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Scour Reduction around Bridge Piers: A Review

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Abstract: *For safe and economical design, scour around the bridge piers is required to be controlled. The performance of any scour protection/controlling device around bridge piers depends on how the device counters the scouring process. Efforts have been made to reduce the depth of scour by placing the riprap around the pier, providing an array of piles in front of the pier, a collar around the pier, submerged vanes, a delta-wing-like fin in front of the pier, a slot through the pier and partial pier-groups and tetrahedron frames placed around the pier. In this paper, a detailed review of the up-to-date work on scour reduction around bridge piers is presented including all possible aspects, such as flow field, scouring process, parameters affecting scour depth, time-variation of scour.*

Keywords: *Bridge Piers, flow field, scour process, scour reduction, time variation.*

I. Introduction

Scour is defined as the erosion of streambed around an obstruction in a flow field (Chang, 1988). The amount of reduction in the streambed level below the bed level of the river prior to the commencement of scour is referred as the scour depth. A scour hole is defined as depression left behind when sediment is washed away from the riverbed in the vicinity of the structure. Local scour refers to the removal of sediment from the immediate vicinity of bridge piers or abutments. It occurs due to the interference of pier or abutment with the flow, which results in an acceleration of flow, creating vortices that remove the sediment material in the immediate surroundings of the bridge pier or abutment.

The problem of scour around an isolated pier has been extensively studied and also documented by several investigators like, Chabert and Engeldinger (1956), Laursen and Toch (1956), Liu *et. al.* (1961), Shen *et. al.* (1969), Melville (1975), Hjorth (1975), Melville and Raudkivi (1977), Ettema (1980), Baker (1981), Jain (1981), Raudkivi and Ettema (1983), Melville and Sutherland (1988), Kothyari (1989), Dargahi (1990), Yanmaz and Altimbilek (1991), HEC-18 (1991), Kothyari *et. al.* (1992 a and b), Garde *et. al.* (1995), Kumar (1996), Dey (1997), Ahmed and Rajaratnam (1998), Graf and Istiarto (2002) and Sheppard (2004).

The process of scour is affected by a large number of variables. The flow, fluid, pier and sediment characteristics are the main variables affecting the pier scour time and spacing between the piers. Depending upon whether the flow approaching the pier is transporting sediment or not, the pier scour is classified as (i) clear-water scour; when approaching flow does not carry any sediment (ii) live-bed scour; when approaching flow carries sediment. In general, the equilibrium scour depths in live-bed conditions are slightly smaller than those in clear-water condition Shen *et. al.* (1969).

The local scour has the potential to threaten the structural integrity of bridge piers, ultimately causing failure when the foundation of the pier is undermined. Besides the human loss, bridge failures cost crores of rupees in direct expenditure for replacement and restoration in addition to the indirect expenditure related to the disruption of transportation facilities. A series of recent bridge failures due to pier scour, as reported by Tafarojnoruz, Ali et al. (2010), Barbhuiya (2004), Wardhana and Hadipriono, (2003), Hoffmans and Verheij (1997) and others rekindled interest in furthering for developing improved ways of estimating the maximum scour depth and protecting bridges against the ravages of scour (Fig. 1).

The design guides, like- HEC-18 (Richardson and Davis, 1995) and the Indian Road Congress Code IRC-78 ("standard" 1983) - require deep and expensive pier embedment in rivers. To reduce this depth of embedment, efforts have been made to reduce the depth of scour by placing the riprap around the pier (Brice *et. al.*, 1978; Croad, 1993; Parola,1993; Yoon *et. al.*, 1995; Worman 1989, (Lim and Chiew, 1996 and 1997); Lim, 1998; Chiew and Lim, 2000; Lim and Chiew, 2001), providing an array of piles in front of the pier (Chabert and Engeldinger, 1956 and Melville and Hadfield,1999), a collar around the pier (Schneible, 1951; Thomas 1967; Tanaka and Yano 1967; Ettema 1980; Chiew, 1992; kumar *et. al.*, 1999, Zarrati *et. al.*, 2004, Zarrati *et. al.*, 2006), submerged vanes (Odgard and Wang 1987), a delta-wing-like fin in front of the pier (Gupta and Gangadharaiah, 1992), a slot through the pier (Chiew, 1992; Kumar *et. al.*, 1999) and partial pier-groups (Vittal *et. al.*, 1994) and tetrahedron frames placed around the pier.

