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REVIEW PAPER

Bridge Failure Prevention: An Overview of Self-Protected Pier as Flow Altering Countermeasures for Scour Protection

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ABSTRACT: The inherent scour process around the bridge piers needs to be considered and crucial to ensure a sustainable and economical bridge design. The performance of any scour protection/controlling devices around bridge piers is determined on how each device counters or minimize the scouring process. Besides the usually adopted bed armouring, abundant studies have been conducted to evaluate the efficiency of flow-altering countermeasures in reducing local scour depth. The flow changes due to the rigid pier are modified in a way to reduce the impinging effect on the bed. This paper discusses the performance and feasibility of self-protected piers, defined as a pier without any additional structure built either next to or at a distance away from the pier. We paid attention to the efficiency of the proposed countermeasures in terms of possible maximum scour reduction and provide the best configuration of each self-protection pier. This review consists of analysis on the openings on pier including internal tubing, slot and pier groups, and modified pier shapes as the flow-altering, self-protected countermeasure alternatives.

Keywords: Flow-Altering Countermeasures, Openings and Modified Pier Shapes, Self-Protected Bridge Pier.

1. Introduction

Bridge is a structure that serves as public conveyance, channelling routes from point to point and is essential to be properly designed including continuous evaluation and improvement (Akbari and Maalek, 2017). It is well constructed according to the localised geological strata such as route across mountain, water bodies (river, lake,

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ocean, etc.), elevated urban highways as well as pathway through interference like landslide and flood (Richardson et al., 2003; Lagasse et al., 1997). Unfortunately, 600 cases of bridge failures around the world were documented for the last 30 years, causing handicap to operation, monetary loss and became major national concern (Prendergast and Gavin, 2014). Data shows that 60% of bridge failures reported worldwide happened due to scour and other hydraulic related issues affecting the bridge structure (Geo-Institute, 2009). Some of the high profile bridge failure cases due to scour reported in New York (in year 1987), Ireland (in year 2009), Canada (in year 2013) and California (in year 2015) (Maddison, 2012). Catastrophic impact of scour usually happened due to flood and typhoon. The estimated damage cost due to bridge failures reported by the US Federal government to be $100 million per event (from year 1964 to 1972) with an average of $20 million per year (from year 1980 to 1989) for bridge restoration works (Rhodes and Trent, 1993). Nevertheless, scour impact on isolated cylindrical pier has an extensive series of studies since the late 1950s (Prendergast and Gavin, 2014; Brandimarte et al., 2012; Keshavarzi and Ball, 2017; Khan et al., 2016; Shrestha, 2015; Keshavarzi et al., 2014; Qi et al., 2013).

Scour is defined as a natural erosion phenomenon caused when the fluid forces (by the flowing water) exceeds the weight of the particle, removes and erodes material from the bed and banks of streams. In the presence of river and marine rigid structures such as bridges, piers and abutments, the disruption and changes of flow accelerates erosion and the development of scour hole at the vicinity of those structures. The depression left behind when sediment is washed away from the bed is defined as the scour hole. The scouring process and erosive actions around the foundations of hydraulic and marine structures is one of the major parameters contributing to the structural instability and casualty.

The horseshoe vortex and down-flow are the primary flow characteristics responsible for the formation of local scour (Kwan and Melville, 1994). The flow velocity decreasing to (almost) zero as the flow approaches the upstream face of the pier, which subsequently caused an increase in pressure. Changes in both velocity and pressure gradient at the upstream of the pier resulted in a high flow velocity down-flow towards the bed. The high intensity down-flow removes the bed material, subsequently creating a hole in front of the base of the pier as it continuously washes the material away. The formation of hole resulted in the flow rolls up and creating a more complex horseshoe vortex when interacting with the coming flow (as shown in Figure 1).

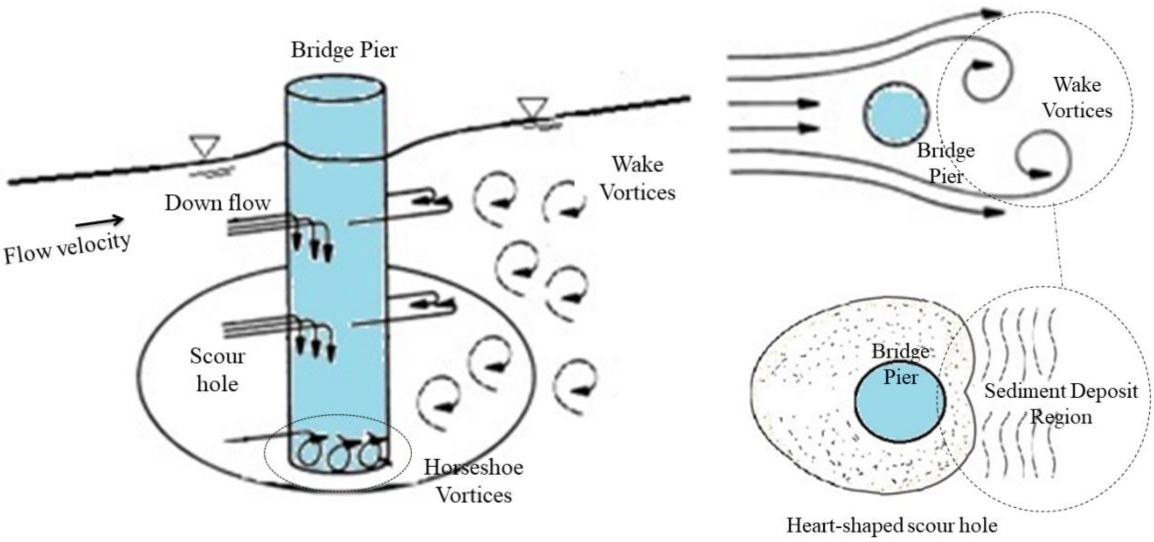


Fig. 1. Schematic diagram of developed scour hole, horseshoe and wake vortices, and heart shaped scour hole

The rate of scour hole development depends on the intensity and magnitude of the downward flow, which is directly correlates with the approaching flow velocity. As the velocity increases, the rate of bed material being transported away from the bed is greater and accelerates the development of the scour hole. The scour around bridge pier is localised, usually started at the nose of a pier (due to the downward flow) and is extended from upstream to the downstream of the pier.

In a homogeneous non-cohesive bed material, scour holes (and the maximum scour depth) begin at near the ±45° (from the midline of a circular pier), and moved upwards to the nose of the pier as the scouring process matures (Porhemmat, 2018). As the depth of scour (hole) increases, the strength of both downward flow and horseshoe vortex is reduced, which decelerates the scouring process. An equilibrium of scour depth (and hole) is reached when the shear stresses of the turbulence structure near bed is no longer able to entrain the bed material into the outer flow. The equilibrium scour hole takes the heart shape as shown in Figure 1, whereby the eroded bed materials from the upstream is deposited at a distance away from the downstream of the pier. The scouring effect to the structural pier integrity is commonly considered in the design based on the maximum scour depth. The term defines the maximum depth measured from the spatially developed scour hole, usually found at the upstream of the pier.

Based on the devastating effects a bridge scour can bring as discussed above, it deserves the attention and effort to minimise the effect caused by local scour. The bridge scour problems are not only relevant to the existing bridges but are also important to ensure safe design practices for new bridges.

Scouring around an isolated (particularly cylindrical) pier has been extensively studied since the late 1950s until present, where strong focuses were placed on scour behaviour and characteristics, prediction of maximum scour depth and scour countermeasures (Ozalp, 2013; Kothyari and Kumar 2012; D'Alessandro, 2013; Tejada, 2014). Flow mechanism of scouring around a bridge pier is very complex and have been exhaustively investigated by various researchers spanning between 1950s and present, where the reader can refer to these references for more information (Khan et al., 2016; Keshavarzi et al., 2017).

2. Scour Reduction at Bridge Piers

Since the emergence of scouring phenomenon, the fundamental target of engineers is to reduce scour and protect the structural pier integrity. Available numerous engineering solutions to minimise scour at bridge piers can be classified as flow-altering and bed-armouring methodologies. Flow-altering countermeasures aim to disrupt the complete formation and decrease the strength of the down-flow and the horseshoe vortex (Chiew and Lim, 2003). On the other hand, bed-armouring countermeasures provide a physical barrier at the bed to dampen the turbulence intensity, subsequently reduce the potential for scouring at the bed. In real practices, large and heavy units are placed within the peripheral vicinity of the pier, which protect (and in a way armouring) the finer size bed material from being eroded. Examples include riprap stones, reno mattresses, cabled-tied blocks or gabions, grouted concrete, pavement, and flexible bed armour, which due to their weight, are not easily removed by the normal flow velocity, with the exception of extreme events.

