Bridge scour protection

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ABSTRACT: Bridge scour protection appears to be increasingly needed to protect foundations from more extreme flooding events. However, the invert level at which the protection is installed can have a significant effect upon flow through bridges and associated flooding levels (Figs. 1 & 2).
Methods to assess this will be outlined along with a review of scour protection types, and arrangements which are effective and beneficial.

1 INTRODUCTION

The general background and reference for this paper is authoritative guidance by CIRIA 'Manual on Scour at Bridges and Other Hydraulic Structures, Second Edition' (2015).

Scour protection is usually installed where there is a threat of bed scour lowering down to bridge foundation levels. When this condition is approached in floods, the flow area through the bridge is usually significantly increased. Generally, it is beneficial to install scour protection with invert levels to match scour levels and avoid unnecessary raising of flooding levels.

Methods to estimate the increased discharge of bridges with lower inverts will be referenced allowing better consideration of this effect in scour protection design, wider flood modelling and management.

Scour protection types will be outlined and characterized by their nature and failure modes. The relative merits of these types will be outlined for bridge protection.

In recent times, rock protection has been mostly used, but it has a relatively high construction thickness (Fig. 1).

The stability of thinner protection types (Fig. 2) generally depends upon the reliability of joints and edge details to prevent flow from getting under the protection. This has a large effect on protection thickness and design methods will be referenced.

The use of insitu concrete mattress in combination with rock falling edge aprons will be described and established design methods presented. Case history examples of usage will be presented as listed below:

- *Cogrie Viaduct, Lockerbie, UK*
- *Iford Bridge, Bornmouth, UK*
- *Waycroft Bridge, Somerset, UK.*

This paper may be of interest to highways, rail and local authorities, design engineers, contractors and other bridge owners.

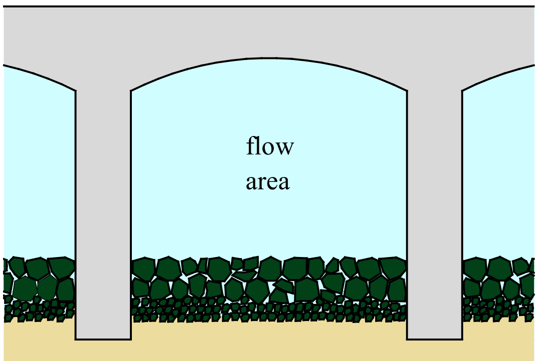


Figure 1. Rock protection

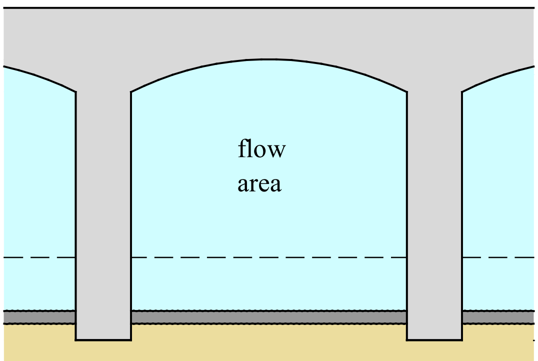


Figure 2. Thinner protection

2 FLOW AND SCOUR AT BRIDGES

Information on scour threshold velocities for various bed materials is outlined in CIRIA (2015). It also outlines general scour behaviour at bridges as shown in Fig. 3 and presents guidance to assess natural scour, constriction scour and local scour.

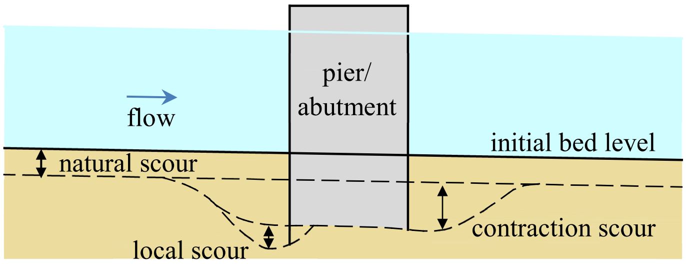


Figure 3. Bridge Scour (CIRIA 2015)

The constriction at a bridge creates higher flow velocities and when this exceeds the scour threshold velocity, contraction scour occurs.

