TECHNICAL REPORT ON THE PROJECT

EMBEDDING TECHNIQUES FOR ASSESSING DEBRIS-INDUCED SCOUR WITHIN PRACTICE

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INTRODUCTION

Background

In the last decades, scientists, engineers and practitioners have become increasingly aware of the risks from debris blockage at bridge piers. Large wood is transported in rivers especially during flood events, in which debris could be entrapped by structures such as bridge piers, and may initiate an accumulation. The localised acceleration of the flow can substantially exacerbate the scour at the base of the pier that would normally occur with the pier alone, and consequently the risk of structural damage or collapse of the structure. Piers that have spread foundations, as most of the UK masonry bridge stock, are more prone to this problem. It was estimated that in the last century approximately more than a third of the bridge failures in the UK caused by scour involved the accumulation of woody debris (Benn, 2013). Similar figures were also observed in the US (Diehl, 1997).

In 2015 the University of Exeter was awarded an EPSRC grant for the project *Risk Assessment of Masonry Bridges Under Flood Conditions: Hydrodynamic Effects of Debris Blockage and Scour*, the primary aim of which was the development of a robust method for estimating the scour depth at a bridge pier with debris accumulations. This research involved a comprehensive experimental investigation at the University of Exeter using a large flume. A total of 46 experiments was carried out. The results from these experiments along with those from others in literature were used to develop a functional relationship for predicting the maximum scour hole depth at a bridge pier.

To implement the results from the research within the practice of non-academic partners, the University of Exeter in partnership with Devon County Council (DCC) started a project funded under an EPSRC Impact Accelerator Account (IAA) award. The IAA award focused specifically on trialling the methodology on DCC's assets and using the knowledge to propose amendments to the current scour assessment practice, as recommended by the Highways England (HE) guidance document BD 97/12. BD 97/12, in its current form, acknowledges the importance of debris accumulations, but does not provide a systematic methodology to assess the effects of debris on scour.

This report summarises the findings from the work undertaken as part of the IAA award. In particular, it summarises the proposed amendments to BD 97/12 and illustrates the impact of these changes on scour assessment practice via a number of full-scale case studies.

METHODOLOGY

The proposed amendments to BD 97/12 are aimed at including the effects of debris on scour and involve two levels of analysis:

1) definition of structures liable to debris accumulations, and
2) evaluation of the scour risk due to debris accumulations in terms of the scour depth and structure vulnerability.

These two levels correspond to the two level approach to scour assessment in BD 97/12 where level 1 aims to identify structures that are potentially at risk to scour and level 2 focuses on a detailed evaluation of the scour risk.

Level 1 assessment

To include debris accumulations as one of the situations that would require a level 2 assessment, the original flow-chart of the BD 97/12 (Figure 3.2 in BD97/12) has been amended by adding the question '*Are accumulations of debris at the structure likely?*'. If the answer to this question is a '*Yes*', the scour assessment would progress to level 2. Figure 1 shows the amended flow-chart with the inclusion of this question. The question has been positioned carefully in the chart to ensure that debris accumulations are considered, but only in a context where these accumulations would constitute a risk for excessive scour (e.g. where no scour protections are in place).

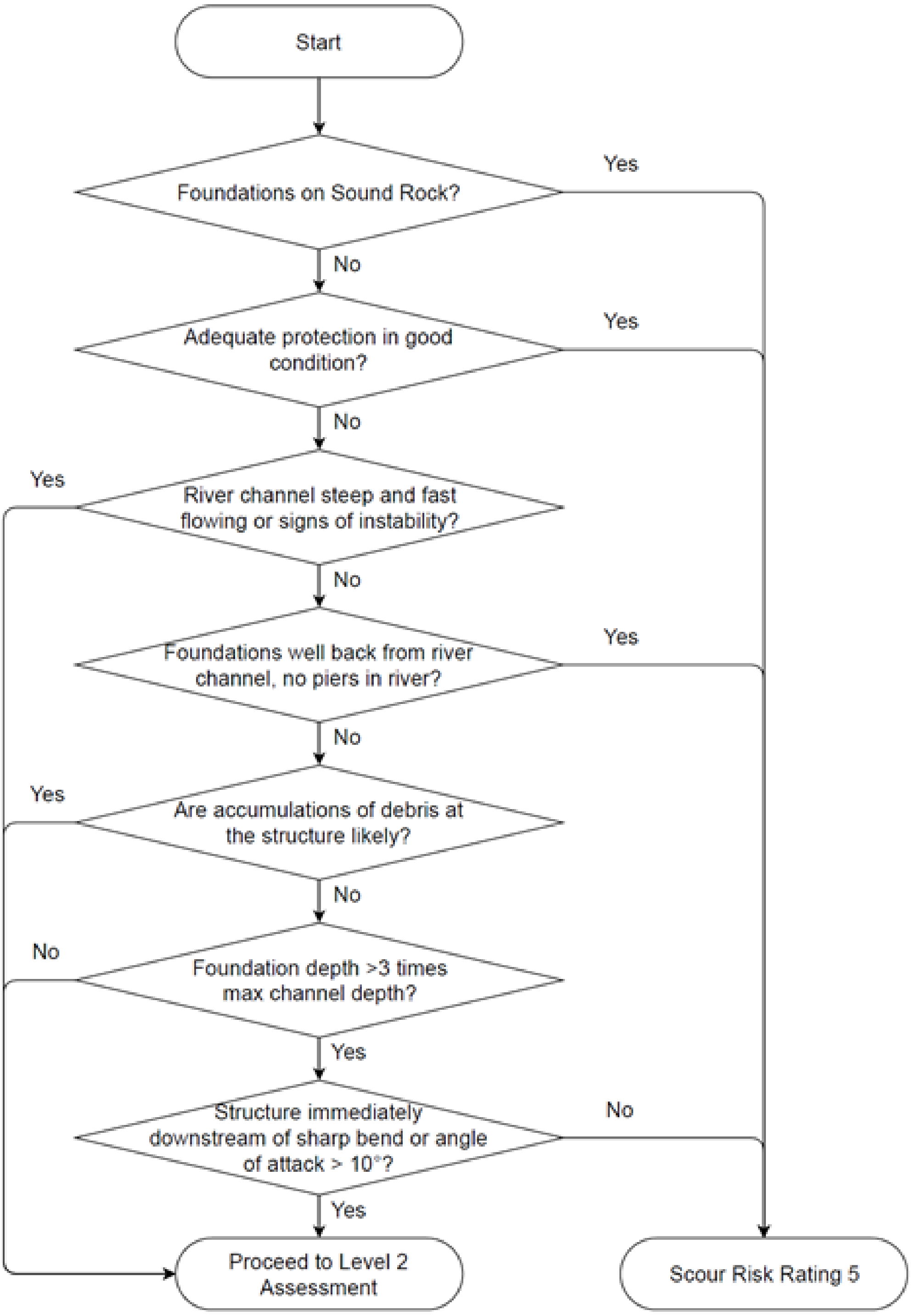

Figure 1 – Flow-chart for Level 1 scour assessment in BD 97/12 amended to include debris effects

To help engineers to classify whether a structure as liable to debris accumulations or otherwise, an approach based on direct and indirect evidence of debris accumulations has been developed as shown in Figure 2. The first three questions in the flowchart are about direct evidence or history of debris jams at a structure. These include photographic evidence, removal work logs, inspection reports etc.

The last three questions attempt to infer if debris accumulations may occur in the future, despite no evidence of accumulation at the bridge being available. The indirect observations include the location of the structure downstream or upstream of other structures with a history of debris and the location of the structure downstream from river banks or floodplains with abundance of trees. A value for the debris factor D is also given in the flowchart, according to the evidence of debris accumulations available for a structure (i.e. direct and indirect). D is used for evaluating a priority factor as described next in this report.