The most commonly adopted and widely used bed armouring method is riprap, by layering large stones onto the bed, around the bridge pier (Tabarestani and Zarrati, 2015). Similar to other types of bed armouring, the riprap layer relies on the heavy individual components to protect the localised bed around bridge pier against scour. Although the riprap layer is popular approach for piers in both fluvial and marine environment, the method proved not to be effective and prone to failure. In general, majority of the proposed bed armouring countermeasures managed to produce scour reduction (to a certain extent); however, they were not able to provide a consistent protection due to secondary scour and stability issue, particularly for the pier and bed attachment types. Secondary scour occurred at the edge of scour protection (structures), promoting more vortices within the piers' vicinity and accelerating the scour process (Veerappadevaru et al., 2011). Thus, the stability of the scour protection is compromised, losing its functions to hindering bed scouring and accelerating the development of local scour around bridge pier. Based on the extensive research spanning about 25 years, five failure mechanisms associated with the use of riprap layer at bridge piers have been identified (Chiew, 2003). The mechanisms of failures include due to shear, winnowing, edge, bedform-induced and bed-degradation induced. Each of these failure mechanisms plays a role in causing the eventual breakdown of the riprap layer either total disintegration or embedment failure. Through these two failures, the riprap is no longer functional dampening the (intensive) flow energy and loses its initial protection to the bridge piers.

The main function of the flow-altering devices is to reduce the shear stresses (and turbulence intensity) on bed by diverting the downward flow and hinders the complete formation of horseshoe vortex. This approach has been exhaustively conducted to reduce the depth of scour around a pier since 1950s and continuous improvement is seen coming into the 21st century. Examples of flow-altering countermeasures studied include sacrificial piles and sills, collars, and slots (Tafarojnoruz, 2010). Researchers kept innovating and discovered new methods such as surface guide panels, internal connecting tubes, threading, sleeve and downstream bed-sill (Tafarojnoruz et al., 2012a).

The flow-altering countermeasures itself can be classified into two categories, i.e. self-protection and physical attachment, shown here in Figure 3. Self-protection indicates that there is no other structure attached to the bridge pier, whereas the physical attachments marking an additional structure either next to or a distance away from the pier. The self-protection category can be further categorised into shape modification and openings through the pier. Self-protection category has high potential on minimising secondary scour (due to no auxiliary structure) and obtaining the optimum pier shape reduced the needs of additional countermeasures of bed armouring. Therefore, it is economical for long-time usage and does not require frequent maintenance. This article paid attention to the methods defined as self-protection, whereby their feasibility in reducing scour depth will be discussed in detailed.

3. Flow-Altering Countermeasures: Self-Protected Pier

3.1. Internal Openings through Piers

The internal opening through piers is an approach in the flow-altering countermeasures by creating a small size of hole(s) into the piers. The strength of the down-flow and the horseshoe vortex is weakened by allowing fractions of incoming flow to pass through the openings inside a pier or among smaller piers. The opening configurations like internal connecting tubes, pier group, and slot were discussed.

3.1.1. Internal Connecting Tubes

This type of countermeasures consists of internal connecting tubes within the pier to lessen the effect of the downward flow and the vortex formation. Abdel-Motaleb (1997) proposed an opening ($0.1d$, where d is the pier size) placed at the front side of the pier and connected with two other openings (with similar diameter) at the opposite pier sides, forming a fork-type openings. The flow would pass through these openings and the connecting tubes due to the pressure gradient. The changes in flow pattern released the stagnation of the flow in front of the pier and reduced the downward flow velocity component. Kumar (1999) also undertook a series of experiments examining the effectiveness of a pier opening in reducing scour. An opening could be effective in reducing scour, particularly if multiple openings are extended to the near bed. Even so, the efficiency of an opening reducing the scour depth depends on the approach flow angle, where high obliquity flow is not suitable.

Abd El-Razek et al. (2003) reported that several parameters like inclination angle of a tube connecting the openings β, distance of side openings with respect to the upstream opening X_I and the opening diameter d_I have effect on the scour reduction performance (Figure 2a). Varying openings, d_I/d, $X_I\ /d$ and angle of tube β were tested. It showed that the opening reduced the maximum depth scour and scour hole volume, where the best reduction of 39% occurred at the angle of opening (β = 90°, $X_I\ /\ d$ = 0.5 and d_I/d = 0.125). The depth of scour was found to be inversely proportional to the diameter of the opening at β = 90°. For circular pier, the best alignment for the openings is the T-slot type (Abdel-Motaleb, 1997; Abd El-Razek et al., 2003) (Figure 2a). The configuration of three openings research by Abd El-Razek et al. (2003) was extended by Grimladi et al. (2009a), Grimladi et al. (2009b) and Moncada-Metal et al. (2009). Their findings support the favourable scour reduction using internal tubes by 39%. Entesar and El-Ghorab (2013) studied on pier shapes (circular, square, and rectangular), opening sizes (d_I = $0.1d$, $0.15d$ and $0.2d$) and vertical spacing ($0.5d$, $1.0d$ and $1.5d$) between tubes on the scour at the upstream side. The openings were placed in a vertical uniformly spacing, starting at a distance of b above the mean bed level (Figure 2b). Openings with a diameter of $0.2b$ and vertical spacing equal to b showed that the scour depth is reduced by 45% and the volume of the scoured material has been significantly decreased up to 64%. On the other hand, the vertical spacing of $0.5b$ and b provided similar results with $0.2b$, which showed the independence of scouring profile with the spacing distances for all flow conditions. As such, the optimised condition for internal connecting tube is vertical spacing $s = b$ and opening diameter of $0.2b$.

3.1.2. Pier Group

Pier group is composed of two or more individual smaller piers having the same diameter (d) supporting the bridge span load (Figure 3). The half parts of pier group length is submerged and the rest of the pier remains above the water surface up to the bridge deck. Vittal et al. (1994) replaced a solid pier by three smaller piers at a specific angular layout in partial and full pier groups' configurations. The partial pier group has $h_g < h_u$, where h_g is the height of the pier group above the bed and h_u is the height of water level (Figure 3a.i). The full pier group extends the individual pier height above the water surface giving $h_g \geq h_u$. The full pier group configuration ensures that for high water level or extreme flow events, the pier is capable to respond in a similar manner. One of the objectives in assessing the pier groups' methods is to investigate the optimised angular θ (from the flow direction) for the pier placement, between 0 to 120° (Figure 3a). For a full pier group with varying sediment size, flow depth and pier orientation θ, the maximum scour reduction was about 39% when $\theta =$ 30°. The results indicate that the pier orientation of $\theta = 60°$ produced the maximum scour depth, and that a decrease in h_g/h_u resulted in higher scour. However, the scour mechanisms for pier group are much more complex, and design local scour depth is thus, more difficult to predict.

