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THE PHYSICS OF LOCAL SCOUR AT BRIDGE PIERS

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The relation between the depth of local scour at a bridge pier and its dependent parameters is discussed. The dependent parameters describe the flood flow and bed sediment characteristics, the geometry of the bridge pier and the rate of development of local scour. Emphasis is given to the underlying physics of the process of local scour. Recent research findings are included. Limitations in knowledge of the process are noted. The discussion is restricted to local scour at unsubmerged bridges in straight channels with beds comprising homogeneous, alluvial sediments. Flow contraction effects are assumed to be absent. Superstructure submergence effects are considered separately. Additional factors, such as sediment cohesion, layered strata, bedrock effects and scour at bridges subjected to tidal flows and waves are not considered.

Key Words : *local scour, bridge pier, scour process, physics*

1. INTRODUCTION

The numerous complexities associated with bridge scour have caused scour to be one of the most active topics of civil engineering research. The subject of local scour at bridge piers has attracted significant research interest for more than 100 years and there are literally hundreds of local scour publications. A majority of these deal with laboratory model studies of local scour. In the last twenty years, several comprehensive summaries of local scour at bridge piers have been published, including Breusers and Raudkivi (1991), Wallingford (1993), Richardson and Davis (1995), Hoffmans and Verheij (1997), Hamill (1999) and Austroads (2000). Earlier, significant contributions were made by Chabert and Engeldinger (1956), Laursen and Toch (1956), Laursen (1958, 1962 and 1963), Shen *et al.* (1966, 1969), Breusers *et al.* (1977), Raudkivi and Sutherland (1981), Dargahi (1982), Raudkivi (1986) and Melville (1988).

Melville and Coleman (2000) present, in Section 6.2 of their book, a detailed discussion of the mechanics of local scour at bridge piers and abutments. The purpose of this paper is to present a comprehensive description of the process of local scour at bridge piers. Material from Melville and Coleman (2000) is used extensively and is updated where more recent information is available. In particular, recent research results are presented, which show that local scour depths at field scale may be significantly reduced from those observed in the laboratory. The recent research studies are those of Ettema *et al.* (1998), Sheppard *et al.* (2004) and Ettema *et al.* (2006).

(1) Similitude

The relation between the depth of local scour at a bridge pier d_s and its dependent parameters can be written

$$\begin{aligned} d_s = f\big[& \text{Flood flow}\,(\rho, \nu, V, y, g), \\ & \text{Bed sediment}\,(d_{50}, \sigma_g, \rho_s, V_c), \\ & \text{Bridge geometry}\,(b, Sh, Al), \text{Time}\,(t)\big] \end{aligned} \qquad (1)$$

where ρ and ν = fluid density and kinematic viscosity, respectively; V = mean approach flow velocity; y = flow depth; g = acceleration of gravity; d_{50} and σ_g = median size and geometric standard deviation of the sediment particle size distribution; ρ_s = sediment density; V_c = critical mean approach flow velocity for entrainment of bed sediment; b = pier width for piers; Sh and Al = parameters describing the shape (including floating debris)and alignment of the pier; t = time; and f denotes “a function of”.

For a given pier, three length scales affect the scour process – pier size (typically width is used), flow depth, and bed sediment diameter. Whereas it is usually straightforward to have model pier dimensions proportionate with flow depth, there is a lower limit in linking particle diameter relative to pier width and flow depth. As particle diameter decreases, the physical behaviour of particle beds changes. For d_{50} below about 0.7mm, a bed may form ripples, while for d_{50} below about 0.1mm, inter-particle cohesion becomes increasingly pronounced. These changes affect scour at a pier.

Assuming constant relative density of sediment, i.e. neglecting ρ, and ρ_s, (1) can be written as

$$\frac{d_s}{b} = f\left(\overbrace{\frac{V}{V_c},\frac{y}{b},\frac{V^2}{gb},\frac{Vb}{\nu}},\overbrace{\frac{b}{d_{50}},\sigma_g},\overbrace{\frac{Vt}{b},Sh,Al}\right) \qquad (2)$$

The first four parameters on the right-hand side of (2) are flow-related and represent, respectively: the stage of sediment transport on the approach flow bed, termed the ***flow intensity***; the depth of flow relative to the size of the foundation, termed the ***flow shallowness***; and an Euler number and a Reynolds number. The Euler number relates approach-flow stagnation head and pier width. The next two parameters are sediment-related and represent the pier size relative to the sediment median size, termed the ***sediment coarseness*** and the sediment nonuniformity, σ_g. The final three terms are a time scale for the development of scour (Vt/b) and the pier geometric parameters, Sh and Al.

The pier width appears in several of the parameters, it being important to note that pier width exerts influences in terms of flow shallowness (b/y), relative roughness (b/d_{50}), vorticity and frequency of coherent turbulent structures (V^2/gb and Vb/ν), rate of scour development (Vt/b) and pier shape and alignment.

In the following sections, the influence on local scour depth of these parameters is discussed. The discussion is restricted to local scour at ***unsubmerged bridges*** in ***straight channels*** with beds comprising ***homogeneous, alluvial sediments***. Flow contraction effects are assumed to be absent, and the pier spacing is assumed to be large enough that the scour process at each pier is independent of other piers and the bridge abutments. Superstructure submergence effects are considered separately. Additional factors, such as sediment cohesion, layered strata, bedrock effects and scour at bridges subjected to tidal flows and waves are not considered.