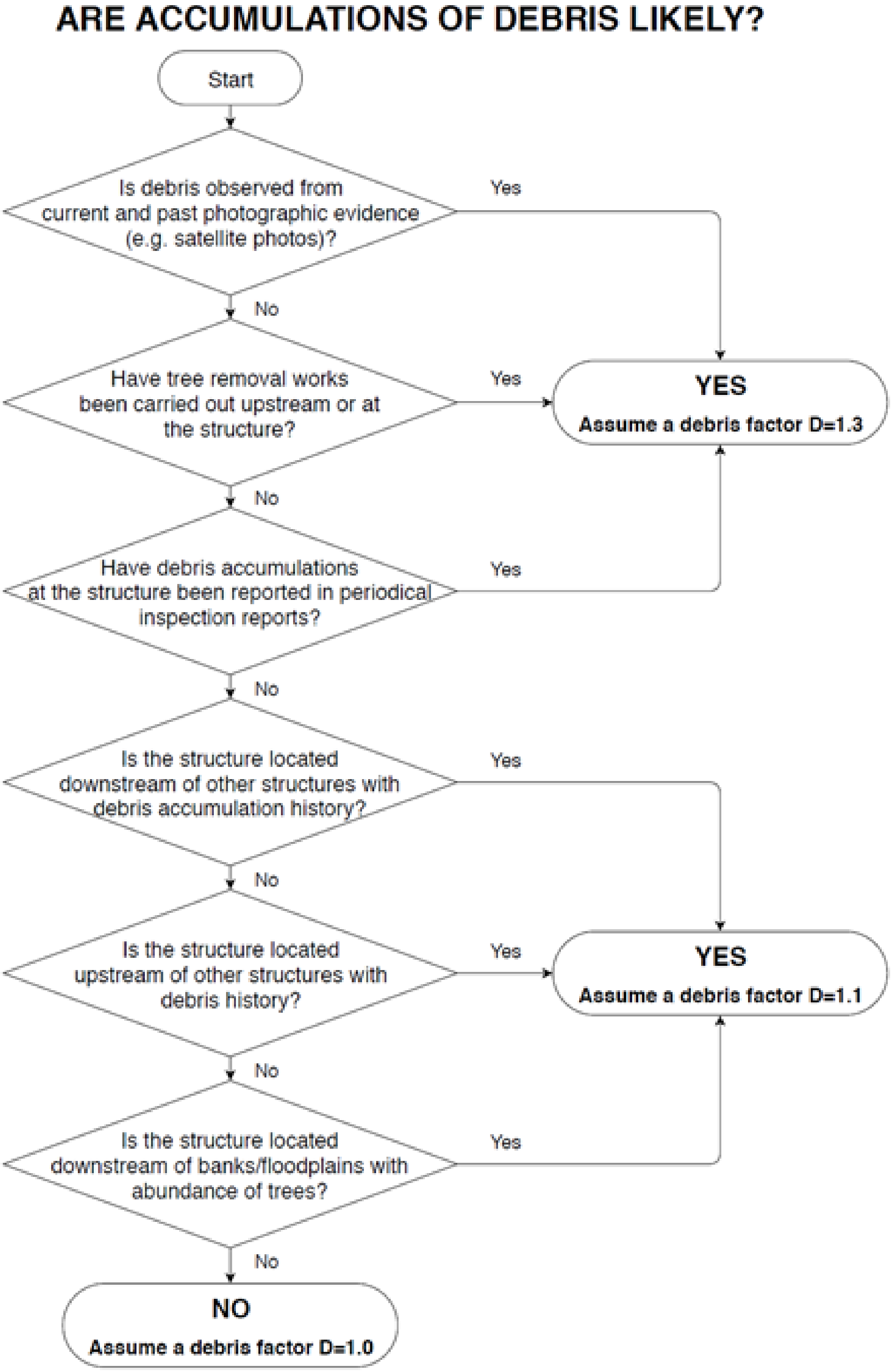

Figure 2 – Flow-chart for assessing whether a structure is liable to debris accumulations

BD 97/12 evaluates a priority factor to quantify the importance and vulnerability of a structure. This factor is used currently only for scour risk rating and does not account for the risk from debris accumulations, although debris may exert additional loads, exacerbate scour and damage bridge structures.

This report proposes two amendments to the evaluation and use of a priority factor. First, a debris factor D is introduced within the equation for evaluating the priority factor. D will include the risk posed by debris. When there is clear evidence of debris accumulation history, D=1.3. For structures with no history of debris accumulations but likely to be prone to debris accumulations, D=1.1. For structures that are unlikely to have debris accumulations, D=1.0. D has been assessed through the flow-chart in Figure 2. Therefore, the priority factor P_f according to the BD 97/12 has been modified as follows:

$$P_f=H \cdot M \cdot Tr \cdot V \cdot D$$

in which the debris factor D has been included as an additional term.

The second amendment proposed is the use of the priority factor for prioritisation of structures in need of a scour assessment, in addition to its current use for assessment of scour risk rating. The bridge stock of Devon County Council has been used for the methodology development and validation. With over 3000 bridges, prioritising of structures was necessary for a cost-efficient allocation of resources. The bridges have been analysed on a desk-based approach, preliminarily excluding those structures that were known to have scour protections or sound rock foundations, and then producing a priority factor for all the other structures. Then, bridges have been selected for scour risk assessment (at both level 1 and level 2 analyses) based on the highest Pf obtained. This method is based on the assumption that it provides a measure to identify those structures that are more vulnerable in the event of scour, since P_f includes the importance of the road passing on the structure, the history of scour, the foundation type and material, and the debris history.

Level 2 assessment

A second major work has been the inclusion of a scour debris factor f_d in the formula for the computation of the scour hole depth. The formula in the BD 97/12 has been amended as:

$$D_T=1.5W_p f_{ps} f_\alpha f_y f_d$$

The debris factor f_d was based on the work by Ebrahimi et al. (2018), as well as the work on the size of debris accumulations by Panici and de Almeida (2018) and the size of the debris design log by Diehl (1997). This study proposes the employment of two approaches for the estimation of f_d: a simplified and a rigorous method.

Simplified method for f_d

The simplified method is a three-step process that requires the use of charts and simple calculations for the estimation of the debris scour factor f_d and that requires only a limited number of input data. The method is explained as follows:

1st Step. Using the average width of the channel upstream of the bridge (B) and the upstream velocity (vu), find the debris accumulation area (A_D) and the debris accumulation upstream length (K) through figures 3 and 4.

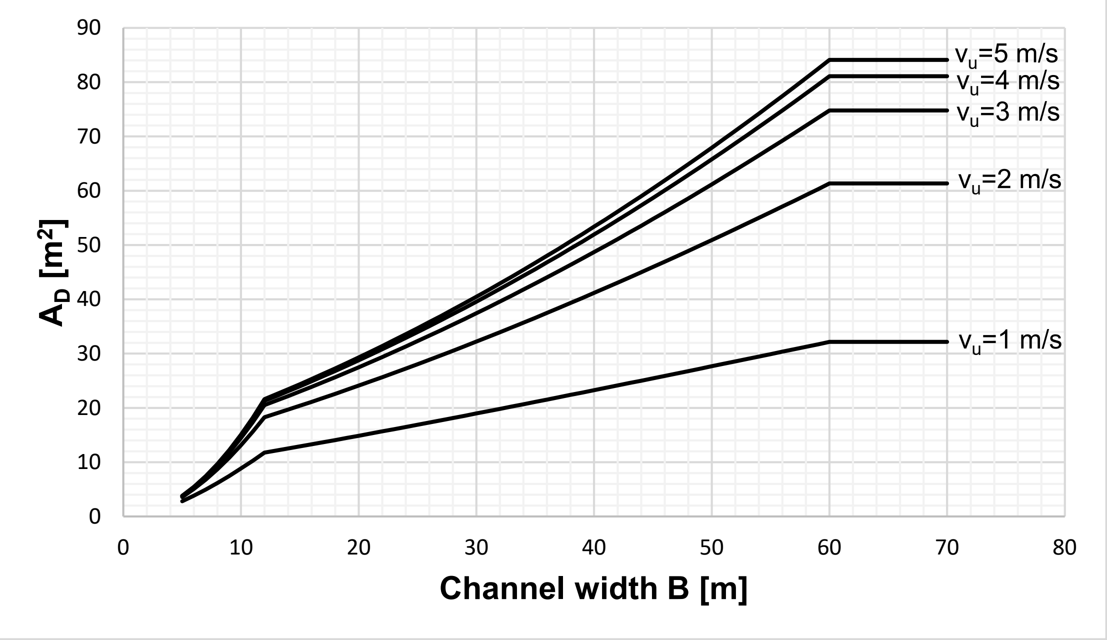

Figure 3 – Chart for estimation of the debris accumulation area A_D

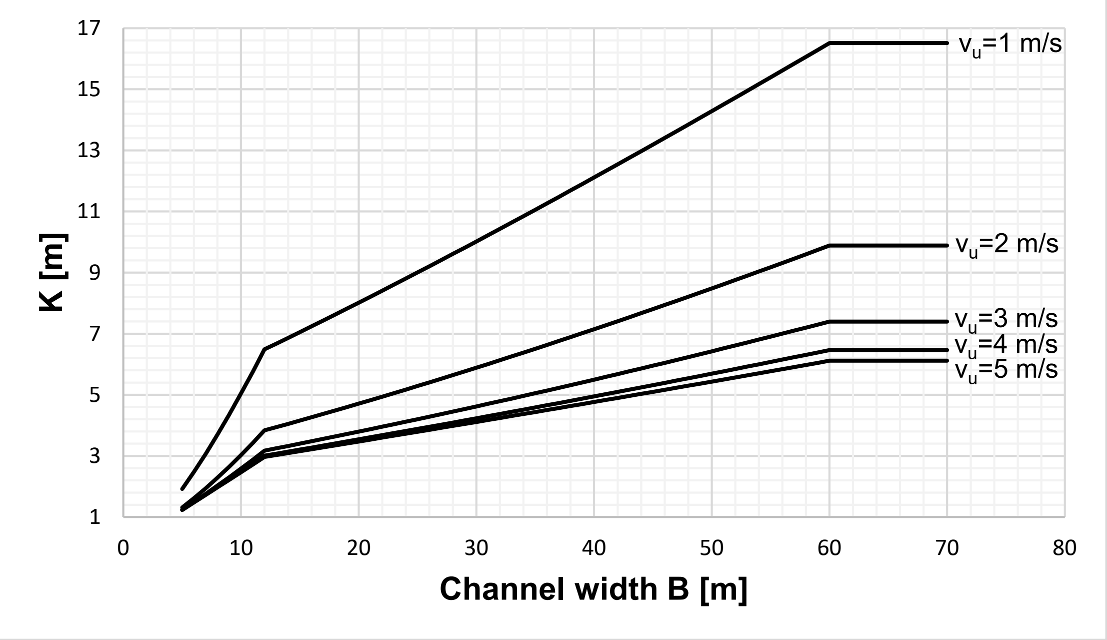

Figure 4 – Chart for estimation of the debris upstream length K

2nd Step. Calculate the ratio between the debris accumulation area (A_D) and the free-flow area upstream of the structure (A) in percentage; calculate the ratio between the debris length (K) and the width of the structure in the channel, e.g. the pier width (W_p).

3rd Step. Use the ratios obtained in step 2 to find the debris factor f_d from Figure 5.