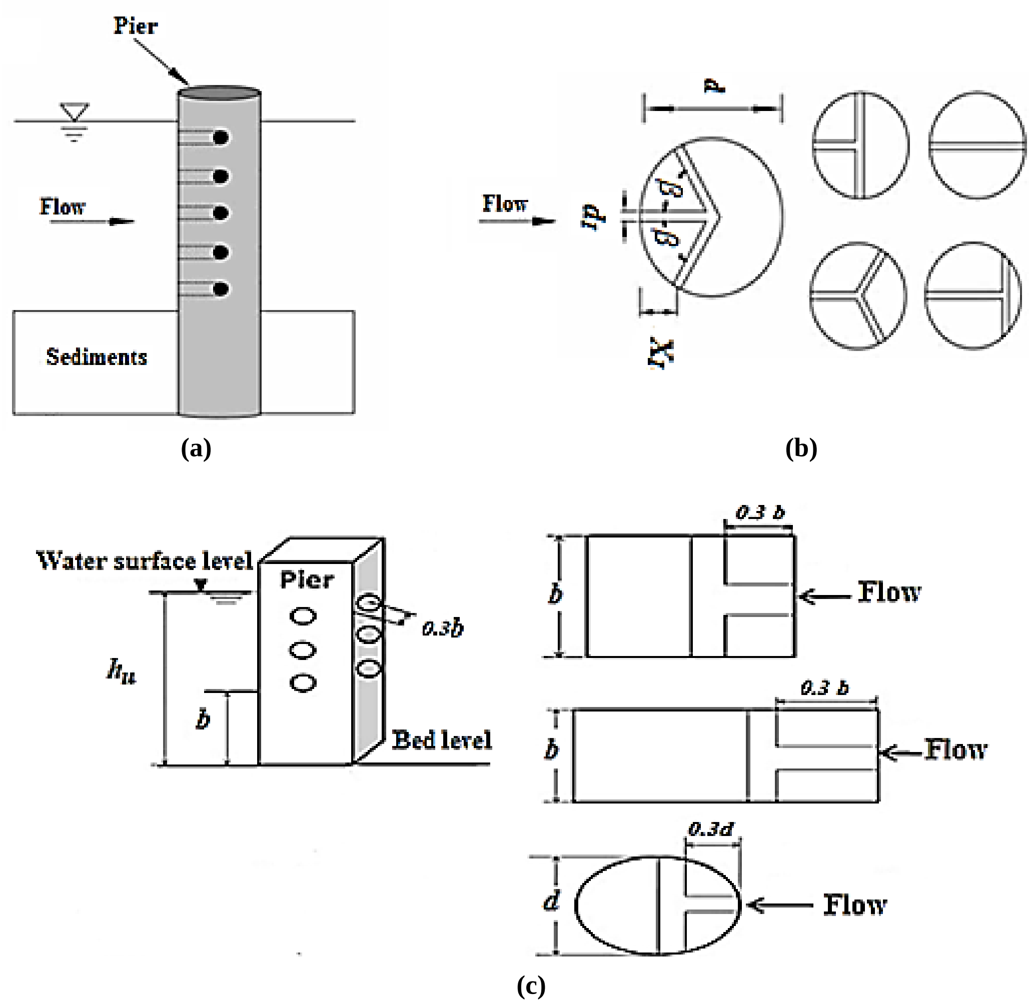


Fig. 2. Schematic diagram of internal connecting tubes: a) Side view; b) Typical cross-sections (Redrawn from Abd El-Razek et al., 2003) and; c) Different pier shapes and opening arrangement (Redrawn from Entesar et al., 2013)

Ezzeldin et al. (2006) studied the replacement of one pier with three smaller piles, and several parameters such as the Froude number, the piles' gaps and pile group orientation on scour depth. Definition sketches for the piles' arrangements used in the experimental program are shown in Figure 3. These arrangements can be classified into a single pile, three triangular piles with $\theta = 0°$ and 180°, and the spacing between piles s_p were 1, 2, 3 and $4d$. The best orientation observed was $\theta = 0°$ because, the reduced interference from the adjacent piles produced minimum scour depth and maximum reduction in scour hole depth. This indicates that pile spacing ratio has a significant effect on the dimension of scour hole. However, at higher Froude number, the angular spacing (θ) effect break off at 180° configuration produced a similar reduction in scour depth as the 0° orientation arrangement.

Lança et al. (2013) assessed the performance of emergent group of piles (with 3×4 arrangement) based on time, pile arrangement spacing s_p, and skew angle. The maximum scour depth at the rear piles (of the first column) was obtained when the skew angle is at its maximum orientation (30°) due to the upstream piles-induced energetic wake vortices. The prediction of maximum scour depth (for group of piles) using equations developed based on the single pier is often underestimated, due to the different hydrodynamic changes within the pier area. However, a safety factor of 1.2 is sufficient and deemed accurate to estimate the scour depth for the pier with group of piles (Lança et al., 2013).

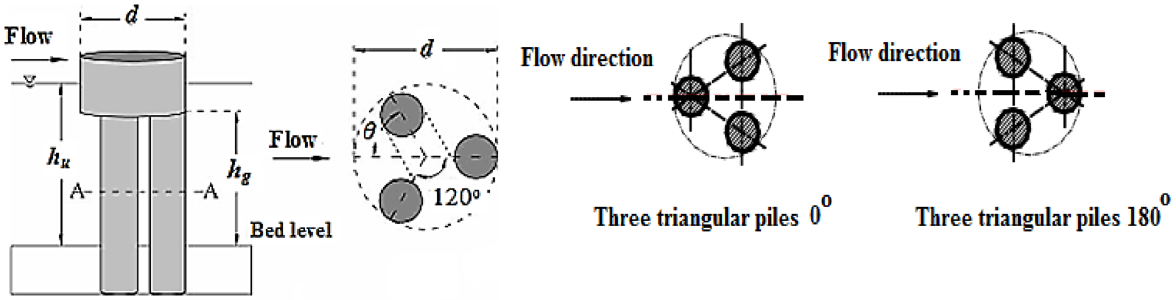
Replacing the solid pier with seven smaller piers (forming hexagonal) at three different orientations (i.e. regular, angled and staggered) was proposed by Yagci et al. (2017), here shown in Figure 3. In the regular configuration, two of the hexagon sides are aligned with the flow direction. In the angled configuration, the array is rotated by θ = 15° (that is counter clockwise from the previously discussed clockwise), while in the staggered configuration it is rotated by θ = 30°. The pile spacing varied from 0.26, 0.85, 1.44 and $2.03d$, and based on the recommendation from Vittal et al. (1994), the height of the piles was higher than water depth ($h_g > h_u$). Results showed that the array of cylinders was able to generate 27% less scour volume and 22% less scour depth in comparison to a single solid cylinder, where the best reduction was achieved for the regular arrangement with the piles were spaced at $2.03d$.

Liang et al. (2013) and Li et al. (2016) studied on the scour behaviour around twin-pile groups 0°, 30°, 45°, 60° and 90° (Figure 3c). At each angular orientation, the distance between the two piles was varied, with the s_p/d ratio, ranging from zero to five. In the case of a pile group, the scour hole is no longer radially symmetric and unbalanced, of which is expected due to the asymmetrical pier position. The location of maximum scour depth changes with s_p/d ratios and orientations. The maximum scour depth was found either in between the spacing when the $s_p/d \leq 0.6$, or at the shoulder of the piles when $s_p/d > 0.6$. Based on the maximum scour depths around a single pile, the depth around the tandem twin-pile groups are slightly smaller. On contrary, the scour depths for the side-by-side twin-pile groups are significantly larger, particularly when the pile spacing s_p/d is small. Interestingly, the measured maximum scour depth recorded for the side-by-side twin-pile groups with no separation was found to be almost twice the single piles' scour depth. For group piles, the interaction of vortices from every single pile modified the flow pattern around the piles, of which influence how the scour is developed (Li et al., 2016). The flow pattern is no longer as systematically described in Figure 1, but the wakes from the upstream pier interacts and influence the flow pattern between the piers and at the downstream pier. The angle of the incoming flow (onto the piers) is also a significant parameter in defining the maximum scour depth. As the flow skew angle increases, both the scouring rate at the initial stage and the equilibrium scour depth are accelerated due to higher intensity of horseshoe vortex. The increasing projected width of the piles onto a plane normal to the flow promotes stronger vortices.