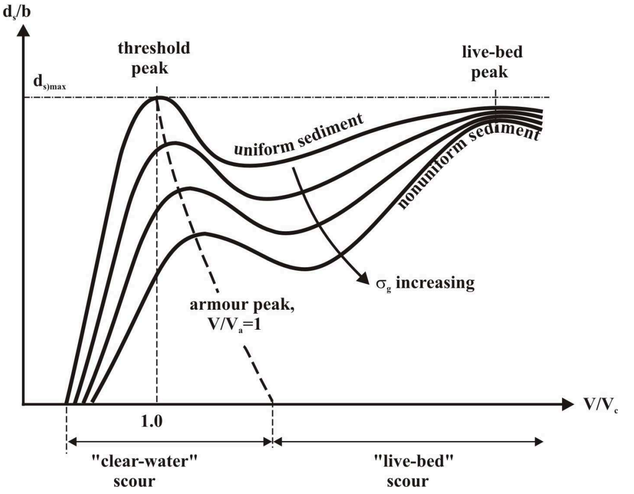


Fig.1 Local scour depth variation with flow intensity

2. EFFECTS OF PARAMETERS

(1) Effect of Flow Intensity {local scour factors: flow intensity}, V/V_c

The variation of local scour depth at piers with flow intensity (and approach flow velocity), as evident from laboratory data (Chabert and Engeldinger, 1956; Shen *et al.*,1966; Maza Alvarez, 1968; Ettema, 1980; Raudkivi and Ettema, 1983; Chiew, 1984; Baker, 1986) is shown in Figure 1.

Under clear-water conditions, the local scour depth in uniform sediment increases almost linearly with velocity to a maximum at the threshold velocity. The maximum scour depth is called the ***threshold peak***. As the velocity exceeds the threshold velocity V_c, the local scour depth in uniform sediment first decreases and then increases again to a second peak, these changes being relatively small, but the threshold peak is not exceeded providing the sediment is uniform. The second peak occurs at about the transition flat bed stage of sediment transport on the channel bed and is termed the ***live-bed peak.***

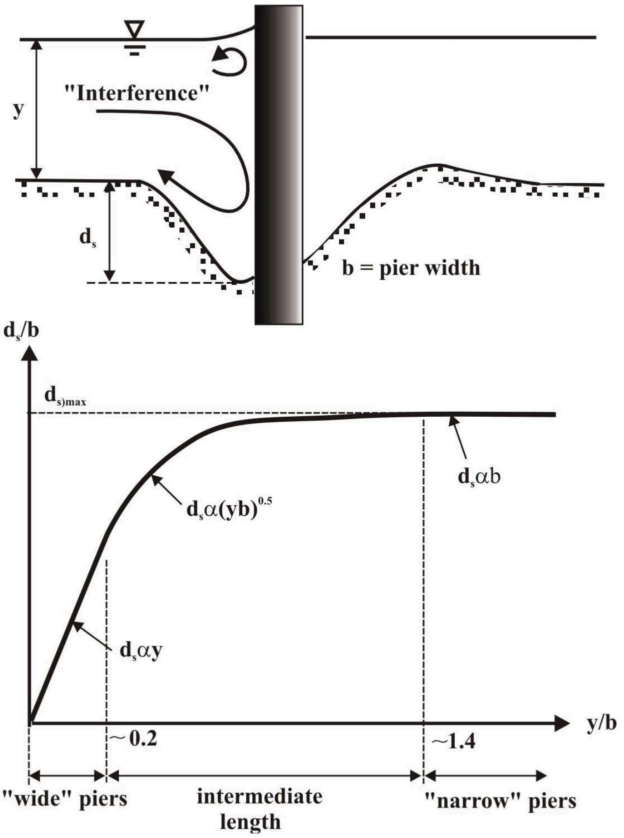


Fig.2 Local scour depth variation with flow shallowness

The scour depth variations under live-bed conditions are a consequence of the size and steepness of the bed features occurring at particular flow velocities (Chee, 1982; Chiew, 1984; Melville, 1984; Raudkivi, 1986). The steeper and higher the bed forms, the lesser the observed scour depth because the sediment supplied with the passage of a given bed form is not fully removed from the scour hole prior to the arrival of the next bed form. The live-bed peak occurs at about the transition flat bed condition when the bed forms are very long and of negligible height. Antidunes dissipate some energy at higher velocities and the local scour depth appears to decrease again. The magnitude of the scour depth fluctuations due to bed-form migration is approximately equal to the half-amplitude of the bed forms, indicating that the scour depth due to bed forms is about one-half the bed-form height (Shen *et al.*, 1966; Chee, 1982; Chiew, 1984).

For nonuniform sediments, the scour depth maxima are termed the ***armour peak*** V_a and the ***live-bed peak***. Armouring occurs for $V<V_a$ and the scour depth is limited accordingly. Beyond V_a, the armouring diminishes and live-bed conditions pertain. The live-bed peak occurs at the transition flat bed condition when all particle sizes in the nonuniform sediment are in motion. At the live-bed peak, the scour depth is about the same for uniform and nonuniform sediments of the same median size.

(2) Effect of Flow Shallowness {local scour factors: flow shallowness}, *y/b*

Flow shallowness *y/b* represents the effects of the depth of flow in relation to the pier width.

For deep flows compared to the pier width, that is for narrow piers, the scour depth increases proportionately with pier width and is independent of *y*. Conversely, for shallow flows compared to the pier width, the scour depth increases proportionately with *y* and is independent of b; while for intermediate depth flows, d_s depends on both *y* and *b*. These trends are shown schematically in Figure 2.

In deeper flows, the strength of the horseshoe vortex and associated downflow is related to the transverse size of the pier. Thus, the scour depth is dependent on the pier width. For example, the maximum depth of scour at a relatively narrow circular bridge pier is about 2.4 times the pier diameter, irrespective of the flow depth.

For intermediate size piers (or intermediate flow depths), flow depth influences local scour depth when the horseshoe vortex is affected by the formation of the surface roller. The two vortices have opposite directions of rotation. In principle, so long as they do not interfere with each other, the local scour depth is independent of flow depth, that is, the scour occurs at a narrow pier. With decreasing flow depth, the surface roller becomes more dominant and renders the base vortices less capable of entraining sediment. Thus, the local scour depth is reduced for shallower flows. This trend is shown in the laboratory data of many researchers, including: Chabert and Engeldinger (1956), Laursen and Toch (1956), Laursen (1963), Hancu (1971), Bonasoundas (1973), Basak (1975), Breusers *et al.* (1977), Jain and Fischer (1979), Ettema (1980), Chee (1982), Chiew (1984), and Raudkivi (1986).