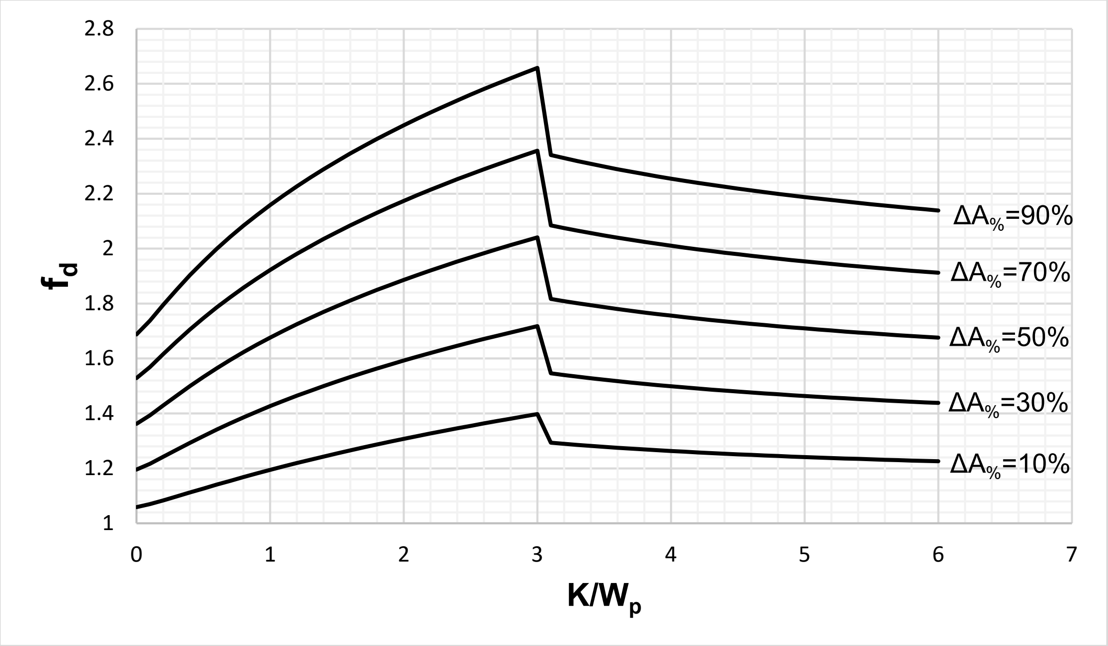

Figure 5 – Chart for estimation of the scour debris factor f_d

This method simplifies some of the effects due to the shape of the debris accumulation, the depth of flow between the base of the jam and the river bed, and the flow velocity relatively to the competent mean velocity. As a result, the simplified method may overestimate the debris factor f_d.

Rigorous method for f_d

The rigorous method is based on the estimation of the scour debris factor f_d via using equations derived from regressions of experimental tests.

First, the design debris length L must be defined. The following formulae by Diehl (1997) can be used:

$$L=B \quad \text{for } B<12\ m$$

$$L=\frac{B}{4}+9 \quad \text{for } 12\ m\leq B\leq 60\ m$$

$$L=24 \quad \text{for } B\geq 60\ m$$

Where B is the average width of the channel. The design debris length defines the size of the debris accumulation, based on Panici and de Almeida (2018):

$$W=L\left(0.774+0.939e^{-6.139Fr_L}\right)$$

$$H=L\left(0.394-0.458e^{-5.770Fr_L}\right)$$

$$K=L\left(0.246+1.178e^{-15.039Fr_L}\right)$$

Where W, H and K are, respectively, the width, height and length of the jam and are sketched in figure 6 and

$$Fr_L=\frac{v_u}{\sqrt{gL}}$$

where v_u is the upstream flow velocity and g the gravity acceleration.

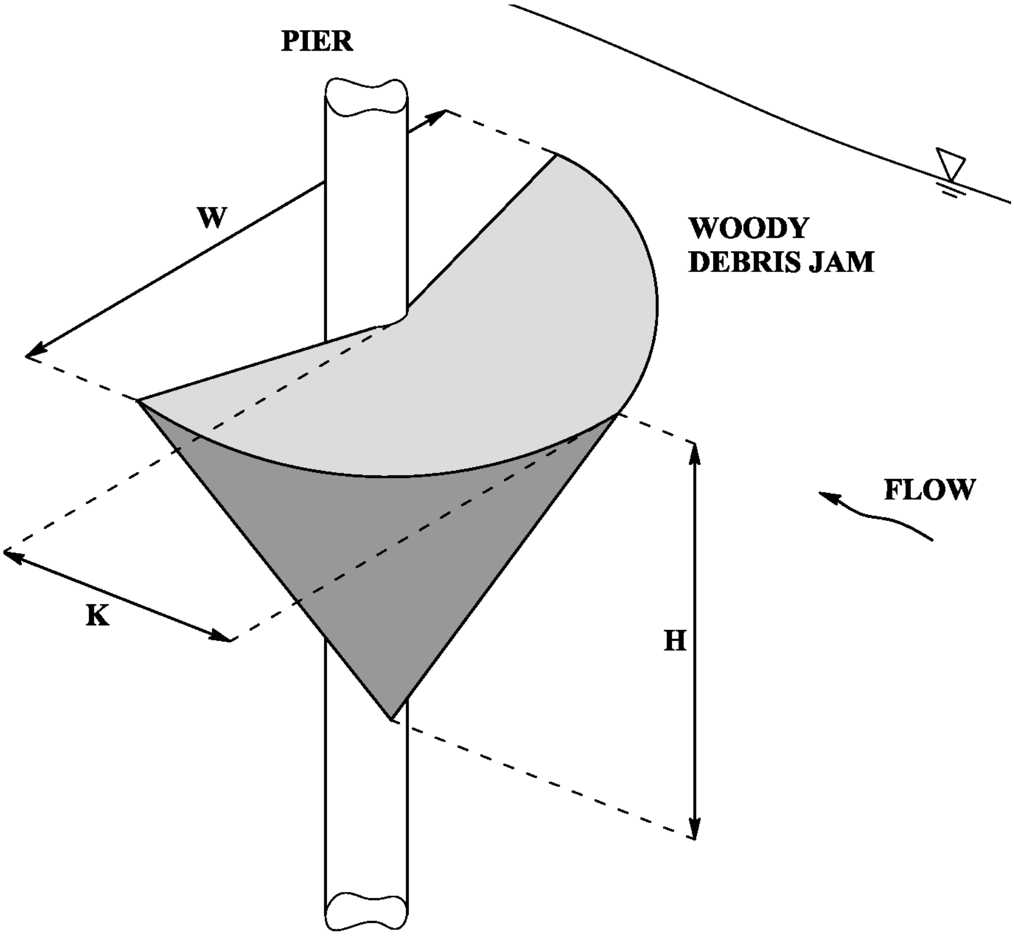

Figure 6 – Conceptualised sketch for a debris accumulation

The debris scour factor f_d can then be found as:

$$f_d = K_1^{0.19} K_2^{0.30} K_3^{0.30} K_4^{0.11}$$

Where K_1, K_2, K_3, and K_4 are factors depending on the size of the debris, the size of the structure, the flow conditions, the properties of the sediments. These factors can be found as:

$$K_1 = \begin{cases} 1+0.28\Delta A_{\%}^{0.5}\left(\frac{K}{W_p}\right)^{1.2} & \text{for } \frac{K}{W_p} \le 3 \\ 1.5+\frac{1.5\Delta A_{\%}^{0.5}}{\left(\frac{K}{W_p}\right)^{1.1}} & \text{for } \frac{K}{W_p} > 3 \end{cases}$$

$$K_2 = 1+0.002\Delta A_{\%}^{1.7}$$

$$K_3 = -0.58\left(\frac{h_d}{h}\right)^2 + 0.71\left(\frac{h_d}{h}\right) + 0.87$$

$$K_4=\begin{cases}\dfrac{v_u}{v_{comp}} & for\ \dfrac{v_u}{v_{comp}}\leq 1\\ 1 & for\ \dfrac{v_u}{v_{comp}}>1\end{cases}$$

where $\Delta A_{\%}$ is the relative blockage area, i.e. the ratio between the debris area A_D and the free flow area A; K/W_p is the ratio between the debris jam upstream length K and the structure size relative to the flow W_p; h_d/h is the ratio of the distance h_d between the bottom of the debris and the riverbed h_d, and the water depth h; v_u/v_{comp} is the ratio between the flow velocity v_u and the competent mean velocity v_{comp}. For situations where $H<h$, the accumulation can be assumed of triangular cross-section, hence the area A_D is given by $WH/2$, and the final factor f_d must be reduced by 16%, according to experimental analysis by Ebrahimi et al. (2018). If $H>h$, the ratio h_d/h is assumed 0 and the debris area A_D is a trapezoid found by the formula

$$A_D=\begin{cases}\dfrac{WH}{2} & for\ H<h\\ \dfrac{Wh}{2}\left(2-\dfrac{h}{H}\right) & for\ H\geq h\end{cases}$$

In this case, no reduction is applied.

The input data required for the estimation of the debris factor f_d did not need any additional measurement or computation beyond those used for current level 1 or level 2 assessments.

The next sections show the results from the employment of the above described methodologies to the bridge stock of the Devon County Council, as well as to some structures owned by Highways England in the Devon area.

RESULTS AND DISCUSSION

Prioritisation of Level 1 and 2 assessments

The prioritising process has been applied to 838 bridges under the management of the Devon County Council. These structures were ordered in descending order of their priority factor values. This allows for a logical and risk-based approach of sequencing the level 1 and level 2 inspections for bridges and is superior to the approach previously adopted by Devon County Council that was based exclusively on the type of road. The new approach is more holistic by including additional factors that were not originally accounted for.

Furthermore, the use of the debris factor highlights how the importance of several structures changed. Table 1 shows the 20 structures with the highest priority factor computed using the proposed debris factor D. The table also shows the priority factor of the same bridges as computed using the priority factor approach currently in BD 97/12. It can be observed that including the risk from debris accumulations changed the priority ranking of these bridges.