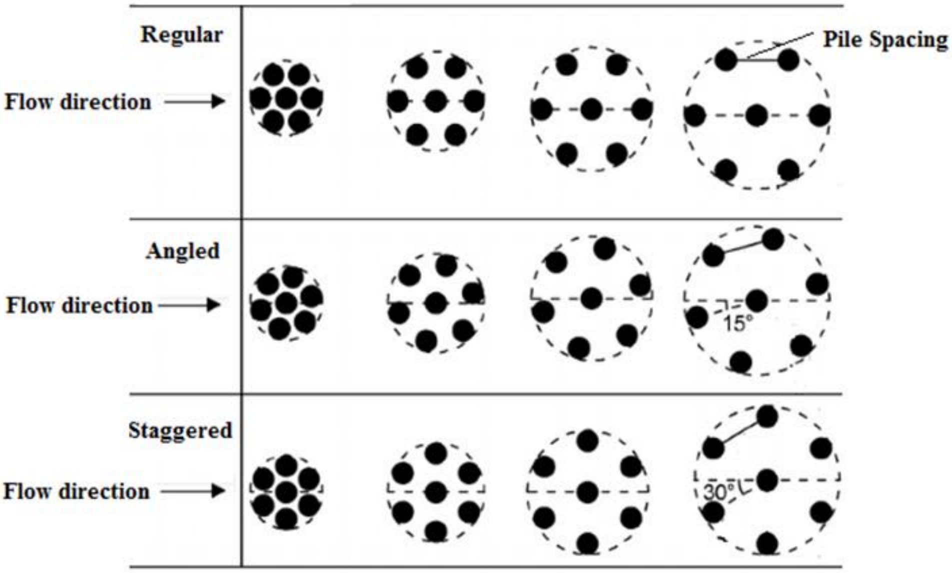
Ataie-Ashtiani and Beheshti (2006) investigated the effect of various configurations of piles setting, piles spacing s_p, flow rates and sediment sizes to reduce the maximum scour depth (Figure 3d). Eight configurations with varying geometric placement (2×1, 1×2, 2×2, 2×3, 2×4, and 3×2) were tested, whereby the piles spacing was varied from 0 to $6d$. The scour at a group of piles is different from the scour induced by a single pile, whereby the piles spacing become an important factor. Smaller pile spacing causes a larger interference between the piles (Ataie-Ashtiani and Beheshti, 2006; Papanicolaou et al., 2010). For very small pile spacing$s_p \leq 1.5d$, the pile group behaves as a single pier, as was further supported by Amini et al. (2012). The local scour developed at individual pier interferes with each other and formed a bigger hole at the upstream pile (Amini et al., 2012; Movahedi et al., 2012). The interference effect diminishes for $s_p > 2$–$4d$, whereby the scour holes and scour ridges were separated and individually formed. In tandem case, the maximum scour depth increases with increasing piles spacing and reaches the maximum value when $s_p = 2d$. In addition, the scour depth at the rear pile is consistently smaller than the single-pile case. The relatively smaller size and lower intensity horseshoe vortex at the rear pile compared to the single pile, along with the localised live bed conditions (that is the removed material from the front pile is transported onto the rear pile's scour hole) contributed to the much lower rear pile's equilibrium scour depth. For the side-by-side piles, the measured maximum scour depth is approximately 50% deeper than the single-pile's when $s_p = 0.25d$. Higher scour depth may be partly due to the increased size of the horseshoe vortex and partly to the very strong constricted flow between the two neighbouring (smaller distance) piles. The flow between the two piers is accelerated due to contraction, changing the vertical and transverse deflections of the flow around pier (Ataie-Ashtiani and Aslani-Kordkandi, 2012). However, two piers act as a single pier when $s_p < 0.25d$. By adding two more rear piles to make as 2×2 pile group increases the maximum scour depth to about 63% more than the value obtained for the single pile when the pile spacing equals to $0.25d$. Comparing to the two-pile, side-by-side arrangement for s_p/d < 4, and the scour depth increases by about 10–13% due to the reinforcement effect exhibited by the downstream piles. The lowering of bed level at the rear piles accelerates the scouring process by promoting more bed material entrainment, which leads to a deeper scour. The position of the maximum scour depth varies not only with the types of pile group, but also more importantly with the pile spacing. The evolution of scour profile and depth for the 2×3 group changes with s_p/d is interestingly similar as the profile obtained for the 2×2 group. As the number of tandem piles increases, the increased effect of compressed horseshoe vortices promotes more scouring, as was shown in the 2×3 group. The minimum scour depth was recorded for the tow-pile, tandem arrangement of the 1×2 pile group. For larger pier group, the effect of compressed horseshoe vortices is larger than the reinforcement (Papanicolaou et al., 2010). The shielding effect by the front piles reduced the approach velocity at the rear piles, which in consequence decrease the scour depth. This effect is enhanced by the sediment deposited downstream of the first row of the pile group. The pile spacing determines whether more or less scour will developed. At $s_p \leq d$, the scour depth can be twice as more whereas at $1.5d < s_p > 6d$, the scour depth reduces and the pier group works as scour countermeasure.

3.1.3. Pier Slot

A slot is an opening, cast within the pier (where the depth of the opening can be up to d), allowing part of the flow to pass through the pier itself. The basic principle of a pier slot is to divert the down flow, modifies the flow velocities around the pier and subsequently reducing the impinging effect onto the bed (Grimaldi et al., 2009b). The width, length, and location of the slots govern the performance in reducing the scour depth. The slot is responsible to minimise scour by changing flow rotation, and to delay the scouring by preventing flow streams from encountering channel bed. Although often found in rectangular, slots could be in various shapes like quadrangle or orbicular with different dimensions, and varying levels of positions.



(a)



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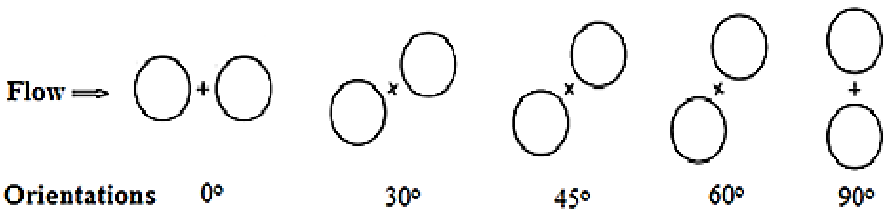

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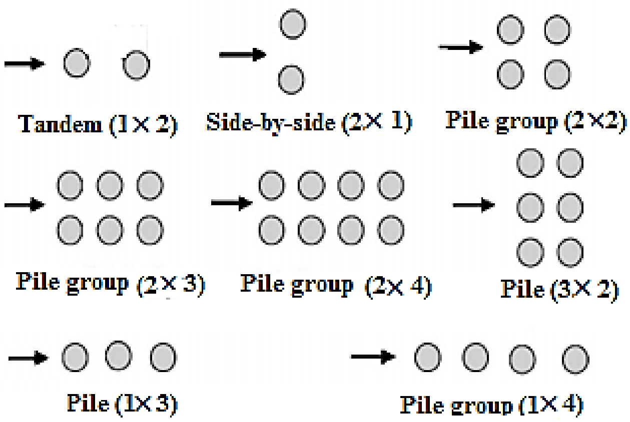


(d)

Fig. 3. a) Schematic representation of partial pier group including side view, and cross sections (Redrawn from Vittal et al., 1994 and Ezzeldin et al., 2006); b) The different of array configurations of seven smaller piers (Redrawn from Yagci et al., 2017); c) Five orientations of the twin-pile group (Redrawn from Liang et al., 2012) and; d) Pile groups used in experiments (Redrawn from Ataie-Ashtiani and Beheshti, 2006)

Figure 4a illustrates the consequential flow changes around of a cylindrical slotted pier. The work of slots as an alternative for scouring countermeasure started with Breusers et al. (1977), who tested the scour reduction potential of a cylindrical pier split along the axis of symmetry. Despite promising results of up to 30% scour reduction, this shape was not considered for further study since debris (particularly during high flow events) would highly likely clog the slot.

Tanaka and Yano (1967) performed another early study on the effect of square slot size on a cylindrical pier. Interestingly, this study found that the slot had little effect on the scouring profile. The length scale of the down flow and horseshoe vortex systems, which correlates with the pier diameter, was much larger than the slot and therefore it had no effect on scouring. It was suggested that a proportional slot size to the pier diameter ensures a better performance in altering the local flow behaviour, and subsequently further improved the efficiency of slot as scour countermeasure (Alabi, 2006).

In literature, researchers paid attention to investigate the best placement and size of slot. Chiew (1992) initiated the research by experimentally studied the effect of slot size and placement on a cylindrical pier. Tests were performed using slot widths of $0.25d$ and $0.50d$, and varying lengths (h_s) ranging from $2d$ to $4d$. Slot placement either near to surface or near bed with $h_s > 2d$, was able to produce a 20% reduction in the scour depth (Figure 4b).

The concept underlying the utilisation of slots as a flow-altering countermeasure is dependent upon on its location on the pier. Slots located close to the bed divert the down-flow through the slot opening rather than driving it into the sand bed; this reduces the intensity of the horseshoe vortex and down-flow (Chiew, 1992) (Figure 4b).

The presence of a slot through a cylinder pier alters and redistributes the local profiles of velocity and turbulence characteristics. The approach flow accelerates towards the slot, changing the velocity direction and weakening the down flow. The acceleration creates significantly higher stream-wise, slightly amplified vertical, but reducing the spanwise turbulence intensities (Tafarojnoruz et al., 2012a).

Kumar et al. (1999) investigated scour reduction efficiency by varying the lengths h_s of the slots and the angles of flow attack α. A slot width ratio of $0.25d$ and two slot length different configurations were tested, i.e. $h_s = h_u$ and $h_s > h_u$. Scour depth decreased with increasing length of the slot, h_s and the scour depth is predicted to be even less if the length of the slot is extended up to the bed, which was taken and proved by Tafarojnoruz et al. (2012a). The sinking depth slot $-h_s$ (that is the length of slot from the bed level) is suggested to be approximately the predicted scour depth based on the pier shape to achieve maximum scour reduction. Grimaldi (2009) suggested that the optimum $-h_s = 0.33h_u$ with possible 30% reduction.