Fig. 1. Photo of schohaire Creek Bridge April 5, 1987 (Courtesy of the National Bridge Inventory Web Page)

A comprehensive review of the up-to-date studies on various scour countermeasures is presented, placing special emphasis on recently proposed methods while also revisiting studies of former methods.

II. Reduction and Protection of Scouring around Bridge Piers

Scour around bridge piers as a result of flooding is the most common cause of bridge failure (Richardson and Davis, 1995; Johnson and Dock, 1996; Lagasse *et. al.*, 1995; Melville and Hadfield, 1999). The bridge failures result in excessive repairs, loss of accessibility, or even death (Chiew, 1995).The potential cost including human toll and monetary cost of bridge failure due to scour damage has highlighted the need for better scour prediction and protection methods. A large depth of foundation is required for bridge piers to overcome the effect of scour which is a costly proportion. Therefore, for safe and economical design, scour around the bridge piers is required to be controlled.

The problem of local scour of sediment around bridge piers has been studied extensively for several decades. The design guides, like- HEC-18 (Richardson and Davis, 1995) and the Indian Road Congress Code IRC-78 (“standard” 1983) - require deep and expensive pier embedment in rivers. To reduce this depth of embedment, efforts have been made to reduce the depth of scour by placing the riprap around the pier (Brice *et. al.*, 1978; Croad, 1993; Parola,1993; Yoon *et. al.*, 1995; Worman 1989, (Lim and Chiew, 1996 and 1997); Lim, 1998; Chiew and Lim, 2000; Lim and Chiew, 2001), providing an array of piles in front of the pier (Chabert and Engeldinger, 1956 and Melville and Hadfield,1999), a collar around the pier (Schneible, 1951; Thomas 1967; Tanaka and Yano 1967; Ettema 1980; Chiew, 1992; kumar *et. al.*, 1999, Zarrati *et. al.*, 2004, Zarrati *et. al.*, 2006), submerged vanes (Odgard and Wang 1987), a delta-wing-like fin in front of the pier (Gupta and Gangadharaiah, 1992), a slot through the pier (Chiew, 1992; Kumar *et. al.*, 1999) and partial pier-groups (Vittal *et. al.*, 1994) and tetrahedron frames placed around the pier.

III. Flow Pattern and Mechanism of Scouring

The performance of any scour protection device around bridge piers depends on how the device counters the scouring process. Flow mechanism of scouring around a bridge pier is very complex and has been investigated by various researchers (Chabert and Engeldinger, 1956; Hjorth, 1975; Melville, 1975; Melville and Raudkivi, 1977; Dargahi, 1990; Ahmed and Rajaratnam, 1998 and Graf and Istiarto, 2002).

The vortex system and down-flow are the principal causes of local scour. At the upstream face of the pier, the approach flow velocity goes to zero. This causes an increase in pressure. Due to this phenomenon the water surface level in front of pier increases. As the flow velocity decreases from the surface to the bed, the dynamic pressure on the pier face also decreases downwards. The downflow digs a hole in front of the base of the pier, rolls up and by interaction with the coming flow forms a complex vortex system (Fig.2.).

