stability and requirements for possible remedial action. The following sections suggest a means for quantifying the 'Added Ratings', and it is anticipated that no additional data is required beyond that given by the proposed revised RT5143 standard.

7.2 Structure Blockage

7.2.1 The EX2502 method deals with blockage by increasing the local scour at a structure according to the availability of debris in the watercourse. This debris availability is determined by a score (from 1 to 7) as indicated in Figure 7.2. Thus a high score of 7 indicates a high debris availability (or alternatively, either a previous history of debris blockage or current blockage) and a low score of 1 indicates minimum debris availability.

Figure 7.2: EX2502 scores for blockage due to trapped debris

Classification for blockage by Debris								
Catchment vegetation	Heavily forested		Wooded		Fertile, bank vegetation		Few trees and bushes	
Catchment slope								
Steep	☐	7	☐	5	☐	4	☐	2
Hilly	☐	6	☐	4	☐	3	☐	2
Moderate	☐	5	☐	3	☐	3	☐	1
Flat	☐	4	☐	2	◉	2	☐	1

7.2.2 The above scoring method states that debris is available in the catchment according to the amount of vegetation and the catchment slope (which enables the debris to be transported by a flow). It is also relevant to include the contraction of the flow at the structure to further assess the probability of structural blockage. A contraction ratio (CR) may be defined, according to the parameters required for the EX2502 method, as:

Contraction ratio = width of floodplain and channel/ width of flow under the bridge

Using the EX2502 floodplain width (W_O), underbridge width (W_B), floodplain depth (Y_O) and underbridge depth (Y_B), the contraction ratio becomes:

$$CR = 1 + (W_O \ / \ W_B) * (Y_O \ / \ Y_B)$$

It follows that the EX2502 debris score (DS) and the contraction ratio may be combined to give a blockage number (BN), thus:

$$BN = CR * DS$$

Thus a high debris score (or high debris availability) combined with a high contraction ratio (or high flow restriction at the structure) can be used as an indication of a high likelihood of blockage (and BN) and a high priority rating. Some practical values are now proposed.

7.2.3 Values for the floodplain width/underbridge width ratio were estimated from the NRStructures database containing 2,924 structures (Chapter 2). Of the latter, 1,379 structures had ratios which were actually measured from indicative floodplain maps or field surveys. (This sample is therefore actual data; it did not use the default values given by the EX2502 method.) A histogram of these data is plotted in Figure 7.3 (using a logarithmic scale due to the large range), and it is seen that the width ratio may vary between 1 and about 500.

7.2.4 Since the debris score varies from 1 to 7 and the floodplain depth/underbridge depth varies from 0 to 1, the blockage number will vary from 1 to a maximum of about 3,500. A priority rating may therefore be assigned in logarithmic sequence, as indicated in Table 7.1. The following examples may then be hypothesised from this table:

- For low potential debris availability and no floodplain: DS = 1; CR = 1 + 1 * 0.3 = 1.3; BN = 1.3; priority is low.
- For high debris availability and EX2502 default floodplain width: DS = 7; CR = 1 + 5 * 0.4 = 3.0; BN = 21; priority is medium.
- For high debris availability and a wide floodplain: DS = 7; CR = 1 + 40 * 0.4 = 17; BN = 119; priority is high.

7.2.5 It is worth noting that practical experience of using contraction ratios for assessment purposes is that in a small number of cases the value can be misleading – especially if it derived from relatively coarse data such as indicative floodplain maps. For culverts the contraction ratio is often exaggerated.

Figure 7.3: Histogram of Floodplain width/Underbridge width ratios for 1,379 structures

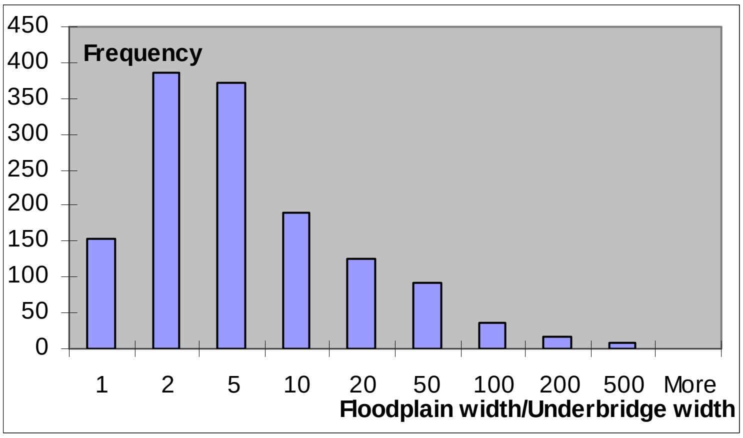


Table 7.1: Structure Blockage Rating

Blockage number	Blockage Rating	Priority
<5	12	Low
5 - <10	13	Low
10 - <20	14	Medium
20 - <50	15	Medium
50 - <100	16	High
100 - <200	17	High
200+	18	High

7.2.6 Ideally, it would be relevant to test the 5 known failures caused by culvert blockage (Table 5.3) using the above rating method. Unfortunately there is insufficient information on floodplain widths or depths for these events, and thus any rating would be unreliable. Furthermore, the 5 culvert blockage events are for small watercourses where little data on flooding is gathered by the land drainage authorities. It follows that the structure blockage ratio survey should, in future, include a detailed assessment of the event by Network Rail.

7.2.7 Since the above blockage procedure remains untested, it is recommended as a subject for future research. Nevertheless, there is no question that structure blockage alone has been the sole cause for structure failure and subsequent collapse. It must therefore be addressed.

7.3 Scour Protection

7.3.1 A major issue in assessing scour protection using the EX2502 method is that there are only two choices - either the scour protection or invert is adequate or inadequate. If the scour protection or invert is adequate, the structure is automatically given a low priority rating. If the scour protection or invert is inadequate or non-existent, then the structure is rated for scour as if there were no protection. There is therefore no gradation for scour protection, such as may be expected for the many different types of protection works encountered. There is also no guidance as to what constitutes adequate or inadequate protection.

7.3.2 In contrast, a "Scour Risk Assessment – Rapid Procedure" has been proposed by Riddell (personal communication) which considers scour protection in greater detail, and from which a scour protection rating may be estimated. This method has been used with success in Scotland. The procedure attributes a score to the types and condition of protection works (Table 7.2), and assigns a rating according to the total score (Table 7.3). Note, however, that the procedure presumes that if structures have had no scour protection in the past, it is unlikely that they will exhibit scour problems in the future. Such a presumption is contrary to the EX2502 method, and is therefore excluded herein.

Table 7.2: Summary of scores for Scour protection type and condition

Scour Protection type	Score
Concrete bags	4
Timber sheet piling	3
Stone filled wire baskets/mattresses	3
Steel sheet piling	2
Concrete/masonry footing or plinth	2
Dumped/placed loose stone invert	2
Pitched stone invert	1
Concrete invert	1
Other form of protection	1 - 4
Scour Protection condition	
Sound, secure, no signs of movement, cracking or undermining	0
Movement of stone, cracking, undermining, exposure, failure	5

Table 7.3: Scour protection rating

Total score	Protection rating	Priority
1	12	Low
2	13	Low
3	14	Medium
4	15	Medium
6	16	High
7	17	High
8	18	High

7.3.3 It is relevant to ascertain a scour protection rating for a documented invert undermining scour event (Table 5.3) - at Monks Brook in Dec 2002. The following failure detail was recorded in the failure database:

At the southern end of the structure a section of the structure has collapsed ...... This is due to scour action of the watercourse undermining approximately eight metres of the brick barrel and southern head wall. Inspection of the southern head wall and wing walls shows indications of significant historic movement.

Since the culvert protection is described as a brick culvert with head and wing walls, it comes under the "Other form of protection" type and scores between 1 and 4 (based upon an inspection). This protection has shown historic movement, and therefore scores 5 for condition. The total score is at least 6, and thus the structure is high priority. Note that an EX2502 rating would probably give a low priority rating for this structure, as the historic movement may be overlooked.

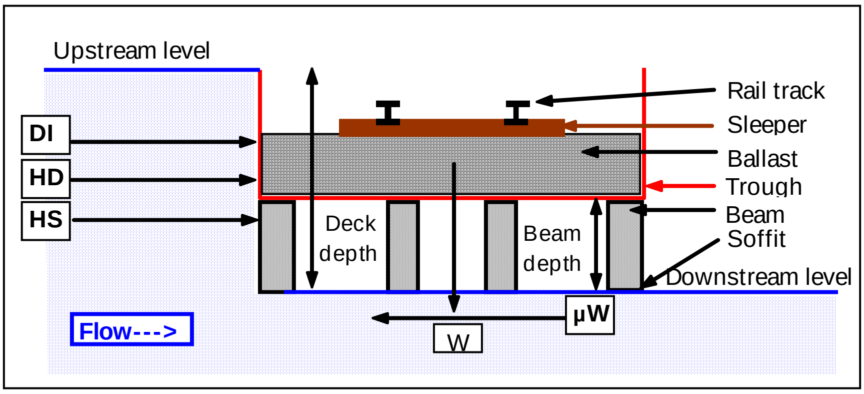
7.4 Bridge Deck Loading

7.4.1 Before conducting a bridge deck loading analysis, it must be established whether the design flood will reach the soffit of the bridge deck. The following qualitative criteria are used for the design flood level, and these must be numerically established during a site survey:

- highly likely to reach the structure soffit and a bridge deck loading analysis is recommended.
- possibly may reach structure soffit under extreme conditions and a bridge deck loading analysis is recommended.
- unlikely that water will reach structure soffit.
- will never reach structure soffit.

7.4.2 The analysis of hydraulic forces or loads on bridge decks were first considered in detail by Farraday and Charlton (1983). Since then, various design procedures have been produced, and a recent method proposed in the Highways Agency “Design manual for roads bridges” (1994, Vol.1, Section 3, Part 6) has been computerised for rapid use. The latter code is named “HALoads” and evaluates the applied hydraulic loading on a bridge deck due to hydrostatic loads (HS, due to the water pressure on the submerged deck), hydrodynamic loads (HD, due to the lift and drag forces on the bridge elements) and debris impact loads (DI, which is defined as the collision force equivalent to that exerted by a 3 tonne log arrested within a distance of 75 mm from the bridge element). These hydraulic loads are resisted by the frictional component (μW) of the bridge weight load (W), where μ is the coefficient of friction equal to about 0.3. The 4 loads are illustrated in Figure 7.4 for a maximum load condition where the flood level is at the top of the bridge deck and the downstream side of the bridge deck is unsubmerged.

Figure 7.4: The maximum state of hydraulic loading on a bridge deck



7.4.3 If the bridge structure has piers, the total applied and resistive loads must be apportioned to each bridge element (that is, abutments and piers). A safety factor may then be defined for each element as the ratio:

Safety factor = Deck resistive load for an element / Applied load to an element

The lowest safety factor for the bridge elements is evaluated, and inevitably, a safety factor < 1 will indicate a high risk condition. A rating table for the lowest safety factor in a bridge structure may thus be prepared as in Table 7.4.