Tafarojnoruz et al. (2012b) further explored on the effect of sinking depth on scour reduction. They suggested the best slot configuration with possible reduction up to 35% is with width of $w_s = d/4$, length $h_s = d_s + h_u/2$, and $-h_s = d_s$. Recall that d_s is the equilibrium scour depth. As placing slot at near water surface does not provide significant improvement on the scour reduction, it is recommended that the slot is placed at near bed and extending it well below bed level. Advantages include reduce the problem of pier buckling and less risk in getting blocked by floating debris. Sinking depth slot proved to be the critical parameter in slotted pier when Khodabakhshi and Farhadi (2014) also obtained high percentage of scour reduction up to 39.7% when $h_s = d$. It is anticipated that deeper h_s would further mitigate the scour profile around the pier.

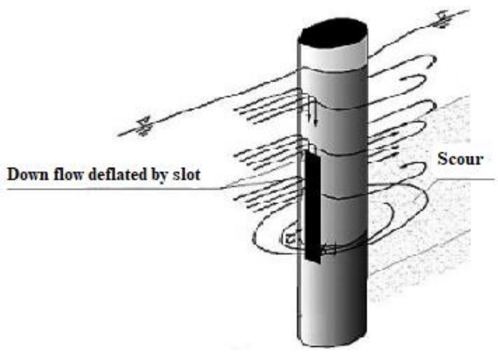
High performing slot arrangement at the bed was observed where the slots were located close to water surface were not effective in reducing local scour, whereas a scour reduction of 18% was achieved when using slots with length equal to $2d$ located close to the bed (Heidarpour et al., 2003). He tested the efficiency of slotted circular and round-nosed piers where round-nose piers showed a more convincing scour reduction than the circular pier. The work of Moncada-Metal et al. (2009) also echoed and confirmed that the optimal location for slots is near the bed. They investigated the effect of increasing h_s by systematically increased $0.28d$, starting from the bed level up to the water surface. Increasing the slot length from the bed level to the water surface resulted in an improved efficiency between 60% and 88%. Increasing h_s evidently has better scour protection (Tafarojnoruz et al., 2012b; Grimaldi et al., 2009b; Moncada-Metal et al., 2009). Higher slot depth translates into more opening, which assisted in more flow diversion across the pier and weakens the strength of down flow. The approach of flow depth plays a crucial role in predicting the scour depth since smaller scour depth was correlated with reduced effective depth of the flow.

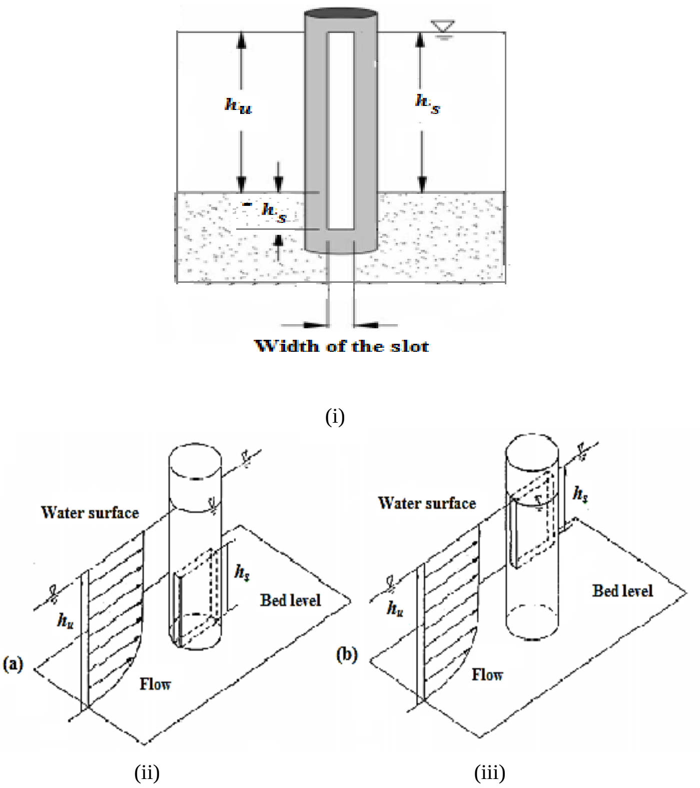
Most of the studies previously discussed utilised the width of slot as $0.25d$ (Chiew, 1992). Mahan and Jahromi (2017) conducted an interesting investigation examining the effect of slot geometrical design on the scour around circular bridge pier. Three different of slots sizes i.e. $w_s > h_s$, $w_s = h_s$ and $w_s < h_s$ were examined stretching from stream bed to the water surface. Their results indicate that slotted pier with $w_s < h_s$ has the better reduction (up to 20%) and that the h_s is more critical factor than w_s in reducing the scour depth. The slotted pier was proved efficient in the unidirectional flow, where the angle of flow impacting on the pier is in the normal direction to the pier (i.e. 0°). There were scarce studies available assessing on the efficiency of slotted pier based on the flow directions. Kumar et al (1999) investigated the effect of angle flow attack (α = 10°, 20°, 30°, and 45°) on the performance of slotted pier. The effectiveness of slots lessened as the angle of attack increases, which is the similar cases with other flow-altering countermeasures. Although a percentage of scour reduction was visible for lower angle of attack, the reduction is fully offset at 20° angle of attack where the scour depth is similar as without slots (Kumar et al., 1999). The extended slot (that is with sinking slot depth) has better performance but only up to angle of attack of 40°. At higher angle than 40°, the slotted pier ceases to be effective, no longer provide efficient protection and have similar scour profile to the piers without slots. The slots lose its functionality at higher angle due to the direction of the incoming flow directly hit the pier (as if without protection).

In the past, slotted piers were constructed with standard shape slots, whereby limited studies were available on the non-geometric shape slot. The scour depth reduction for cylindrical pier models with various types of slots such as 0° to 180° (Parallel slot), 0° to 120° (Y-slot), 0° to 90° (T-slot) and 0° to 45° (Sigma slot) was tested by Setia and Bhatia (2013) (Figure 4c). The width of all the slots was $0.25d$, the height of the slot varied from $0.5d$ to $2.5d$ and the bottom of the slot was flushed with the sediment bed. The proposed countermeasure is proved more effective when the slot is placed at near bed, as suggested by previous researches. The parallel and Y-slots, placed at d above the sediment bed are able to reduce scour by 50% and 40%, respectively. The other slots, namely T and sigma slots show far too small improvement to be of any significance. It is believed that poor performance shown by T and sigma slots is due to the slots' arrangements which only run up to the middle of the pier, resulting in a partial recoil of the flow into the upstream direction, and contributed additional disturbance in the flow. Hajikandi and Golnabi (2017) explored further the performance of the Y and T-shaped slots by varying the angle of downstream slot opening and side opening size (Figure 4d). The size of downstream scour for the Y-shaped slot was observed to reduce as the angle between the downstream slot faces was reduced. Results also indicate that Y-shaped slots were more effective than the T-shaped slots in reducing scour hole, which is consistent with the findings made by Setia and Bhatia (2013).

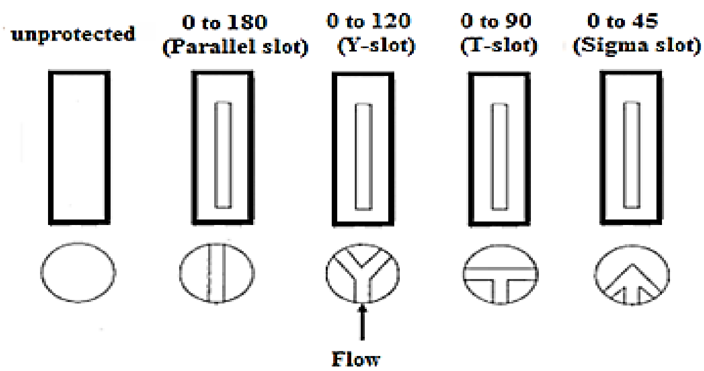
A highest efficiency of 59% in scour volume reduction was achieved for the best Y2-shaped (with 150° angle) configuration (refer to Figure 4). However, the enhanced performance is only 6% more than the usual straight slot, indicating that a complicated slot shapes and opening is not entirely necessary. Elongated pier has promising potential to reduce scour depth compared to the circular pier, which is not the case with elongated slotted pier (Azevedo et al., 2014). The reduction of maximum scour depth was smaller in case of elongated piers when compared to the circular piers, where the scour reduction for slotted circular was 10% more than the elongated slotted pier. The slot does not constitute a high proportion of reduction of scour in the case elongated piers when compared with elongated piers without the slot.