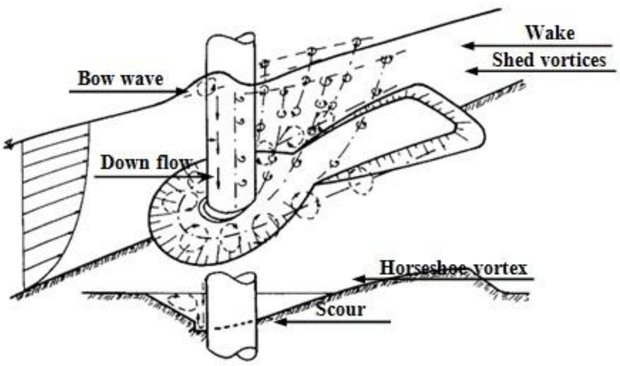

Fig. 2. Diagrammatic flow pattern at a cylindrical pier (after Raudkivi, 1986)

Based on mechanism of scour, countermeasures to control the local scour at bridge piers can be grouped in two categories.

IV. Armoring Devices

Using this device, the streambed resistance is increased by placing the riprap and gabions around the piers. Several researchers (Brice *et al.*, 1978; Croad, 1993; Parola, 1993; Yoon *et. al.*, 1995; Chiew, 1995; Worman 1989, (Lim and Chiew, 1996 and 1997); Lim *et. al.*, 1998; Chiew and Lim, 2000; Lim and Chiew, 2001) have attempted to determine the size and extent of the riprap layer.

4.1 Scour Protection Using Rip-Rap

One of the methods to stop the scouring action of horse-shoe vortex is to provide materials, which cannot be detached from its position. The use of riprap stones to deal with pier scour problems is very common in civil engineering practice. However, riprap layers often fail to protect bridges during floods despite placement of riprap stones around its foundation. One of the main reasons of such failure is the general movement of sediment during severe flood conditions. During floods, a live-bed condition with the presence of bed features, *e.g.* ripples and dunes, is very likely to occur. The movement of bed sediment along the channel and the propagation of bed features cause the immobile riprap stones to lose their stability, eventually embedding into the bed. This type of failure, earlier reported by Lim *et al.*, (1998) and Chiew and Lim (2000), has also been reported by Brice *et. al.* (1978), Croad (1993) and Lim and Chiew (1996 and 1997) in field and laboratory studies, respectively. Various design criteria have been suggested (Bonasoundas, 1973; Neill, 1973; Richardson *et. al.*, 1993; Posey, 1974; Breusers *et. al.*, 1977 and Chiew, 1995). The parametric studies on the embedment process of riprap stones have also been conducted (Chiew, 1995; Chiew and Lim 2000; Hager, 2006).

V. Flow Altering Devices

Using flow altering devices, the shear stresses on the riverbed, in the vicinity of pier, are reduced by altering the flow pattern around a pier which in turn reduces the scour depth at the pier.

Attempts have been made by several investigators to reduce the depth of scour around a pier using flow altering devices (Schneible, 1951; Chabert and Engeldinger, 1956; Thomas, 1967; Tanaka and Yano, 1967; Ettema, 1980; Odgard and Wang, 1987; Chiew, 1992; Gupta and Gangadharaiah, 1992; Chiew, 1992, Vittal *et. al.*, 1994; Melville and Hadfield, 1999; Kumar *et. al.*, 1999; and Zarrati *et. al.*, 2004, 2006).

5.1 Scour Reduction using Slots

Reduction of scouring by indirect method can be achieved by using a slot through the pier, which helps to pass most of the flow through it because of a favorable pressure gradient and balance would be left to cause much reduced scour damage (Chiew, 1992;Vittal *et. al.*, 1994; Kumar *et. al.*, 1999). The basic principle of using a slot is either to divert the downflow away from the bed, or to reduce the downflow impinging on the bed. The width, length and location of the slot are significant parameters. When the slot is placed near the bed, the oncoming flow at the bottom boundary layer accelerates through the slot as a horizontal jet.

