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Assessment the Effects of Different Parameters to Rate Scour around Single Piers and Pile Groups: A Review

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Abstract

Bridge foundations are subjected to local scour and in many occasions, local scour causes failure of bridges. The designer must seek ways to guide and control the process so as to minimize the risk of failure. Guidance comes both from controlled studies in laboratories and from field experiences, both the successes and particularly the failures. Despite much study, the principles of analysis of scouring are not well established and the results of various investigations often show different trends. Therefore, proper knowledge regarding local scour around bridge foundations is of utmost importance. The main objective of this research is to review the literature on local scour around bridge pier (both theoretical and experimental investigations) including scour reducing measures. This research also attempts to summarize the present state of understanding the effects of different parameters on the local scour. The review begins by introducing some basic concepts and terminology of scour before detailing the key relationships between parameters that are understood to influence the scour process. 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. The outcome of the review revealed that further work is needed on various aspects of scour.

1 Introduction

Scour refers to the removal of material by running water. Scour criteria are involved with physical conditions pertaining to the threshold of motion for the material. There is a worldwide concern on damage of bridge caused by local scour around bridge pier. The major damage to bridges at river crossings occurs during floods. Figure 1 shows the Shi-Ting-Jiang Bridge and Shi-Ting-Jiang Bridge that collapsed due to severe bridge scour during a flood.

Local scour refers to scour caused by a local obstruction such as bridge piers, abutments, and other objects that obstruct the flow in different ways. Local scour can be recognized as an abrupt decrease in bed level due to erosion of bed material by the local flow structure induced by obstruction set in the channel. Engineers have been assessing scour conditions at existing bridges and determining the need for scour mitigation [31]. Since scour prediction equations can result in estimates of scour that are different from the observed field values, designers should allow for the provisions of protective measures, such as riprap around the piers and abutments. Therefore, proper knowledge regarding local scour and its protection are very much essential for hydraulic engineers.

Experience has shown all too often that scouring can progressively undermine the foundation of a structure. Because, complete protection against scouring is usually prohibitively expensive. Major floods and the scour being produced by them can be so large as to present daunting challenges to the engineer. Natural scouring can cause dramatic changes in the plan, cross section and even location of a river bridges and are sometimes left behind "in the dry" as a consequence of changes in natural channel. Rivers with sand bed display complex systems of bed features, which translate downstream with appreciable variation in local bed levels.

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Fig. 1 Scour-induced bridge collapses **a** Shi-Ting-Jiang Bridge and **b** Pan-Jiang Bridge

2 Different Types of Scour

Scour refers to the removal of material by running water. Scour criteria are involved with physical conditions pertaining to the threshold of motion for the material. This threshold point of incipient motion can be determined by the universally famous Shield's diagram. Scouring is a natural phenomenon, but the types of scouring can be classified depending on the location and sediment transport capacity of the rivers and streams.

2.1 General Scour

General sour occurs through a change in the river regime. The result is an overall lowering of the river's longitudinal profile. In many situations, general scour is associated with human intervention through the introduction of some form of barrier at the upstream. The barrier prevents the transport of sediment into the reach. However, the flow in the river still allows sediment transport, resulting in general degradation of the bed level dams are common example of this situation. The time frame involved with the human initiated scour is relatively short, but the geomorphologic changes of rivers take long time.

2.2 Local Scour

Local scour and its control is the subject of interest of the present study. Therefore, it is necessary to understand the mechanism of local scour and the influencing factors. Local scour refers to scour caused by a local obstruction such as bridge piers, abutments, and other objects that obstruct the flow in different ways. Local scour can be recognized as an abrupt decrease in bed level due to erosion of bed material by the local flow structure induced by obstruction set in the channel. Figure 2 shows the typical appearance of local scour around bridge piers.

3 Mechanism of Local Scour

Breusers et al. [16] defined scour as a natural phenomenon caused by the flow of water in rivers and streams. It is the consequence of the erosive action of flowing water, which removes and erodes material from the bed and banks of streams and also from the vicinity of bridge piers and abutments. Mohamed et al. [49] defined scour as the lowering of the level of the river bed by water erosion such that there is a tendency to expose the foundations of riverine structures such as bridges. Scour around an obstruction, like piers caused mainly by the following three effects:

1. Horseshoe vortex combined with the down flow in front of the pile;

Fig. 2 Photograph of local scour at rectangular piers

2. Vortex shedding (wake vortex) at the back of the pile;
3. Contraction of streamlines at the side edges with surface roller [65].

Local shear stresses and the initial scour holes propagate upstream around the perimeter of the structure causing local scour to meet on the centerline [36]. The subsequent development of the scour hole is due to a strong down-flow in front of the cylinder. At the upstream of the pier, the approach flow velocity goes to zero and the stagnation pressure decreases. This causes a downward pressure gradient that drives the down-flow at the upstream face of the pier. The maximum velocity of the down-flow reaches 0.8 times the mean approach flow velocity and occurs in the scour hole at about one pier diameter below the bed level. The down-flow acts like a vertical jet and removes sediment at the face of the pier [45].

Horseshoe vortex forms due to the separation of flow at the upstream rim of the scour hole. It is characterized by a high level of turbulence and vortices. This extends downstream, past the sides of the pier before becoming part of the general turbulence. Such vortex system produces high shear stresses on the bed beneath them and it is very efficient in transporting the dislodged sediment particles by vertical jet away from the pier [3].

It has long been established that the basic mechanism causing local scour at piers is the down-flow at the upstream face of the pier and formation of vortices at the base [19, 23, 24, 62, 28, 51]. The flow decelerates as it approaches the pier coming to rest at the face of the pier. The approach flow velocity, therefore, at the stagnation point on the upstream side of the pier is reduced to zero, which results in a pressure increase at the pier face. The associated stagnation pressures are highest near the surface, where the deceleration is greatest, and decrease downwards [46]. In other words, as the velocity is decreasing from the surface to the bed, the stagnation pressure on the face of the pier also decreases accordingly i.e. a downward pressure gradient. The pressure gradient arising from the decreased pressure forces the flow down the face of the pier, resembling that of a vertical jet. The resulting down-flow impinges on the streambed and creates a hole in the vicinity of the pier base.