It is practically important to acknowledge that debris accumulation may occur, particularly during high flow and extreme flood events, which may block the slot opening. The effectiveness of the slots is subsequently reduced whilst pose high risk on the strength of pier structure. Despite higher slot length ensures effective scour countermeasure, the size and location of the slots must be considered to ensure continuous structural stability and integrity. Slotted pier is a useful method for reducing scour depth and is suitable for both short and long terms (Grimaldi et al., 2009b).

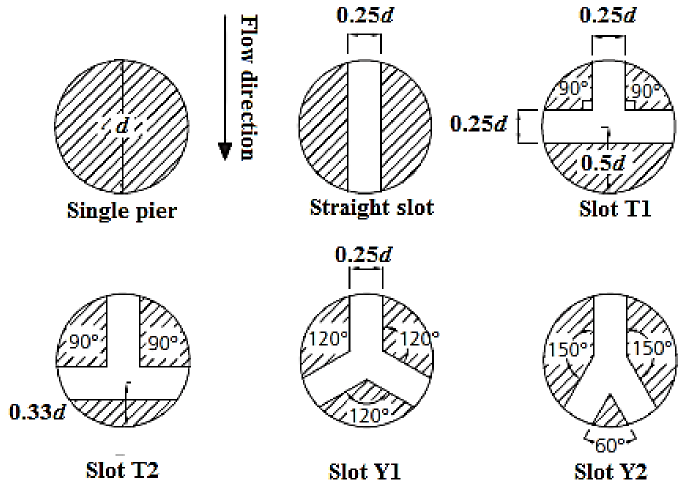




(a) (b)



(c)



(d)

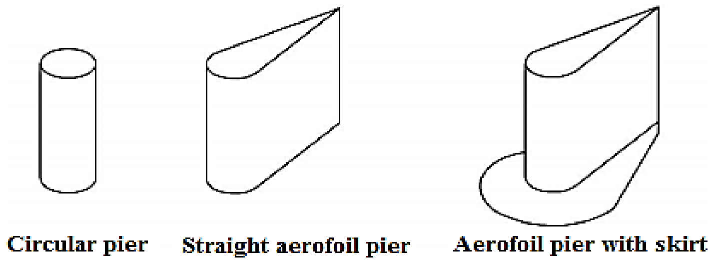
Fig. 4. Descriptions and diagram on pier slot: a) Schematic view of slotted pier and vortices around it (Redrawn from Mahan and Jahromi, 2017); bi) Sinking depth of slot (Redrawn from Grimaldi et al., 2009b); bii) Bridge pier with a slot near the bed and; biii) bridge pier with a slot near flow surface (Chiew, 1992); c) Various types of non-geometric slots (Redrawn from Setia and Bhatia, 2013) and; d) Schematic illustration of the different slot configurations(Redrawn from Hajkandi and Gulnabi, 2017)

3.2. Modification of Pier Shape

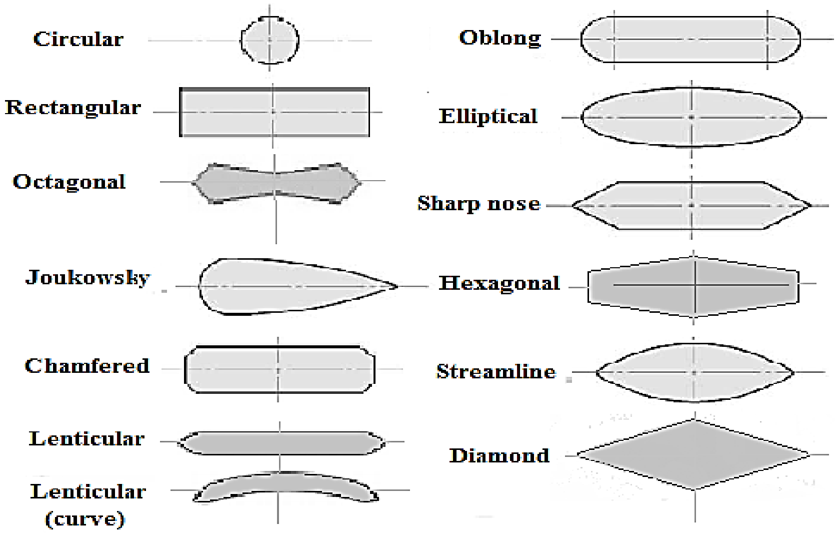
Bridge piers have been built with various shapes (depending on the design consideration), where the frequently constructed piers are the elementary geometrical shapes of circular, rectangular, and square. Since the maximum scour depths are formed upstream, especially at the pier nose, the shape at the back of pier (downstream) has minimal effect on the development of (upstream) scour depth. The influence of pier shape on the scour depth is often determined by using the shape factor. Melville and Chiew (2000) cited the work of Mostafa et al. (1994) recommended the shape factors value for uniform piers, where the term uniform describes the piers having constant section throughout their depth. The results of his study showed that a circular pier produced minimal scour while a rectangular pier with blunt ends resulted in higher degree of scouring. In practice, the shape of piers is important only if the axial flow is retained because even a small angle of attack will eliminate the benefit of a streamlined shape in reducing local scour.

In the past few years, there has been an interest in modifying pier shape to provide self-protection against the local scour. Researchers were creative and came up with various exciting arrangement, with the same objective to evaluate the possibility of low maximum scour depth, compared to the (simplest) cylindrical pier. Studies have begun to change the shape of piers from the traditional shape to aerofoil, lenticular, streamline, elliptical, to name a few, with the main objective to reduce the intensity of down-flow and hinder the complete formation of horseshoe vortex.

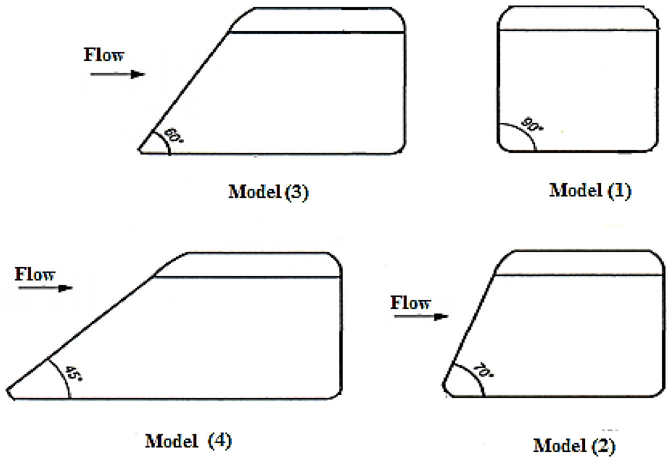
Initially, studies focused on varying geometric pier designs before experimenting different approach on external encasing with material such as plates and threaded cables, increasing the surface roughness of the pier. It was realised that most of the modified pier shape studies only paid attention to the measurement of maximum scour depth and did not go into detail on the hydrodynamic changes and influence on the formation of horseshoe vortex. Thus, this section dedicates on the practicability of the proposed design and the possible reduction of maximum scour depth. All studies discussed here were investigated under clear water conditions (that is $\frac{V}{V_c} < 1$), in a unidirectional flow with the performance of the geometrical shapes is majority was compared to the simplest circular shape.