The scour process at wide piers features a zone of slow moving fluid existing ahead of the pier on the line of symmetry. In this zone, scour activity is reduced and the central portion of the width of the pier is ineffective in generating scour. For wide piers in sand beds, bed-forms begin to develop at the base and exit of a scour hole, these bed-forms increasing the scour resistance of the scour boundary. Also, proportionately more time is needed to develop the scour hole at a wider pier.

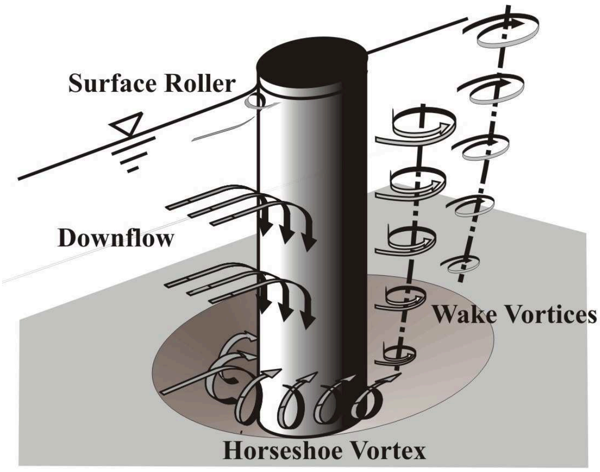
(3) Effect of Euler Number and Reynolds Number

Ettema *et al.* (1998) presented a few preliminary data suggesting that 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. The non-linearity can result in laboratory flume studies of local scour leading to deeper scour holes, relative to pier width, than any likely to occur in the field.

Many laboratory experiments have been undertaken using sands to model sand bed rivers. Consequently, the model bed material relative to the pier size is larger than its scaled counterpart in the field. To ensure similitude of the state of bed mobility requires that the value of V/V_c be maintained the same in the laboratory and the field, implying that the flow velocity used in the laboratory may need to be larger than that derived from Froude scaling of the flow velocity in the field. Hence, the Froude number used in laboratory experiments may be larger than that for the corresponding field conditions.

Ettema *et al.*'s (1998) data show that scour depth, relative to pier width, may increase with Euler number, V^2/gb. They argued that the parameter V^2/gb is useful for describing energy gradients for flow around a pier. It can be considered to express the ratio of stagnation head $V^2/2g$ to pier width. Flow-field similitude requires preservation of flow patterns such that pressure heads along flow paths scale directly with the geometric scale relating a model pier in the laboratory to a pier in the field. For the same stagnation head $V^2/2g$, steeper gradients occur at narrower piers. A narrower pier will induce a smaller value of d_s/b than a wider pier in the same flow field.

More recently, Ettema *et al.* (2006) noted that a practical implication of the inability to concurrently scale pier size, flow depth and sediment size in flume experiments, is inadequate similitude of large-scale turbulence generated by flow around piers. They pointed out that the parameters V^2/gb and Vb/ν can be interpreted as expressing similitude in the energy and frequency of eddies shed from the pier. The parameter V^2/gb is in effect a normalised expression of vorticity of wake vortices. Because vorticity is roughly proportional to approach velocity V, the implication is that narrower piers in the same approach flow produce stronger eddies.



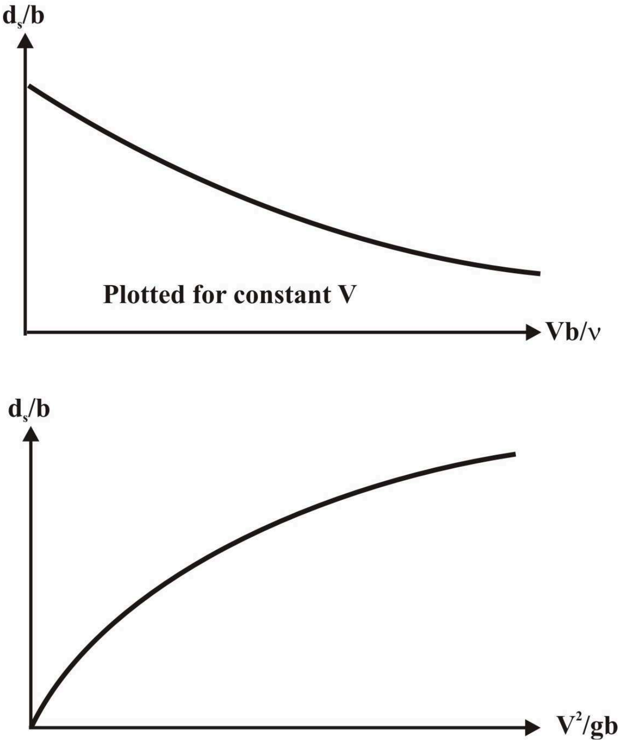


Fig.3 Local scour depth variation with large-scale turbulence

Given the range of length scales commonly used in scour experiments, Reynolds number (*Re*) in terms of viscous effects is unlikely to have direct bearing on scour depth. However, *Re* also influences the frequency of shedding of vortices, *n*. For typical values of pier size and flow velocity used in flume experiments and also in the field, *Re* is in the range 10^3 to 10^5, for which the Strouhal number (nb/V) is about 0.2 for circular cylinders. Thus for piers in the same approach flow *V*, the frequency of shedding of vortices is inversely proportional to the pier size, i.e. narrower piers in the same flow generate eddies at a greater rate.

The effects on local scour depth of inadequate scaling of strength and frequency of vortex shedding are shown schematically in Figure 3. The diagrams are consistent with the limited data presented by Ettema *et al*. (2006).

(4) Effect of Sediment Coarseness {local scour factors: sediment coarseness}, b/d_{50}

The influence of sediment size on local scour depth is shown schematically in Figure 4.