The strength of the down-flow reaches a maximum just below the bed level. The down flow impinging on the bed is the main scouring agent [46]. Figure 3 shows the flow and scour pattern at a circular pier. The strong vortex motion caused by the existence of the pier entrains bed sediments within the vicinity of the pier base [35]. The down flow rolls up as it continues to create a hole and, through interaction with the oncoming flow, develops into a complex vortex system. The vortex then extends downstream along the sides of the pier. This vortex is often referred to as horseshoe vortex because of its great similarity to a horseshoe [4]. Thus
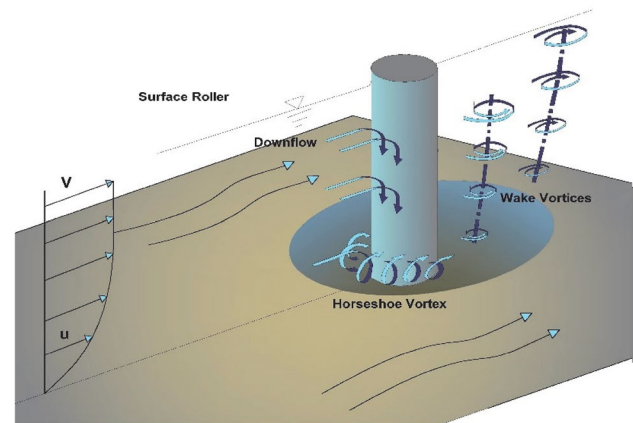

Fig. 3 Flow and scour pattern around a circular pier

the horseshoe vortex developed as a result of separation of flow at the upstream face of the scour hole excavated by the down-flow. The horseshoe vortex itself is a lee eddy similar to the eddy or ground roller downstream of a dune crest [16]. The horseshow vortex is very effective at transporting the dislodged particles away past the pier. The horseshoe vortex is as a result of scour but is not the cause of scour. As the scour depth increases, the horseshoe vortex strength diminishes, which automatically leads to a reduction in the sediment transport rate from the base of the pier [34].

As shown in Fig. 3, besides the horseshoe vortex in the vicinity of the pier base, there are also the vertical vortices downstream of the pier referred to as wake vortices [12]. The separation of the flow at the sides of the pier produces the so called wake vortices. These wake vortices are not stable and shed alternately from one side of the pier and then the other. It should be noted, however, that both the horseshoe and wake vortices erode material from the base region of the pier.

4 Classification of Local Scour

Scouring can also be classified according to sediment transport capacity as clear water scour and live bed scour. Chiew and Melville identified two main classifications of local scour at piers based on the mode of sediment transport by the approaching stream, namely clear-water scour and live bed scour. These classifications depend on the ability of the flow approaching the bridge to transport bed material [10].

4.1 Clear Water Scour

Clear water scour occurs when the bed material upstream of the scour hole is not in motion. Therefore, no replenishment of the scour hole takes place. The bed shear stress

away from the scour hole will be equal to or less than the critical shear stress, Tc (the shear stress above which bed particles will begin to be set into motion by the flow) of bed material. With clear water scour, the depth of the scour hole continues to grow until equilibrium is reached, i.e., when the combination of the temporal mean bed shear stress, To and the turbulent agitation near the bed is no longer able to remove bed material from the scour hole.

4.2 Live Bed Scour

Live bed scour occurs when sediment moves from both upstream and downstream of the scour hole. In case of live bed scour, the bed shear stress is larger than the critical shear stress of the bed material. Bed forms develop with live bed scour on the channel bed. Equilibrium scour depth in live bed scour is reached when the time average amount of sediment entering the scour hole is equal to the time average amount of sediment leaving the hole.

As discussed in previous section, scour is the erosion of sediment from around the foundation of a structure situated in flowing water, such as in river and coastal environments. Images of the scour process at different points through time around a cylinder are shown in Fig. 4. Under unchanging flow conditions (such as a unidirectional current with constant depth-averaged velocity) the scour process evolves through time with a distinctive curve when considering the increase in scour hole depth [59].

5 Influence of Parameters

In the literature, a classification of the particular flow processes and their direct influence on scour evolution is widely used, which can be subdivided by means of structural type and typical diameter as well as by the nature of load. Besides the bed material properties and structural dimensions, influencing factors of load components are mainly given by

(1) approach flow velocity, (2) flow depth, (3) pier width, (4) gravitational acceleration, (5) pier length if skewed to the main flow direction, (6) size and gradation of the bed material, (7) angle of attack of the approach flow to the pier, (8) pier shape, (9) bed configuration, and (10) ice or debris jams.

According to Breusers et al. [16] and Ansari et al. [1] the parameters listed above can be grouped into four major headings, viz.
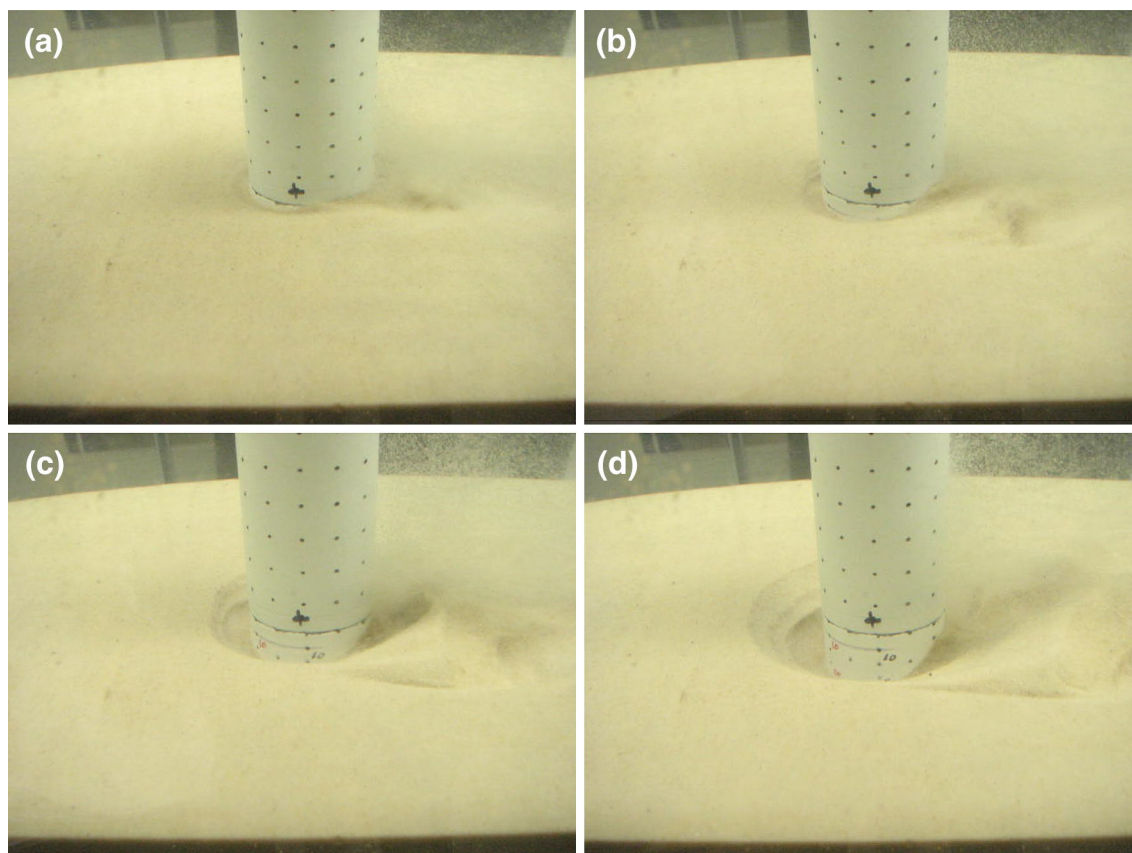