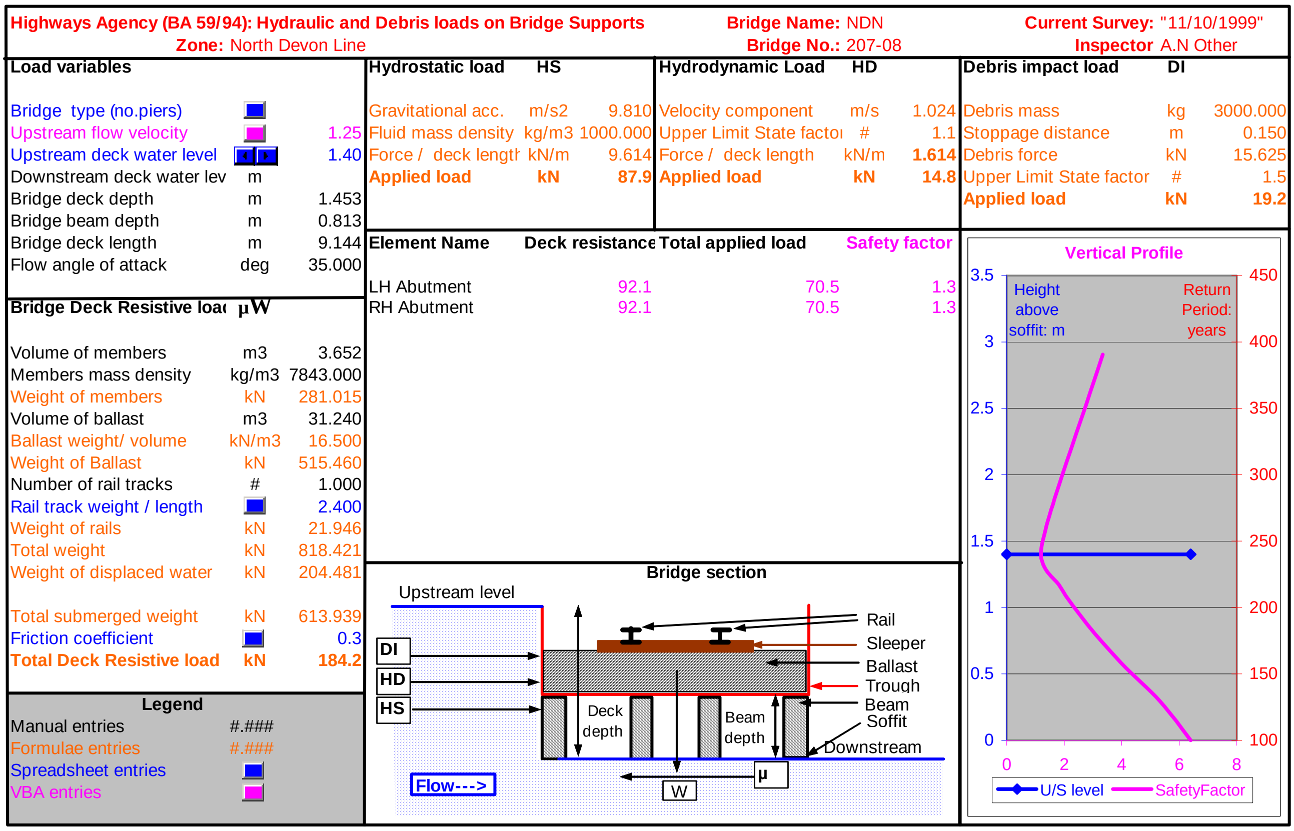
Table 7.4: Bridge Deck Loading rating

Safety factor	Bridge Deck rating	Priority
2.00	12	Low
1.75	13	Low
1.50	14	Medium
1.25	15	Medium
1.00	16	High
0.75	17	High
0.50	18	High

7.4.4 Note that the above analysis apples only to bridges with a rectangular deck which is usually resting by gravity on the pier and abutment foundations. It does not apply to arched bridges, since the bridge deck is then fully integrated with the structure. For arched bridges, the structure itself is sufficiently massive so that there is usually little risk due to hydraulic loading. However it should be noted that some viaducts may have been built hollow to reduce the dead weight.

7.4.5 As an example for bridge deck loading, Figure 7.4 illustrates the computations abstracted from the computer code “HALoads” for a small, ballasted rectangular bridge in North Devon. It is seen that the abutments have a safety factor of 1.31 and therefore have a medium priority, bridge loading rating of 15.2. A recent (02/12/1996) EX2502 rating of 16.36 placed this structure at high priority, and therefore the bridge deck loading risk is of less importance than bridge scour risk for this particular bridge.

Figure 7.4: Summary page for bridge loading from the computer code “HALoads”



7.5 Ice Loading

7.5.1 Although it is unusual for ice loading to be a significant problem in the UK, there is one particular example in the bridge failure database where this has occurred. The following account was reported for the failure of the Solway Viaduct in the winter of 1880/1881:

The rivers Esk and Eden had frozen in the upper reaches of the Firth, and when the thaw came, great chunks of ice reported as being as much as 27 yards square and 6 foot thick were carried into the bridge's piers on an ebb tide travelling at 10-15 mph. Fortunately there had been no loss of life but 45 of the 193 piers and 37 girders had collapsed.

7.5.2 The forces due to ice impact on piers or abutments must be analysed as for the other types of deck loading considered above, and similarly compared against the bridge deck resistive load. A particular method for ice loading is given in the American Association "Standard Specifications for Highway Bridges" (AASHTO, 1993). The horizontal force (F) of an ice sheet on a bridge element is given therein by:

$$F = C * P * t * w * C(w/t)$$

where C is a coefficient for the inclination of the element nose to the vertical, P is the effective ice strength (given by tables), t is the ice thickness, w is the pier or abutment width and C(w/t) is a coefficient depending on the w/t ratio.

7.5.3 The following data illustrates an example of the horizontal ice force for the Solway Firth viaduct failure:

C = 1.0 for an inclination of the element nose to the vertical between 0 and 15 degrees;

P = 700 kN/m^2; t = 2 m; w = 1.5 m; C(w/t) = 0.8 (from tables)

Thus F = 1.0 * 700 * 2 * 1.5 * 0.8 = 1680 kN

Note that these forces are considerably larger than the hydraulic forces estimated for the small North Devon bridge of 9 m span (Figure 7.4).

7.5.4 The ice loading priority rating may be estimated using the same safety factor evaluation as for bridge loading (Table 7.4), however the safety factor is now:

Safety factor = bridge resistive force / ice loading force

7.6 Embankment Failure

7.6.1 Embankment failure can occur by itself, or as the consequence of other failures. For example, the following abstract was reported for Nant Rhydycar in Dec 1979:

A culvert under the embankment of a disused mineral railway became blocked during an unusually long period of heavy rainfall from 26-27 December 1979. Waters were impounded to the full height of the 7-metre high embankment, before the structure failed abruptly. Two lives were lost when the dam-burst flood met obstructions in the watercourse, the waters rapidly filling the ground floor of housing at Rhydycar.

For such a case, the failure has been recorded as a culvert blockage herein, and embankment failure is considered as a sole event to be rated accordingly.

7.6.2 Although embankment failure may be initiated upstream by scour at the high shear stress region near to the main channel, most of the embankment is in the floodplain and probably subject to near stagnant, ponding flood water. The geotechnical stability of slopes is a complex subject. However, since the above analysis on bridge deck loading enumerates hydraulic effects only, such an approach is also used for embankment failure. It is therefore considered that embankment failure is predominantly caused by hydrostatic pressure forces which increase as the water level rises. The analytical problem therefore becomes that of estimating the safety factor given by (Figure 7.5):

Safety factor = embankment resistive force / hydrostatic force

7.6.3 The embankment resistive force is estimated similarly to that for bridge loading, being the weight of the earthen embankment, ballast and rails per metre of length along the embankment multiplied by a coefficient of friction. The hydrostatic force is estimated similarly to the bridge deck hydrostatic force, except the embankment is sloped at an angle (α) of about 30^o to the horizontal, thus:

$$\text{Hydrostatic force} = 0.5 * \gamma * h^2 / \sin\alpha = 9810 * h^2 \text{ per metre of embankment length}$$

where γ is the specific weight of water and h is the flood level height at the embankment.

7.6.4 It may also be important to consider saturation followed by collapse through fluidisation as a potential cause of failure. The Muirton floodbank at Perth, built of permeable material as an agricultural floodbank, failed in this way because of prolonged differential head causing piping and slippage. Road and railway embankments are not designed as dams or water retaining structures and have no impermeable cut-off.

7.6.5 The following example illustrates a safety factor estimate for the above embankment failure at Nant Rhydycar, where an embankment of 6 m top width is assumed with the 7 m height and 30^{o} side slopes:

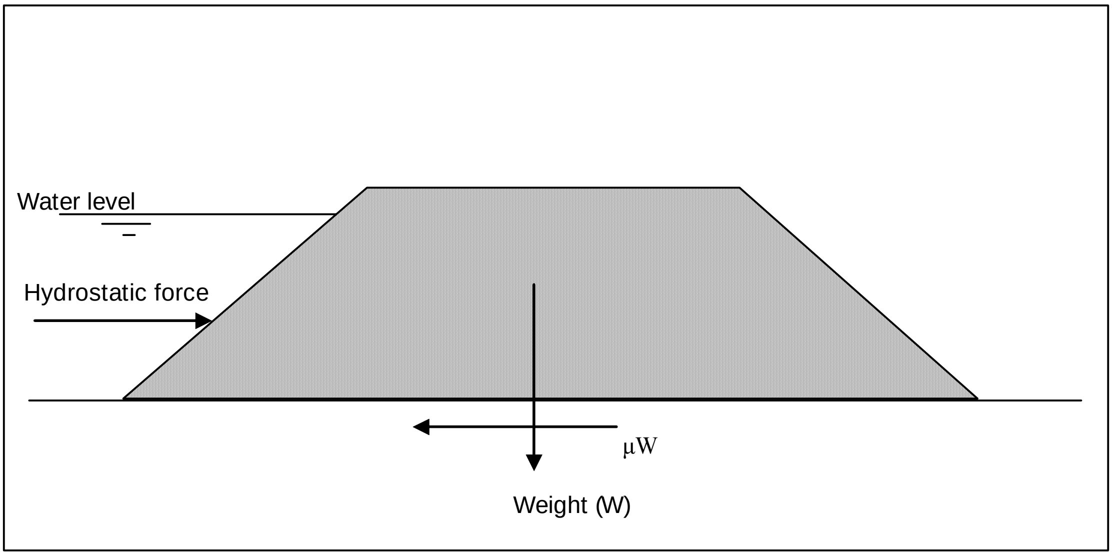
Embankment resistive force = friction coefficient * weight of embankment per unit length

= 0.3 * 2650 * 9.81 * 0.6 * 7 * 7.732 = 254 kN/m

Hydrostatic force = 9810 * 7 * 7 = 481 kN/m

The safety factor therefore evaluates to 0.53. Using the same table for safety factors as for bridge loading (Table 7.4), the priority rating is thus very high at 17.9. This was of course evidenced by the actual failure.

Figure 7.5: Hydrostatic loading used for rating embankment failures



7.7 Channel Modification

7.7.1 It is important to identify any changes that have occurred in a watercourse since a structure was built, particularly recent changes which have not yet combined with an extreme flood. Such changes lead to channel modification, which in turn has been identified as a cause for structure failure (Table 5.4).

7.7.2 The influence of dredging has particularly been identified as common cause of channel modification. There are other activities which produce channel modification, and these have been summarised in "Scour Risk Assessment – Rapid Procedure" (Riddell, personal communication). Such activities are repeated herein to give a channel modification rating in accord with the EX2502 method. Since channel modification is considered probable if there exist channel activities near to the structure, the method depends on identifying all such activities that may affect water levels or bed levels at the structure (Table 7.5). A 'Modification Score' is then estimated for each activity, and a final rating associated for the total score.

Table 7.5: Summary of scores for waterway activities that may affect a structure

Activity	Modification Score
No change	0
Removal or breaching of a weir or dam within 300m of the structure	1
Dredging/gravel abstraction within 300m of the structure	2
Construction of floodbanks within 50m of the structure	2
Construction of an outfall within 25 of the structure	2
Unnatural obstructions	2
Riverbank protection works within 50m of the structure such as walls/ gabions	3
Channel widening, realignment or regrading within 100m of the structure	3

7.7.3 A Modification Score of zero requires no further action. A score greater than zero should result in further investigation of the possible effects of removal. As ownership of modification works can be difficult to establish, such investigations should not wait upon confirmation of who was responsible for the change.