Circular pier
Straight aerofoil pier
Aerofoil pier with skirt

(a)


Circular
Rectangular
Octagonal
Joukowsky
Chamfered
Lenticular
Lenticular (curve)
Oblong
Elliptical
Sharp nose
Hexagonal
Streamline
Diamond

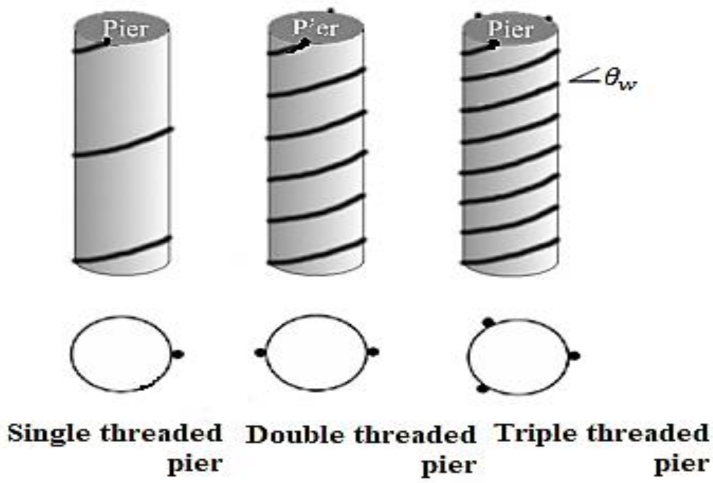
(b)


Flow
60°
Model (3)
90°
Model (1)
Flow
45°
Model (4)
Flow
70°
Model (2)

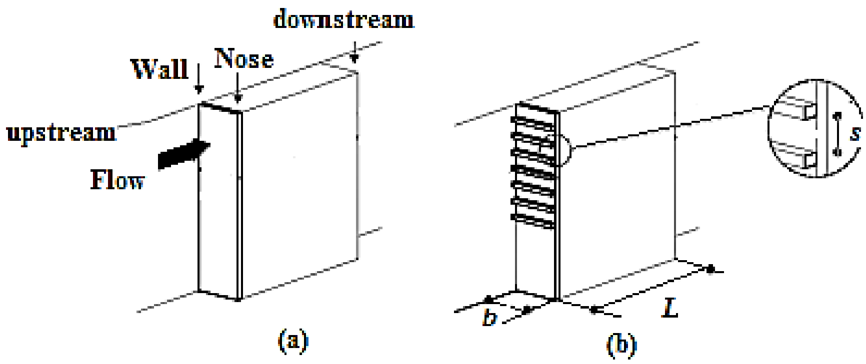
(c)


35 cm
Oblong 15°
Oblong 10°
Oblong 5°
Oblong 0°
Circular 15°
Circular 10°
Circular 5°
Circular 0°
Elliptical 0°

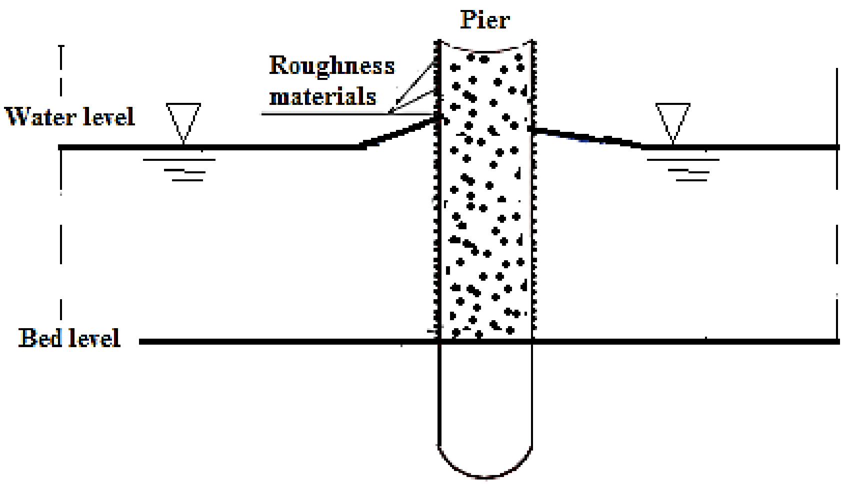
(d)



(e)



(f)



(g)

Fig. 5. Schematic diagram of: a) Circular, straight aerofoil, and skirted aerofoil piers (Redrawn based on Gibson, 2010); b) Varying pier shape models (from Ahmed Helmy et al., 2017); c) Angled-nose rectangular pier (Habib et al., 2018); d) Oblong, circular and elliptical piers models (Nimnim and Al-Khaqani, 2017); e) helically wired piers (Redrawn from Dey et al., 2006); f) Element-roughened abutment (Redrawn from Radice and Davari, 2014) and; g) Roughened with homogeneous sediment pier (Redrawn from Abdulhaleem, 2017)

Gibson (2010) conducted local scour testing under clear water conditions on circular, straight aerofoil, and skirted aerofoil bridge pier in a non-uniform erodible cohesionless bed material (Figure 5a). Results from experimental testing show ranges of 26% to 40% reduction in scour hole volume for the straight aerofoil and skirted aerofoil piers, respectively, were observed in comparison to the circular pier.

Symmetrical aerofoil shaped piers are effective in reducing the extent of local scour hole. The base-skirt provides additional effective countermeasure in reducing local scour depth, where the influence of horseshoe vortex was significantly reduced due to the intensity of impinging down-flow be dampened by the skirt. Aerofoil shaped pier reduced drag force up to 26% (based on circular pier) and has significantly less of vortex shedding than the circular pier (Drysdale, 2008). The intensity reduction in horseshoe vortex translates into less scour volume, within the similar range (Christensen, 2009). Further modifying the aerofoil shape pier by putting slots (as previously described) in the structure was found to significantly increase the efficiency of scour volume reduction to 85%.

Ismael et al. (2015) also worked with the same types of aerofoil pier, but were creative by reversely positioned of an aerofoil bridge pier that is the sharp nose is now facing the flow (hereafter named as the downstream facing round-nosed bridge pier). As the front surface area is significantly reduced, the down-flow was deflected which subsequently resulted in smaller vortex provide little impact on the formation of scour. Out of the three types studied, i.e. circular, upstream facing round-nosed and downstream facing round-nosed piers, interestingly, the newly positioned aerofoil pier provides the most scour reduction. The maximum scour depth was less about 54 % and 40%, compared to the circular pier and upstream facing round-nosed pier, respectively. The changes of turbulence profile at the front pier of downstream facing round-nosed managed to reduce the scour volume by more than 80% (than the circular pier). Relocating the bridge pier (as is located downstream facing to the flow) is an effective countermeasure in reducing local scour depth.

Al-Shukur and Obeid (2016) studied various shapes of bridge pier to minimize local scour with varying Froude numbers. The tests were performed on ten different shapes, i.e., circular, rectangular, octagonal, chamfered, hexagonal, elliptical, sharp, Joukowsky, oblong and streamline (Figure 5b). Results showed that the scour upstream of the pier is directly proportional with the exposed area of the upstream nose of a pier. Rectangular pier consistently produced the greatest scour depth while the streamline shape produced the smallest scour depth. The streamline shape was identified as the best pier shape for reducing maximum scour depth by up to 56% in comparison to circular shape.

The performance of octagonal shaped pier is also studied by Farooq et al. (2017). Using this shape, the rate of scour depth was reduced up to 9.1% compared to the circular pier. The percentage of reduction is near to the ones obtained in Al-Shukur and Obeid (2016), with 17% of scour reduction when octagonal pier shape is used. The efficacy of non-conventional shape pier was further explored by Helmy et al. (2017), introducing two new shapes i.e. lenticular and lenticular with curve (Figure 5b). Experiments were conducted along with the elliptical and hexagonal piers, with three angles of inclination piers (i.e. 0^o, 2.5^o and 5^o). Zero inclination angles were found to be the best position for all studied shapes in reducing the scour depth. The lenticular curve showed the best performance of 44% reduction from the maximum scour depth.

Kamini et al. (2018) observed that the decrease in the maximum scour depth is not only strongly influenced by the shape of a pier, but the sediment samples (of uniform and non-uniform) and flow depth too, play the important roles. Their experiments were conducted on three different shapes of piers, i.e., circular, diamond and elliptical to investigate the effect of shape on local scour with non-uniform sand bed (σ_g = 1.6, d_{50} = 1.18, and σ_g = 2.0, d_{50} = 2.36, where σ_g is the geometric standard deviation). It was observed that elliptical shape pier has the least scour depth than diamond and circular shapes throughout the experiments. An approximately 15% reduction in local scour depth can be achieved by an elliptical pier when compared to a diamond-shaped pier. Elliptical shaped pier reduced 10% less of scour depth compared to the commonly used circular shaped pier.

Habib et al. (2018) investigated the effect of nose angle to provide pier self-protection on local scour upstream of a rounded-edge rectangular pier (Figure 5c). Four nose angles were studied: 90^o, 70^o, 60^o and, 45^o. Note that as this study did not compare to the circular pier, the control pier shape is the 90^o nose angle that is the common rectangular pier. The scouring pattern was also investigated for four angles of attack α equivalent to 0^o, 10^o, 20^o and 30^o. Analysis showed that the decrease in nose angle (θ) from 90^o to 45^o decreases the scour hole dimensions from 24 to 43%, when compared to the (control) rectangular pier. The relative scour length and width also showed a decreasing trend with maximum reduction of 30% and 8% respectively, at α=0^o. Not only restricted to normal flow direction, the nose angled bridge piers managed to reduce the scour formation for up to 30^o angle of attack. The percentage of scour reduction is inversely correlated with higher angle of attack. However, even at the highest angle of 30^o, high scour reduction was visible (up to 27%), in particular for bridge pier with 45^o nose angled. The sloped nose pier modifies the shape of receiving flow impact, disrupts the uniformity of down flow, thereby reducing the strength of horseshoe vortex at the bed. Lower nose angle indicate higher surface area receiving the flow, whereby the usual formed down-flow is disrupted as the structure is no longer vertical flat surface.