Fig. 4 Initial stages of scour development at a cylindrical pile: **a** 3 s, **b** 15 s, **c** 42 s, **d** 105 s after the initiation of scour

- Approaching stream flow parameters: Flow intensity, flow depth, shear velocity, mean velocity, velocity distribution and bed roughness.
- Pier parameters: Size, geometry, spacing, number and orientation of the pier with respect to the main flow direction (i.e., angle of attack).
- Bed sediment parameters: Grain size distribution, mass density, particle shape, angle of repose and cohesiveness of the soil.
- Fluid parameters: Mass density, acceleration due to gravity and kinematic viscosity.

5.1 Flow intensity

Flow intensity is defined as the ratio of the shear velocity to the critical shear velocity or the ratio of the approach mean velocity to the critical mean velocity [44]. Under clear-water conditions, the local scour depth in uniformly-graded sediment increases almost linearly with velocity to a maximum at the threshold velocity [10]. The maximum scour depth is reached when the ratio of shear velocity to the critical shear velocity is equal to one and the corresponding maximum scour depth is called the threshold peak. As the velocity exceeds the threshold velocity, the local scour depth in uniform sediment first decreases and then increases again to a second peak, but the threshold peak is not exceeded provided the sediment is uniform. The same trend was observed by [36, 4, 47, 9]. The general conclusion was that the maximum local scour depth in uniform sediments occurs at the threshold condition for clear-water scour conditions.

5.2 Flow Depth

The influence of flow depth on the scour depth has been discussed by many authors [36, 52, 13, 7]. The presence of the pier in the channel causes a surface roller around the pier and a horseshoe vortex at the base of the pier. Flow depth affects local scour depth when the horseshoe vortex is affected by the formation of the surface roller (or bow wave) that forms at the leading edge of the pier. The two rollers, (i.e., the bow wave and the horseshoe vortex) rotate in opposite directions. In principle, as long as there is no interference between the two rollers, the local scour depth does not depend on the flow depth but depends only on the pier diameter. In such an instance, often called deep flow, the local scour is said to occur at narrow piers. As the flow depth decreases, the surface roller becomes relatively more dominant and causes the horseshoe vortex to be less capable of entraining sediment. Therefore, for shallower flows, the local scour depth is reduced. Subsequently, in a very shallow flow, the local scour is dependent on the flow depth and the local scour is said to occur at a wide pier. Melville and Chiew [44] claimed that these trends are evident in the laboratory data of many researchers, including Chabert and Engeldinger [7], Laursen and Toch [36], Breusers et al. [16] and Ettema [56].

The variables influencing the equilibrium scour depth at culvert outlets are listed as below

$$d_s = \int \left(\rho, \mu_0, u_0, d_0, H, W, W_0, g, \rho_s, d_{50}, \sigma_g, K_s \right) \quad (1)$$

where d_s = maximum depth of scour, ρ = density of water, μ_0 = dynamic viscosity of water, d_0 = outlet height of culvert, H = depth of water in the downstream of the receiving channel, W = width of the receiving channel W_0 = width of the outlet, g = acceleration due to gravity, ρ_s = density of sediment bed material, d_{50} = median sediment size σ_g = geometric standard deviation of the bed material K_s = shape factor of culvert.

5.3 Grain Size, Sediment Coarseness and Gradation

The sediment coarseness as defined by Melville and Coleman is the ratio of the pier width (D) to the mean grain size of the sediment material (d_{50}) (i.e. D/d_{50}) [10]. According to the authors, the local scour is affected by the sediment size as long as the sediment coarseness ratio $D/d_{50} < 50$. For $D/d_{50} > 50$, the local scour is not influenced by the sediment coarseness. For pier scour, Sediment gradation is usually characterized using the geometric standard deviation of the sand size, $\sigma_g = (d_{84}/d_{16})1/2$. For natural river sand, σ_g is about 1.8 while for uniform sand σ_g is about 1.3 [7]. Ettema et al. [15] studied the effect of sediment gradation on the local scour depth at a circular pier under clear-water scour conditions. He conducted his experiments at the threshold of motion condition for the median size of the sediment material used. The conclusion reached was that the rate of scour hole development and the equilibrium scour depth decreases as the standard deviation of the particle size distribution increases. For a non-uniform sediment material (i.e. at a higher value of σ_g), armouring occurs on the approach flow bed and at the base of the scour hole around the threshold condition, $\frac{u}{u_c} \cong 1$. The armouring at the base of the scour hole leads to a considerable reduction of the local scour depth. However, sediment non-uniformity has only a small effect on the scour depth at a high value of $\frac{u}{u_c}$, where the flow is capable of entraining most grain sizes within the non-uniform sediment.

5.4 Shape of Pier

Pier shape is an important parameter in determining the amount of local scour a pier will experience. The effect of the pile are mainly determined by its size although there are other effects, which may be significant, such as shape of the pier, angle of attack of the flow with respect to the

pier axis, the ratio of the channel width to the pier width, the aspect ratio, surface condition of the pier, orientation of the pile groups, in the case of a pilled foundation, blockage of flow channel by debris collecting at the pier.

Two classifications of piers exist, namely blunt-nosed and sharp-nosed. The blunt-nosed pier is characterized by the presence of a horseshoe vortex system about the upstream end of the pier where maximum scour occurs. In contrast, the sharp-nosed pier divides the flow, and experimental observations have shown the horseshoe vortex system does not form about the upstream face. When perfectly aligned with the flow, there is no scour at the nose of the sharp-nosed pier. However, when tested at an angle to the flow, the pier is easily converted to the blunt-nosed pier class and even deeper scour may occur. Chabert and Engeldinger tested the range of pier shapes where the lenticular pier achieved the best result with a reduction in scour depth with reference to the basic rectangular shape of around 27% [7].