Table 1 – Priority factors computed with and without debris factor D for Devon County Council bridges

Bridge code	Bridge name	Priority factor (no debris)	Debris factor *D*	Priority factor (with *D*)
710	STEPS BRIDGE	1.56	1.3	2.028
3366	NEWNHAM	1.56	1.3	2.028
128	TAW	1.26	1.3	1.638
197	LIFTON	1.26	1.3	1.638
428	PUSLINCH BRIDGE	1.26	1.3	1.638
760	CROCOMBE BRIDGE	1.26	1.3	1.638
1323	HATCH BRIDGE	1.26	1.3	1.638
1374	STAVERTON BRIDGE	1.26	1.3	1.638
1460	LODDISWELL MILL	1.26	1.3	1.638
1472	NEW MILL	1.26	1.3	1.638
1603	FORDTON	1.26	1.3	1.638
3615	BEAFORD	1.26	1.3	1.638
3674	WEARE GIFFORD	1.26	1.3	1.638
330	BEDFORD	1.62	1	1.62
1564	STOKE CANON BRIDGE	1.44	1.1	1.584
3341	MOLE	1.56	1	1.56
3404	BRAYFORD	1.365	1.1	1.5015
3618	BLACK TORRINGTON	1.365	1.1	1.5015
2003	WEYCROFT	1.44	1	1.44
2818	BUCKLAND BRIDGE	1.44	1	1.44

Case studies

The application of the scour depth estimation through simplified and rigorous methods is illustrated for 9 structures of both Devon County Council and Highways England. The amended priority factor is also included as part of the scour risk assessment. This section shows a step-by-step application to three bridges and finally a comparison across all 9 structures.

Newnham Bridge (3366) – Devon County Council

Newnham Bridge had the highest priority factor among the Devon County Council bridges. In May 2016 a Level 2 Scour assessment was carried out, the main findings of which are summarised in table 2. This bridge has a record of debris accumulated at the pier, which was assessed by the available records of tree removal works at the structure. Thus, this bridge has been considered as liable to debris accumulations and according to figure 2 its debris factor has been assumed as *D*=1.3.

Table 2 – Input data for Newnham Bridge

Input	Value
Channel width B	30.6 m
Upstream flow velocity v_u	2.97 m/s
Pier width W_p	1.8 m
Upstream flow area A	123 m^2
Competent mean velocity v_{comp}	1.95 m/s
Water depth h	4.6 m

Simplified method

At first, the size of the debris accumulation area A_D and the debris upstream length K is found through the charts in figures 7 and 8:

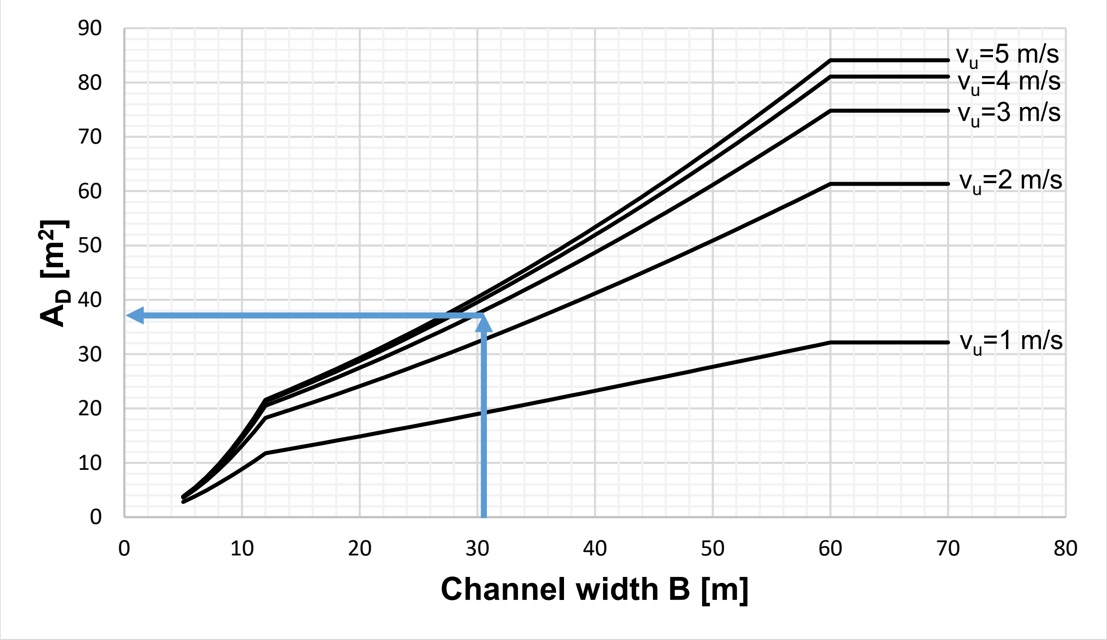

Figure 7 – Application of the simplified method to Newnham Bridge for the debris area

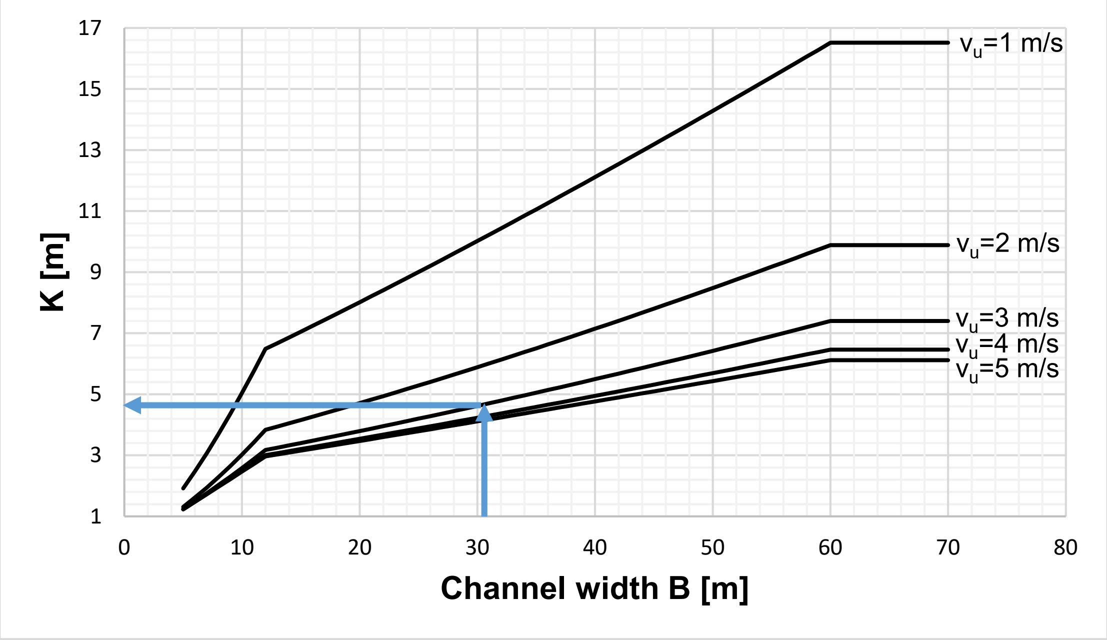

Figure 8 – Application of the simplified method to Newnham Bridge for the debris upstream length

Which resulted in A_D=37.5 m^2 and K=4.6 m. The two ratios required by the simplified method were $\Delta A_{\%}$=30.5 and K/W_p=2.56. The debris factor f_d was then estimated in figure 9:

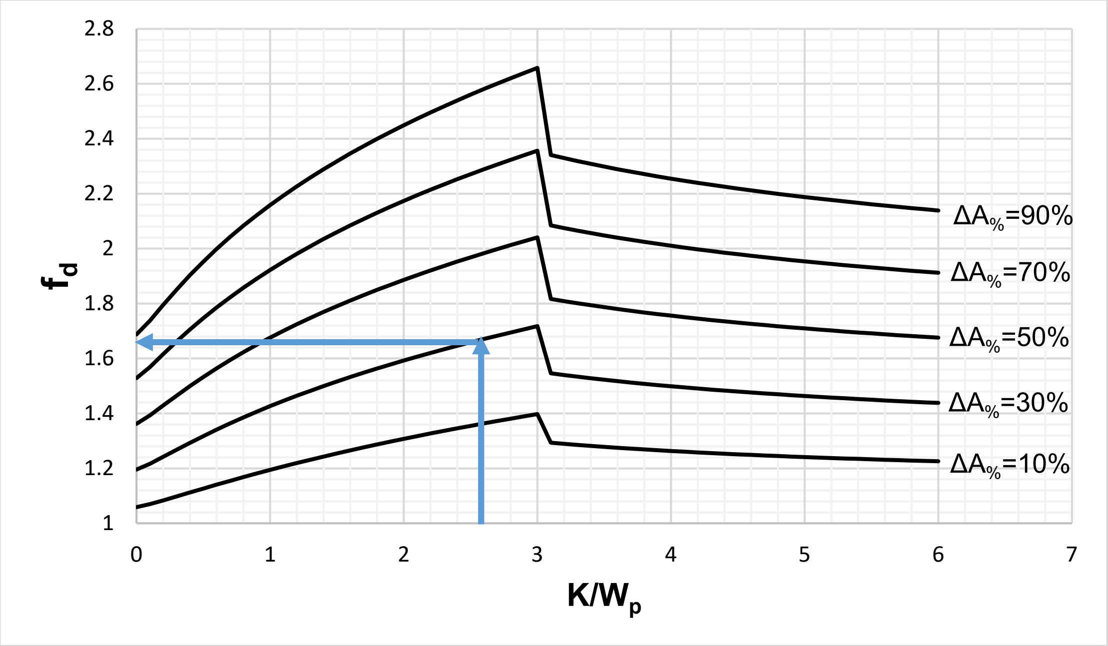

Figure 9 – Application of the simplified method to Newnham Bridge for the scour debris factor

Thus, the debris factor was estimated as f_d=1.67, resulting in a local scour D_L=3.156 m and a total scour D_T=6.906 m.

Rigorous method

Table 3 shows the step-by-step calculation for estimating the size of the debris accumulations, using formulae by Diehl (1997) and Panici and de Almeida (2018).