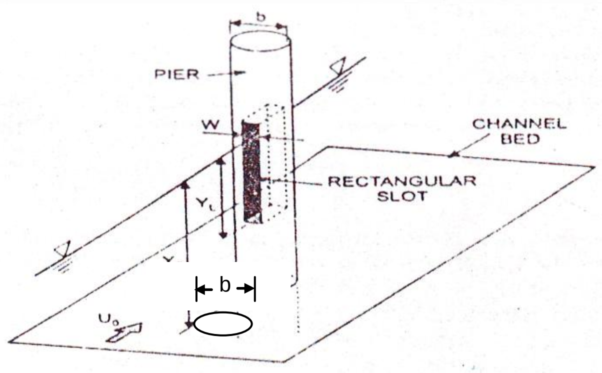

Fig.3 Slot through a pier

Since the downflow at the pier is perpendicular to the jet, the latter deflects the downflow away from the bed, reducing its scouring potential. There are limitations on the use of a slot through pier. The danger of choking of the slot space due to debris and floating materials is very high. They also reduce the strength of pier structure. Hence, they cannot be considered as good scour protection device. Chiew (1992) proposed a vertical slot in a cylindrical pier of scour reduction. Kumar *et. al.* (1999) also used piers slot for scour reduction (Fig. 2.28). Various types of slots as shown in Fig. 2.29 have been used by several investigators

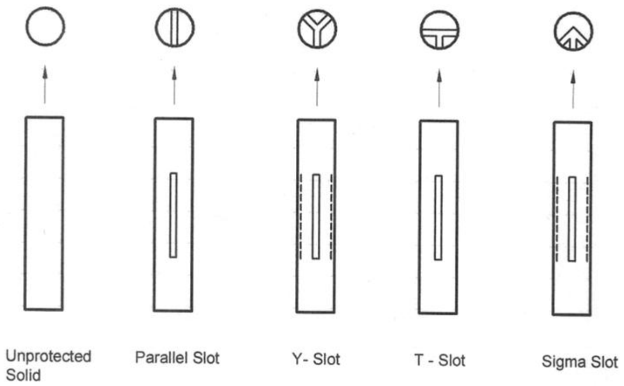

Fig.4 Various Types of Slots

5.2 Scour Reduction using Collar

When a collar is installed around the pier, the direct impact of the down flow on the streambed is prevented, which not only causes reduction in the maximum scour depth but also the rate of scouring is also reduced considerably. Reduction in the rate of scouring reduces the risk of pier failure when the duration of flood is low.

The scour reduction efficiency of collars has already been established in earlier studies (Zarrati *et. al.*, 2006; Zarrati *et. al.*, 2004; Kumar *et. al.*, 1999; Chiew, 1992; Ettema, 1980; Tanaka and Yano, 1967; Thomas 1967; Schneible, 1951). Chiew (1992) also tested a collar with an effective width of three times the pier diameter installed at 0.2b above the sediment bed together with a slot 0.25 D wide with a length of $2b$ near the bed and reported zero scour depth at the pier. Kumar *et. al.* (1999) performed a series of experiments on effectiveness of collar for control of scouring around circular bridge piers. They concluded that with a collar at the bed when W is 4 times pier width, there will be no scour in front and sides of the pier, but a deep scour hole forms at the pier's rear. For the use of collars around piers Kumar *et. al.* (1999) derived design relationship (1)

$$\left(\frac{ds_p - ds_c}{ds_p}\right) = 0.057\left(\frac{B}{b}\right)^{1.612}\left(\frac{H}{Y_0}\right)^{0.837} \tag{1}$$

Where:
ds_p = depth of scour on pier without a collar
ds_c = depth of scour on pier with a collar
B = diameter of collar
b = diameter of circular pier
H = elevation difference between water surface and collar surface
Y_0 = depth of water above bed elevation

Zarrati *et. al.* (2004) conducted a series of experiments using a collar for control of scouring around rectangular pier having a collar with the same width all around the pier. They used two sizes of collars $(W = 2b$ and $W = 2b)$. As the rectangular piers are sensitive to the angle of attack of flow and scour depth around them increases rapidly with an increase in angle of attack (Laursen and Toch, 1956; Ettema *et. al.*, 1998), Zarrati *et. al.* (2004) also performed some experiments with varying angles of attack. A pier fitted with a collar is shown in Fig. 5.