Another influential study of pier shapes was undertaken by Laursen and Toch, who investigated local scouring around bridge piers and abutments [36]. It was shown that streamlining does reduce the depth of scour, but this effect is lost if the pier is not aligned with the flow. Guidelines given by Melville suggest that the shape of a pier can influence scour depths by up to 20%. A square-nosed pier experiences scour depths about 20% greater than a sharp-nosed pier, and 10% greater than either a cylindrical or round-nosed pier. It is noted that shape effects are neglected for flow angle in excess of 5° [17]. Figure 5 shows a schematic illustration of some pier shapes. The effect of pier shape has been reported by many researchers [42, 36, 4, 13, 15, 20, 32, 48, 53, 70].
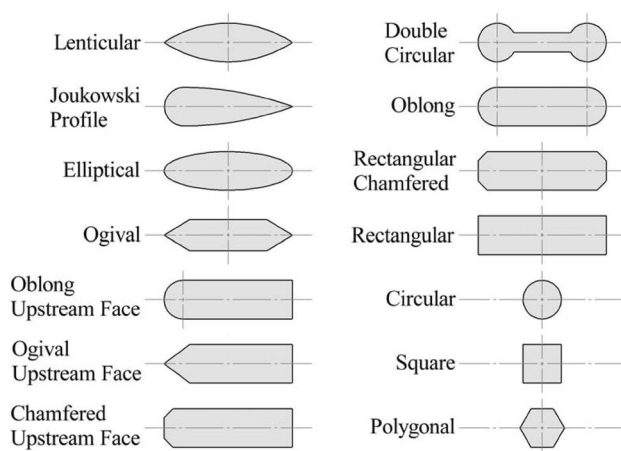

Fig. 5 Schematic illustration of some pier shapes

5.5 Pier Slot

The purpose of a slot passing through the pier is to divert the down flow through the slot opening, thereby reducing its erosional capacity. The width, length, location and protective ability afforded by this countermeasure is still under discussion. Breusers et al. tested the scour reduction potential of a cylindrical pier split along the axis of symmetry [42]. Results produced scour reduction of 24% to 38%. Tanaka and Yano tested a cylindrical pier with a square hole directed to the main flow direction and concluded that the scale of the down flow and horseshoe vortex system was much larger than the slot and therefore it had no effect on scouring [45]. The efficacy of slots, of different lengths and at different angles of attack, was studied through experiments by Kumar et al. [33]. A slot is shown to be effective in reducing scour, particularly if it extends into the bed. Nevertheless the slot is practically ineffective if the approach flow has a high obliquity with respect to the slot.

5.6 Alignment or Angle of Attack

The effect of alignment, also referred to as the influence of the angle of flow attack, is the effect of the angle between the direction of the bridge pier and the direction of the flow. The depth of local scour for all shapes of pier is highly dependent on the alignment or orientation of the pier to the flow. However, the exception to this is a circular pier. As the angle of attack increases, the scour depth increases due to the increase in the effective frontal width of the pier. The effect of the pier length is insignificant if the pier is aligned with the flow. If the pier is skewed to the flow, the pier length has a substantial effect on the scour experienced. For example, Melville and Coleman [45] demonstrated that the local scour depth at a rectangular pier of an aspect ratio of eight is nearly tripled at an angle of attack of 300 when compared to the same pier aligned with the flow. The depth of scour has been shown to be functionally related to the projected width of the pier. Here, the projected width of the pier is the width normal to the flow direction. Therefore, the projected width of the pier, which increases with the angle of attack of the flow, is related to the scour depth. As the angle of attack increases, the point of maximum scour depth moves along the exposed side of the pier towards the rear, and the scour depth at the rear becomes greater than at the front face of the pier. Multiplying factors for angle of attack for different pier length–width ratios proposed by Laursen and Toch are commonly used [36]. In general, angle of attacks greater than 5–10° are to be avoided [3]. In practice, the angle of attack at bridge crossings may change significantly during floods for braided channels, and it may change progressively over a period of time for meandering channels.

5.7 Effect of Time

Local scour may occur for two distinct sediment transport conditions: (i) Clear-water scour, which occurs when the bed sediment particles are not entrained by the undisturbed approach flow and consequently the sediment material removed from the scour hole is not refilled by the approach flow; (ii) Live-bed scour, occurring when the approach flow has the capacity to entrain the upstream bed material and the scour hole is continuously supplied with sediment from upstream. Figure 6 illustrates the typical scour depth time evolution of those distinct situations (Clearwater and the live-bed). Clear-water equilibrium scour depth is reached when the flow becomes unable to remove particles from the scour hole. Equilibrium scour depth in live-bed conditions is attained when the average amount of sediment leaving the scour hole equals the average amount coming in; it is reached much faster than in clear-water flow conditions and it fluctuates around an average value reflecting the passage of bed forms.

Chabert and Engeldinger assumed that equilibrium occurs when the scour depth does not change "appreciably" in time [7]. Ettema reported that there are three distinct phases of the scour process [15]. He named them as the initial phase, principal phase and equilibrium phase. These phases are as follows:

1. The initial phase is characterized by the rapid scouring due to the down flow at the pier upstream face; the horse-shoe vortex does not play an important role and the sediment transport starts at the sides of the pier;
2. The principal phase is dominated by the horse-shoe vortex action; during this phase, scour occurs in a narrow strip around the pier. As the scour hole develops, the strength of the horse-shoe vortex and the down flow gradually become unable to remove sediment from the entrainment zone;
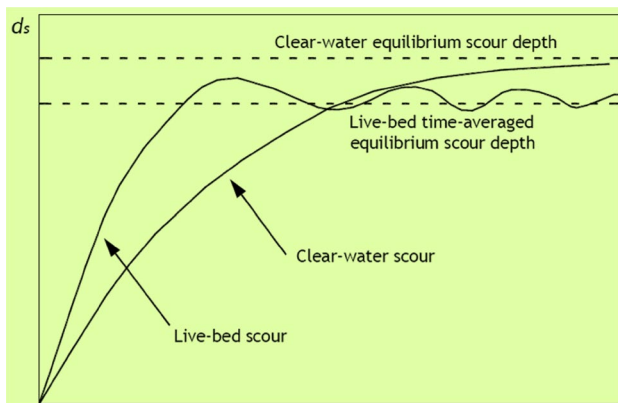

Fig. 6 The typical scour depth time (clearwater and the live-bed)

3. The equilibrium phase is reached when no further "significant" development in the scour hole exists.

Franzetti et al. described equilibrium as the state of scour development where no further change occurs with time and stressed that this condition may take an infinite time to occur [20]. Oliveto and Hager argued that equilibrium cannot be achieved in finite time and that the scour hole never stops to develop; they have stated that end scour as the equilibrium state between vortical agents and the resistance of sediment to be scoured does not normally exist [52]. In opposition, other authors assume that equilibrium can be observed in finite time. Several methods can be found in the literature for the identification of the onset of the equilibrium phase. Ettema defined the time to equilibrium, te, as the time after which less than 1 mm of incremental scour depth is achieved in a 4 h period [15]. Cardoso and Bettess suggested that the equilibrium phase is achieved when the slope of plots of the scour depth versus the logarithmic of time changes and tends to zero. However, Radice et al. pointed out that this approach may also fail since scouring can be triggered again, after the observation of long lasting quasi-horizontal plateaux [55]. Melville and Chiew assumed that equilibrium is practically achieved when the increment of scour depth is less than 5% of the pier diameter in 24 h [44]. Coleman pointed out that the equilibrium scour hole may continue to deepen at a relatively slow rate long after equilibrium conditions were thought to exist; they have extended the criterion of Melville and Chiew and defined the equilibrium time as the time at which the scour rate reduces to 5% of the smaller of the foundation length (pier diameter or abutment length) in a 24 h period [11]. Grimaldi suggested a more restrictive criterion: according to this author, equilibrium is reached when scour rate is less than 0.05Dp/3 in 24 h [22].