The nature of flow through bridge constrictions is further described in a technical report by Benn et al (2004) in chapters 5 and 6 (Fig. 5.1) where the afflux or upstream rise in level at a bridge is outlined. Formulas are also given for discharge at both bridges and culverts which suggests an increase in bridge opening depth has a proportional or greater increase in discharge. This indicates the effect of bridge invert level upon flood discharge flow and flooding levels. Consideration of this effect can be included in flood models for particular situations and is likely to have increased value where flooding is a problem. In some situations, it may be advantageous to lower existing protection invert levels.

3 SCOUR PROTECTION INVERT LEVEL

The recent guidance by CIRIA (2015) suggests the elevation of scour protection should be carefully considered and placed where practical below the level of natural and contraction scour. (Fig 3).

Invert level selection could often involve consideration of the following influences:

- *contraction scour level*
- *foundation level*
- *scour protection type and thickness*
- *effect on discharge/ flooding levels*
- *constructability and cost*
- *environmental effects.*

Environmentally, lower protection invert levels are preferred so natural bed material generally covers the protection. Bridges can be a favoured location for salmon spawning, particularly where gravels occur.

Lower invert levels provide greater capability to cope with flood debris blockage. It also creates scope for river bed lowering without creating a weir effect on river bed levels.

Scour protection should be arranged to provide good hydraulic flow profiles through bridges with modest slopes where required. Unnecessary steps in invert levels or blockages possibly from old or temporary repairs should be avoided. Inverts with low roughness also assist hydraulic discharge.

4 SCOUR PROTECTION TYPES

4.1 *General failure modes*

Scour protection types can be characterized by their nature and failure modes as listed in Table 1 below.

Rock protection general fails in rolling/sliding particle displacement from the turbulent hydrodynamic action upon it (1). Insitu concrete protection generally fails due to flow suction uplift (2) or from edge underscour failure with trapped flow pressure (3) as shown in Table 1. Prefabricated mattress of various manufactures and types are generally not continuous or generic materials, are more complex and potentially have multiple modes of failure.

4.2 *Basis of design*

Design methods should be based upon an understanding of the likely failure modes.

Design for rock stability at bridges is relatively well developed as shown in CIRIA (2015), with common size and thickness outlined in Section 5.

For insitu concrete and prefabricated mattress types, the reliability of joints and edge details is fundamental to performance and selection of an appropriate design method. Where flow can enter under these protection layers, trapped flow pressure can cause uplift failure at relatively lower flow velocity and a design method following Raes et al (1996) is shown in Section 4.3

Where insitu concrete protection types have reliable joints and edges, an established design method by Pilarczyk (2000) can be used as shown in section 4.4. Where protection is impermeable, the additional thickness needed to resist uplift suction at bridge constrictions can be assessed using Bernoulli's equation.

Where prefabricated mattress types have reliable joints and edges Section 4.5 refers to established design methods from CIRIA (2015).

Reliable edge protection needed to insitu concrete and prefabricated mattress types is outlined in Section 4.6. The use of rock falling edge aprons is promoted due to the additional falling protection depth they provide and the ability to monitor and maintain them if necessary.

Designers should consider carefully the reliability of protection systems and their constructability in the working conditions. Where design methods are being used for protection with reliable joints and edges, this reliability needs to be specified and achieved.

4.3 *Design for trapped flow pressure*

Where reliable joints and edges are not provided to insitu concrete and prefabricated mattress types, the trapped flow pressure can be estimated from Bernoulli's equation as shown in work by Raes et al (1996) who proposed an equation for protection thickness D_{min}:

$$D_{\min} = \frac{C_L U_b^{\,2}}{2\Delta g} \tag{1}$$

Where coefficient C_L = 0.5 for open joints and C_L = 1.0 for underscoured edges; U_b = design bed velocity; Δ = buoyant relative density.

This method is also included in PIANC Report 180 (2015) guidance for berth scour protection.

Figure 4 shows example stability curves for this method with Δ = 1.3 (suitable Δ and safety factor should be considered by the designer).