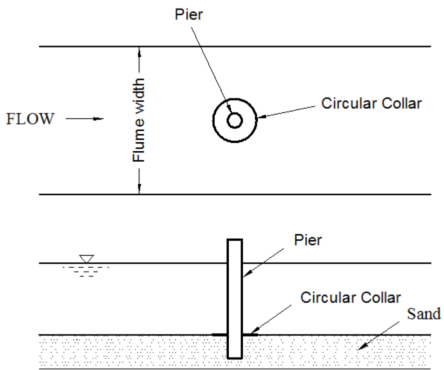

Fig.5 Schematic illustration of a pier fitted with a collar

Zarrati *et. al.* (2006) examined experimentally the scour depth reduction efficiency of collar around a group of two circular piers aligned with the flow (Fig.6) and transverse to the flow (Fig.. 7).

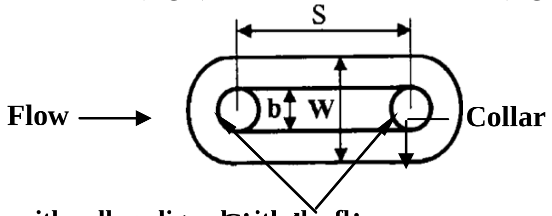

Fig. 6. Group of two piers with collar aligned with the flow

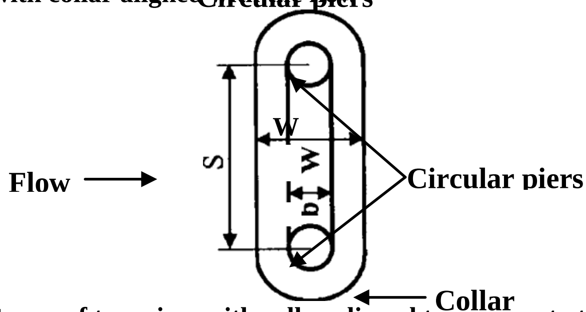

Fig. 7. Group of two piers with collar aligned transverse to the flow

The space between two piers was covered with rip-rap. The data showed that in the case of two piers in line, combination of continuous collars and riprap results in the most significant scour reduction. Experiments however, indicated that collars were not so effective in reduction of scouring around two transverse piers.

5.3 Scour Reduction using Sacrificial Piles

A group of piles located upstream of the pier generates as many turbulent wakes as the number of piles and creates relatively low velocity wake region with interacting individual pile wakes. The net result is reducing the horse-shoe vortex strength and consequent reduction in scour depth significantly. Vittal *et. al.* (1994) studied a group of three circular smaller size cylinders as a replacement of an equivalent pier having a diameter circumscribing the three smaller size cylinders to reduce the scour depth.

Chabert and Engeldinger (1956), conducted experiments to investigate the scour reduction using sacrificial piles. A recent laboratory study of use of sacrificial piles to protect pier against scour is reported by Melville and Hadfield (1999). They concluded that effectiveness of sacrificial piles as a scour counter-measure is dependent on the velocity flow angle and flow intensity. For sacrificial piles are ineffective as scour counter-measure under live-bed condition. For sacrificial piles produces moderate reduction in scour depth. Submerged piles were found slightly more effective than full depths. Finally they concluded that sacrificial piles may not be recommended as effective scour counter-measure, unless the flow remains aligned and the flow intensity is small.

5.4 Foundation Caissons

Chabert and Engeldinger (1956) investigated a circular pier founded on a circular caisson and concluded that the best system appeared to be a caisson having diameter three times the diameter of pier and the top elevation above half the diameter of the pier below the natural bed. They reduced the scour depth one-third that reached with the pier alone.