5.8 Contraction Ratio

The equilibrium depth of local scour at a pier is affected by the contraction ratio. For the purpose of experimental investigations, the width of an experimental flume should be at least eight times the pier size for clear-water scour conditions so that blockage effects are minimized. For live-bed scour, the flume width should be at least 10 times the pier size for scour depths not to be reduced due to bed features being modified as they propagate through the constriction.

5.9 Froude Number

An investigation by Jain and Fischer concluded that scour depth under live bed conditions is influenced by the flow velocity and results of the experiments were presented by plotting scour depth versus the Froude number, F_r [29]. They concluded that for $F_r > F_{rc}$ (Froude number at

critical velocity), scour depth first slightly decreases and then increases with an increase in Froude number. Scour depths at high Froude numbers were found to be higher than maximum clear water scour depth. Since the Froude number is a linear function of approach velocity, it can be said that for a given approach depth, scour depth is directly proportional to the approach velocity.

Scour depth at piers does not scale linearly with pier width unless there is more or less complete geometric similitude of pier, flow and bed sediment particles [15]. Many laboratory experiments have been undertaken to model sand bed river but the model bed material relative to the pier size is larger than its scaled counterpart in the field. Ettema et al. [15] show that scour depth relative to pier width may increase with pier Froude number. Flow field similitude requires preservation of flow patterns such that pressure head along flow path scale directly proportional with the geometric scale relating a model pier in the laboratory to a pier in the field.

5.10 Pile Diameter

One of the most influential variables on scour depth is the pile diameter, which is used extensively to normalise the scour depth enabling data from different piles to be collapsed onto one curve. This is because the scour depth increases approximately linearly with pile diameter (Raudkivi and Ettema [57]). Raudkivi and Ettema also found that the time to equilibrium scour depth increases with pile diameter because the scour hole volume is proportional to the cube of the pile diameter and hence larger piles have larger scour holes which take longer to erode [57].

5.11 Velocity

When discussing the relationship between ambient depth-averaged velocity and scour depth, it is important to differentiate between the clear water and live bed regimes. The use of a non-dimensional velocity parameter, $v_i = v/v_{cr}$, known as flow intensity which describes the velocity condition in respect to the critical velocity for the sediment, distinguishes between the live bed and clear water regimes depending on whether the flow intensity is above or below 1. The use of flow intensity rather than flow velocity not only takes into account regime change but also enables data from different sediment sizes which have different critical flow velocities to be collapsed onto one curve. Some researchers prefer to normalize shear stress or shear velocity parameters with the corresponding critical value as these are the true drivers for scour, but the trends are essentially equivalent, and the velocity intensity parameter is more commonly used due to ease of measurement.

Melville [43], Chiew [9], Raudkivi and Ettema [57] and Raudkivi [56] reported that the equilibrium scour depth increases almost linearly with flow velocity through the clear water regime. Melville plotted a large set of laboratory data which despite some scatter demonstrates this trend clearly [45]. Melville showed that the timescale of the scour process also increases linearly in the clear water regime to a peak at critical velocity, before decreasing through the live bed regime mirroring the scour depth trend and indicating that larger scour holes take longer to erode [43].

6 Scour at Complex Structures

Due to interaction and interference of flow and sediment transport processes, scour pattern, depths and extents at pile groups might differ from single pile formations. Therefore, distances and alignments of the piles are additional key factors influencing the scour process. In addition to the local scours at single piles, global scour formation around the entire structure may occur due to local obstruction, flow constrictions and further turbulence generation, leading to larger scour depths with deepest local scours typically formed at the edge corners of a pile group. As no general formulation for scour at pile groups has so far been found due to numerous influencing factors mentioned above, generally leading to differences in scour formation and depths, the reader is referred to the respective literature for further information, see e.g. [27]. Mechanisms affecting scour at pier groups summarized by Gothel are as follows [21]:

6.1 Reinforcing

When piles are placed such that their scour holes overlap, the bed level behind the scour hole decreases, and the overall depth of the scour hole increases.

6.2 Sheltering

The velocity of flow at the face of a pile decreases as the flow IS diverted due to the presence of an upstream pile.

6.3 Shed Vortices

The scour depth at a pile may increase if the pile is placed in the path of vortices shed from an upstream pile. The scouring potential of these vortices depends on flow velocity and position of the downstream pile.

6.4 Compressed Horseshoe Vortex

An increase in scour depth will occur when two or more piles are placed transverse to the flow and in close proximity to each other.

In addition to the aforementioned, comparatively simple cylindrical structures, complex foundation types are widely used in offshore engineering, especially for offshore wind turbine foundations and platforms like tripods, triples, jacket, bucket, gravity base or semi-submersible floating platform foundations. Regarding scour formation, only little detailed and general knowledge exists for such complex types. At present, an estimation of scour depths is therefore often carried out by use of an equivalent diameter describing the overall foundation and taking this as an input value for one of the classical scour depth formulations, originally derived for single pile structures. Due to the complexity of occurring flow and scour pattern, this approach is however affected by huge uncertainties. Furthermore, a direct application of pile scour approaches typically leads to unphysically large, theoretical scour depths. Experience on scour around complex offshore structures is therefore mainly gained by means of physical modeling for the particular cases. A direct application to other foundation types is nearly impossible in most cases. As offshore foundation structures are mainly constructed and erected for industrial purposes, experiments on scour risk and protection mechanisms are mainly carried out in this context, for which reason only little information is made publicly available. Regarding scour development around such foundations, it can generally be stated that both the flow and hence the resulting scour pattern may significantly differ from those of single pile. In case of composed structures, e.g. given for the majority of offshore wind turbine foundations with a cylindrical tower on top of a submerged substructure, flow fields in the upper part around the structure might be similar to cylinder regimes. The ground may however not be affected by these flow conditions due to blockage and flow disturbance through the structure itself.