7.7.4 It follows that all of the 4 bridge failures caused by channel modification due to dredging (Table 5.4) should be rated as high priority structures (PR = 16). As it happens the EX2502 ratings for the four were 17.20, 17.35, 16.43 and 17.20 for these particular failures anyway even without the additions. The values with the additions should be used for the Overall Priority Rating.

7.8 Summary

7.8.1 It is thus concluded that there can be 6 additional priority ratings to the original EX2502 bridge scour rating for the structural risk of failure. It is recommended that these ratings need to be included in all priority analyses, and that pilot studies be initiated to verify the above methods proposed.

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8 FINDINGS/DISCUSSION

8.1 Incidence of Failure

- A total of 15 fatalities and perhaps 4-5 times that number of injuries can be attributed to scour/flood failure of railway bridges or culverts on the UK railway system since the 1840s. Of these, 2 fatalities were to local residents and not railway staff or passengers. Only 6 of the fatalities can be attributed directly to drowning and the rest are most likely to have been as a cause of injuries from the resulting derailment. Two of the fatalities were due to failure of a non-operational section of track with flood water building up behind the railway embankment.
- None of the fatalities appear to have occurred during flood incidents causing failure of multiple structures. This may suggest that the risk to life is greater from severe, highly localised storms rather than large-scale flooding.
- The high incidence of summer/early autumn flood events leading to failure mainly as localised high intensity rainfall on small catchments is of particular note. These events are likely to be at time of reduced vigilance for flood management and a particular risk must be for the washout of a relatively small bridge/ culvert just before a train arrives as a result of a localised thunderstorm on a small steep catchment.
- In terms of financial consequences, an annual loss of at least £1 million a year can be suggested on the basis of a statistical average of, at least, one bridge failure every 2.5 years. There are several incidents however where multiple structures have failed during a single flood episode.
- Although not studied as part of this research, it is clear that in addition to bridge/culvert failures there have been many embankment/cutting slips and pipe/drain failures as a result of heavily rain and flooding. These failures appear to be more widely spread geographically during times of severe bad weather but there appears to be no incidence of fatalities resulting from them.

8.2 Causes of Failure

- Bridge failure due to flooding is most commonly associated with 'extreme' but not necessarily 'very rare' floods. The average event rarity for the failures analysed (Table 6.2) is about 160 years. A 200 to 250-year return period flood therefore appears to be the sort of event, which includes most of the failures that are purely flood related.
- The very rare floods appear to be so destructive that is hard to imagine any reasonably economic bridge protection measure that would withstand the associated forces, other than to ensure that the bridge/culvert opening is wide enough to accommodate these floods.
- The most common form of failure of bridges is undermining of abutments or piers by scour. Existing assessment procedures (EX2502) would have largely predicted these, although there is perhaps insufficient emphasis on the role debris can play. The remaining failure episodes analysed were caused by at least 6 other failure types (Chapter 7) – none of which would have necessarily have been identified using existing assessment procedures. Existing assessment procedures appear to be particularly poor for culverts.
- Accommodation bridges accounted for 10% of the total bridge failures. These structures are generally not currently assessed for flood or scour risk unless they are known to be in the floodplain.
- As part of this research, numerous incidents of embankment failure have been encountered. Although not formally considered, it is worth noting that 'washouts' at the transition from cutting to embankment appears as a common location for these failures.
- The existing 'default' foundation depth of 1.0 m used for preliminary scour assessments (when the foundation depth is not known) is close to the median of the observed values. An uncertainty of ±1 was then shown to exist for the priority rating.
- The current 16.0 Priority Rating threshold used in EX2502/RT5143 to define those structures requiring more detailed assessment and remedial action can now be associated with a flood return period of 30 years (Chapter 6). And a threshold for a flood return period of approximately 200 years is about 15.1.

- o Based on the historical incidence of failure there is a 40% chance of at least one structure failure per year on the rail network. This is unacceptably high. It may also increase as a result of climate change, but equally have reduced as part of actions being taken since the 1980s. However there is no statistical evidence that the incidence of failure is changing.
- o Movement of bridge piers and abutments (in some cases hours before actual failure) is a possible easily 'monitorable' parameter that could form part of flood safety plans. Past attempts at monitoring scour have been unsuccessful because of the difficulties of keeping instrumentation running in such an aggressive environment. The monitoring of gross movement of structure supports can be undertaken in a more protected/accessible environment.
- o Land use change such as change of farming practice at a catchment scale (e.g. for contributing areas of 25 km^2 or greater) are unlikely to greatly change the risk of failure. Much more important are change of practices that may lead to a change in the quantity and type of debris being washed downstream.

8.3 Predicting Floods

8.3.1 This research has shown that floods with the capability to damage railway structures can be expected with some regularity. However, the prediction of the floods that could cause damage is extremely difficult for the following reasons:

- The science of flood forecasting is still far from exact and has a large degree of uncertainty. Rainfall forecasting is unlikely in the short or medium term to provide a means of taking effective mitigation measures as it is currently available at too large a spatial scale. It is also not possible to distinguish between rain that will cause damaging floods and rain that will lead to river levels that will not pose a risk to railway infrastructure. Prediction of flow or water level is more promising but this will require installation of suitable monitoring equipment at vulnerable structures and within the catchments upstream.
- The risk of damage to a structure depends on many local factors and not just the occurrence of a flood. Amongst the most importance of these are debris build up and modifications to the river channel in the vicinity of the structure.
- Many of the most potentially vulnerable structures lie in small, upland catchments where extreme rainfall and floods are particularly difficult to forecast with sufficient lead time to allow any kind of 'real-time' response action such as line closures.

8.3.2 For small catchments (with areas less than 25 km^2) or where the time to peak of flooding is less than 4-6 hours then physical measures of scour and flood protection must be given priority. Use of flood forecasting as part of flood action planning will be most reliable in larger river catchments (where in much of the UK a service is provided by the Environment Agency or the Scottish Environmental Protection Agency).

8.4 Design Floods/ Acceptable Risk

8.4.1 This research has already shown that the majority of the past structure failures have been caused by floods of a severity of around 200-500 years or less. However the estimation of return periods for past events can be very uncertain. For assessment purposes, a design flood of 200 - 250 years therefore appears appropriate. For planning purposes, a return period of 100 to 200 years for flooding is now widely used as an acceptable level for 'low to medium risk' developments such as housing and a 1,000 year for high risk infrastructure such as hospitals (see Planning Policy Guidance 25 for England, Technical Advice Note 15 for Wales and Scottish Planning Policy 7 for Scotland. For structures with a particular high impact of failure such as high speed lines where no warning can be provided, or where flood waters could impound behind embankments and be released suddenly, a 1000-year return period may be more appropriate.

8.4.2 However, for new or replacement structures, a slightly different approach can be taken. The design life of a structure is commonly between 30 and 150 years, depending on the size and nature of structure being designed. A structure would normally be designed to withstand a flood flow of a given magnitude, the design flood, which has a certain probability of occurring. The probability is normally expressed in terms of return period, with a return period of *N* years likely to be exceeded, on average, once in *N* years. It is not normally appropriate - although in practice it is often done - to use the design life of a structure as the return period of the design flood. The danger of doing so is illustrated by considering a structure with a design life of 100 years, which is designed for a 100-year return period flood. This would have a 63% chance of experiencing a flood of that magnitude or greater over its life.

8.4.3 The CIRIA (2002) design guide on scour protection recommends a more rigorous approach to deciding what probability of the design flood being exceeded over the structure's design life is judged to be acceptable. The probability of exceedance, P_r, the design life, Ly, and return period, N, are connected by the following formula:

$$P_r = 1 - (1 - (1 / N))^{Ly}$$

from which it can be shown that the relationship between the return period and the design life varies with the acceptable degree of risk as follows:

$P_r = 0.60$ N = 1.1 Ly (approx.)
$P_r = 0.50$ N = 1.5 Ly (approx.)
$P_r = 0.40$ N = 2.0 Ly (approx.)
$P_r = 0.30$ N = 2.8 Ly (approx.)
$P_r = 0.20$ N = 4.5 Ly (approx.)
$P_r = 0.10$ N = 9.5 Ly (approx.)

8.4.4 Thus, for example, if a 20% chance ($P_r = 0.2$) of the design flood being exceeded during the 50-year design life of a structure is judged acceptable, then a design flood with a return period of *N =50 x 4.5* = 225 years should be used. Due to safety factors included in the foundation design, a small exceedance of the design flood would not normally be expected to result in the failure of a bridge; this can make it more difficult to judge what constitutes an appropriate probability of exceedance for use in design.

8.4.5 In the UK, a flood return period, *N,* of 100 to 120 years is often used for the design of new structures, although a range from about 30 years for minor rural roads to 150 years or more for motorway or trunk roads is also typical. In the United States, bridges are generally designed to withstand a 100-year flood with a load factor of about 1.5 to 2.0 against collapse; a separate check is also made to ensure that the bridge will survive what is termed a 'superflood', with the load factor for the structure remaining greater than 1.0. The superflood is normally taken to be the 500-year return period event. The stability of foundations at existing bridges is also checked for the superflood. The risk equation indicates that, for a typical bridge with a 100-year design life, US practice can be considered as equivalent to accepting an 18% probability that the load limit of the bridge might be exceeded during this period.

Table 8.1: Indicative values of return period for design of new structures against scour failure (after CIRIA 2002)[4]

Type of structure	Return period, N as multiple of design life, L_y, of structure for specified probability of exceedance, P_r			
	Design Flood		Super Flood	
	P_r	N	P_r	N
Minor structure (e.g. small culvert)	0.6	1.1 L_y	0.4	2.0 L_y
Minor crossing	0.5	1.5 L_y	0.3	2.8 L_y
Major crossing	0.4	2.0 L_y	0.2	4.5 L_y
Motorway, trunk road, rail crossing	0.3	2.8 L_y	0.1	9.5 L_y

8.4.6 It should be noted that the figures given in the above table are only indicative. It is normal practice for asset owners to define their own design criteria using a risk assessment based on the values and consequences of failure for their particular assets.

8.4.7 Ideally, 'acceptable' levels of risk must also take into account the impact of possible damage or failure. For instance the acceptable probability of an event is different if there is risk to life compared to say, the risk of damage to a structure requiring remedial work but which does not impair its load

4 May R, Ackers J and Kirby A. *Manual on Scour at Bridges and other Hydraulic Structures*, 2002. CIRIA, London.

carrying capacity. This consideration of consequence is often considered in other industries and countries[5].

8.4.8 In practice there are many uncertainties in flood estimation and risk analysis, and despite the impression given by the various tables and formulae, the determination of suitable design flood events is still a matter of considerable judgement. While scour depths do generally increase with return period, the incremental increase for reasonably severe and severe floods is often small. Hence the ‘outcome’ in terms of required mitigation measures for a 100, 200 or even a 500 year event is usually the same.

5 Safety of Structures in Water. Recommendations for the surveillance and indications for the construction of new structures. Swiss Federal Roads Authority. 2002.

> Based on the results of this research and practice elsewhere (e.g. in planning guidance) it is recommended that the design flood for scour assessment and scour protection design should be based on a uniform and consistent 200-year return period flood event. A higher value (of 1,000-years) may be appropriate for structures with a particular high impact of failure such as high speed lines where no adequate warning can be provided, or where flood waters could impound behind embankments and be released suddenly.

8.5 Concluding Remarks

8.5.1 Comparison of the fatality statistics from this study with those across the whole of the industry (e.g. Evans, 2003)[6] suggest that there are other priorities for improving railway safety other than considerable expenditure on preventing scour and flood damage. Improving the cost-effective resilience of railway bridges to flooding has to have regard for the costs & consequences of failure, not just for their frequency. The railway industry should follow best practice, and while it may not be economically sensible to prevent all flood failures, it is important that the risk to railway users and staff is mitigated where possible. It is therefore timely that the widespread dislocation experienced in rail operations through the Autumn/Winter 2000 floods in England and summer 2003 in Scotland, and the results of this research, encourage the railway industry to ensure flood risks are acknowledged and managed.