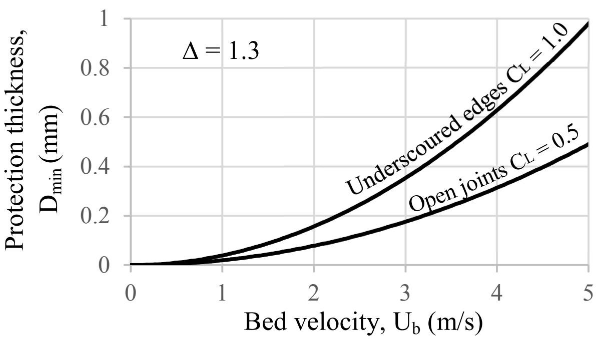


Figure 4. Protection thickness (Raes) for open joints and unprotected edges

4.4 *Design for insitu concrete protection*

For insitu concrete protection where reliable joints and edges are provided, design for flow can be based upon Pilarczyk's formula with various stability coefficients, plus examples of thickness and stability curves by Pilarczyk (2000).

Turbulence at bridges is a significant factor and is generally influenced by the degree of flow constriction and pier widths. Table 2 shows turbulence factors from Pilarczyk (2000) with stability coefficients C_L interpreted by the authors for bridge flow conditions which engineers can review and assess for particular bridge structures with reference to CIRIA (2015) and Rock Manual; CIRIA (2007).

(Pilarczyk's Turbulence Factor is variously shown as K_T or K_T^2 in presentations of his formula. In either case the numerical value shown in Table 2 should be used.)

Figure 5 shows the concrete thickness needed for these various stability coefficients C_L using equation (1).

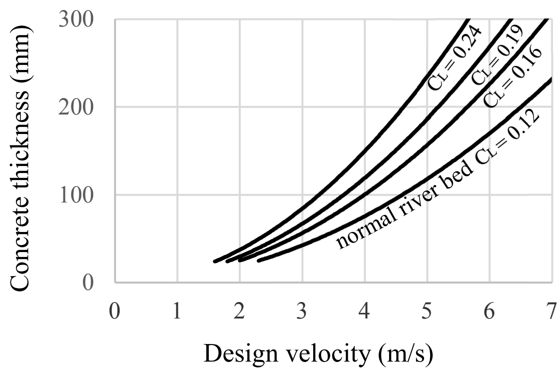


Figure 5. Concrete thickness for turbulent flow at bridges with reliable joints and edges

These curves relate to the thickness of insitu concrete slabs or concrete mattress with a relatively low surface undulation, below 50 mm, and panels of some 3-5 m width. The design velocity can be taken as the vertically averaged flow velocity in the constriction V_2, ignoring the locally higher flow around piers, due to the load distribution properties of concrete slabs.

Where the protection is impermeable, the suction uplift generated at the bridge constriction can be estimated from Bernoulli's formula as:

$$\text{Suction} = \frac{\rho_w (V_1 - V_2)^2}{2} \tag{2}$$

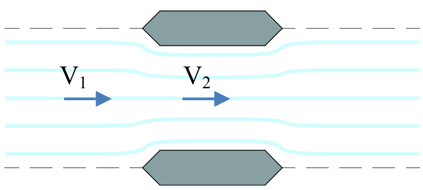


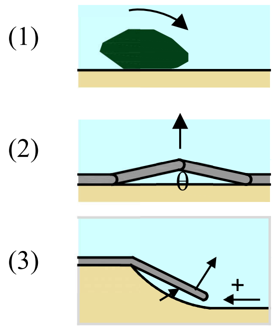
Figure 6. Bridge constriction

The required concrete thickness D_{min} can then be conservatively estimated by:

$$D_{\min} = \frac{C_L \rho_w U_b^{\,2}}{2\Delta g} + \frac{SF \rho_w (V_1 - V_2)^2}{2\Delta g} \tag{3}$$

Table 1. Principal failure modes.