Nimnim and Al-Khaqani (2017) examined the effect of non-prismatic bridge pier, compared to the commonly used prismatic shape (Figure 5d). Three well established prismatic shapes of circular, elliptical and oblong were assessed, with the non-prismatic shape was obtained by sloping at a degree of 5°,10°,15° at the middle pier section, thus creating a wider diameter at the bottom section. The sloping effect do influence the maximum scour depth, whereby the most sloping angle of 15° produced the highest scour reduction. The 15° mid-sloped oblong pier reduces the maximum scour depth by 27.6% as compared with the 15° mid-sloped circular pier shape. Increasing the mid-sloped angle from 0^o to15° reduces the maximum scour depth by percentage 62.5% for oblong and 47.3% for circular pier. The oblong piers have a slight advantage (in reducing scour depth) over circular shape for both fine and coarser sediment size. In general, the use of non-prismatic circular or oblong piers is better than the prismatic piers to reduce the maximum depth of scour. It is believed that low intensity of impinging down flow onto the bed not only significantly reduce the erosion capacity, but also disrupts the formation of high strength horseshoe vortex.

Dey et al. (2006) changes the surface roughness of a circular pile by spirally wrapped a circular pier with helical wires forming a threaded pile (Figure 5e). The wire is aligned in a sloping threading angle of θ_w depending on the cable-pile diameter ratio. Three types of threading, i.e. single, double and triple threaded were investigated and the performance is compared to the non-threaded circular pier. The decrease in scouring improved with greater cable diameter and number of thread, but with smaller threading angle θ_w. In the steady current flow, a 46.3% reduction in maximum scour depth was reported with the utilisation of triple threaded pile, wrapped with cable-pile diameter ratio of 1 at 15° threading angle. This proposed cost-effective method reduced the strength of both down flow and horseshoe vortex, subsequently promoting less scour development around the bridge pier. Their study ultimately opened a pathway for new ideas and outside of the box pier shape as alternatives to scour countermeasure. Even so, the industry is yet to visualise the concept onto the real construction of the bridge piers.

Roughening elements as the possible local scour countermeasure seem to be a popular approach. Radice and Lauva (2012) introduced roughened pier by installing horizontally 10 mm size of plate along the wall width. The vertical spacing between each roughening element is at 30 mm. The performance of roughened element is rather convincing with 14.1% and 5.3% scour reduction at the wall and nose, respectively. The roughening elements weakened the vortex action on the bed material. Despite high potential of scour reduction, the high roughening ratio (that is the total roughened elements to the pier size) is slightly bigger than the cable-pier ratio proposed by Dey et al. in 2006, 0.33 to 0.1 to be precise provides unattractive concept in terms of technical design. It is worth to highlight that the roughened elements even perform better than the slotted wall.

Radice and Davari (2014) further explored on the detailed design of roughened elements as alternatives to scour countermeasure. Varying size of plate and spacing in between were investigated for a short duration of scour development (Figure 5f). The best scour reduction with up to 25% was obtained when the ratio of roughened element width to spacing is ($s = 0.2b$). Due to their high performance during short scour process, this proposed method was suggested as the scour countermeasure mechanism for small bridges on small creeks, where the flood events occurred in a short time scale. Abdelhaleem (2017) took the similar approach to investigate the feasibility on cylindrical bridge pier. Instead of uniform geometric plate design, the surface of the pier was roughened using various sediment sizes. The uniformly distributed sediment with the mean sizes equal to $0.02d$, $0.03d$, $0.10d$ and $0.24d$, were glued around the pier.

Figure 5g provides a representation of the sediment-roughened pier. Although the roughened piers resulted in extended scour hole length upstream of the bridge piers by a percentage up to 10%, the maximum scour depth, surface area and the scour hole volume were reduced up to 29.6%, 13.1% and 42.5% (less than the non-roughened cylindrical pier), respectively.

The summary of reduction potential from the best configuration of various pier shape assessed, important characteristics including flow and sediment size were tabulated in Table 1. This table was built and presented to provide a holistic view on the shapes examined, suggested approach and its associated plausible maximum scour depth reduction. Data shows that the highest percentage of maximum scour depth reduction is 62.5%, employing the mid-slope 15^{o} oblong pier. Although the performance is better for finer sediment size, compared to coarse sediment, the percentage of reduction is still relatively high, compared to other shapes. In general, pier with sloping, nose-round, streamline and elliptical, which produced low drag forces have higher potential in reducing local scour.

4. Conclusions

Even though the findings of a large number studies carried out on flow-altering countermeasures of local scour around bridge piers have provide a better understanding of the problem, it remains unexplored in many cases. For example, in the case of internal connecting tubes and slots device there are yet studies discussing on the effect of debris during extreme flood events. In addition, these two methods of the pier slots and internal connecting tubes have possibility to weakening the concrete blocks of structures. As for all existing methods of scouring modifying pier shape countermeasures have their advantages and disadvantages, the advantages it offers self-protection for the pier. The disadvantages are increasing the cost of the piers building, and the difficulty of build some forms as lenticular (curve) shape and octagonal.

Table 1. Comparable performance of modified pier shapes to the reduction of maximum scour depth reduction around the bridge pier

References	Shape	Froude number	Sediment size d_{50}	Best shape	Maximum scour depth reduction
Habib et al. (2018)	Rounded-edge rectangular pier with slope nose 90º, 70º, 60º and 45º	0.11 to 0.79	0.39 mm	nose angle θ = 45º	24 to 43%,
Kamini et al. (2018)	Circular, diamond and elliptical	0.27	1.18 mm And 2.36 mm (σ_g=1.2 and 2)	elliptical	14.5%
Abdulhaleem (2017)	Roughened cylindrical pier	$0.23 \leq F_n \leq 0.40$	0.362 mm		29.63% -13.07%
Nimnim and Al-Khaqani (2017)	Elliptical, circular and oblong piers with mid-sloped angles of 0º, 5º, 10º and 15º	0.23 to 0.29	0.25 mm and 0.66 mm	mid-slope (15°) with oblong cross	22.5% and 27.6%
Ahmed Helmy et al. (2017)	Elliptical, polygon (hexagonal), lenticular and lenticular with the curve	0.15 to 0.33	-	lenticular (curve)	44%
Al-Shukur and Obeid (2016)	Circular, rectangular, octagonal, chamfered, hexagonal, elliptical, sharp, Joukowsky, oblong and streamline	0.17-0.28	0.71mm (σ_g= 1.14)	Streamline	56%
Ismael et al. (2015)	Circular, upstream and downstream facing round-nosed	-	-	downstream facing round-nosed*`	83 %
Radice and Davari (2014)	Roughened vertical wall abutments	0.34 to 0.48	0.9 mm (σ_g=1.2)	s=0.2b	25%
Dey et al. (2006)	Cable threaded (single, double and triple)		0.26mm	Triple threaded	46%
Gibson (2010)	Circular, straight aerofoil, and skirted aerofoil	0.383	-	skirted aerofoil	40%
Farooq (2017)	Octagonal, octagonal with pier, octagonal threaded, slotted octagonal		0.42mm	Octagonal collar	26.9%

Note: *As the scour volume. All percentages given in the table are calculated based on the scour depth obtained by the circular pier in the associated study. Where available, the standard geometric deviation of sediment distribution σ_g is given.

There is also a lack of study on new variables to determine the effectiveness of protection methods to prevent scour like ice cover, debris and waves due to winds. Natural riverbed sediments are non-uniform and armouring of beds occurs in the upper reaches of hilly rivers because of natural sorting of bed sediments by high flow velocity. Most of the studies only considered uniform sediment. An in-depth investigation has to be done to determine the adequacy of the available countermeasures in dealing with present typical flood situation. Numerous studies, to date, have often been carried out in direct channels. In some special cases, however, due to the necessity in the construction of the proposed projects or the changes caused by the river, some bridges are built on river bends about which research studies are still scarce. Subsequently, we need to study the channels with degree bend to know how they affect protection methods.

5. Acknowledgements

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