7 In-Situ Measured Scour Development

Similar to experimental results on scour development at complex offshore foundations, field measurement data on scour have hardly been reported in recent years. With the upcoming change in energy supply and thus resulting erection of new wind farms, more information on actual scour development cases is now available [27, 60, 27, 68, 67, 63]. Some results are exemplary summarized here. Rudolph et al. report of and analyze scour measurements for different (typical) types of offshore structures [60]. Their analysis includes bathymetry survey charts; underwater video records and spud can penetration reports. Furthermore, results are compared to empirical formulations. For a monopile foundation with $D = 6$ m in shallow water, i.e. water depth between 5.2 m and 11 m, erected in 1997 without scour protection, a maximum scour depth of 6.3 m (S/D = 1.05) was observed after about 4.7 years, while an equilibrium stage was not reached. Comparison to empirical scour depth formulations gave best results when applying to flow and tidal flow formulations. In the same report, scour development around a jacket structure, again erected in 1997 but in moderate water with a depth of 24 m is given. The so far measured scour depths at the single platform legs reach up to 2.0–3.5 m, while a large global scour hole with a radius of 50 m developed around the entire structure.

A summary of various wind park monitoring campaigns is given in Whitehouse et al., all regarding monopile foundations [67]. At Barrow wind farm location, relative scour depths S/D of 1.21 were measured several months after erection. For monopiles installed in Kentish Flats, relative scour depths around 0.34D were observed, while depths of up 1.38D were recorded at Scroby Sands wind farm, altogether showing highly different depth developments, depending on the given load conditions at the particular locations.

8 Experimental Studies

Numerous investigations on scouring phenomena around offshore structures have been carried out in the last decades. Data have predominantly been obtained from laboratory tests in wave and current flumes, wave basins or combined laboratory facilities, see e.g. compilations in [9, 7, 11, 57, 60, 25, 69] in recent years additionally by the use of numerical model data. Laboratory tests often led to empirical formulations on spatial and time-dependent scour developments. Due to a lack of field data, a validation of the results with regard to prototype scales has rarely been possible. On the whole, the number of investigations on scour caused by waves or a combination of waves and currents is rather limited compared to investigations on scour caused by unidirectional currents like in river bed situations [6]. Furthermore, the main focus has been on comparatively simple structures like vertical cylinders, which might be due to the fact that cylindrical piers are widely used in fluvial and marine environments. Furthermore, cylindrical structures led to several damages in recent years, e.g. as foundations for bridge piers. Equilibrium scour depths were mainly regarded, which are the most important factor for overall structural dimensioning and stability analysis.

Potential maximum local scour depth from experimental studies in the laboratory may vary significantly in real field because of the following reasons:

1. Formulae are based on limited data
2. Simplified conditions in the lab
3. Generally laboratory flumes are rectangular in cross section and these have smooth and fixed walls
4. In real field situations, channels are non-rectangular in cross section with mobile banks and over bank flow

occurs frequently and lateral flow distribution is non-uniform
5. Generally predictive scour equations from laboratory flume tend to estimate excessive pier scour than real field
6. Complexities of flow field
7. Variation in channel boundary materials

Hodi studied the effect of blockage and dens metric Froude number on bridge pier local scour by doing experimental studies [26]. Experiments were conducted in two flumes of different widths utilizing piers of various diameters. Significant blockage effect (greater difference in scour geometry) was observed increasing the blockage ratio from 2.2 to 5%. Further he noted that small changes in the absolute value of dens metric Froude number can have a large influence on maximum scour depth and scour geometry. Mohamed et al. carried out laboratory experiments and field data studies to obtain pier scour information [50]. They compared the measured scour depths obtained from the laboratory experiments with computed scour depths using selected formulae. It appears that Laursen and Toch [36] and the CSU formulae give reasonable prediction, while Melvile and Sutherland [47] formulae appear to over-predict the depth of scour for both the laboratory model and field prototype. The over prediction in the case of field results is even greater compared with that of the laboratory model.
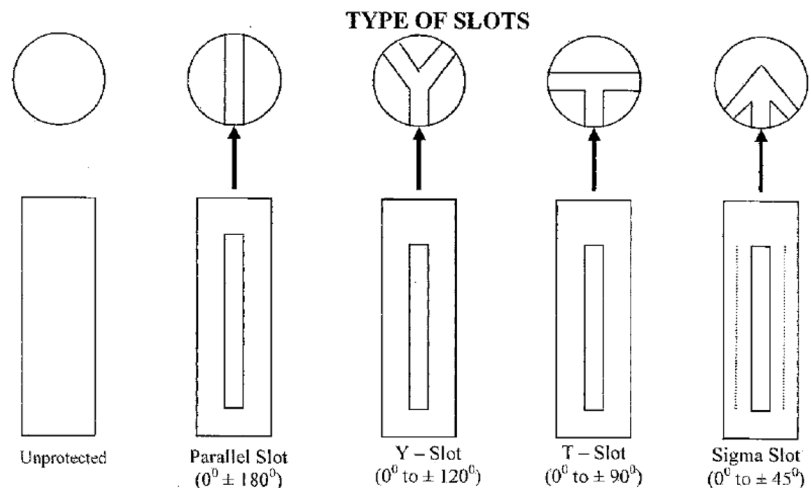
A laboratory investigation has been carried out by Baldev Setia1 and Upain Kumar Bhatia to determine the scour depth reduction for cylindrical pier models with rectangular slots [61]. They suggested that a parallel slot and a Y-slot with optimum dimensions as 0.25D wide, 1D above and 0.75D below the sediment bed are able to reduce scour by 50% and 40% respectively. Figure 7 presented Different types of slots based on the experimental studies on the scour reduction by slots through a pier.

Ettema et al. experimentally established a direct trend (values of normalized scour depth increased when cylinder diameter decreased) between equilibrium scour depth and the intensity and frequency of large-scale turbulence shed from each vertical cylinder in a sand bed [18]. Carollo et al. described the results of the turbulence intensity in gravel bed channels by using an acoustic Doppler velocimeter (ADV) in a laboratory flume [6]. The collected data allowed the velocity fluctuations to be measured and the large-scale turbulent structure to be analyzed. On the basis of their measurements, the writers observed an ordered sequence of long-term large-scale vortices moving downstream with the same velocity as the mean, and producing a motion of fluid toward both the bed and the free surface, involving the whole flow depth. Moving from the bed towards the free surface, even if the size of the large scale vortices increases, the turbulence phenomenon intensity decreases.

Mubeen Beg conducted a study based on the scour reduction by using a collar around a pier group [2]. He used a collar plate having a width equal to 2.5 times the model pier diameter, as shown in Fig. 8. The findings of this study demonstrated that the application of collar to the group of two circular cylindrical piers aligned at 0°, 15°, 30° and 45° angles of attack, produces 87.05, 58.97, 51.85, and 48.4% reduction in the maximum scour depth respectively. The scour and deposition patterns around piers group aligned at 45° angle of attack with and without collar are presented in Fig. 9.