8.5.2 This study shows that existing assessment procedures can be improved upon at little additional cost. Also the collection and recording of information on damage incurred and water levels reached after a flood will be valuable in developing effective management procedures.

8.5.3 Programmes of checks, inspection and maintenance are a critical concern, regardless of the 'design' standard of flood resilience adopted. The T-year flood at a particular site is as likely to happen next year as in any other year, and climate change appears more likely to increase than decrease risks.

8.5.4 Because of the large number of river crossings on the British railway network, and the partial spatial dependence in extreme rainfalls and flooding, the annual risk probability of a T-year flood *somewhere on the British railway network* is many times greater than 1/T. When an extreme event occurs, it is quite likely to affect multiple structures and could affect several railway links.

8.5.5 The risk to railways is not that a big flood will occur but that a big flood will cause bridges, culverts and embankments to fail. In analogy to other areas of river flood defence, there are two main issues:

- To design and maintain structures to a high standard, so that failures are tolerably infrequent;
- To take precautionary action – to reduce impacts – when a major flood threatens.

A feature of bridge failure due to scour is that appreciable pier or abutment movement often precedes collapse. This suggests scope to consider a generic real-time monitoring system to detect abnormal pier/abutment movements.

[6] Evans, A.W. 2003. *Transport fatal accidents and FN-curves: 1967-2001*. University College London Research Report 073 for Health and Safety Executive, HSE Books, 30 pp.

9 RECOMMENDATIONS

9.1 Scour & Flood Risk Assessments

9.1.1 Enhancements to the existing EX2502 scour assessment procedure are required if it is to cover the full range of flood-related risks and all the types of structure maintained by railway operators. The current draft revision to the RT5143 Group Standard (due for publication in the summer of 2004) already contains suggested changes. The Group Standard includes additions to the structures to be assessed (by adding embankments and also those structures within a flood risk area but not necessarily over a watercourse) and also the requirement to gather additional data on past flood/scour incidents and changes to the river channel.

9.1.2 The scour and flood risk assessment should consider the river channel/ watercourse for at least 100m upstream and downstream of the structure and further downstream where weirs exist in the channel.

9.1.3 Consideration should be made of the possibility of impoundment of significant volumes of water to a significant depth at railway embankments and the consequences if this was to cause failure of the railway embankment.

9.1.4 The outcome of any scour/flood risk assessment should be an overall Priority Score which will reflect the priority for proactive management measures. To allow consistency with existing assessments, a scale of 10-20 is suggested in keeping with the existing EX2502 procedure with a threshold of 15.0 above which structures will require additional measures other than that already undertaken as part of the examination and inspection cycle.

9.1.5 Where coring or other information of foundation depth is unavailable then a default depth of 1.0 m should be used for the purpose of scour risk assessment. However, it should be clearly stated in any report or database that this depth is an assumed depth based on the average depth from a wide range of railway structures. It is also recommended that a value of unity should be <u>added</u> to the priority ratings that are based on an assumed foundation depth.

9.1.6 Where foundation depths are known, it is important to re-check the depth relative to the river bed level. The bed level should be a representative level within any scour feature to the river bed.

9.1.7 The suggested revised scour and flood assessment techniques described in chapter 7 should be 'pilot tested' on 50 or so representative railway structures and the methodology refined. The procedure should be included as part of the new Network Rail 'Flood Risk Management Best Practice Guidelines' currently being prepared. EX2502 should be incorporated unaltered as an Appendix to this guidance.

9.2 Acceptable Risk

9.2.1 A 200-year return period or 0.5% annual probability flood should be the basis of assessment of structures for scour and flood risk and for the design of new structures with a 1,000 year (0/1%) for scour/flood prone structures on high speed lines with no adequate flood warning or for situations where significant volumes of water can pond behind the railway embankment.

9.3 Underwater Examinations

9.3.1 Current railway standards require an underwater examination of structures as part of an integrated structure examination and assessment programme. However, there is currently no consistent guidance on how these examinations should be carried out and documented and this has often led to a significant reduction in their value for assessing scour risk. The following interim guidance is suggested until such time as a detailed specification can be developed.

<u>Examination</u>

The examination should include all the support elements of the structure, including those piers and abutments normally out of the watercourse. The examination should cover the condition of the supports (noting any signs of erosion, missing blockwork or pointing) for at least 1 m above ground level or river level as appropriate.

Bed levels should be recorded on a 'grid' basis extending at least 10 m upstream and downstream of the faces of the structure or the extent of any invert plus 10 m. The spacing of this grid should be every 0.5 m around the circumference of the supports at a distance 0.3m from the structure, and elsewhere on a grid of 2 m spacing for spans greater than 6 m spacing and 1 m for spans less than 6 m. For soft bed material, both a 'soft' and 'hard' bed level should be recorded by means of applying manual pressure to a ranging pole.

Reporting

It is essential that all bed level surveys and examinations are recorded to a common datum which can be readily re-used for future examinations and will allow estimation of relative changes to bed levels. Ideally the datum should be to Ordnance Datum Newlyn but can be to a fixed and clearly identifiable mark to the structure.

The bed level survey data should be provided as a digital ASCII format file as x,y,z (easting, northing and elevation above datum) and also as a scaled contour plot. A specified deliverable should be a plot showing the difference in bed levels between the current and most recent past survey.

9.3.2 The underwater examination guidance should be included as part of the new Network Rail 'Flood Risk Management Best Practice Guidelines'.

9.4 Coring to Establish Foundation Depth

9.4.1 Diamond coring of supports for brick and masonry structures remains the most reliable method of establishing foundation depth. A minimum of one 75 mm diameter core per bridge support is required. The core should continue to at least 0.5 m below the underside of the bridge foundation. Those supports that are clearly located above flood level should be cored. As a 'rule of thumb' this should include all supports where ground level at their base is 4 m or lower than normal river level. The location of the core should be at the point of lowest bed level as shown on the most recent underwater examination survey. If a survey is not available it should be within 2 m of the upstream face of the structure.

9.4.2 For each of the supports being cored, river bed/ground levels should be recorded every 0.5 m around the circumference of the supports at a distance 0.3 m from the structure.

Reporting

9.4.3 As with underwater examination reports, the core log must be related to a consistent and reproducible datum and preferably the same as used for underwater examinations.

9.4.4 The coring guidance should be included as part of the new Network Rail 'Flood Risk Management Best Practice Guidelines'.

9.5 Public Relations

9.5.1 Through press appetite for stories about public-service failures, it is commonplace for the public to be told that British railway systems are unreliable and poorly managed. Can a review of historical flood-induced rail-bridge failures help to temper this by providing an appropriate perspective?

9.5.2 Some of the history is awe-inspiring, especially with regard to the very rapid replacement of failed structures. For example, it is said that the viaduct at Apperley Bridge near Bradford was rebuilt, and the line reopened, within five weeks of the failure (see 1866 Aire at Apperley Bridge BIRDIE). Swift remedies were still evident a century later, following the August 1948 floods in the Scottish Borders and the September 1968 floods in Surrey.

9.5.3 However, other references (including parts of Ransom, 2001)[7] contradict the idea that there was an earlier age in which railway operations were more resilient to extreme weather. There were *... the wrong kind of ...* stories then as now:

> *We now come to the last of the [year's - 2000] exceptional phenomena. The snow-storm which disorganized the railway, telegraphic and telephonic systems at the end of the year. ... It was owing to this semi-fluidity of the snow that the damage to trees and telegraphic wires was so excessive for the snow was sticky rather than dusty, and almost precisely twice its usual density.* [See 1886 Bride at Burton Bradstock BIRDIE in Appendix B.]

9.5.4 Revisiting flood disruptions – encountered by the railway industry in an earlier era – might be used to convey the message that the railway system has always had to cope with natural conditions that are occasionally overwhelming.

9.6 Future Work

[7] Ransom, P.J.G. 2001. *Snow, flood & tempest: Railways & Natural Disasters*. Ian Allan Publishing, 176pp.

9.6.1 The following items may be considered for further work by RSSB or Network Rail:

- A 'pilot study' to verify and 'fine tune' the suggested new assessment procedure for scour and flood risk and to provide text for incorporation in the new Network Rail 'Flood Risk Management Best Practice Guidelines'.

- Further research into improved methods for determining foundation depth of structures and the range and type of foundations that can be expected.

- Further research into the instrumentation of structures to detect movement of supports as an early indicator of possible undermining. Past work on trying to measure scour directly have proved problematic due to the aggressive nature of the river bed environment and inadequate equipment reliability. Instrumentation at deck level may prove more reliable.

- Additional work to identify appropriate risk management measures for structures found to be of high priority. A range of measures will be required as the risk will vary even for structures of similar priority scores due to factors such as the impact of failure and also its predictability.

- Additional work to produce simple means of identifying risk from ponding of water behind embankments and the impact of a sudden breach.

- Production of 'time to peak' maps and flood warning provision maps to identify those parts of the railway network where adequate flood warnings and lead in time (at least 2 hours) is possible. These maps will allow resources for additional scour protection measures to be targeted on those structures where sufficient warning time cannot be provided with current technology.

- The development of software to reduce the time needed to undertake scour and flood risk assessments.

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APPENDICES

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APPENDIX A: Database of known rail bridge failures due to flooding/scour

Note:

This listing only contains a selection of the fields contained in the database.

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Data Sources

The basis of the database of railway structure failures due to scour has been a compendium of structures gathered by JBA staff over the last 10 or so years. This database held information on the date (sometimes approximate) and location of the failure and sometimes a description of the bridge and cause of failure. However, the listing was never considered complete as entries have been compiled as and when information became available from other studies and was never assembled from a systematic search of available records. For this project the list has been supplemented by a systematic search for mentions of flood-related bridge failures gained from the following primary sources:

- Network Rail Structures Records held at Waterloo, Swindon, Birmingham, York, Manchester, Liverpool Street and Glasgow
- Rail Property/ BRB Residuary Records held at York
- Accident Reports of the Board of Trade held at the Public Records Office, Kew and the National Railway Museum, York.
- Accident Reports of the Railway Inspectorate.
- Ransom, P J G. 'Snow Flood & Tempest – Railways & Natural Disasters'. Ian Allen Publishing, 2001.
- Simmons, J & Biddle, G. 'The Oxford Companion to British Railway History'. Oxford University Press, 1997.
- Holt, L T C. 'Red for Danger. The Classic History of British Railway Disasters'. Sutton, 2001.
- 'British Railway Disasters'. Ian Allen Publishing , 1996.
- British Hydrological Society. 'Chronology of British Hydrological Events'.
- Web searches.

In general, bridge failures tend to be recorded – and the impression from the searches undertaken is that few tend not to be recorded – either in newspapers or in surviving railway records. Hence the 81 failures listed are likely to be reasonably close to the total number of bridge failures. Failures of smaller structures – such as culverts and 'cattle creeps' are less well recorded and for several of the flood events there is reference to other 'washouts' and failures, but no information on numbers or locations.

It should be borne in mind that many structures will also have been damaged in flood and needed repair. These incidents are not as well documented in the available records and many more have probably occurred than have been revealed from the searches made. A damaged structure has only been included in the 'failure' list if it meant the line was inoperable.

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APPENDIX B:
Data on severity of events leading to structure failure

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Methods Used
Where possible, methods were generally based on Flood Estimation Handbook (IH, 1999) recommendations. The Flood Estimation Handbook is generally referred to as the FEH. The starting point in investigation of each incident was the grid reference of the bridge site and the incident date.

Although an attempt has been made to avoid the over-use of abbreviations, some will undoubtedly have slipped through. If encountered, the abbreviation BR refers to *British Rainfall* (a yearbook formerly published by HMSO), not the more obvious British Railways.