Type	Principle Failure Mode	
ROCK	Particle displacement	(1)
INSITU CONCRETE	Uplift panel failure	(2)
- Concrete mattress	Edge underscour	(3)
- Concrete Slabs		
PREFABRICATED MATTRESS	Joint failures	
- Concrete block mattress	Unit movement	
- Gabion/reno mattress	Edge underscour	(3)
	Others	



General stability principal:
Scour protection fails when the hydrodynamic loads upon it exceeds the stabilizing resistance.

Table 2. Turbulence Conditions at Bridges

Turbulence Intensity r (TI)	Pilarczyk's Turbulence Factor K_T	Turbulence Conditions at Bridges	Stability Coefficient C_L
0.12	1.0	Normal river beds	0.12
0.20	1.2	Upstream edges to beds	0.14
0.25	1.35	Low bridge constriction - variable bottom and slope configurations	0.16
0.35	1.6	Typical bridge constriction	0.19
0.50	2.0	High bridge constriction - wide piers	0.24

C_L is taken from Fig. 3 or Fig. 5 depending upon joint and edge reliability; U_b = design bed velocity; ρ_w = density of water; V = average flow velocity; SF = suitable safety factor. Where weep holes or filter points are provided, the constriction suction effect can be discounted appropriately according to their effectiveness. Where bridges have an unusual hydraulic arrangement or wide piers, the suction uplift for design can be obtained by CFD modelling, Wolfson Unit (2004 & 2008).

Insitu concrete naturally provides rigid slab protection of a similar nature to historic masonry or brick inverts. Settlement of bed material at bridges is not normally an issue unless there is a layer of organic or very soft material. Where this is not remove, slight flexibility can be achieved using smaller panel sizes with increased thickness where required.

4.5 *Design for prefabricated mattress types*

For prefabricated mattress types with reliable joints and edges, design methods are provided in CIRIA (2015). Due to the flexible nature of these protections, guidance is given to use the local flow velocity at bridge piers of twice the approach velocity. This can have a very significant effect, and engineers may wish to consider the average velocity over an effective width of protection where a degree of load distribution is possible.

4.6 *Design of edge protection*

Robust edge details are very important to preventing underscour of insitu concrete and prefabricated mattress aprons; the location, depth and detail of which are usually key in determining the extent of the required area of protection.

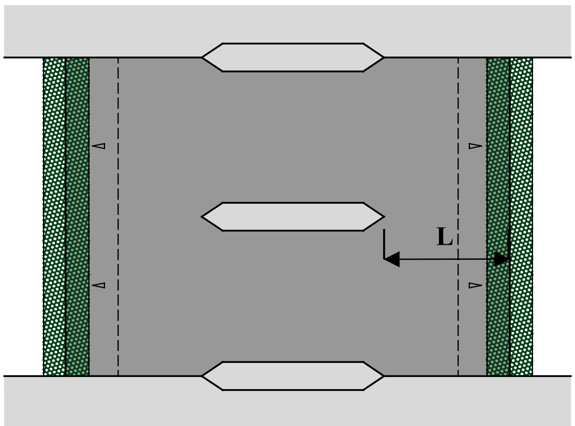


Figure 7. Edge protection

Where feasible, in order to reduce the length of edges it is generally recommended that the protection should extend across the full width of the channel between bridge piers (Fig. 7).

Edge details should be located upstream and downstream sufficiently away from the structure to be beyond the influence of higher constriction flow and with a protection depth greater than the scour potential at that location. Generally this distance (L) is suggested as a minimum of 4 m or 3× pier width, whichever is greater. For angled flow approach these distances should be increased. Figure 7 shows a plan on a typical mattress apron.

To form reliable edge protection, it is often desirable to embed edges and infill trenches with suitably designed rock to act as falling edge aprons as shown in Figure 8. Rock falling edge aprons provide greater resilience to edge scour as they deploy and provide better risk management against unexpected scour events, they also allow monitoring and maintenance where required.

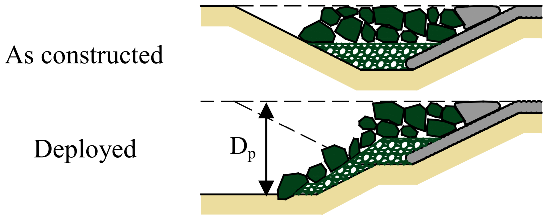


Figure 8. Rock falling edge

The effect of debris build up against the upstream piers can have a significant impact on scour depth and location and consideration can be given to suitably extending the upstream protection.