Data from small-scale laboratory experiments

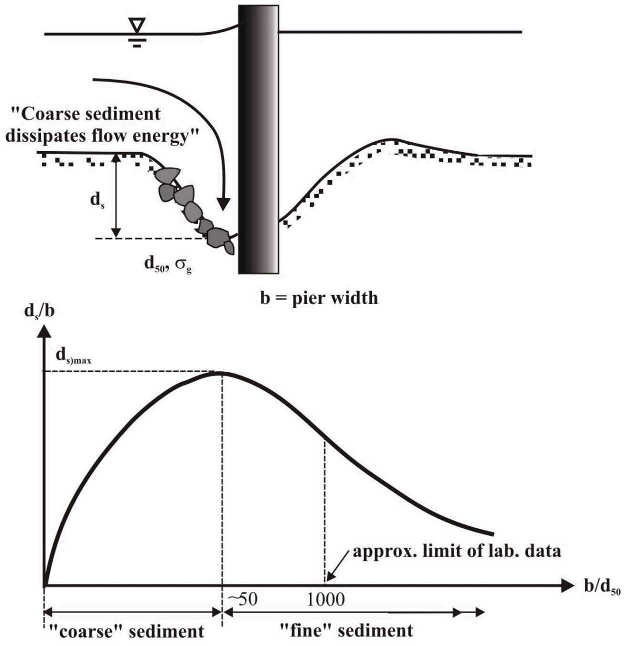


Fig.4 Local scour depth variation with sediment coarseness

show that, for uniform sediments, local scour depths are unaffected by sediment coarseness unless the sediment is relatively large. Ettema (1980) explained that for smaller values of the sediment coarseness ratio ($b/d_{50} < 50$), individual grains are large relative to the groove excavated by the downflow and erosion is impeded because the porous bed dissipates some of the energy of the downflow. When $b/d_{50} < 8$, individual grains are so large relative to the pier that scour is mainly due to erosion at the sides of the pier and scour is further reduced.

For much larger values of b/d_{50}, representative of prototype sized piers founded in sandy materials, recent data by Sheppard *et al.* (2004) demonstrate significant scour depth reductions for increasing b/d_{50}. The reductions for $b/d_{50} > 50$ are shown schematically in Figure 4.

Sheppard *et al.* (2004) used three different diameter circular piers (0.114, 0.305 and 0.914 m), three different uniform cohesionless sediment diameters (0.22, 0.80 and 2.90 mm) and a range of water depths and flow velocities. The tests extended the range of ratios of b/d_{50} to 4155.

(5) Effect of Sediment Nonuniformity {local scour factors: sediment nonuniformity}, σ_g

Ettema (1976, 1980) carried out systematic laboratory studies of the effects of sediment nonuniformity on local scour depth under clear-water conditions at piers. Similar studies under live-bed conditions were conducted by Chiew (1984) and Baker (1986).

Figure 5 summarises the trends evident from these studies. Around the threshold condition, $V/V_c \approx 1$, armouring occurs on the approach flow bed and at the base of the scour hole. The armoured bed in the

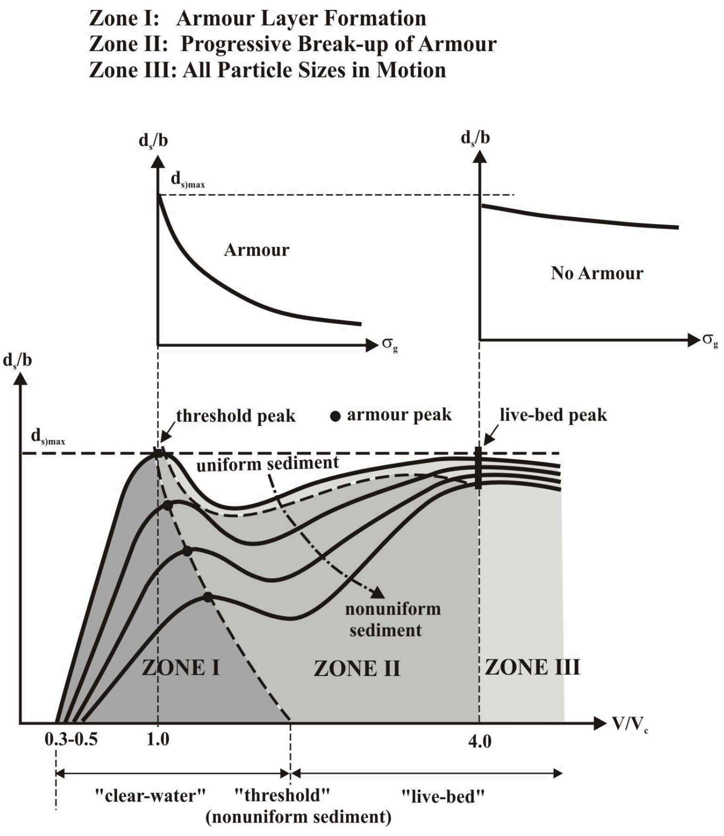


Fig.5 Local scour depth variation with sediment nonuniformity

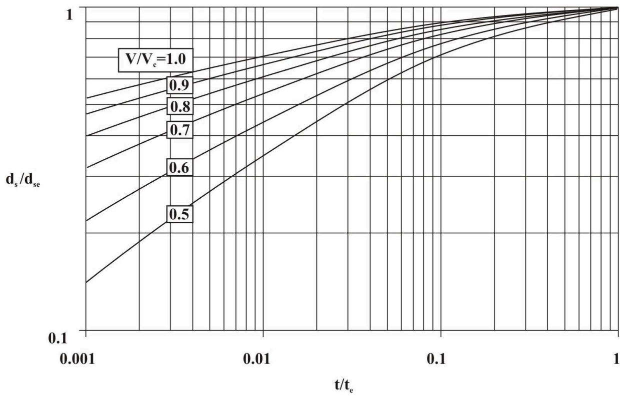


Fig.6 Temporal development of local scour depth at piers under clear-water conditions

erosion zone at the base of the scour hole significantly reduces the local scour depth. Conversely, at high values of V/V_c, when the flow is capable of entraining most grain sizes within the nonuniform sediment, sediment nonuniformity has only a minor effect on the scour depth. At intermediate values of V/V_c, the effect of σ_g reduces progressively with increasing flow velocity between these two limits, as more and more of the grains are transported by the flow.