Shen and Schneider (1969) investigated a variant of the caisson system in which the caisson surrounded by vertical lip (cut off sheet pile) was used. The main idea was to contain the horse-shoe vortex in side an enclosure allowing it escape downstream. The lip certainly allows a reduction in dimensions of the caisson.

5.5 Delta-wings like Passive Device

The geometrical feature of delta-wing like passive device shown in Fig. 8. The passive device was developed using aerodynamic principal flow past delta-wing like plate with negative angle of attack. This position of delta-wing reverses the sense of rotation of trailing vortices.

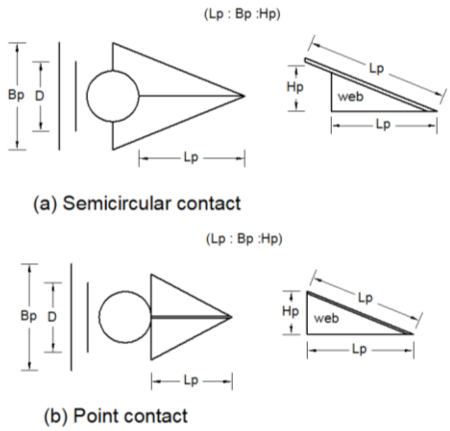

Fig.8. Definition of a delta wing-like passive device (after Gangadhariah and Gupta, 1992)

When this device attached to the leading edge of the pier junction, it modifies rotational direction of the horseshoe vortex as shown in Fig.8. Reversal in the direction of rotation of horseshoe vortex causes the scouring away from the pier and depositing the sediment near the pier. This action strengths the stability. Gangadhariah and Gupta (1992) proposed the use of a delta wing like device infront of the pier for scour reduction.

5.6 Other Methods of Scour Protection

Among other methods available in literature a few are discussed here. They are submerged vanes (Iowa vanes), slanting vanes on the front face of the piers and armoring using different types of artificial material (Parker *et. al.*, 1998).

5.7 Submerged Vanes

Various vanes rectangular plates were held at an angle in the horizontal direction of flow. They diverted the flow to one side and also caused tip vortices generation at their rear edge. These tip vortices were able to disrupt the horse-shoe vortex which might result in reduction in scour depth. The array of vanes provided upstream of the pier directed the eroded sediment into the scour hole and thus retarded the scouring process. Sketch showing dimensions and plan layout in front of bridge piers is shown in Fig.9.

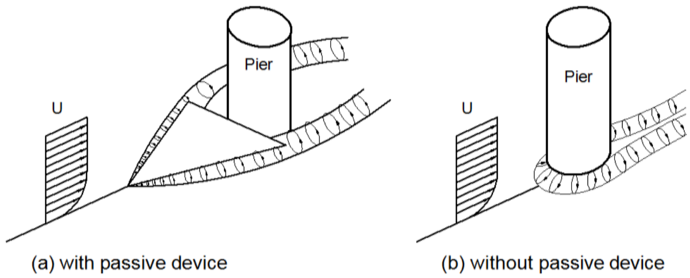

Fig.9. Flow Modification by Passive Device (after Gangadhariah and Gupta, 1992)

5.9 Submerged Vanes

Various vanes rectangular plates were held at an angle in the horizontal direction of flow. They diverted the flow to one side and also caused tip vortices generation at their rear edge. These tip vortices were able to disrupt the horse-shoe vortex which might result in reduction in scour depth. The array of vanes provided upstream of the pier directed the eroded sediment into the scour hole and thus retarded the scouring process. Sketch showing dimensions and plan layout in front of bridge piers is shown in Fig.10.