Catchment details
The Flood Estimation Handbook (FEH) CD-ROM 1999 was used:

- To identify/verify the catchment relevant to the failure incident;
- To extract catchment descriptors;
- To estimate (by eye) an approximate catchment centroid;
- To look (amongst gauged catchments detailed in the FEH) for a possible donor catchment relevant to flood estimation at the subject site;

For gauged catchments, further catchment details were taken from the standard summaries presented on the flood data CD-ROM published in Volume 3 of the FEH, augmented by descriptions from the Hydrological Data UK *Hydrometric Register and Statistics: 1991-95*. [A new register, covering 1996-2000, was published in March 2003: too late for use in this investigation.] Given the large number of catchments to be investigated in this study, reference was seldom made to more detailed catchment information. However, soil maps and topographic maps of an appropriate scale should always be consulted in any site-specific investigation.

Digital catchment data
Contrary to recent publicity, the digital catchment data given on the FEH CD-ROM are reliable in most parts of the UK. However, the prudent analyst will check that catchment boundaries correspond to those indicated on 1:25000 maps in areas where the mapped drainage path mapped at 1:50000 is obscured (in urban areas) or looped (e.g. in very flat areas).

No particular problems were encountered with the digital data for catchments related to the bridge-failure incidents listed. However, in a few cases it proved necessary to move the quoted site a small distance so that it fell on the digital representation of the relevant watercourse. In two cases – the Exe at Cowley Bridge and the Thames at Osney incidents – the river is multi-channelled, so that not all floodwater passed under the relevant bridge. [For reasons of identifiability, the FEH digital drainage-paths form a unique *tree* with no loops.] Any corrections or special adjustments made are indicated in Section 1 (*Miscellaneous notes*) of the relevant BIRDIE.

Event/incident details
A range of techniques was used to explore the details of the flood event thought to have given rise to the bridge-failure incident. Reports inevitably intertwine information about the flood event and information about the bridge failure. No attempt was made to disaggregate the two kinds of information. This means that some of the BIRDIEs include information that might not be always expected to appear. Occasionally, the BIRDIE presents anecdotal information alongside factual reports. In determining the weight to attach to a particular item, the reader is encouraged to take due account of the extent to which the particular report is original and contemporary rather than derivative or recollected.

Information sources

<u>British Rainfall yearbooks</u>

Copies of the British Rainfall yearbooks were viewed in the National Hydrosciences Library at Wallingford and in the Met Office national meteorological archives at Edinburgh and Bracknell. Table 2.1 indicates the extent to which this was useful.

<u>Chronology of British Hydrological Events</u>

The BHS Chronology of British Hydrological Events (CBHE) was consulted for events up to and including 1930, the nominal end-date of the chronology. However, it was found that the archive sometimes included information about more recent floods, and the CBHE was therefore consulted for all events. Column CBHE of Table 2.1 summarises the extent to which this was useful.

Internet

Some general web-searches were undertaken to elicit additional information about particular incidents. This was undertaken in particular depth in cases where there was uncertainty about the incident details supplied. Column www of Table A summarises the extent to which this was useful.

Some reference was made to historical map information. For copyright reasons, the relevant maps are not reproduced in the report. Please enquire if you require guidance. The main maps presented in the report are images taken from the FEH CD-ROM 1999.

Unless websites state that information is not to be reproduced under any circumstances, useful information has generally been included in the relevant BIRDIE. The relevant website address is always given, so that: (i) the ownership of the material is clear, and (ii) the reader can download the relevant information for their own use. Some information has been reformatted to make the BIRDIEs readable. Appearance of information in the BIRDIEs should not be interpreted as publication; the original source should always be checked and quoted.

British Library Newspaper Library

Selective searches were made in the British Library Newspaper Library (BLNL) at Colindale, North London. These were intended both to plug gaps and to demonstrate the extent of additional information that can be found if resources are given over to the task. The visit made was exploratory, and not charged to the project. Column BLNL of Table 2.1 summarises the extent to which this was used.

Whilst necessarily time-consuming, accessing newspapers in the BLNL was found to be relatively efficient in comparison to visiting regional, municipal or local libraries (or newspaper offices), where a visit might at best yield useful information about no more than one or two incidents. Newspaper reports have the potential to reveal additional information about specific flooding incidents and their impacts. Newspapers sometimes provide additional rainfall (and weather) information, and can be especially valuable in indicating the location and duration of heavy rainfall. However, searching for, recovering and interpreting such information is inevitably time-consuming.

Books/reports

The recent book by Ransom (2001) was found to be especially useful. Other books consulted are referenced in the relevant BIRDIE. Citations by JBA of information quoted in (e.g. Ian Allen) books were not re-checked, although some sections of Archer (1992) were consulted for amplification of the remarks quoted.

Rainfall data

Visits to the Met Office national meteorological archives at Edinburgh and Bracknell were made to find/retrieve rainfall data from paper archives to which there is public access. Because of the separate archives, particular care was required in researching rainfall data for incidents close to the England-Scotland border. Emphasis was given to finding daily rainfall data for the period implicated in the incident, and to obtain at least a pen picture of the relative wetness of the preceding period. Monthly rainfall data were consulted for those incidents for which little or no daily rainfall data could be found on or close to the catchment.

In a study of this scale, it was rarely practical to search explicitly for hourly rainfall data: desirable though this would be for many incidents, especially for events from the 1930s onwards (when recording rain gauges began to become more prevalent). However, note was taken of any annotations about the temporal and spatial pattern of rainfall. Likewise, any comments about antecedent snow, air temperatures and windspeeds (that might promote snowmelt) were noted.

One reward for the labour of consulting original paper records is to see any additional notes made by the observer. Occasionally, one also gets to see deletions or corrections, and remarks that indicate that a particular observation was disbelieved or over-ruled in Met Office quality control.

Related work

The RAINSEARCH program was used to extract list of Met Office registered rain gauges nominally operating in given year. The program searches a recent version of the RAINMASTER catalogue, ranks gauges according to distance from site of interest, and notes bearing. RAINSEARCH was developed by DWRconsult, prior to the project.

Table A Information sources for event/incident details (prior to 1930)

Incident			British Rainfall (BR)	CBHE	www	BLNL	Other
Date	**River**	**Location**					
20 Jan 1846	Medway	Tonbridge	N/A	×	×	✓✓	Ransom (2001)
~ Feb 1846	Sheppey	Shepton Mallet	N/A	×	×		Little found about this event
29 Sep 1846	Tower Burn	Cockburnspath	N/A	✓	✓		Ransom (2001)
24 May 1847	Dee	Chester	N/A	×	✓✓		Not a scour or flood event!
~ Jun 1848	Tower Burn	Cockburnspath	N/A	×	×	✓	Ransom (2001)
~ Mar 1855	Trent	Kelham, Newark	*Ignored – not a scour failure*				
16 Nov 1866	Aire	Apperley Bridge	✓	✓	✓		Ransom (2001)
~ Feb 1868	Severn	Caersws	✓	×	✓		Ransom (2001)
~ Feb 1868	Carno	Pontdolgoch	✓	×	✓		Ransom (2001)
13 Nov 1869	Tees	Cleasby	✓	✓	✓		Archer (1992)
9 Jul 1870	Dee/Dent	Dent	✓	✓	×		Ransom (2001)
28 Dec 1879	Tay	Dundee	*Ignored – not a scour failure*				
16 Nov 1886	Aire	Apperley Bridge	×	×	×		Ransom (2001)
~ Dec 1886	Thames	Osney, Oxford	×	×	✓		Little found about this event
25 Dec 1886	Bride	Burton Bradstock	✓✓	×	✓		Incident added by DWR; same storm as affected Selham
26 Dec 1886	Stream	Selham	✓✓	×	×		Ransom (2001); NERC (1990)
31 Jan 1901	Burn of Buckie	Buckie, Morayshire	×	×	×		Buckie Advertiser (via Paul Hart)
15 Jun 1914	Baddengorm Burn	Carrbridge	×	✓	×	✓✓	British Rainfall 1923 discusses this event
23 May 1918	Calder	Horbury	✓	×	×	✓	
12 Feb 1920	Calder	Horbury	✓	✓	×	✓	
8 Jul 1923	Bogbain Burn	Carrbridge	✓✓✓	✓✓	×	✓✓	Ransom (2001)
9 Jun 1924	Erewash	Ripley	×	×	×		Nothing found about this event

Key N/A Not applicable Blank Not attempted
× Tried but nothing significant found ✓ Something found (# ticks indicate significance)

Table A Information sources for event/incident details (1930 onwards)

Incident			British Rainfall (BR)	CBHE	www	BLNL	Other
Date	**River**	**Location**					
23 Jul 1930	Esk	Glaisdale	✓✓	✓	✓		
~3 Sep 1931	Esk	Glaisdale	✓✓	✓	×		
21 Jun 1936	Mochdre Brook	Newtown	✓	N/A	✓		
12 Aug 1948	Eye Water	***	✓✓	N/A	✓✓		Ransom (2001)
12 Aug 1948	Wooler Water	Haugh Head	✓✓	N/A	✓		Archer (1992)
26 Oct 1949	Lil Burn	Ilderton, Northumberland	✓	N/A	×		Archer (1992)
19 Nov 1951	Stream	Midhurst	✓	N/A	✓		NERC (1990)
12 Dec 1964	Ystwyth	Llanilar	✓✓	N/A	×		
15 Sep 1968	Wey	Godalming		N/A			
15 Sep 1968	Mole	Cobham		N/A			Surrey Comet
5 Jun 2000	Swale	Richmond		N/A	✓✓		
				N/A			

Key N/A Not applicable Blank Not attempted
× Tried but nothing significant found ✓ Something found (# ticks indicate significance)

Rarity assessments

Rainfall rarity assessments were made for a number of incidents, using the FEH Volume 2 rainfall frequency procedure, as delivered by the FEH CD-ROM 1999. In a few instances, formal flood rarity assessments were also made. More often, the assessments of flood rarity were subjective ones: blending the rainfall rarity with hydrological experience.

Incidents investigated

Table B shows only the incidents investigated in England, Scotland and Wales. For convenience, the relevant computer files are arranged in four folders: England, Scotland, Wales and Borders. The latter grouping refers to incidents in the England-Scotland border region, and was adopted because of the twin relevance of the Bracknell and Edinburgh meteorological archives. Columns excluded from Table 3.1 held information peripheral to the this study. Where appropriate, rows were re-ordered to present the incidents in (perceived) chronological order.

Priorities

Greater emphasis was given to investigating some incidents than others. This was necessary both to explore the relative effectiveness of different search methods and to reflect the different levels of information likely to be available for each incident. Incidents leading to rail-bridge failure were given more attention than those leading only to road-bridge failure. Pilot work gave particular emphasis to the August 1948 floods at Wooler and on the Eye Water.

Greater emphasis was given to earlier than later events. Researching rainfall data for flood incidents from 1961 onwards is better undertaken by an organisation with access to the computerised national dataset of daily rainfall data. It is relatively inefficient to retrieve these data from paper records in the Meteorological Office archives, when the data are known to have been computerised. Yet, few organisations engaged in applied hydrology in the UK have a more cost-effective option.

Reporting

Introduction to BIRDIEs

A semi-standard reporting system was devised to show structure whilst being flexible enough to incorporate additional information found for some incidents but not others. This is the Bridge Incident Review Document Investigating Extremeness (BIRDIE). For clarity, the BIRDIEs are named according to the incident year, the watercourse and the location.