(6) Effect of Time {local scour factors: time}

The process of scouring is asymptotic. Under clear-water scour conditions, the scour depth develops asymptotically towards the equilibrium depth of scour. Under live-bed conditions, the equilibrium depth is reached more quickly and thereafter the scour depth oscillates due to the passage of bed features past the pier or abutment.

In order to achieve equilibrium conditions in small-scale laboratory experiments of clear-water scour depth development at bridge piers, it is necessary to run the experiments for several days. Data obtained after lesser times, say 10 to 12 hours, can exhibit scour depths less than 50% of the equilibrium depth.

Most equations for depth of local scour give the equilibrium depth and are, therefore, conservative regarding temporal effects. For the live-bed conditions that typically occur in floods, equilibrium scour depths are often appropriate, although there are bridge sites where limits in the duration of scouring influence live-bed scour depths. Conversely, where clear-water scour conditions exist, the equilibrium depth of scour is typically overly conservative. Piers founded on the flood-plain may be subjected to clear-water scour conditions, because vegetation restricts sediment movement.

The shape of the flood flow hydrograph is important as well as the flood duration. Typically, the flood duration determines if the equilibrium live-bed scour will develop. After the flood peak passes, the flow recedes. The duration of the recession period is also important. With flow recession, clear-water conditions may prevail, which could induce additional scour, especially if near-threshold conditions are maintained over a considerable period.

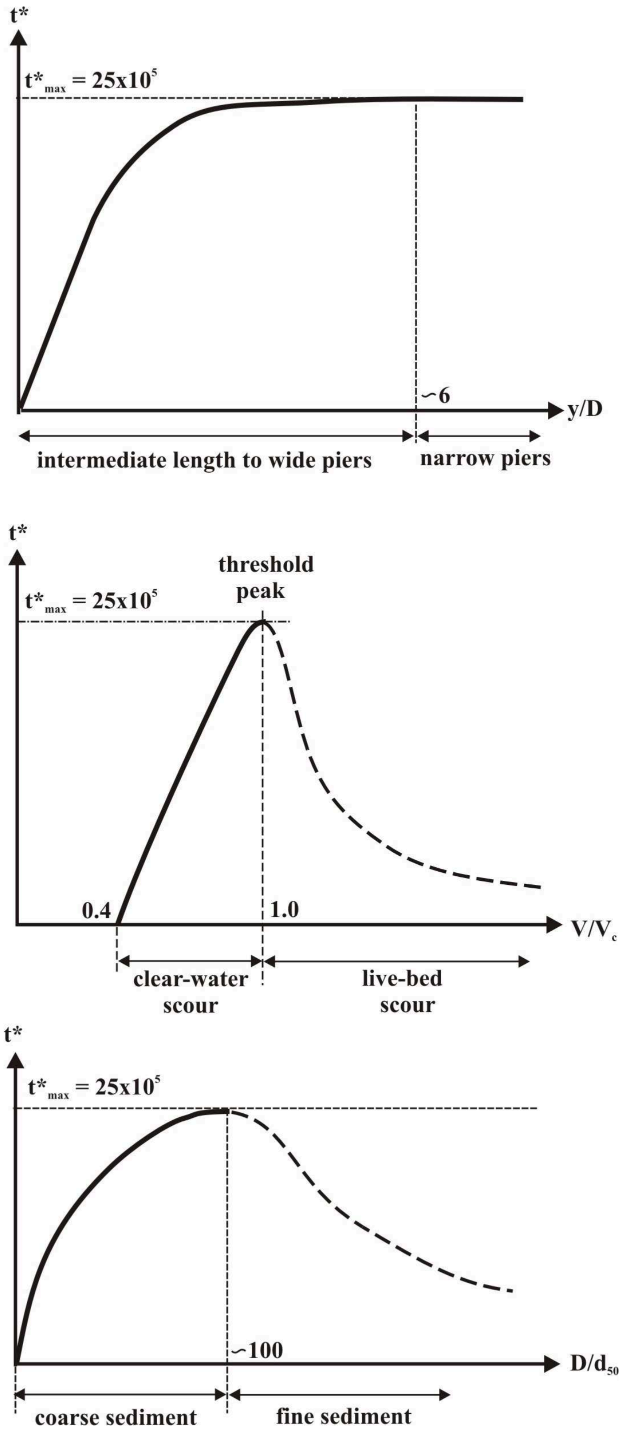


Fig.7 Equilibrium time scale variation with flow shallowness, flow intensity and sediment coarseness

Chiew and Melville (1996) and Melville and Chiew (1999) presented many laboratory data that

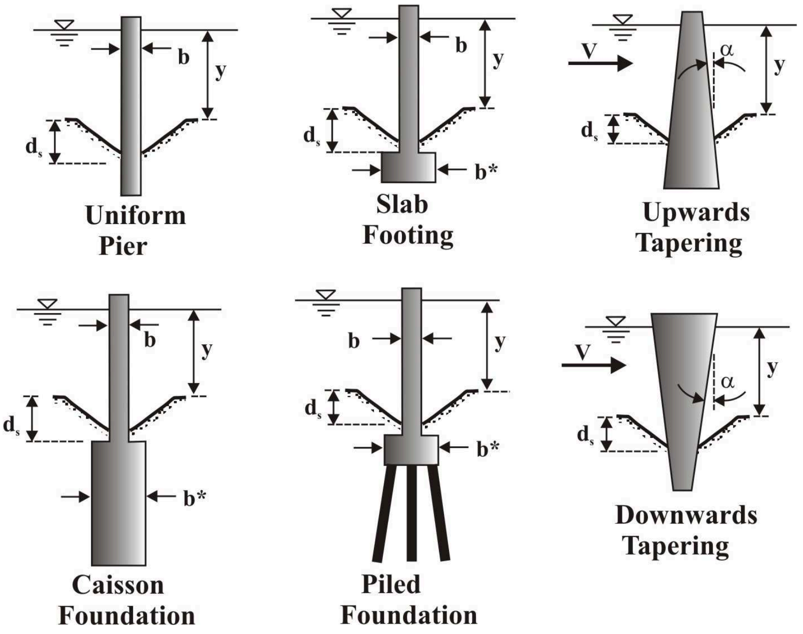


Fig.8 Examples of complex pier shapes

describe the temporal development of local scour at narrow circular bridge piers (of diameter *D*) under clear-water conditions. The data are well represented by the curves plotted in Figure 6, which show that local scour depths at the same stage of development (t/t_e, where t_e is the time to develop the equilibrium depth of scour) are reduced at lower values of V/V_c.