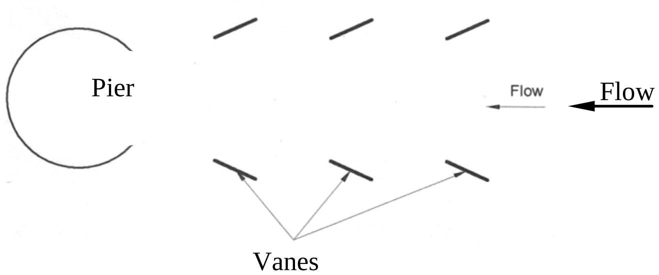

Fig.10. Definition sketch of submerged vanes (after Parker *et. al.*, 1998)

5.10 Slanting Vanes on Front Face of Piers

Slanting vanes with downward orientation were attached on either side of splitter plate locating on the line of symmetry of the pier front face. The details of the vane are shown in Fig.11. The design principal of this is to suppress down swelling zone of horse-shoe vortex. This device needs further testing for its use.

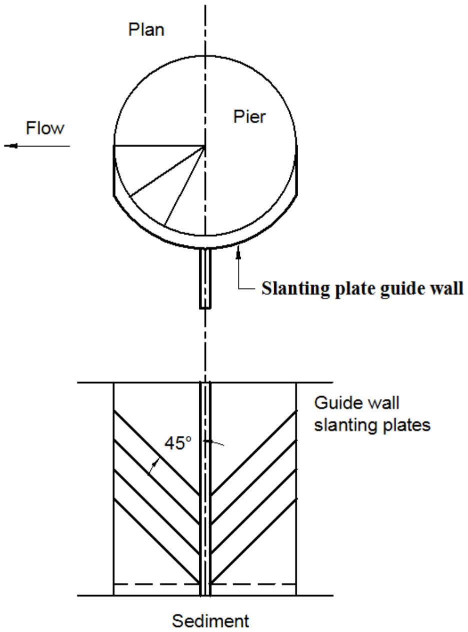

Fig.11. Slanting vanes attached to pier (after Parker *et. al.*, 1998)

5.11 Stone Gabion with Geo-textile Filter

Stone gabions consist of bundles of stones laid in wired net box and each gabion is interconnected with the neighboring stone box. Geotextile filter is used below the stone gabion. This is needed to stop the suction of sediment from the bed through the gabion due to resulting reactions of scouring mechanisms. Geotextile filter is of non-woven type.

5.12 Use of Tetrapods as Artificial Rip-Rap

Artificial materials like tetrapods (Fig. 12.) may be stacked around bridge pier. They interlock themselves by creating good bond in between. Their performance as scour protection device is good. (Parker *et. Al.*, 1998).

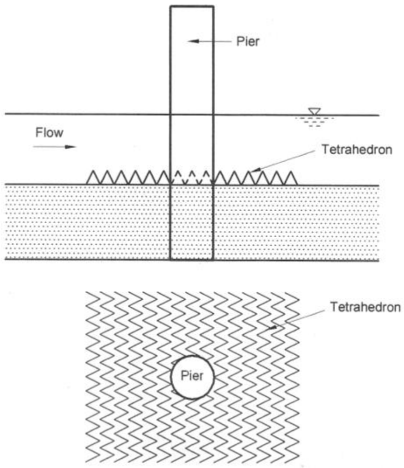

Fig. 12. Definition sketch of placement of tetrahedron frames (after Parker *et. Al.*, 1998)

5.13 Concrete Filled Fabric Mats

These are similar to riprap. Concrete filled fabric mats are laid around the bridge piers. They form rigid surface, which prevents scouring action. (Parker *et. al.*, 1998).

VI. Conclusions

Flow altering devices can be more economical, especially when the riprap material in required amount is not available near the bridge site or is expensive. However, there are certain limitations on the use of these flow altering devices to reduce the scour depth at piers. A slot may be blocked by floating debris. In addition to this, its construction is difficult. Sacrificial piles may become ineffective when the flow approaching the piers changes its direction. A thin collar plate skirting around bridge piers at or below the bed level which diverts the down flow and shields the streambed from its direct impact is therefore, a very effective mean of protection against scour. The application of collar around a single cylindrical and rectangular pier has been tested; however, scanty information is available in literature about the application of collar on group of piers.

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