Table 3 – Application of the rigorous method to Newnham Bridge for the debris accumulation size

Output	**Numerical value**	**Formula**
L – design debris length	16.65 m	$L=B/4+9$ *for 12 m<B<60 m*
Fr_L – debris Froude number	0.232	$Fr_L=v_u/(gL)^{0.5}$
W – debris accumulation width	16.64 m	$W=L(0.774+0.939e^{-6.139Fr_L})$
H – debris accumulation height	4.57 m	$H=L(0.394-0.458e^{-5.770Fr_L})$
K – debris accumulation length	4.69 m	$K=L(0.246+1.178e^{-15.039Fr_L})$

Since *H<h*, the resulting accumulation can be assumed of half-conical shape, hence a triangular cross-section, resulting in $A_D=WH/2=37.98$ m^2. Table 4 shows the step-by-step calculations for the estimation of the debris factor f_d.

Table 4 – Application of the rigorous method to Newnham Bridge for the scour debris factor

Output	**Numerical value**	**Formula**
$\Delta A_\%$ – relative debris blockage	30.88	$\Delta A_\%=A_D/A$
K/W_p – debris-pier ratio	2.61	K/W_p
h_d/h – relative depth ratio	0.008	$(h-H)/H$ *for h>H*
K_1	5.912	$K_1=1+0.28\Delta A_\%^{0.5}(K/W_p)^{1.2}$ *for K/W_p<3*
K_2	1.682	$K_2=1+0.002\Delta A_\%^{1.7}$
K_3	0.875	$K_3=-0.58(h_d/h)^2+0.71(h_d/h)+0.87$
K_4	1.000	$K_4=1$ *for* $v_{comp}<v_u$
f_d – debris scour factor	1.574	$f_d=K_1^{0.19}K_2^{0.30}K_3^{0.30}K_4^{0.11}$

Since $H<h$ and the debris area is assumed triangular, the reduction factor of 84% must be applied, that means f_d=1.322. The local scour is now D_L=2.499 m and the total scour D_T=6.249 m.

Scour Risk Assessment

The pier foundation depth D_F is not known for this bridge; hence, it will be assumed as either 1 m or 2 m. Figure 10 shows the Scour Risk Rating for the two situations considered above, respectively in green for the former and in brown for the latter.

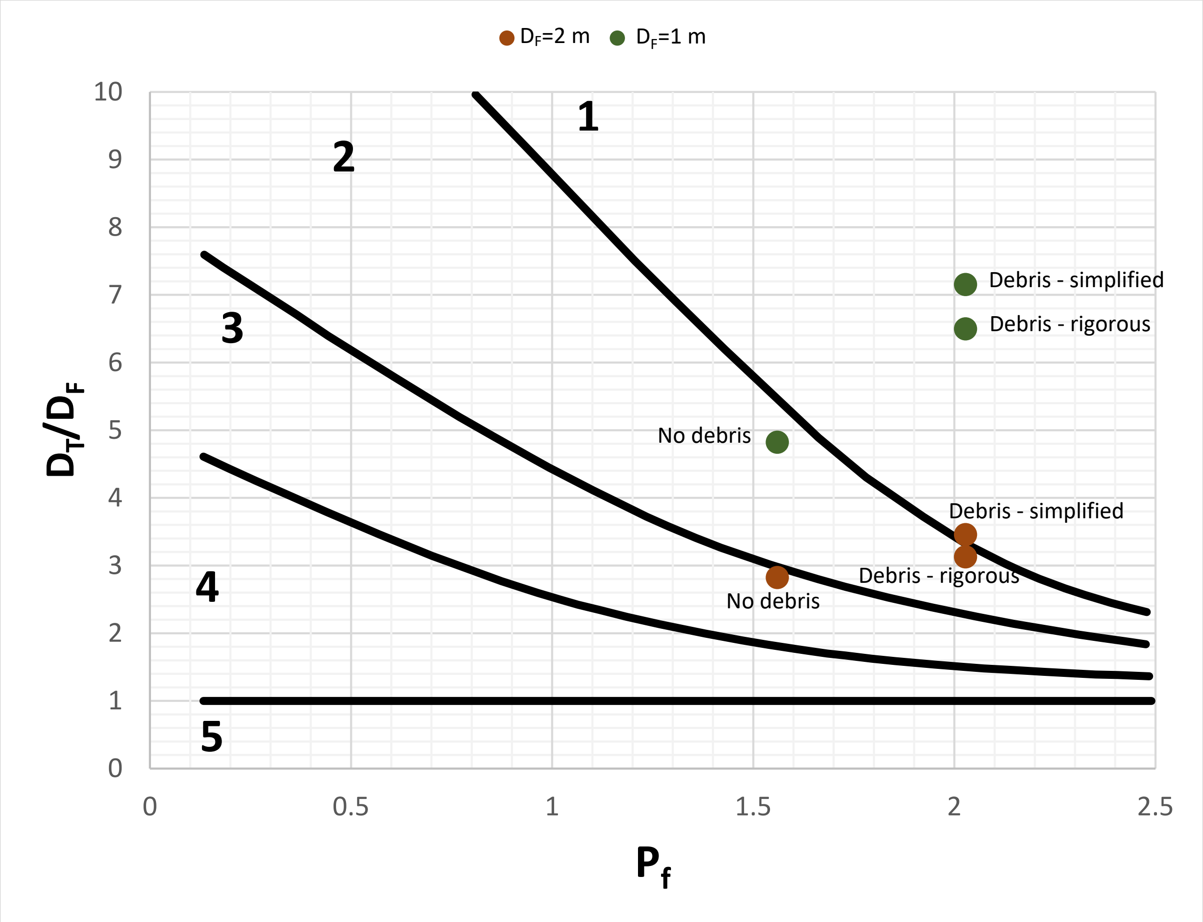

Figure 10 – Scour Risk Rating for Newnham Bridge. Brown points are D_F=2 m and green points are D_F=1 m

For the foundation depth assumed D_F=1 m, the risk rating was 1 in any case, irrespectively of the inclusion of debris effects. However, it can be observed that the inclusion of the debris effect on scour significantly increases the scour depth and therefore the importance of this risk rating. On the other hand, for a foundation depth of 2 m the situation is more varied. In a context of no debris accumulations, the risk rating is 3. Employing a simplified method would overestimate the scour depth in such a way that the amended rating would be 1. In this situation, adopting a rigorous method would be advised. The rigorous method provides a scour risk rating of 2, which is more realistic increase.

Steps Bridge 710 – Devon County Council

Steps Bridge resulted one of the highest among the priority list of the Devon County Council bridges. In July 2019 a Level 2 Scour assessment was carried out, the main findings of which are summarised in table 5. This bridge has a record of debris accumulated at the pier, which was assessed by the available records of tree removal works at the structure. Thus, this bridge has been considered as liable to debris accumulations and according to figure 2 its debris factor has been assumed as D=1.3.

Table 5 – Input data for Steps Bridge

Input	**Value**
Channel width B	20.15 m
Upstream flow velocity v_u	2.73 m/s
Pier width W_p	2.428 m
Upstream flow area A	72.56 m^2
Competent mean velocity v_{comp}	2.93 m/s
Water depth h	2.53 m

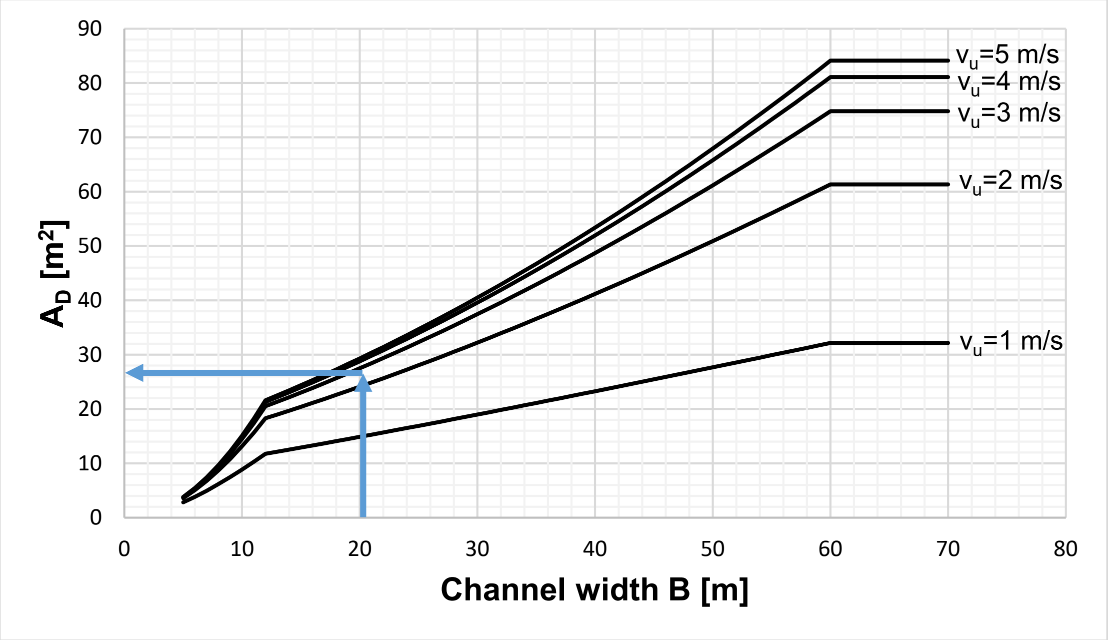

Figure 11 – Application of the simplified method to Steps Bridge for the debris area