Melville and Chiew (1997) show also that both t_e and d_{se} are subject to similar influences of flow and sediment properties, as might be expected because they are inherently interdependent. Their plots show the dependence of a (dimensionless) equilibrium time scale t^* ($=Vt_e/D$) on flow shallowness (y/D), flow intensity (V/V_c) and sediment coarseness (D/d_{50}). The trends evident in these data plots are illustrated in Figure 7.

The equilibrium time scale increases with y/D for shallow flows and becomes independent of y/D for deep flows. The apparent limit to the influence of flow shallowness on t^* occurs at $y/D \sim 6$. The maximum value of t^* is about 2.5×10^6. The middle diagram shows that the equilibrium time scale increases rapidly with flow intensity for clear-water scour conditions, attaining a maximum value at the threshold condition. At higher live-bed flows, t^* is expected to rapidly decrease again, as shown by the dashed line. The lower diagram indicates that t^* increases asymptotically with D/d_{50}. The limit to sediment coarseness influence on t* occurs at $D/d_{50} \sim 100$. At higher values of D/d_{50}, t^* is expected to decrease as shown by the dashed line.

Finally, it is important to point out there is only scant information on the time development of clear-water local scour at piers considered wide or of complex geometry. The data and the formulations upon which the time-development relationships are based do not take into the account shape or alignment, nor do they adequately account for values of b/y and b/d_{50} in ranges found for wide piers, and therefore are of questionable validity when scaled, or applied, to wide piers and long skewed piers.

(7) Effect of Pier Shape

Shape (multiplying) factors for ***simple piers***, that is piers having constant section throughout their depth, have been proposed by several investigators, including Tison (1940), Laursen and Toch (1956), Chabert and Engeldinger (1956), Garde (1961), Larras (1963), Venkatadri *et al.* (1965), Yaroslavtiev (as given in Maza Alvarez, 1968), Dietz (1972), Neill (1973) and Richardson and Davis (1995). In practice, shape factors are only important if axial flow can be ensured. Even a small angle of attack will eliminate any benefit from a streamlined shape.

Complex piers include piers with piled foundations, caissons, and slab footings, and also tapered piers, as illustrated in Figure 8.

For piers tapered on the upstream and downstream faces, the slope, in elevation, of the leading edge of the pier affects the local scour depth. Downwards-tapering piers induce deeper scour than a circular pier of the same width, and vice-versa. Shape factors for local scour at tapered piers have been proposed by Neill (1973), Chiew (1984) and Breusers and Raudkivi (1991).

For piers founded on a (wider than the pier) slab footing, caisson or pile cap, the footing, cap or caisson with the top below the general bed level can