Table C Headings used in BIRDIEs

Sections	Subsections
Header information	[Map from FEH CD-ROM 1999]
Miscellaneous notes	
JBA entry	
Tabular information	Table 1: Notes on subject catchment and possible donor catchments
	Table 2: FEH catchment descriptors
	Table 3: List of gauges potentially operating in year of incident (by RAINMASTER)
Notes from *British Rainfall* yearbook and rainfall archives	Rainfall depths
	Rainfall profile
	Antecedent condition
	Impacts
Other extracts	Books/reports
	Newspapers
	Web sources
	Maps
Rarity assessments	Rainfall rarity
	Flood rarity
Verdict	
Classification	
References	

Section headings are shown in Table C. Not all headings appear in all BIRDIEs. [Non-appearance means that there was nothing to report, or nothing found, under that heading.] Where present, the rainfall rarity and flood rarity subsections are occasionally extensive.

Although the present volume includes some summary tables, the reader is encouraged to study the relevant BIRDIE, one document per flood incident. These are included at the end of this Appendix.

Classification system adopted

Where possible, the bridge-failure incidents were classified into one of five categories defined in Table D. The category names have been chosen in the context of rail-bridge flood safety. Whereas a 50 or 100-year event would be considered rare in terms of river flood risk generally, the human & economic implications of rail-bridge failures call for higher standards than for river flood defence to riparian property. Consequently, the language adopted here speaks of a 200 or 500-year flood as being rare.

Table D Classification of rail-bridge flood-failures

Category	Associated flood return period (years)
Not induced by fluvial flood	N/A
Flood-assisted failure, but a relatively minor flood	2, 5, 10, 20
Induced by a relatively rare flood	50, 100
Induced by a rare flood	200, 500
Induced by an exceptionally rare flood	1000, 2000, 5000

No particular basis is offered for the categorisations in Table D. The return periods shown should not be interpreted as implying any perceived or acceptable standard for rail-bridge design against flood-failure.

Findings

The main outcome from the study is the classification of bridge-failures presented in the penultimate column of Table E. This fulfils the stated objective of the study. In part to allow the possibility of extension or update, the findings of Table E are not further summarised.

Table E Classification of British rail-bridge flood-failures

Incident			Classification of failure	Comment
Date	River	Location		
20 Jan 1846	Medway	Tonbridge	Failure probably induced by quite a rare flood, but aggravated by poor design and gravel extraction.	
~ Feb 1846	Sheppey	Shepton Mallet	Too little information to classify.	BIRDIE not constructed for this incident. Too little information.
29 Sep 1846	Tower Burn	Cockburns-path	Induced by a relatively rare flood.	
24 May 1847	Dee	Chester	Not induced by fluvial flood	BIRDIE not constructed for this incident. [Iron bridge; flawed design]
~ Mar 1855	Trent	Kelham, Newark	Not induced by fluvial flood	BIRDIE not constructed for this incident. [Ice pressure]
16 Nov 1866	Aire	Apperley Bridge	Induced by a flood that was at least relatively rare	Ransom (2001): Piers and viaduct reconstructed in five weeks. Estimate had been six months.
~ Feb 1868	Severn	Caersws	Flood induced but insufficient information to assess rarity.	Probably less rare than concurrent flood at Pontdolgoch.
~ Feb 1868	Carno	Pontdolgoc h	Flood induced but insufficient information to assess rarity.	Probably more rare than concurrent flood at Caersws.
13 Nov 1869	Tees	Cleasby,	Flood induced, but not	Bridge was said to be a

Table E Classification of British rail-bridge flood-failures

Incident			Classification of failure	Comment
Date	**River**	**Location**		
		Darlington	a rare flood.	temporary structure. Could look at Merrybent & Darlington Railway Co archives, held in North Yorkshire County Record Office, Northallerton.
9 Jul 1870	Dee/Dent	Dent	Induced by a rare, highly localised, flood.	Affected structures were road bridges. Two workers constructing Settle & Carlisle Railway drowned.
~ Dec 1886	Thames	Osney, Oxford	Details uncertain – but unlikely to have been caused by a rare flood	
26 Dec 1886	Bride	Burton Bradstock	Induced by a relatively rare flood	
26 Dec 1886	Stream	Selham	Induced by a rare flood	Exceptional combination of conditions conducive to flooding on a relatively permeable catchment: extremely high antecedent groundwater level, (reported) frozen ground and moderately heavy rainfall/snowmelt.
31 Jan 1901	Burn of Buckie	Buckie, Morayshire	Not induced by fluvial flood	
15 Jun 1914	Baddengorm Burn	Carr Bridge	Induced by a rare, highly localised, flood	
23 May 1918	Calder	Horbury	Flood-assisted failure, but a relatively minor flood	
12 Feb 1920	Calder	Horbury	Flood-assisted failure. Occurred 2 days after a flood – but not a rare one. Bridge was in disrepair.	
8 Jul 1923	Bogbain Burn	Carr Bridge	Induced by a rare, highly localised, flood	
9 Jun 1924	Erewash	Ripley	No evidence of heavy rainfall found, but further information required.	A search of local newspapers is required to confirm the date and circumstances of this incident.
23 Jul 1930	Esk	Glaisdale & district	Induced by a rare, relatively localised, flood.	
4 Sep 1931	Esk	Glaisdale & district	Induced by a rare flood, though not as rare as July 1930.	Assessment assumes failure occurred at height of flood on 4 Sep 1931, not on 3 Sep (the failure date implied by JBA).
21 Jun 1936	Mochdre Brook	Newtown	Probably induced by a relatively rare flash-flood, though the verdict is speculative	Check a local newspaper for thunderstorm details and impacts.
? Mar 1947	Trent	Shardlow	Induced by a relatively rare (or wholly rare) flood.	Check that failure occurred in March 1947 and not in the notable (but less severe) flood of February 1946.
12 Aug 1948	Eye Water	Grantshouse/Shawbraes	Induced by a rare flood.	

Table E Classification of British rail-bridge flood-failures

Incident			Classification of failure	Comment
Date	**River**	**Location**		
12 Aug 1948	Wooler Water	Haugh Head	Induced by a rare flood, though not as rare as for the Eye Water.	
26 Oct 1949	Lil Burn	Ilderton	Induced by a relatively rare flood.	
19 Nov 1951	Stream	Midhurst	Probably induced by a relatively rare flood	Antecedent wetness was exceptional.
12 Dec 1964	Ystwyth	Llanilar	Induced by a moderately rare flood …	… but not rare enough to account for the failure
15 Sep 1968	Wey	Godalming		
15 Sep 1968	Mole	Cobham		
18 Oct 1987	Tywi	Glanrhyd	Induced by a relatively rare flood.	Look for daily rainfall data for gauges 500200-502500; also for 467200-468000 and 481600-481900. Search for info about 1852, 1875, 1894 and 1931 Tywi floods.
6 Feb 1989	Ness	Inverness	Failure induced by a relatively rare fluvial flood, aggravated by tidal interaction.	Assessment might be strengthened by a historical review of flood levels at/near Inverness.

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APPENDIX C:
EX2502 Analysis of historic bridge failures

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Summary

The database of known rail bridge failures detailed in Appendix A contained 90 events for the UK. Since there was minimal information on the Northern Ireland events, the database was initially reduced to 88 events for Great Britain only. The data records enabled the rapid calculation by computer of a "Priority Rating" (PR) that indicated the degree of risk associated with bridge failure due to channel scour. The calculation method was that designed by HR Wallingford (1992) and was published as HR Document Number EX2502. The computation method has been updated from the previously used code named "BSIS"; it is now named "NRScour".

Of these 88 GB events, 25 were inappropriate for analysis by the EX2502 method for the following reasons (Table C1 summarises these data):

- The structure was a culvert and failed by blockage or invert scour
- The structure was an embankment
- The structure failed due to hydraulic loads washing away the bridge deck
- The structure failed due to ice loads
- The failure was not flood related
- There was insufficient information on the mode of failure

A database table consisting of the remaining records for 63 railway bridge failures in Great Britain was compiled (Table C2 summarises this table). Of the 63 bridge failures, the exact locations of 10 could not be positively identified, thus leaving 53 records (Table C3 summarises this table).

The earliest year of recorded bridge failure was 1846, and therefore river channel information was acquired from the First Edition of OS County maps at the 1:10,560 scale. These were published between the years 1847 and 1893. For the more recent bridge failures (postdating 1950 say), recent 1:10,000 scale OS maps were used to provide river slope data, and modern digital overhead photographs aided the analysis. Additionally, "Indicative Floodplain Maps" (IFM) published by the Environment Agency were used to estimate the 100 year floodplain widths at river sites for all bridge failures within England and Wales. A compilation of all maps and photographs used for this study is given in
Appendix D.

The EX2502 priority rating is computed as a function of the ratio of Total scour depth (TS) and foundation depth (FD). The major assumptions used in analysing historic bridges were that the foundation depth and bridge element dimensions (abutments or piers) were unknown. Foundation depth was assumed as 1.0 m throughout, and it has been shown in Chapter 6 that this gives a 67% chance of unit uncertainty in the priority rating. There was less error in the magnitudes of element plan length dimension, since they could be scaled by the stream width. However, element width dimensions were mainly unknown, and therefore average widths taken from a previously analysed database of 9305 bridge elements (contained in the "NRStructures" database detailed in Chapter 6) were used.

The final analysis of the 53 bridge failures showed that 31 of the bridges were in the "High Priority" category before failure, and in need of scour protection. This number of bridges comprised 62% of the total, and may be compared with 30% "High Priority" bridges from a total of the 2924 bridges analysed from the "NRStructures" database. It was found that the High Priority ratings for these bridge failures were mainly caused by siting the structures at large angles to the river channel axis (called a large "Angle of Attack", AA, for the incident flow.) Of the 53 bridge failures 88% had AA>0, whereas only 38% from the 2924 bridges recently analysed had AA>0.

Table C1: List of 25 structural failures not analysed using the EX2502 method

Date	Structure	Description of Failure	Classification	Hydraulic Classification
Feb 1846	Viaduct	Slow collapse of Charlton Viaduct. 2 of	Is this a flood failure?	Not flood related.
Jul 1847	Bridge		Bridge deck floated aw	Deck loading
Aug 1866	Bridge		Flood floated the bridge	Deck loading
Mar 1881	Culvert	A culvert near Ladmanlow on the Cromf	Dam break.	Culvert blockage
1881	Viaduct	The story of the Solway Junction Railwa	Failure of piers as a res	Ice loading
Dec 1886	Bridge	Possibly an embankment failure.	Failed embankment	Embankment scour
Jul 1870	Bridge	Not sure whether this is a confusion with	the road bridge	Insufficient data
Jul 1923	Bridge	6 bridges (of which 5 were road bridges	River reverting to its for	Embankment scour
Jun 1936	Bridge	Stone arch - 25ft span collapsed during	Debris loading.	Deck loading
Sep 1946	Embankment	In the early hours of the morning of the	Dambreak flood as a re	Embankment scour
Aug 1948	Culvert	A culvert through a 52ft-high embankm		Culvert blockage
Oct 1949	Embankment		Washout of embankme	Embankment scour
Nov 1951	Culvert	Engine of freight train fell into gap	Washout of embankme	Embankment scour
Oct 1954	Culvert	Culverts partially collapsed	Insufficient data.	Culvert blockage
Feb 1962	Culvert	16 culverts washed out.	Insufficient data.	Culvert blockage
Jul 1968	Viaduct	Viaduct weakened.	Pier undermining?	Insufficient data
Sep 1968	Bridge	One of two brick arches destroyed and	Water pressure plus loc	Deck loading
Dec 1979	Culvert	A culvert under the embankment of a di	Dam-burst flood	Culvert blockage
Jan 1991	Bridge	Floods damaged bridge	Insufficient data.	Insufficient data
Jan 1994	Bridge	Damaged bridge supports		Insufficient data
Oct 1997	Bridge	Disused line	Insufficient data.	Insufficient data
Oct 2000	Embankment	Washout of 30ft of track and also bridge	Embankment washout.	Embankment scour
Dec 2000	Embankment	Wash out of both the main line to Bristo	Embankment washout.	Embankment scour
Oct 2002	Embankment	Water flowed onto track and along line ·	Embankment gullying.	Embankment scour
Dec 2002	Culvert	At the southern end of the culvert a sec	Undermining of abutme	Culvert invert scour