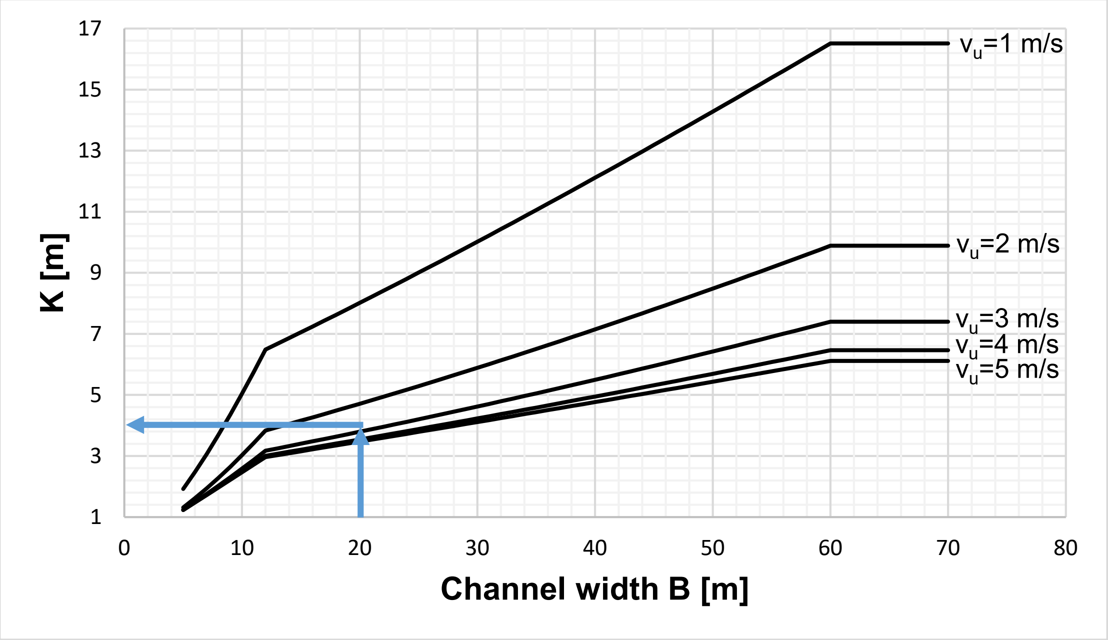

Figure 12 – Application of the simplified method to Steps Bridge for the debris upstream length

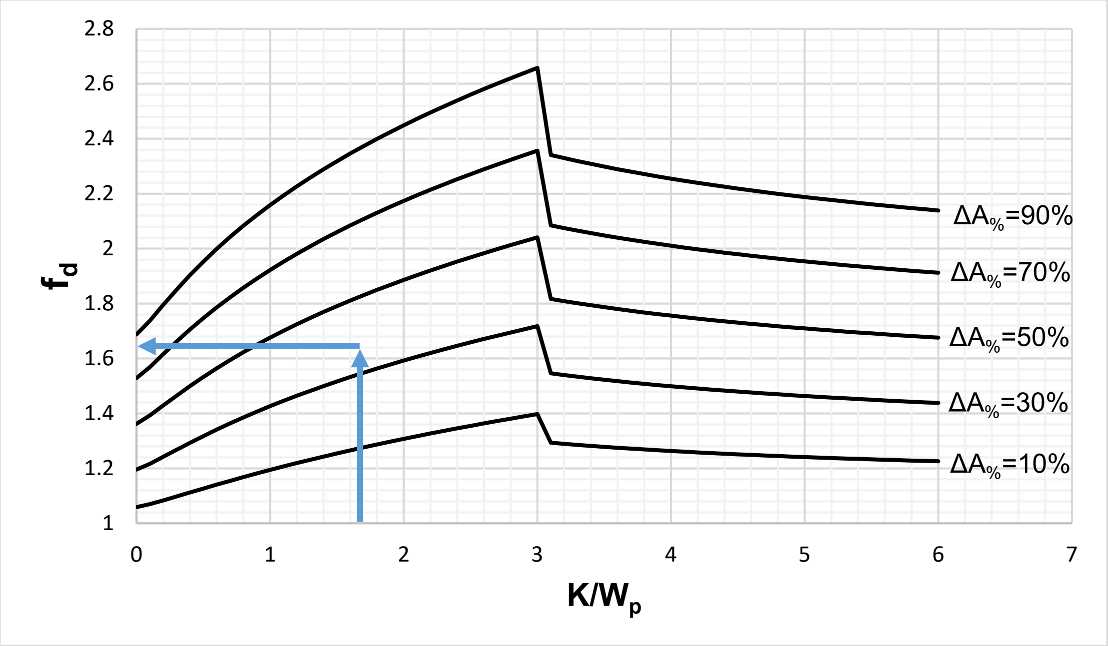

Figure 13 – Application of the simplified method to Steps Bridge for the scour debris factor

Simplified method

At first, the size of the debris accumulation area A_D and the debris upstream length K is found through the charts in figures 11 and 12, which resulted in A_D=27 m^2 and K=4 m. The two ratios required by the simplified method were $\Delta A_{\%}$=37.21 and K/W_p=1.65.

The debris factor f_d was then estimated in figure 13, resulting as f_d=1.64, and providing a local scour D_L=5.970 m and a total scour D_T=7.150 m.

Rigorous method

Table 6 shows the step-by-step calculation for estimating the size of the debris accumulations, using formulae by Diehl (1997) and Panici and de Almeida (2018).

Table 6 – Application of the rigorous method to Steps Bridge for the debris accumulation size

Output	**Numerical value**	**Formula**
L – design debris length	14.04 m	$L=B/4+9$ *for 12 m<B<60 m*
Fr_L – debris Froude number	0.233	$Fr_L=v_u/(gL)^{0.5}$
W – debris accumulation width	14.03 m	$W=L(0.774+0.939e^{-6.139Fr_L})$
H – debris accumulation height	3.85 m	$H=L(0.394-0.458e^{-5.770Fr_L})$
K – debris accumulation length	3.95 m	$K=L(0.246+1.178e^{-15.039Fr_L})$

Since $H>h$, the resulting accumulation will reach the river bed, thus can be assumed of trapezoidal cross-section, resulting in $A_D=Wh/2(2-h/H)$=23.83 m^2. Table 7 shows the step-by-step calculations for the estimation of the scour debris factor f_d.

Table 7 – Application of the rigorous method to Steps Bridge for the scour debris factor

Output	**Numerical value**	**Formula**
$\Delta A_{\%}$ – relative debris blockage	32.84	$\Delta A_{\%}=A_D/A$
K/W_p – debris-pier ratio	1.63	K/W_p
h_d/h – relative depth ratio	0	0 *for* $h<H$
K_1	3.881	$K_1=1+0.28\Delta A_{\%}^{0.5}(K/W_p)^{1.2}$ *for* $K/W_p<3$
K_2	1.764	$K_2=1+0.002\Delta A_{\%}^{1.7}$
K_3	0.87	$K_3=-0.58(h_d/h)^2+0.71(h_d/h)+0.87$
K_4	0.932	$K_4=v_u/v_{comp}$ *for* $v_{comp}>v_u$
f_d – debris scour factor	1.462	$f_d=K_1^{0.19}K_2^{0.30}K_3^{0.30}K_4^{0.11}$

Since $H>h$ and the debris accumulation is assumed to reach the river bed, the reduction factor is not applied. The amended local scour is now D_L=5.310 m and the total scour D_T=6.490 m.

Scour Risk Assessment

The pier foundation depth D_F is not known for this bridge; hence, it will be assumed as either 1 m or 3 m. Figure 14 shows the Scour Risk Rating for the two situations considered above, respectively in green for the former and in brown for the latter.

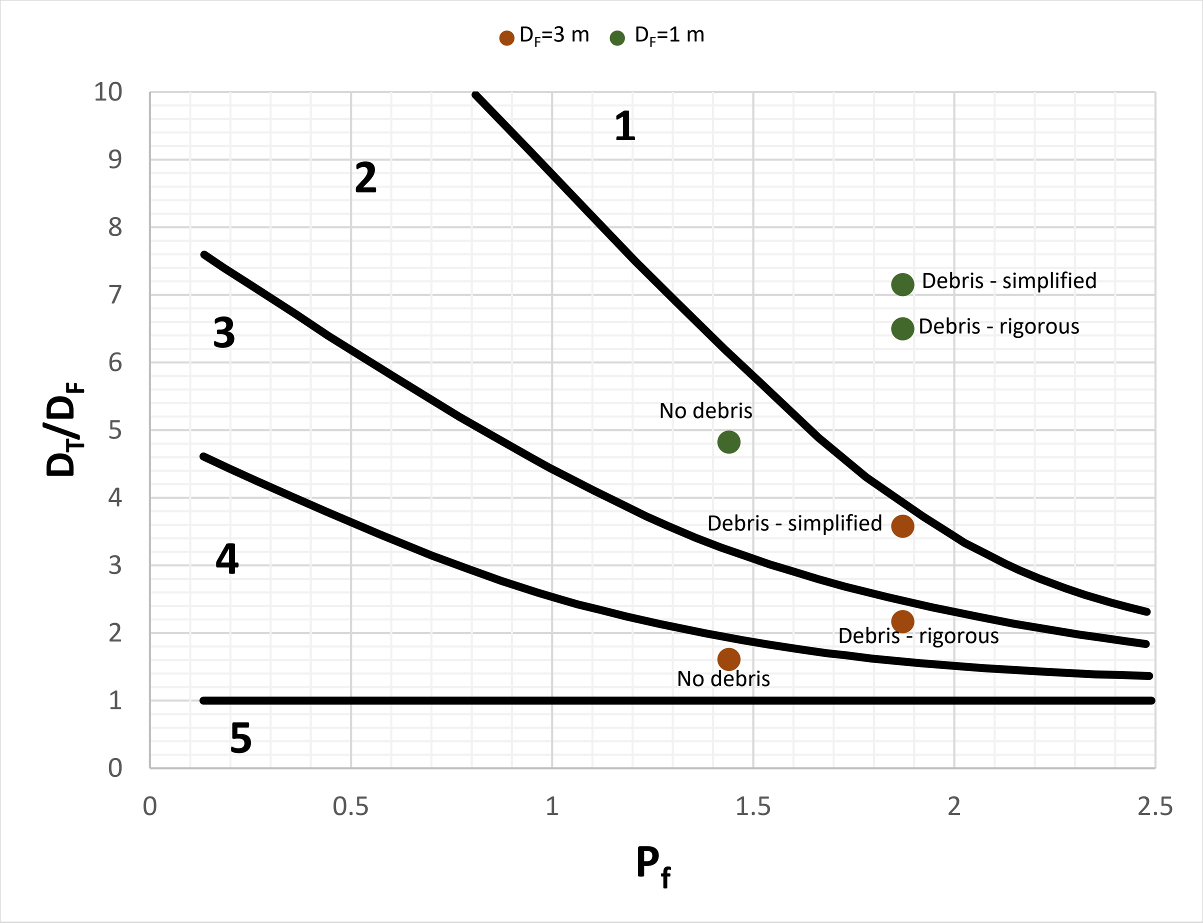

Figure 14 – Scour Risk Rating for Steps Bridge. Brown points are D_F=3 m and green points are D_F=1 m