Ettema et al. presented the data suggesting that the scour depth at piers did not scale linearly with pier width unless there was more-or-less complete geometric similitude of pier, flow and bed sediment particles. The non-linearity can result in laboratory flume studies of local scour (at scale-reduced model piers) leading to deeper scour holes relative to pier width than any likely to occur in the field. The energy associated with turbulence structures in

Fig. 7 Various types of slots

TYPE OF SLOTS

Unprotected   Parallel Slot ($0^0 \pm 180^0$)   Y – Slot (0^0 to $\pm 120^0$)   T – Slot (0^0 to $\pm 90^0$)   Sigma Slot (0^0 to $\pm 45^0$)
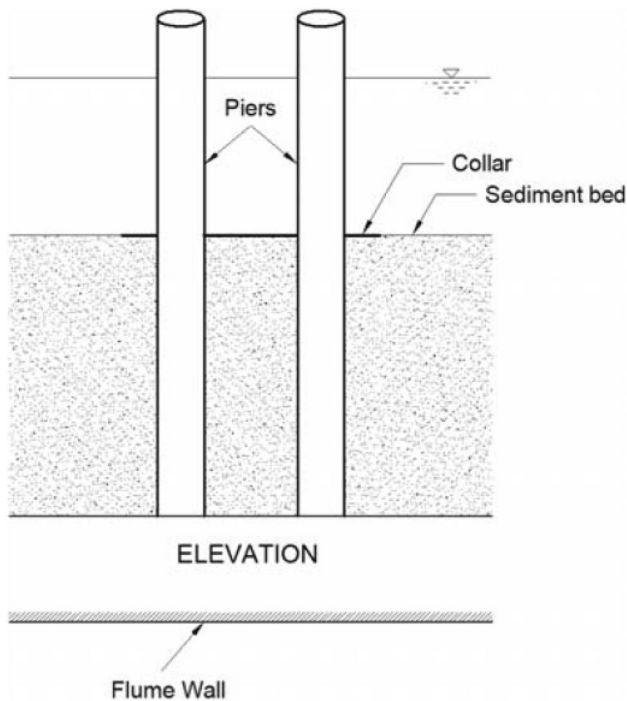
Fig. 8 Arrangement of piers group with collar in the flume

the pier flow field can be characterized in terms of a pier Euler number, $E_u =$ and the frequency of vortex formation and break-up or shedding in terms of pier Reynolds number, which influences the frequency of shedding. They

noted that smaller cylinders in the same flow generate eddies at a greater rate.

M. Qi conducted laboratory experiments with different suction to show suction effects on sediment entrainment quantitatively [54]. When the hydrodynamic forces exerted on the sediment particles just exceed the resistive forces, particles begin to move. This phenomenon is defined as the "incipient motion" or "threshold condition". Only visual observation is not sufficient to determine the precise threshold condition for a specific case. Therefore, various investigators have conducted different methods to identify the incipient motion. The combined results provide an overall view on suction effects on the initiation of cohesionless sediment motion, showing that the downward seepage (suction) increases the critical shear velocity.

Chen and Chiew [8] conducted experiments using a laser Doppler velocimeter by Dantec, with and without suction, and suction rates were 1.53% and 0.86%. The measured data confirmed a significant increase in the near bed velocity and the reduction of velocity near the water surface resulted in the formation of a more uniform velocity distribution with comparison to no suction condition. Schematic diagram of velocity profile is shown in the Fig. 10.

Where, u is the time-average stream wise velocity at a distance y from the boundary, y_0 is vertical displacement of the origin of the mean velocity profile, us is slip velocity at the bed surface and v_s is suction velocity
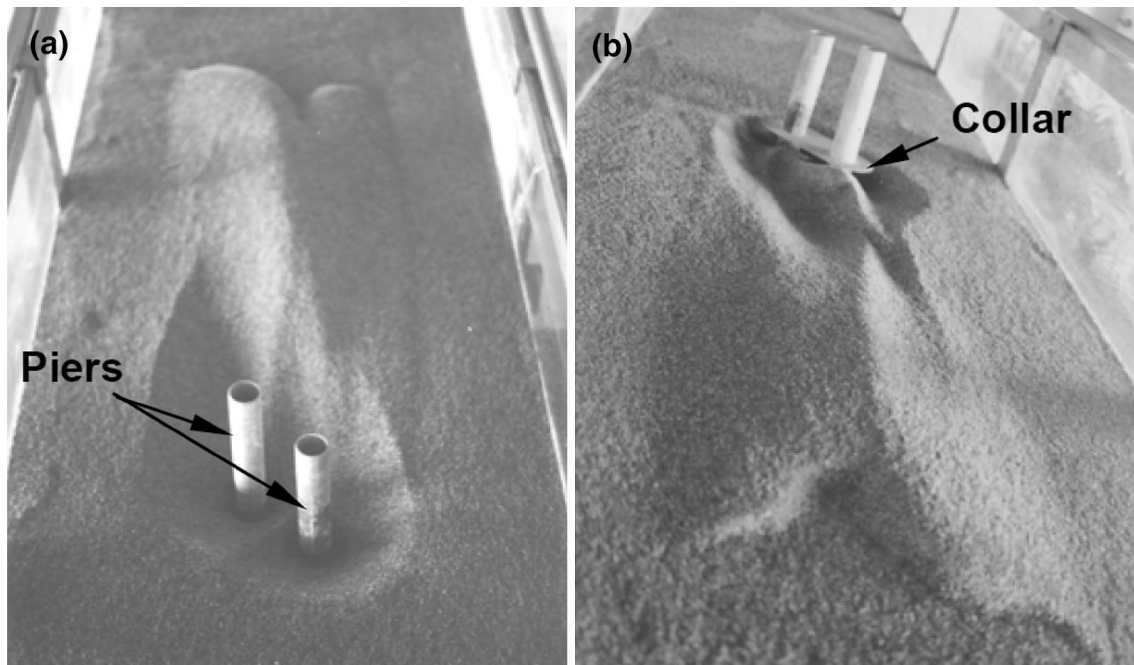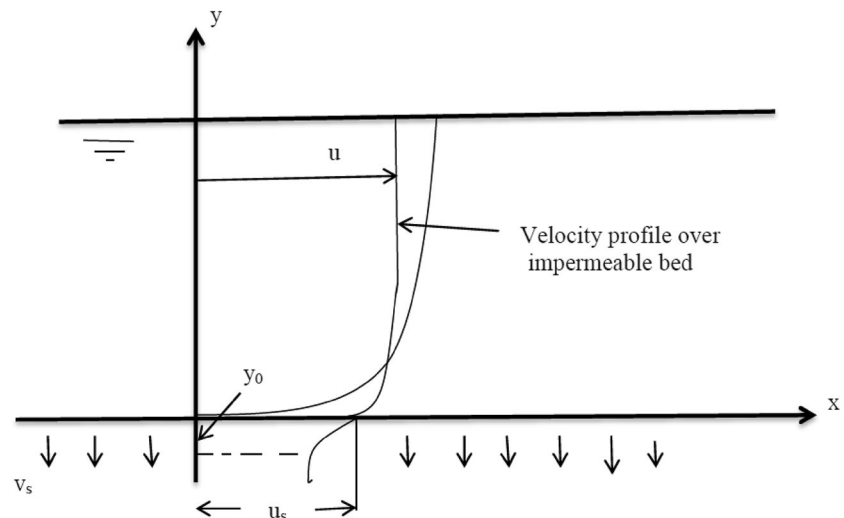