Table C2: List of 63 structural failures that may be analysed using the EX2502 method

Date	Structure	Description of Failure	Classification of Failure	Hydraulic Classification
Jan 1846	Bridge	Timber single-span accommodation	Appears to be an embankment	Scour influenced by dredging
Sep 1842	Bridge	Ransom quotes that this was the worst	Can rule out embankment &	Pier scour
Sep 1842	Bridge		Structure unlikely to have had	Embankment or Pier scour
Sep 1842	Bridge		Structure could have been a	Pier scour
Sep 1842	Bridge		Structures unlikely to have had	Embankment or Abutment scour
Sep 1842	Bridge		Structure unlikely to have had	Embankment or Abutment scour
Sep 1842	Bridge		Structure unlikely to have had	Embankment or Abutment scour
Sep 1842	Bridge		Structure unlikely to have had	Embankment or Abutment scour
Sep 1842	Bridge		Structure unlikely to have had	Embankment or Abutment scour
Sep 1842	Bridge		Structure unlikely to have had	Embankment or Abutment scour
Jul 1847	Bridge	Railway bridge swept away at the same	Single span. Undermining of	Abutment scour
Nov 1866	Viaduct	Voids had appeared in the arch prior to	Unlikely to be undermining of	Pier scour
Feb 1868	Bridge	Wooden bridge over the river held but the a	Embankment failure. Wooden b	Embankment or Abutment scour
Feb 1868	Bridge	Bridge rendered unsafe.	Not clear whether the bridge	Pier scour
Nov 1869	Bridge		Debris blockage? Poor	Insufficient data
Jul 1880	Bridge	Note of several railway bridges failing	Bridge in an incised valley.	Pier scour
Jul 1880	Bridge			Insufficient data
Nov 1882	Bridge	Washed away in storm.	Not possible to classify on	Insufficient data
May 1886	Bridge	Multi-span	Possible undermining of	Pier scour
May 1886	Bridge		Possible undermining of	Pier scour
May 1886	Bridge		Possible undermining of	Pier scour
Aug 1891	Bridge	Insufficient data.	Insufficient data.	Insufficient data
Sep 1891	Bridge	Several other bridges washed away.	Pier or embankment	Embankment or Pier scour
Aug 1912	Viaduct	3-span brick viaduct	Pier undermining during a long	Pier Scour
Aug 1912	Bridge	Bridge collapsed while a freight train was	Pier undermining during a long	Pier scour
Jun 1914	Bridge	Express train became derailed on flood-	Collapsed under weight of	Insufficient data
Sep 1915	Bridge	16 bridges and culverts destroyed in the	Insufficient data.	Insufficient data
Jun 1924	Viaduct	First 2 arches collapsed	Pier scour failure?	Pier scour
Jul 1930	Bridge	Bridge washed away - replacement was	Abutment undermining &	Abutment scour
Sep 1931	Bridge	Bridge washed away	Possible abutment failure?	Abutment scour
Mar 1947	Viaduct	Centre pier undermined	Centre pier undermined during	Pier scour
Apr 1947	Bridge	Single span rectangular opening bridge	Abutment undermining.	Abutment scour
Aug 1948	Bridge	8 bridges and 4 culverts washed away.	Abutment undermining or	Embankment or Abutment scour
Aug 1948	Bridge	8 bridges and 4 culverts washed away.	Abutment undermining or	Embankment or Abutment scour
Aug 1948	Bridge	8 bridges and 4 culverts washed away.	Abutment undermining or	Embankment or Abutment scour
Aug 1948	Bridge	8 bridges and 4 culverts washed away.	Abutment undermining or	Embankment or Abutment scour
Aug 1948	Bridge	8 bridges and 4 culverts washed away.	Abutment undermining or	Embankment or Abutment scour
Aug 1948	Bridge	8 bridges and 4 culverts washed away.	Abutment undermining or	Embankment or Abutment scour
Aug 1948	Bridge	8 bridges and 4 culverts washed away.	Abutment undermining or	Embankment or Abutment scour
Aug 1948	Bridge	8 bridges and 4 culverts washed away.	Abutment undermining or	Embankment or Abutment scour
Aug 1948	Bridge	Following a fall of 6.28in of rain in 24	Local scour and undermining of	Pier scour
Aug 1948	Bridge	Bridge washout	Insufficient data.	Insufficient data
Aug 1948	Bridge	Embankment washout - bridge never	Washout of embankment	Scour influenced by dredging
Oct 1949	Bridge	Centre span of 3 span bridge failed	Undermining of pier.	Pier scour
Oct 1954	Bridge	The swollen River Derwent demolished a w	Embankment washout leading t	Embankment or Abutment scour
Sep 1960	Bridge	Ransom (2001) states that water levels of	Embankment or abutment	Embankment or Abutment scour
Dec 1964	Bridge		Insufficient data.	Insufficient data
Dec 1964	Bridge	Water levels at the bridge rose 12ft above	Undermining of pier.	Pier scour
Sep 1968	Bridge	Flood arch for the River Wey Bridge	Abutment underming/ Culvert	Abutment scour
Sep 1968	Bridge	Flood arch for the River Mole Bridge	Abutment undermining/	Abutment scour
Sep 1968	Bridge		Insufficient data.	Insufficient data
Aug 1969	Bridge	6 culverts and 2 bridges washed out		Insufficient data
Aug 1973	Bridge	Heavy rain caused washout of the		Abutment scour
Oct 1987	Bridge	Two car DMU fell into gap. 4 dead.	Failure of piers due to skewed	Pier scour
Oct 1987	Bridge	8 foot span 'cattle creep' bridge about 70	Abutment failure due to	Abutment scour
May 1988	Bridge	Collapse in flood exacerbated by gravel	Undermining of abutment	Scour influenced by dredging
Feb 1989	Viaduct	Exceptionally heavy rain in late Jan 1989	Pier failure due to undermining -	Scour influenced by dredging
Jan 1993	Bridge	Earth invert of 'cattle creep' bridge taken	Earth invert taken out first and	Abutment scour
Jan 1993	Bridge	Earth invert of 'cattle creep' bridge taken	Earth invert taken out first and	Abutment scour
Jan 1993	Bridge	Central masonry pier of 5-span structure	Undermining of pier.	Pier scour
Oct 1998	Bridge	Masonry arched bridge - washed out	Undermining of abutment	Abutment scour
Jun 2002	Viaduct	Local scour to pier	Local scour of pier exacerbated	Pier scour
Sep 2003	Bridge	Undermining of pier no.1 (from left bank)		Pier scour

Table C3: List of 53 structural failures that were analysed using the EX2502 method

Date	OS Easting	OS Northing	Engineering Line Record	Bridge Number	Indicative Floodplain Mapping	Railway now Dismantled	Recent EX2502 Rating	Historical EX2502 Rating
Jan 1846	556380	146000	RTT	81?	Yes			17.20
Sep 1846	359210	677070	ECM8	Unknown1				15.19
Sep 1846	378610	670330	ECM8	Unknown2				15.93
Jul 1847	204840	067760	Unknown	Unknown3	Yes	Yes		15.77
Nov 1866	419090	438530	TJC3	38	Yes	Yes		16.89
Feb 1868	303130	291650	SBA2	171	Yes			17.61
Feb 1868	300780	294280	SBA2	176	Yes		17.44	17.44
Nov 1869	424590	513410	Unknown	Unknown5	Yes			16.53
Jul 1880	279922	321552	Unknown	Unknown6	Yes	Yes		16.97
Jul 1880	287910	329910	Unknown	Unknown7	Yes	Yes		17.04
Nov 1882	200740	731210	Unknown	Unknown9				17.39
May 1886	381330	253080	Unknown	Unknown10	Yes			16.53
May 1886	345257	279227	Unknown	Unknown10A	Yes			16.37
May 1886	350911	275647	Unknown	Unknown10B	Yes			16.80
Aug 1891	359990	419600	Unknown	Unknown13		Yes		16.35
Sep 1891	347550	637500	Unknown	Unknown14		Yes		16.07
Aug 1912	618240	296030	Unknown	Unknown15	Yes			16.47
Aug 1912	591865	335080	Unknown	Unknown16	Yes	Yes		16.86
Jun 1914	289170	823290	HGL2	237				15.75
Jun 1924	444260	352890	TCC	56	Yes		16.20	16.53
Jul 1930	478820	505040	MBW2	82-1	Yes		18.07	17.03
Sep 1931	478820	505040	MBW2	82-2	Yes		18.07	17.03
Mar 1947	357770	228620	Unknown	Unknown18	Yes	Yes		16.83
Apr 1947	401980	445170	TJC3	78	Yes		16.79	17.79
Aug 1948	381490	665520	ECM8	123				16.40
Aug 1948	381830	665430	ECM8	124				16.47
Aug 1948	382150	665140	ECM8	125				14.78
Aug 1948	382260	664840	ECM8	126				15.22
Aug 1948	382510	664420	ECM8	130				16.36
Aug 1948	384560	663300	ECM8	133				15.60
Aug 1948	386470	662540	ECM8	137				17.38
Aug 1948	393940	662980	Unknown	Unknown19		Yes		16.06
Aug 1948	348199	665103	Unknown	Unknown19A		Yes		16.20
Aug 1948	400430	625370	Unknown	Unknown20	Yes	Yes		16.43
Oct 1949	401760	623640	Unknown	Unknown21	Yes	Yes		16.71
Oct 1954	302960	530040	Unknown	Unknown22A				17.04
Sep 1960	290936	095534	Unknown	Unknown23	Yes			17.34
Dec 1964	260310	276210	Unknown	Unknown24	Yes	Yes		17.23
Dec 1964	312510	308060	Unknown	Unknown24A	Yes		18.01	17.00
Sep 1968	496900	144330	WPH1	17	Yes			17.16
Sep 1968	511940	158270	NGL	15	Yes			16.73
Sep 1968	613767	281822	Unknown	317	Yes			15.55
Aug 1973	190830	781310	Unknown	Unknown25B				16.67
Oct 1987	268760	226930	VOT	22-36	Yes		15.75	17.45
Oct 1987	271620	231150	Unknown	Unknown26	Yes			15.81
May 1988	501480	174130	SWE	71	Yes			17.35
Feb 1989	266280	846020	WCK	3				17.20
Jan 1993	299410	747780	HGL2	Unknown27				16.13
Jan 1993	306490	718410	Unknown	Unknown27A				15.77
Jan 1993	304821	717699	SCM4	Unknown28				16.73
Oct 1998	238703	676835	BCH	79				16.87
Jun 2002	379560	420590	Unknown	Unknown30	Yes			17.21
Sep 2003	444800	383800	CHR	123	Yes		15.84	15.83

Estimating Stream and Structure properties from historic maps

The following procedures were used for estimating stream and structure properties from the First Edition OS maps:

1. The dimension scales were obtained by taking major roads as 6 m width and minor roads as 3 m width. The railtrack was assumed as 2 m width.

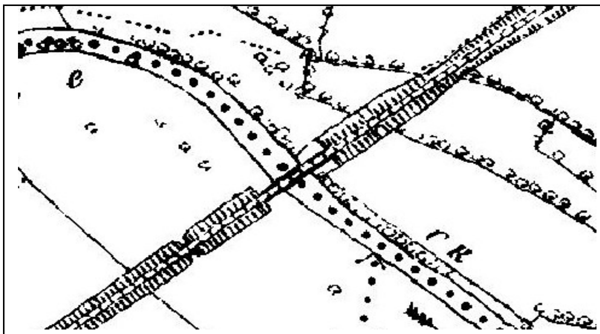
2. Woods and trees were clearly marked along a stream and thus indicated the possibility of blockage at structures.