Rock sizes needed to upstream and downstream toes are more modest when they are located away from increased flow in the bridge constriction (Fig 7).

4.7 *Construction methods*

Most bridge protection work is installed in the wet either in low flow conditions or with the flow slowed or stopped using cofferdams, bunds or over-pumping. For underwater construction, rock, insitu concrete mattress and gabion mattress have been mostly used. Diver work is usually only possible in currents up to 0.5 m/s.

Working in rivers is a high risk activity which benefits from appropriate risk management, experience and consideration of constructability during design.

5 ROCK PROTECTION

5.1 *Construction*

Historically, rock protection has been the main type of scour protection used for bridges. Rock protection generally compromises two layers of rip rap or armour stone upon a bedding/filter layer and often a geotextile filter membrane. The design, specification of construction of the rock protection is well developed and generally understood using authorative guidance. [CIRIA (2015), Rock Manual (2007)].

Rip rap stone with a wider grading than armour is generally preferred as it can be mass placed by excavator bucket.

Rock protection has many good qualities, being porous and flexible, it performs very well as falling edge aprons, and is relatively easy to repair unless the bedding layer is lost.

Where river bed materials are gravels and larger it may be possible to omit the bedding layer, particularly if a wide grading of rip rap can be suitably designed. Rock can be more readily installed in higher currents with suitable increase in construction tolerances and thickness. Rock is relatively easy to maintain when access difficulties are overcome and has good acceptance environmentally.

5.2 *Design*

CIRIA (2015) gives a number of methods for the selection of rock size at bridges. Using the method by Escaramea & May, Figure 9 shows the rock size required relative to the design velocity for various levels of turbulence intensity TI at bridges.

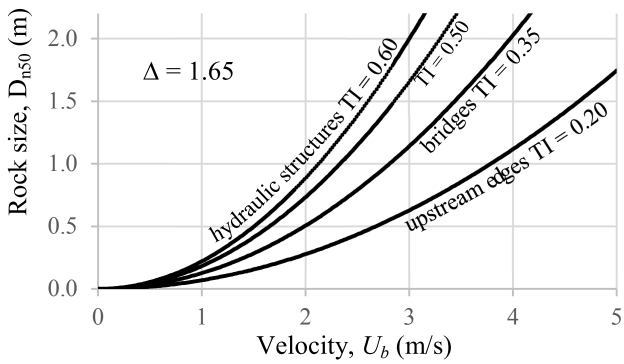


Figure 9. Rock sizes

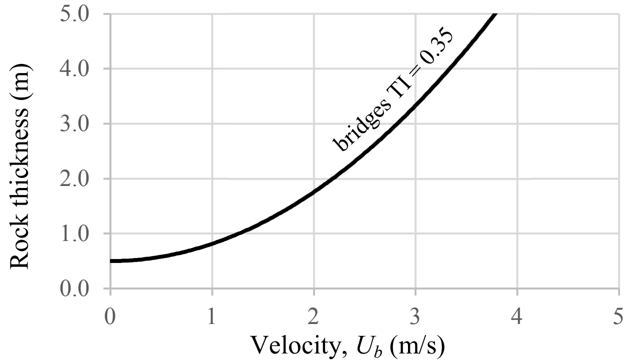


Figure 10. Rock construction thickness

Against bridge piers, the design velocity U_s from accelerated flow against them can be estimated as twice the undisturbed flow just upstream of the structure [CIRIA (2015) box 4.4]. This has a significant effect on rock size.

The relative rock construction thickness is estimated in Figure 10 using the recommended turbulence value TI of 0.35 at bridges and allowing 2 layers of armour plus a 0.5 m bedding layer. Rock thickness is often problematic with relatively shallow foundation depths or with higher velocity.

Where bridge piers are relatively wide with significant flow constriction, flow downstream may tend toward very highly turbulent, equivalent to structures producing very high jets (TI = 0.5).