For the foundation depth assumed D_F=1 m, the risk rating was 2 without debris, whilst increased to 1 including debris effects, irrespectively of the method employed. On the other hand, for a foundation depth of 3 m the situation is different. In a context of no debris accumulations, the risk rating is 4. The use of a simplified method would overestimate the scour depth in such a way that the amended rating would be 2 and very close to 1. In this situation, adopting a rigorous method would be advised. The rigorous method provides a scour risk rating of 3, which is more realistic increase.

A38 Dart Bridge – Highways England

The Level 2 assessment for the A38 Dart Bridge was carried out in March 2015. There is no record of debris accumulated at the pier for this bridge, but the structure is located downstream of other bridges (property of Devon County Council) that suffered debris accumulations in the past. Thus, this bridge has been considered as liable to debris accumulations and according to figure 2 its debris factor has been assumed as D=1.1. Table 8 shows the input data for this bridge.

Table 8 – Input data for A38 Dart Bridge

Input	Value
Channel width B	29 m
Upstream flow velocity v_u	3.28 m/s
Pier width W_p	1 m
Upstream flow area A	169.53 m^2
Competent mean velocity v_{comp}	5.73 m/s
Water depth h	5.19 m

Simplified method

At first, the size of the debris accumulation area A_D and the debris upstream length K is found through the charts in figures 15 and 16:

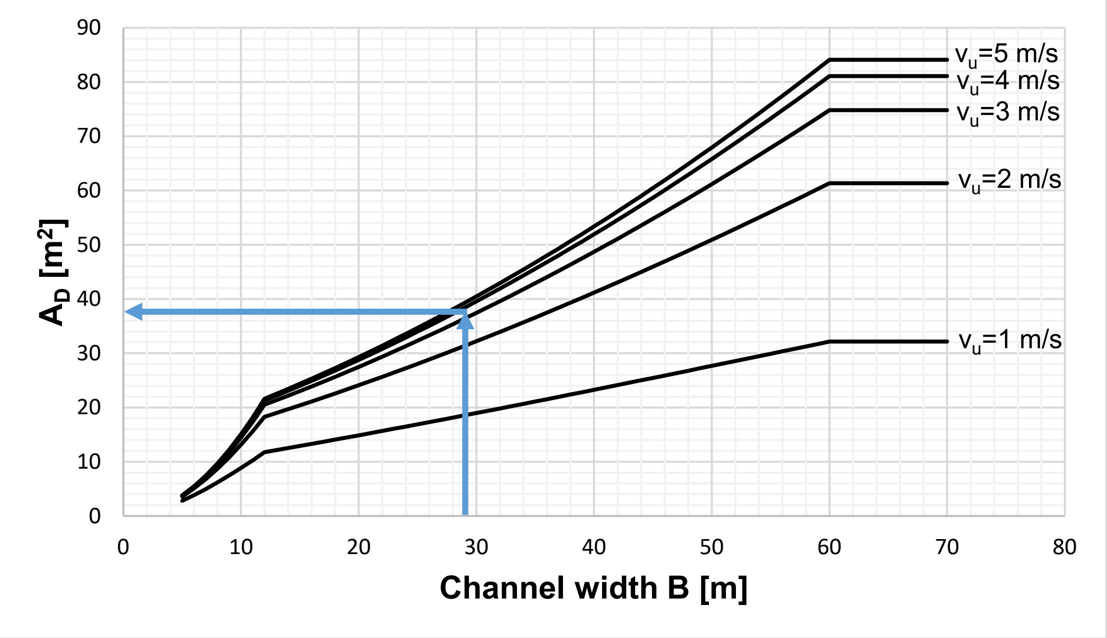

Figure 15 – Application of the simplified method to A38 Dart Bridge for the debris area

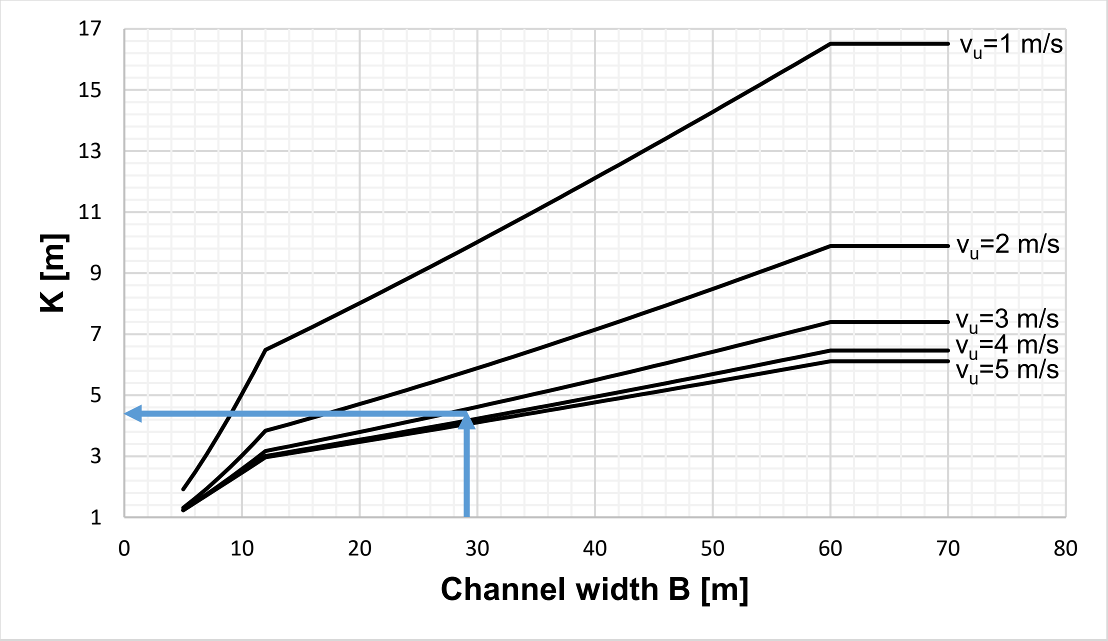

Figure 16 – Application of the simplified method to A38 Dart Bridge for the debris upstream length

Which resulted in A_D=38 m^2 and K=4.4 m. The two ratios required by the simplified method were $\Delta A_{\%}$=22.37 and K/W_p=4.4. The debris factor f_d was then estimated in figure 17:

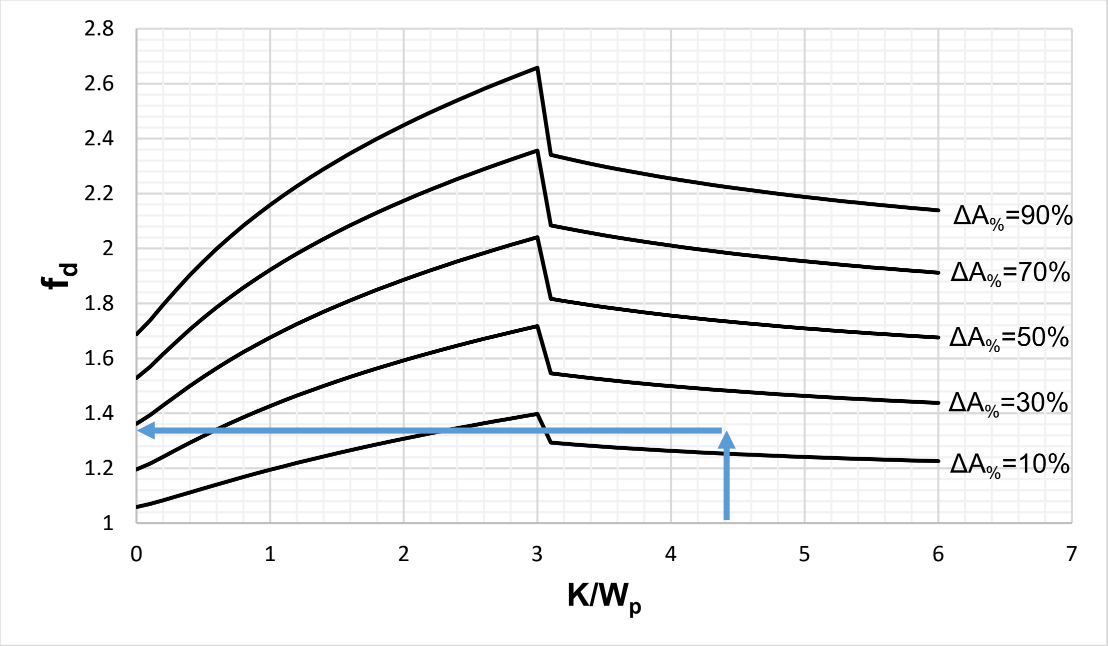

Figure 17 – Application of the simplified method to A38 Dart Bridge for the scour debris factor

Thus, the debris factor was estimated as f_d=1.34, resulting in a local scour D_L=3.618 m and a total scour D_T=7.018 m.