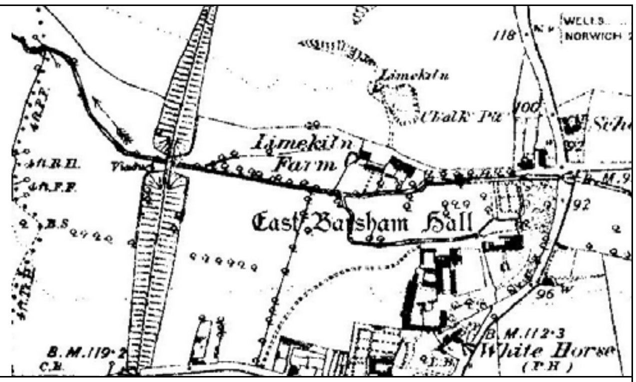
3. Spot heights and benchmarks gave relevant elevations to calculate the upstream slope.

4. In the absence of "Indicative Floodplain Maps" for Scotland, adjacent woods to a stream and associated contours gave the extent of floodplains. If there was any doubt, the EX2502 default floodplain width of 5 * Channel width was used instead.

5. The position and dimensions of abutments could often be discerned from the map detail (Figure C1).

Figure C1: Examples for estimating abutment dimensions and channel position





Abutment assumed to be in the floodplain at the beginning of each embankment, and of length equal to the embankment width	Abutment assumed to be at the channel edge at the beginning of each embankment, and of length equal to the railtrack width

EX2502 Method of Analysis

The scour characteristics at a bridge structure are assumed to be composed of 3 components. The first component is the River Type (TR) and is an estimate of the overall changeability of the river course. It is often called the Regime change (or General degradation), since most rivers are assumed to vary about a steady state called the Regime. In general TR is a function of 3 variables, thus:

TR = f(Stream type, Bank Stability, Flashiness)

where Stream type depends on the size and slope of the river, Bank stability depends on the streambank protection, and Flashiness depends on the upstream slope or tidal velocity (if the stream is tidally influenced). The Stream type and Flashiness were analysed as for modern bridges, and there were no assumptions. It is only the bank stability that is unknown for historic events, therefore a constant and intermediate condition of bank stability was used for all these bridge failure records. Only 2 of the records were tidally dominated, and their flashiness was accordingly assumed as the maximum possible. In summary, the analysis for TR was almost as accurate as that provided by a modern, on-site survey.

The second component is caused by the general reduction of the watercourse dimensions by the structure, and is named General (or Contraction) scour, Gscour. In general Gscour is a function of 4 variables, thus:

Gscour = Stream depth * f(Stream contraction ratio, Angle of attack, Bed material grading)

The stream depth is unknown for historic records, however a default method can be used in EX2502 that gives a reasonable approximation from the known stream width. The Stream contraction ratio is a function of 3 ratios, namely:

- upstream channel and underbridge channel widths
- upstream channel and floodplain channel widths
- upstream channel and floodplain depths

The upstream channel and underbridge channel width could be estimated from the historic maps, and the "Indicative Floodplain Maps" were used to determine the floodplain widths for 27 of the English and Welsh sites. A default method is however given in EX2502 for calculating unknown depths from upstream channel widths, if the data cannot be discerned from the maps.

The incident flow direction to an element (the angle of attack) for a flooded channel is equal to the channel direction at several channel widths upstream, and could be readily estimated from the maps. However, the bed material grading could only be assumed as an average constant value for all records. In summary, the analysis for GScour was slightly less accurate than that provided by a modern on-site survey due to several default estimates for channel and floodplain dimensions, and lack of bed material samples.

The third scour component is caused by flow discontinuities at the structure itself, and is named Local scour, LScour. In general, LScour is a function of 8 variables, thus:

LScour = Element width * f(Element length/width ratio, GScour, Angle of attack, Bed material grading, Blockage risk, Element nose shape, Pier groups)

The Element width variable is the most important. Since it is unknown in the absence of a site survey or site plan, it gives the most uncertainty in an analysis. For this reason, the database of 9305 elements from recent surveys ("NRStructures") was analysed to give average dimensions (Table C4). These statistics were therefore interpolated to estimate the Element width from the estimated Element length data.

Table C4: Average element dimensions

Abutment length: m	16	12	9	6	3
Abutment width: m	0.7	0.5	0.4	0.3	0.1
Pier length: m	16	12	9	6	3
Pier width: m	2	1.6	1.1	0.8	0.4

The estimates for GScour , Angle of attack and Bed material grading have been detailed above. The Blockage risk depends on the upstream vegetation and this could be readily discerned from the maps. The Element nose shape was however unknown, and an average rounded nose shape was assumed throughout. Finally, no pier groups were encountered in the data. In summary, Local Scour was the component with the least estimated accuracy due to the unknown Element width. The uncertainty in Priority Rating for this variable is therefore examined below.

Estimating the Priority Rating

Since long term regime change is the most difficult to assess, it is treated in EX2502 as a separate variable. The summation of contraction scour and local scour is named total scour (TS), and is divided by the foundation depth (FD) to give a preliminary priority (PP), thus:

$$PP = f(TS/FD) = 15 + \ln(TS/FD)$$

The PP range for most bridges is between 10 and 20. The preliminary priority is adjusted for regime (or river type, TR) and the foundation material (FM) to give an adjusted priority rating (PR), thus:

$$PR = f(TS/FD,TR,FM) = 15 + \ln(TS/FD) + TR + FM$$

A mountainous catchment with high flood severity is considered "flashy" and TR = 0. A lowland catchment with low flood severity is considered "non-flashy" and TR = -1. Foundation materials are classified as unknown for which FM = 0, as clay for which FM = -1, and rock for which PR = 10. A final Priority rating (PR) is thus classified as in Table C5.

Table C5: Priority Ratings

Priority Rating	Category	Priority
>17	1	High

16-17	2	High
15-16	3	Medium
14-15	4	Medium
13-14	5	Low
<13	6	Low

Influence of Angle of Attack (AA)

Figure C2: Influence of Angle of Attack on Priority rating

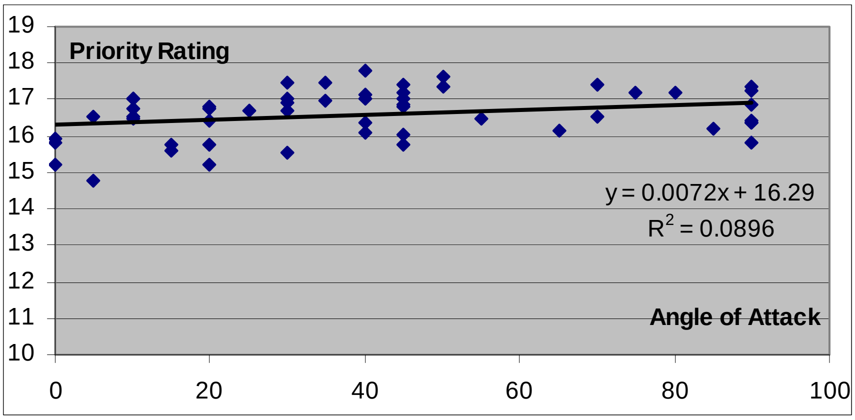


Figure C2 illustrates the Priority Ratings for the 50 bridge failures. Note that 42 of the 53 structures (80%) have high priorities that are greater than 16. This compares with the modern survey ("NRStructures) of 2924 structures that have 30% of high priority structures. The increase of priority with angle of attack is also illustrated in Figure C2, and a weak correlation is demonstrated between the 2 variables.

To demonstrate the influence of the Angle of attack on both General and Local Scour, the data were reanalysed assuming an angle of attack of zero (Figure C3). Note that the number of high priority structures was then significantly reduced. The influence of the angle of attack was therefore to increase the priority rating, on average, by about unity (Table C6).

Figure C3: Influence of Angle of attack (AA) on Priority ratings

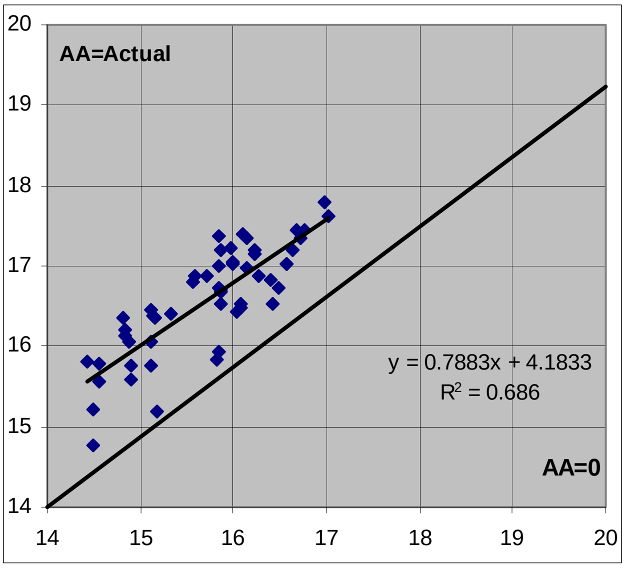


Table C6: Influence of Angle of attack on Priority ratings

Actual AA	Priority Rating	GScour	LScour	TScour
Average	16.18	0.67	4.40	5.07
Stdev	0.79	0.88	3.22	3.72
AA = 0	**Priority Rating**	**GScour**	**LScour**	**TScour**
Average	15.25	0.62	1.54	2.17
Stdev	0.53	0.58	0.70	1.12

Influence of Element width (EW)

Since element width was a major unknown variable in determining Local Scour, its influence was determined by assuming an extreme minimum value of 0.1 m (Figure C4 and Table C7). The "Data EW" shown in Figure C4 and Table C7 are the average values for element widths taken from Table C4 as detailed above. It is seen that if Element widths are reduced to the possible extreme values of 0.1 m, the priority ratings are reduced by about 0.8 and the number of high priority structures are significantly reduced.

In summary, it follows that the major cause for historic bridge failures is due to a lack of scour protection for structures which cross streams at large angles of attack to the bridge streamwise axis. Furthermore, these estimated priority ratings for historic bridges may contain uncertainties of about unity for unknown foundation depth, and unity for unknown element width. Note however that about 10 of the historic failures have been recently analysed, and the element width uncertainty is no longer relevant.

Figure C4: Influence of Element Width on Priority ratings

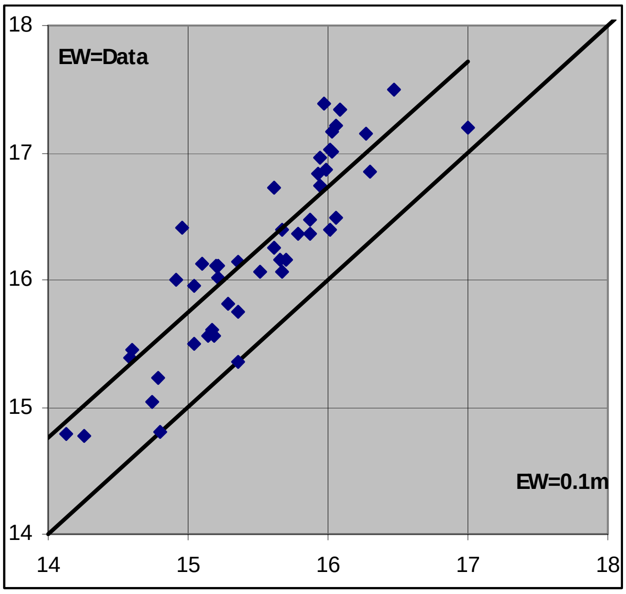


Table C7: Influence of Element Width on Priority ratings

Data EW	Priority Rating	GScour	LScour	TScour
Average	16.18	0.67	4.40	5.07
Stdev	0.79	0.88	3.22	3.72
EW = 0.1 m	**Priority Rating**	**GScour**	**LScour**	**TScour**
Average	15.44	0.67	1.44	2.11
Stdev	0.71	0.88	0.71	1.24

APPENDIX D:
Bridge failure location maps and photographs

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