6 INSITU CONCRETE MATTRESS

6.1 *Construction*

Insitu concrete mattress aprons can be formed either in the wet or the dry. Mattress fabric is placed onto the bed and pump filling with a highly fluid small aggregate micro concrete typically of 35 N/mm² strength.

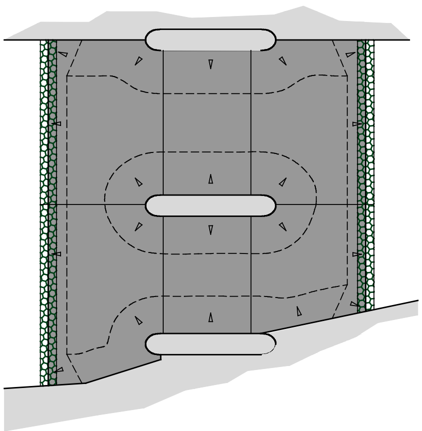


Figure 11. Protection plan (Cogrie Viaduct)

Mattress panels are tailored to suit the shape of the bridge (Fig. 11) and form reliable 'ball & socket' shear joints between panels as shown in Figure 12.

This produces an apron of interlocked concrete slabs which gives high resilience against currents where edges are suitably protected from underscour.

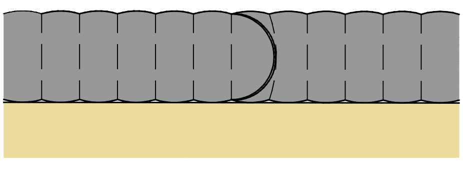


Figure 12. Ball and socket joint

The mattress fabric prevents wash out of concrete before it is set. Concrete mattress installation is practical in currents up to some 0.5 m/s which is often a limit for diver work. Further information on the system is available in a Proserve Technical Note, Hawkswood et al (2014).

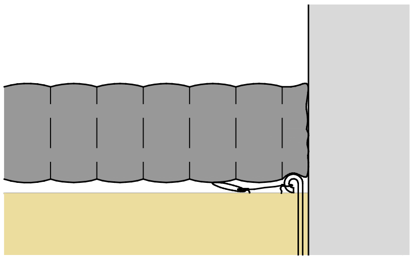


Figure 13. Wall seal

CAD surveys of bridges and river beds upstream and downstream are usually obtained which are used for design assessment and subsequent fabrication of mattress panels to suit the bridge plan profile.

6.2 *Design*

A minimum thickness of 200 mm is generally recommended for debris impact robustness and to allow possible access for maintenance plant.

Uniform thickness/constant thickness mattress types typically have a surface undulation of some 20 mm. In comparison to the design method outlined in section 4.4, where mattress is used with a greater undulation, mattress thickness should be increased accordingly using Pilarczyk's method.

It is important that a positive seal is made between the concrete mattress and the structure. Weep holes can be incorporated into mattress panels where desired.

Concrete mattress has high performance and reliability which is demonstrated by its use for propeller flow and jet action, Hawkswood et al (2014 & 2013). Where the system is installed under water, it should be with the guidance of an engineer experienced with the system and using an appropriate quality control system for marine work.

6.3 *Rock edges*

The combination of concrete mattress protection at the bridge structure with rock edges, as shown in Figure 14, has the following advantages:

- *lower invert level*
- *protection to shallow foundations*
- *protection can be dished (Fig. 14)*
- *good edge protection*
- *good hydraulic profile and performance*

A concrete bolster can be used to retain the edge stone sitting on the mattress where it is not naturally interlocked by neighbouring stone.

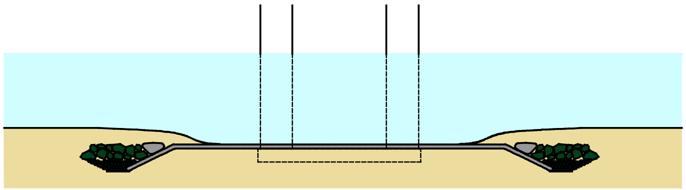


Figure 14. Concrete mattress and rock edge combination.