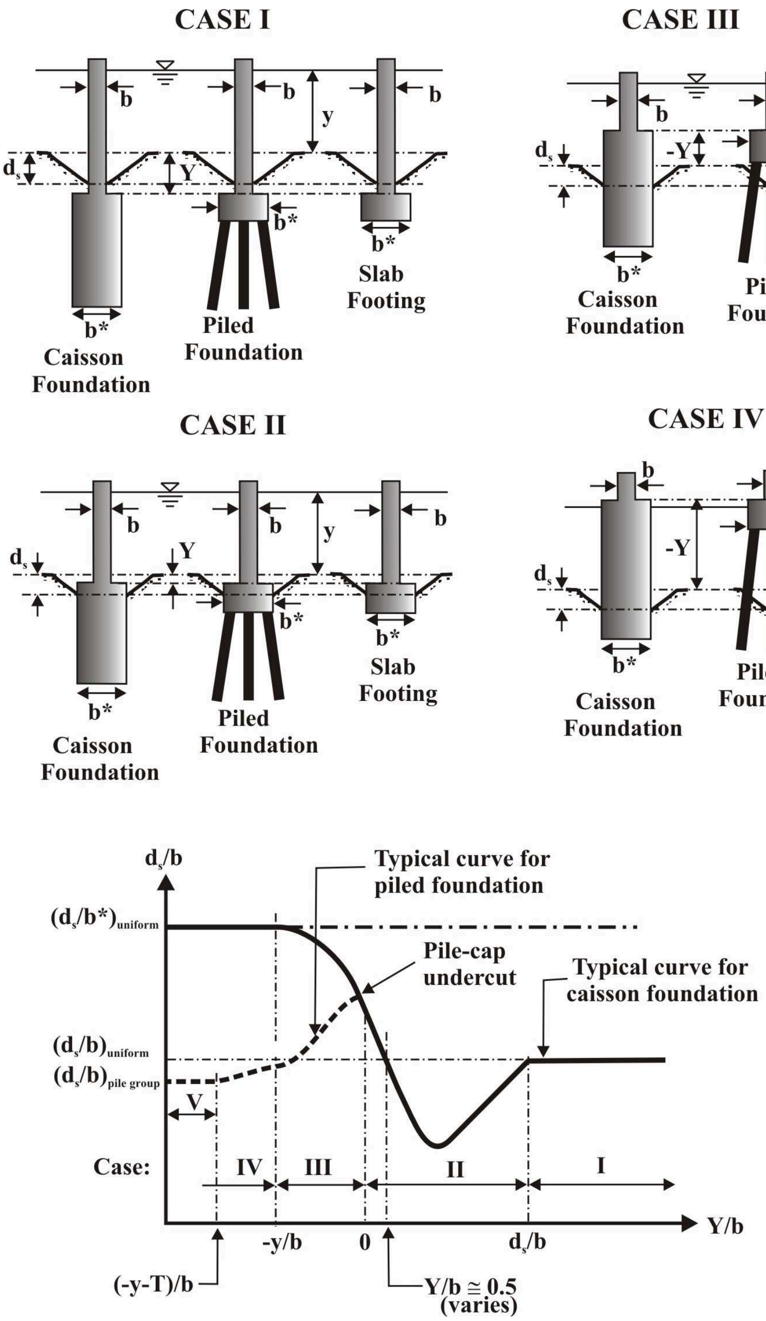


Fig.9 Local scour depth variation with complex pier shape

be effective in reducing the local scour depth through interception of the downflow. However, if the top of the wider foundation element comes to the bed level, or even above, the scour depth is increased. Unless definite predictions are possible, it is dangerous to rely on limitation of the scour depth through flow interception by the wider base element.

At caisson foundations, four cases of local scouring can occur (Figure 9):

- Case I, where the top of the footing, cap or caisson remains buried below the base of the scour hole;
- Case II, where the top of the footing, cap or caisson is exposed within the scour hole below the general bed level;
- Case III, where the top of the footing, cap or caisson is above the general bed level; and
- Case IV, where the top of the footing, cap or caisson is at or above the water surface level.

For Case I, the local scour is unaffected by the presence of the footing, cap or caisson, while for Case II, the local scour typically is reduced from that at a simple pier, due to interception of the downflow. For Case III, the local scour depth can be increased or decreased compared to that at a simple pier. The Case III scour depth at a pier founded on a larger size cap or caisson is increased, with the maximum local scour occurring for Case IV, where the top of the cap or caisson is at or above the water surface level. Cases III and IV scour depths at piled foundations may be increased or decreased. The trends are shown schematically in Figure 9, in which the level of the top of the footing, cap or caisson, Y, is measured from the general bed level and Y is positive downwards.

Investigations of local scour at piers founded on slab footings and caissons have been undertaken by Chabert and Engeldinger (1956), Tsujimoto *et al.* (1987), Imamoto and Ohtoshi (1987), Jones (1989), Jones *et al.* (1992), Fotherby and Jones (1993), Parola *et al.* (1996) and Melville and Raudkivi (1996). Local scour at piers founded on piles has been studied by Hannah (1978), Raudkivi and Sutherland (1981), Jones (1989), Richardson and Davis (1995), Sheppard *et al.* (1995), Salim and Jones (1996), Sheppard and Glasser (2004), Coleman (2005) and Ataie-Ashtiani and Beheshti (2006), among others.

For scour at piled foundations where the pile cap is clear of the water surface (Case V), Hannah (1978) found that the maximum scour depth is closely related to the dimension of the pile group as a whole, as seen from upstream. He recommended that a single line of piles should be used in preference to piers for angles of attack greater than 8 degrees. For Cases I and II, scour at a piled pier is the same as that at a caisson pier. For Cases III and IV, the piles and pile cap are exposed to the flow. Sheppard and Glasser (2004) and Coleman (2005) carried out experimental investigations for these cases. The results are shown schematically by the dashed line in Figure 9. Local scour depth reduces from that for a caisson foundation from the point at which the pile cap is undercut by the flow. The limit for this reduction is the scour depth for Case V, as shown.

(8) Floating debris {local scour: effect of debris}

During floods, many rivers carry appreciable quantities of floating debris such as branches and roots of trees. If the debris becomes caught at bridge piers, it can accumulate into large masses of material normally referred to as debris rafts. A foundation with accumulated material causes a larger obstruction to the flow than without debris; the additional flow obstruction generally causes local scour depths in excess of depths under conditions without debris accumulation.

The likelihood for debris accumulation at bridge piers depends on a number of factors, including the availability of debris material, the potential for such material to be washed into streams and rivers, and the shape of the bridge foundations. In a study of woody debris transport in a Tennessee river, Diehl and Bryan (1993) found that the predominant large debris type comprised tree trunks with attached root masses. Such trees usually fall into a river because of bank erosion. Hence bank instability is an important catchment characteristic in identifying basins with a high potential for abundant production of debris.

McClellan (1994) found, using small-scale laboratory models, that debris accumulations could be formed such that they extend from the water surface to the streambed in all flow conditions. Under low Froude number conditions, the debris rafts tended to be shallow and extensive in plan area, while under high Froude number conditions, the debris rafts tended to be deep and narrow.

A device to deflect debris away from a bridge pier is described by Saunders and Oppenheimer (1993). The deflector, which is designed to generate counter-rotating streamwise vortices in its wake, is positioned so that the vortices migrate to the surface of the water ahead of the pier. The near-surface flow