Rigorous method

Table 9 shows the step-by-step calculation for estimating the size of the debris accumulations, using formulae by Diehl (1997) and Panici and de Almeida (2018).

Table 9 – Application of the rigorous method to A38 Dart Bridge for the debris accumulation size

Output	**Numerical value**	**Formula**
L – design debris length	16.25 m	$L=B/4+9$ *for 12 m<B<60 m*
Fr_L – debris Froude number	0.260	$Fr_L=v_u/(gL)^{0.5}$
W – debris accumulation width	15.67 m	$W=L(0.774+0.939e^{-6.139Fr_L})$
H – debris accumulation height	4.74 m	$H=L(0.394-0.458e^{-5.770Fr_L})$
K – debris accumulation length	4.38 m	$K=L(0.246+1.178e^{-15.039Fr_L})$

Since $H<h$, the resulting accumulation can be assumed of half-conical shape, hence a triangular cross-section, resulting in $A_D=WH/2=37.15$ m^2. Table 10 shows the step-by-step calculations for the estimation of the debris factor f_d.

Table 10 – Application of the rigorous method to A38 Dart Bridge for the scour debris factor

Output	**Numerical value**	**Formula**
$\Delta A_\%$ – relative debris blockage	21.88	$\Delta A_\%=A_D/A$
K/W_p – debris-pier ratio	4.38	K/W_p
h_d/h – relative depth ratio	0.087	$(h-H)/H$ *for $h>H$*
K_1	2.881	$K_1=1.5\Delta A_\%^{0.5}/(K/W_p)^{1.1}+1.5$ *for $K/W_p>3$*
K_2	1.379	$K_2=1+0.002\Delta A_\%^{1.7}$
K_3	0.926	$K_3=-0.58(h_d/h)^2+0.71(h_d/h)+0.87$
K_4	0.572	$K_4=v_u/v_{comp}$ *for $v_{comp}>v_u$*
f_d – debris scour factor	1.240	$f_d=K_1^{0.19}K_2^{0.30}K_3^{0.30}K_4^{0.11}$

Since $H<h$ and the debris area is assumed triangular, the reduction factor of 84% must be applied, that means f_d=1.042. The local scour is now D_L=2.810 m and the total scour D_T=6.210 m.

Scour Risk Assessment

The pier foundation depth D_F is known for this bridge; hence, the relative scour depth is DT/DF=3.268 m and 3.694 m for respectively rigorous and simplified methods. Figure 18 shows the Scour Risk Rating with and without debris for the two employed methods.

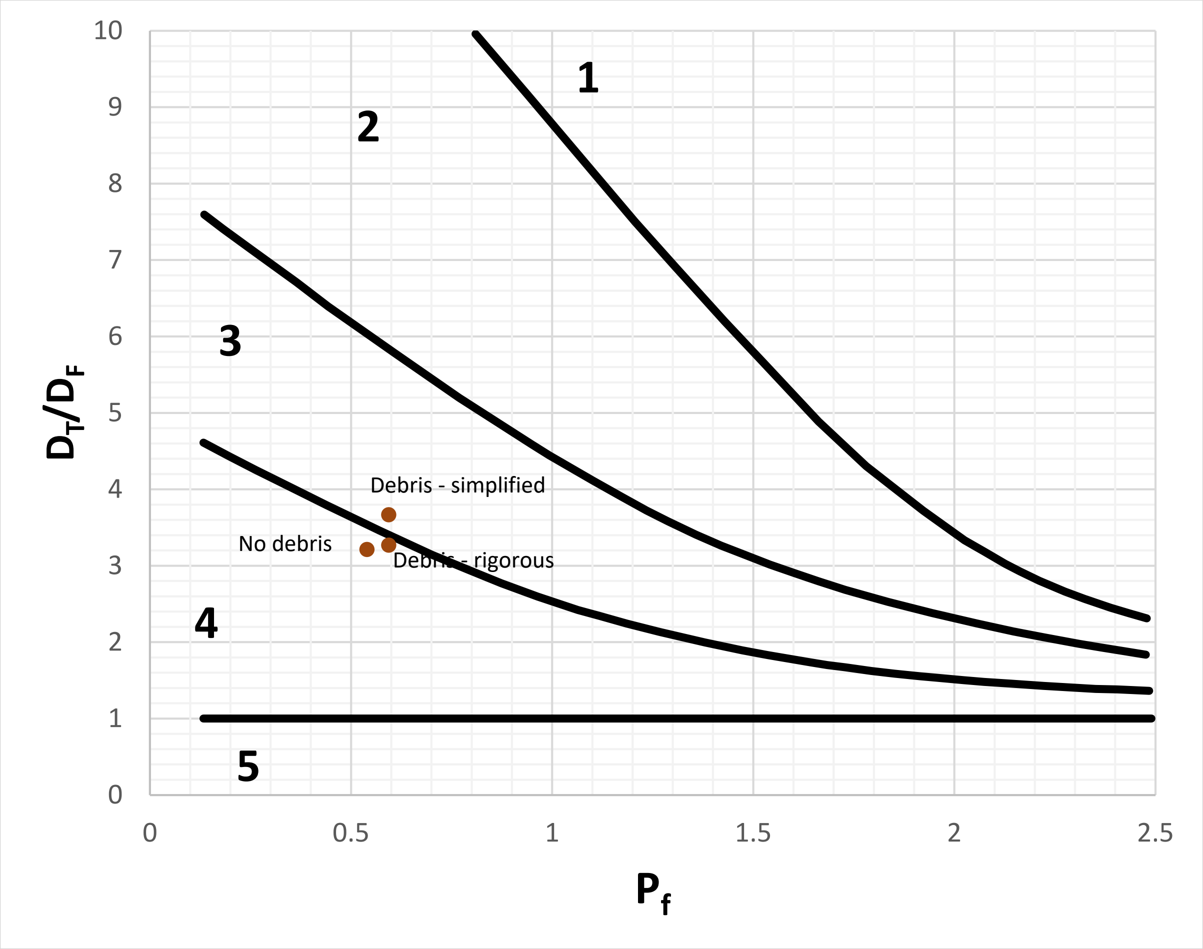

Figure 18 – Scour Risk Rating for A38 Dart Bridge

The scour rating without debris was found to be 4, considering the low priority factor that is used for this structure (suspected bedrock). At the same time, the introduction of the debris factor through the rigorous method does not change the final risk rating, whilst the simplified method overestimates the scour depth (mostly due to the high value of the competent mean velocity and applying no reduction of the triangular shape), increasing the risk rating to 3. In this situation, a rigorous method should be adopted. It is also remarkable to observe that, if debris were directly observed – that means a debris factor D=1.3 – the increase of the priority factor would have led to a risk rating 3 for the rigorous method too.

Other structures

Table 11 summarises the debris factor obtained using both simplified and rigorous methods for 9 structures (including the examples in the previous sections).

Table 11 – Estimation of the debris scour factor for 9 structures

Bridge	**f_d - simplified**	**f_d - rigorous**
710 Steps Bridge (DCC)	1.64	1.46
3366 Newnham Bridge (DCC)	1.67	1.32
1323 Hatch Bridge (DCC)	1.74	1.60
330 Bedford Bridge (DCC)	1.26	1.18
1218 New Bridge (DCC)	2.75	2.30
A38 Dart Bridge (HE)	1.34	1.04
A30 Crowlas Culvert (HE)	1.96	1.64
A30 Dunheved (HE)	1.32	1.01
A38 River Erme (HE)	1.56	1.37

For the structures for which the foundation depth is known (i.e. Highways England structures), the change in risk rating is also reported. In table 12, the risk rating is given for both D=1.1 and D=1.3, since the debris history of these structures is unknown.

Table 12 – Scour Risk Rating (SRR) for 4 structures with and without debris

Bridge	**SRR (D=1.0, no debris)**	**SRR (D=1.1)**		**SRR (D=1.3)**	
		Rigorous	Simplified	Rigorous	Simplified
A38 Dart Bridge (HE)	4	4	3	3	3
A30 Crowlas Culvert (HE)	2	2	1	1	1
A30 Dunheved (HE)	3	3	3	3	3
A38 River Erme (HE)	2	1	1	1	1

DISCUSSION AND CONCLUSION

The causes for the discrepancy between the two methodologies is found in three approximations of the simplified method. First, the effect of the relative water depth h_d/h is not included, whilst it influences the factor K_3. Second, the approach velocity is always assumed higher than the competent mean velocity, which affects the factor K_4. Finally, the 16% reduction that is applied to triangular debris accumulations is not included in the simplified method (although this does not apply to rectangular or trapezoidal shapes, i.e. when the debris jam reaches the river bed).

From the worked examples in the previous sections, it has been observed that the use of the simplified method should be taken with caution. It is advisable when an assessment through a simplified method yields an increase of risk rating (compared to the no-debris case) to employ the rigorous method.

The use of the debris factor D for the priority factor P_f on one hand produces a systematic approach for prioritising structures in need of a scour assessment, especially for situations in which the number of structures to assess is very high. On the other hand, it provides a more conservative approach on the risk rating that is eventually obtained. Despite being more conservative, there is not an increase greater than one class of rating when including the scour effect, when used together with the rigorous method, whilst it can be too conservative with a simplified approach.

In conclusion, this report shows that the proposed amendments enable prediction of the effect of debris accumulations on scour and that these can be employed for scour risk assessments:

- Two approaches have been investigated, namely simplified and rigorous methods. The former neglected some of the factors that may affect the scour depth whilst providing a quick calculation. The latter employed the equations from past research, although requiring a higher amount of calculations.
- The two approaches were tested and compared. The simplified approach might be overly conservative, thus requiring the use of a rigorous method.
- Some real-world cases were employed and showed three different case-studies in which the application of both simplified and rigorous method can be used.

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