Fig. 9 Photo views showing the scour and deposition patterns around piers group aligned at 45° angle of attack **a** without collar, **b** with collar

Fig. 10 Schematic diagram of
velocity profile over permeable
bed with suction [8]

9 Numerical Modeling of Scour Processes

By conducting extensive research with laboratory and field data, various numerical modeling for bridge pier scour have been developed or the numerical simulation of scour or general sediment transport processes, typically two- and three-dimensional models are used, while the choice of dimensionality depends on the specific topic under consideration, e.g. sediment transport in rivers, oceans, bays or harbors or local scour phenomena around fluvial or offshore structures. For larger areas, depth-averaged two-dimensional approaches have proven to be sufficient in many cases, as long as no local flow effects around single objects and hence resulting local transport processes shall be investigated in detail. In that case, the flow field is fully three-dimensional and therefore has to be modeled as such, including an appropriate sediment transport model formulation. While three-dimensional models therefore include more information from the physical nature and hence give more detailed results on scour processes, computational costs are much higher than for two-dimensional models considering a similar case.

More than 35 different formulae have been proposed for scour estimation since 1949. For the estimation of the depth of local scour at bridge piers, 'numerous equations have been proposed [47, 67]. The design approach proposed by Melville and Coleman [45] consider the bridge piers and abutments together and they develop a design method that can be applied in both cases. The design method rests on the following relation for the depth of local scour [20].

$$ds = K_{yB}K_lK_dK_sKK_GK_t \tag{2}$$

where $K_{yB}, K_l, K_d, K_s, K, K_G, K_t$ are flow depth-foundation size factor, flow intensity factor, sediment size factor, pier or abutment shape factor, pier or abutment alignment factor, channel geometry factor and time factor respectively. Several numerical models for local flow field and scour simulations

have been developed over the past years and can therefore are found in the literature. Some of these are briefly described below. The compilation is however restricted to three dimensional models only. It can generally be stated that in all models, only comparatively simple structures were considered.

10 Flow and Scour around Objects and Other Models

It can be noticed that the numerical simulation of flow and scour around cylindrical structure is the case that has mostly been considered in both numerical and experimental studies. This might be due to the fact that the circular cylinder or pier is one of the most widely used geometries for any structures placed in the fluvial and marine environment. Calculations on local scour development around a vertical cylinder have further been carried out in the work of Roulund [58] and later published in Roulund et al. [59], using a steady-state flow approach with a rigid lid at the place of the free surface for a steady-current induced scour development. Only bed load was considered here. The model included modifications on the shear stresses to account for sloping beds and an appropriate sediment sliding procedure. Besides the numerical modeling part, the work included experimental modeling of scour around a cylinder and results were used for a verification of the numerical model. Altogether good results compared to the experiments could be achieved, although certain discrepancy for the final scour depth, especially at the downstream part of the cylinder was given.

A similar work was carried out by Weilbeer, who used TELEMAC-3D software code to model scour around a cylindrical structure and other objects for current flow situations [66]. The approach in the code was however limited to simple objects, as a -grid was used, which builds up on the approach

of a two-dimensional, triangular bottom grid in horizontal plane, which is then projected onto several layers in the vertical. This suppresses modeling of complex object shapes. A general comparison to the data given in Roulund was carried out and several bed load transport model formulations were compared [58]. The work of Gothel [21] further built up on the work of Weilbeer [65], using the same numerical code. In his work, wave load was considered as the main acting load condition leading to local scour. Furthermore, a soil model was incorporated for investigations on the effect of soil and slope stability by use of a Finite Element approach. Only bed load was considered in the model. Data were compared to experimental results from literature, e.g. the work of Roulund et al. and test results on wave-induced scour around a circular cylinder carried out in the Large Wave Flume (GWK) in Hanover [59]. Numerical results however slightly differed from the latter experiments. Another model approach was given by Liu and García, who considered both a two-dimensional, depth-averaged and a three-dimensional numerical model for local scour formation [41]. Open FOAM software code with free surface representation was applied in this work and a sediment transport formulation including bed load and suspended load was implemented. Furthermore, a separate model for soil stability and liquefaction effects was incorporated into the code. For comparison with experiments several test results from the literature were used, amongst others wave-induced scour around a large cylinder and scour formation behind a sluice gate. In addition to experimental investigations on local scour formation at a circular, vertical cylinder under steady current flow conditions, Link [40] carried out numerical simulations on this topic using a vertically layered domain model similar to that given in Weilbeer and Jankowski [66]. Investigations were however limited to an application of an existing flow and sediment transport model here. Further model approaches for investigations on scour around pipelines, mainly in two-dimensional model versions are given in [64, 5, 38, 30]. Model approaches on general sediment transport processes and scouring effects due to waves and in wave flumes are given in [32, 39, 14, 37]. In the latter, investigations on flow and sediment transport processes under breaker bars were carried out using OpenFOAM software code for the hydrodynamic modeling part, and a sediment transport model formulation including bed load and suspended load was further implemented as an extension of the code. Results were compared to both theoretical assumptions and experimental data, achieving altogether good agreement.

11 Conclusion

Local scour and its control is the subject of interest of the present study. A large amount of literature has been published on the local scour around a bridge pier. This literature review has discussed the core parameters that influence the scour process, scour under different conditions and the effect of various parameters on rate of scour. In the current research, definition, mechanism, influencing factors, countermeasures and other relevant features are discussed for clear understanding of the complex phenomenon of scouring and its control. It was demonstrated that there is a significant gap between field measurements of scour and scour prediction techniques based on either laboratory data or analytical models. The need for further research is clear in order to bridge this gap and reduce uncertainty in numerical and experimental techniques. The data collected from this research are being used to improve the knowledge of effects of different parameters to rate scour around single piers and pile groups.

Compliance with Ethical Standards

Conflict of interest The authors declare that there is no conflict of interests regarding the publication of this paper.

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