6.4 *Environmental aspects*

Insitu concrete mattress systems have been used in waterways for over 50 years. They prevent the wash out of concrete whilst it sets with the general requirement for the opening size of the fabric O_{90} to be less than the average sand size D_{s50}.

The rise in water pH levels is normally controlled to be less than a rise of 1 from typical levels of 7.5 to 9 in order not to affect fish stocks or drinking water for human consumption. In rivers, this is usually achieved with the concrete pumping rate being less than 1/60 of the river flow rate and in static water. The volume pumped being less than 1/60 of stagnant water volume. Under present legislation, water pH levels should now be monitored during installation.

7 CONCRETE SLAB PROTECTION

7.1 *Dry construction*

Concrete slab protection can be reliably formed in the dry, where protection areas can de dewatered to suitable levels. However, seepage flows when dewatering are often difficult to predict. Any joints should have dowel bars or similar for shear interlock. Sloping areas for edge embedment are often the most difficult areas to form.

7.2 *Underwater construction*

Tremie concrete slab protection is possible when in cofferdams and bunds where the flow is effectively stopped but not dewatered. Concrete thickness needs to be increased to overcome construction tolerances. During placement, the end of the pump hose should always be submerged in concrete (tremie fashion) to avoid separation of the concrete and a poor quality.

Sloping areas for edge embedment are not feasible in tremie concrete construction which is a limitation.

Joints are difficult to form underwater and are best avoided where possible with larger concrete pours.

7.3 *Design*

Design methods as outlined in sections 4.2 to 4.4 can be used. Pressure relief weep holes are not generally practical with tremie concrete construction.

Suitable edge protection needs careful consideration as it is often difficult to achieve with this form of construction.

8 GABION / RENO MATTRESS

8.1 *Construction*

Wire gabion / mattress boxes are filled with rock and wire laced together to form a scour protection apron. These wire boxes may be prefilled and craned into place or formed insitu. They are normally laid over a suitable geotextile. When being used underwater, they are normally prefilled and craned into place which is often not practical under bridges.

Tailoring of boxes around bridge profiles is an issue along with achieving changes in slope at embedment slopes. Often thickened edges are adopted causing edge upstands which help promote edge scour.

8.2 *Design*

The abrasion and corrosion resilience of the wire boxes and lacing is a fundamental design issue to be assessed.

Where stones or boulders are carried in flow this often causes wire failure to the top of boxes (section 11.1). Little guidance is available on this aspect and engineers may wish to review experience of performance with similar wire and river carried stone size and velocity.

Where reliable boxes, joints and edges can be achieved, the methods outlined in CIRIA (2015) are considered appropriate. Where reliable boxes are to be used, but without reliable edge protection, the designer may consider the method by Raes et al (1996). Although rock gabions/mattresses have a good degree of flexibility, this is not sufficient to act as a reliable falling edge apron and many mattress edges have been lifted from flow pressure associated with underscour.

9 CONCRETE BLOCK MATTRESS

9.1 *Construction*

Precast concrete block mattresses are cast in many forms, often comprising concrete blocks cast with interlinkage by nylon rope, steel cables, nylon mesh or bottom fabric. The connection type, panel size and shape are usually particular to individual manufacturers.

Precast panels are normally craned into place, which makes them impractical for many applications under bridges.

Joint construction between panels is important for reliability and is difficult to achieve underwater considering bed tolerances and siltation. Joints overlapped in the direction of flow have been used if the system is suitable and proven for this.

9.2 *Design*

As block panels are relatively small, a design velocity of 2 × approach velocity is suggested in CIRIA (2015). Where appropriate, the design method by Raes et al (1996) can be used.

Block mattresses are not continuous generic, materials and design for a particular mattress type and application may be best from proven performance in addition to use of general methods shown in CIRIA (2015). Suitable edge protection should be provided to avoid edge underscour failure.

10 CASE HISTORIES

10.1 *Cogrie Viaduct, Lockerbie, U.K.*

Engineer: Scott Wilson

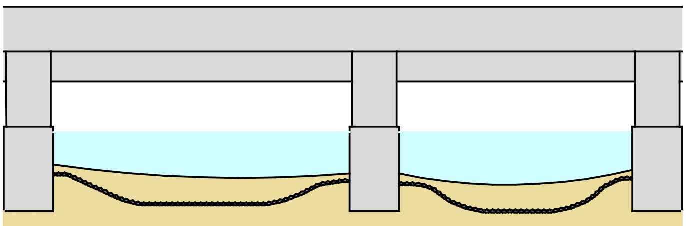


Figure 15. Typical section

Gabion mattress protection had failed due to rock debris carried in the river flow. The concrete mattress protection was designed incorporating a dished channel to accommodate shallow foundation depths, achieve a low invert level and allow the natural deposition of bed material to its original levels providing habitat for salmon fish stocks.

The system was installed in the wet by divers during a summer period of lower flow and with temporary flow deflection.

Mattress panels were rolled up and fixed upstream before being unrolled downstream with zipping to the adjacent panel. Temporary ties were fixed at the river abutments and piers to ensure a positive seal to the structure upon pump filling with micro concrete.

Once mattress installation has been completed, toe trench rock armour was then put in place.

10.2 *Iford Bridge, U.K.*

Engineer: Bournemouth Borough Council
Dive contractor: MMC Diving Services

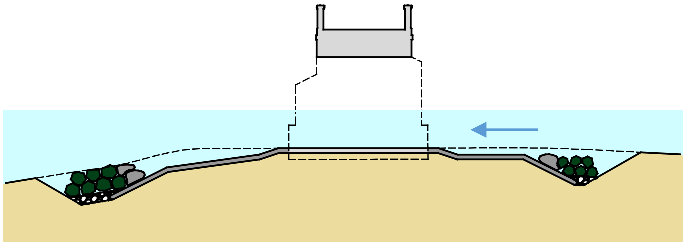


Figure 16. Typical section

The existing bridge had a dished insitu concrete slab invert to the width of the bridge without any formal edge protection which had allowed edge underscour.

An extended protection apron was provided using insitu concrete mattress with upstream and downstream edge protection using toe trenches and rock falling edge aprons. A constant thickness mattress of 220 mm thickness (CT220) was used with reliable ball & socket joints with suitable seal details to existing piers and protection. The protection was installed underwater by divers in periods of relatively low flow.

The level of the toe protection took into account existing bed levels. Larger rock was used downstream due to a higher design turbulence factor which was partially offset by a lower relative flow velocity due to its lower level.

10.3 *Weycroft Bridge, U.K.*

Engineer: JBA
Installation contractor: Suttle Projects

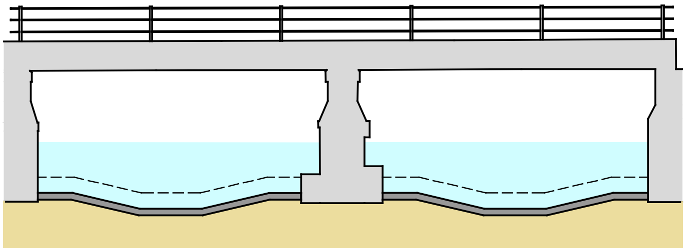


Figure 17. Typical section

The existing bridge has relatively shallow foundations and a 220m thick insitu concrete mattress scour protection apron was provided using a constant thickness mattress with reliable 'ball & socket' joints.

At piers and abutments the mattress was laid some 0.15 m above foundation level and dished in between to effectively maximise the flow area for environmental purposes.

Upstream and downstream mattresses edges were thickened and embedded into toe trenches some 1.6 m below river bed levels

The system was installed in the wet in 3 m stages to help manage the risk of foundation underscour during construction.

11 CONCLUSIONS

Scour protection with lower invert levels can improve discharge and reduce flooding levels. This effect can be appraised in flood modelling for particular locations and help promote wider understanding.

Lower bridge invert levels can generally be achieved using thinner scour protection than rock and these thinner protection types have been reviewed. In particular the importance of reliable joints and edge protection has been presented with associated effect upon performance and design methods.

The effective combination of insitu concrete mattress with rock falling edge aprons has been outlined along with appropriate design methods.

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