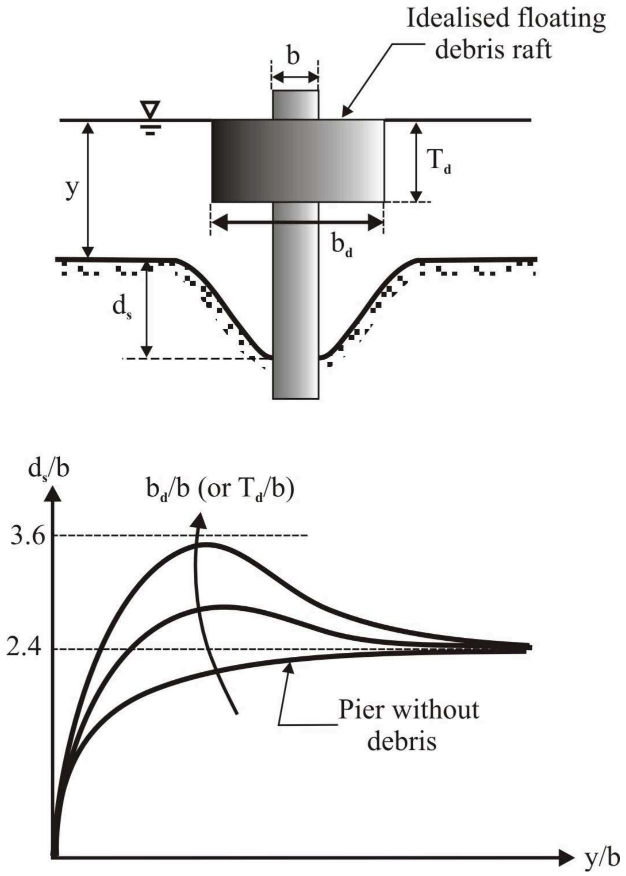


Fig.10 Local scour depth variation with quantity of floating debris

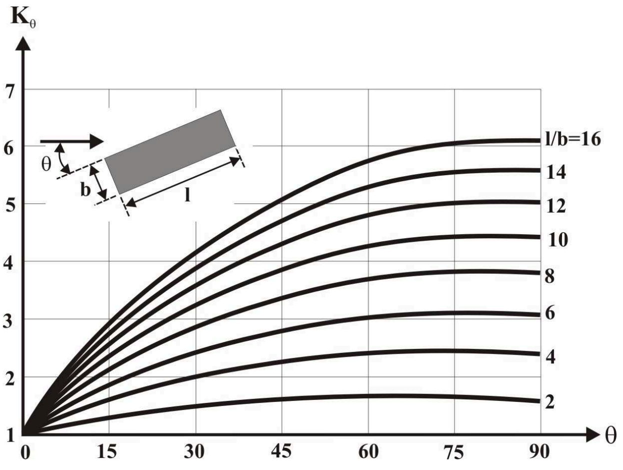


Fig.11 Local scour depth variation with pier alignment

induced by the vortices is intended to deflect any debris safely around the pier.

Dongol (1989) and Melville and Dongol (1992) reported a laboratory study of local scour depths at circular bridge piers with debris rafts. The debris was modelled as an impervious circular cylinder, concentric to the pier and having its upper surface at the water surface level. They proposed an expression for the equivalent size b_e of the uniform circular pier that induces about the same scour depth as the actual pier with accumulated debris. The expression is shown schematically in Figure 10.

It is important to note that most local scour studies have been conducted with relatively narrow piers (typically using slender circular cylinders). Therefore, the influence of the other parameters (flow intensity, flow shallowness, sediment coarseness and nonuniformity, time, macro-turbulence structures and pier alignment) on local scour at wide piers, long skewed piers and piers of more complex shape is less well understood.

(9) Effect of Pier Alignment {local scour factors: foundation alignment}

The depth of local scour for all shapes of pier, except circular, is strongly dependent on the alignment to the flow, θ. As the angle increases (Figure 11), the scour depth increases because the effective frontal width of the pier is increased. Laursen and Toch's (1956) chart of multiplying factors, K_θ, is recommended to be used with most existing pier scour equations. The K_θ values are obtained by normalising the measured scour depths with the value at $\theta = 0°$. The chart was derived for rectangular piers, but can be used for other shapes with care. The data on which the chart is based have never been published.

An alternative relation for K_θ is given in Figure 11. Ettema *et al.* (1998) show that the curves in Figure 11 are reasonably consistent with laboratory data by Mostafa (1994) and also reflect the observation that the maximum scour depth at skewed piers of low aspect ratio (small l/b) occurs at skew angles slightly less than 90°. This latter phenomenon arises because the projected width b_p ($b_p = l\sin\theta + b\cos\theta$ for rectangular piers) of such piers is larger than for θ=90°. For example, the maximum projected width ($db_p/d\theta = 0$) of a rectangular pier with l/b=6 occurs at $\theta = \tan^{-1}(l/b) = 80.5°$. Figure 11 demonstrates the importance of alignment, that is, the local scour depth at a rectangular pier l/b=8 is nearly tripled at an angle of attack of 30°. 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. The use of circular piers, a row of piles or other shapes of low (length-to-width) aspect ratios is beneficial, where such changes in flow alignment are possible.

As noted above, further investigation is warranted to assess the applicability of Figure 11 to wide and skewed long piers in relatively shallow flows.

(10) Effect of Superstructure Submergence {local scour: superstructure submergence}

Scour at a submerged bridge is shown in Figure 12. Submergence of the superstructure leads to an increase in the scour at the bridge foundations compared to that at an unsubmerged bridge. Some guidance is available for estimation of scour depths

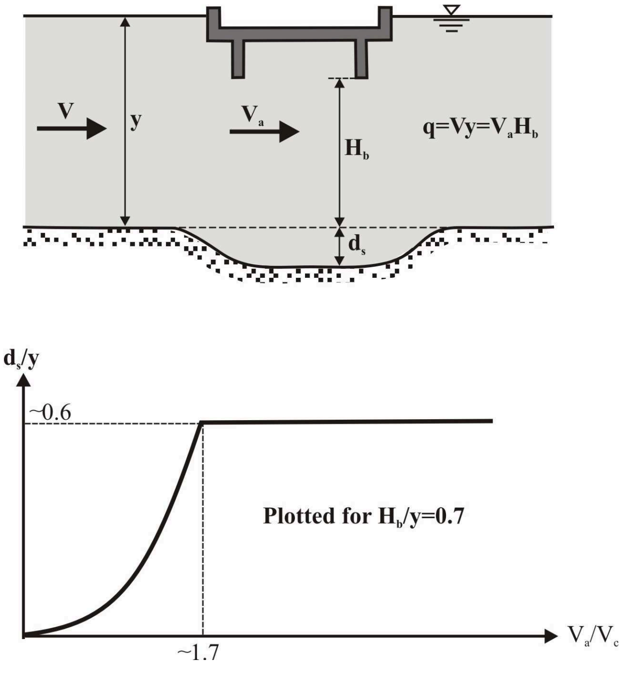


Fig.12 Scour at a submerged bridge, also known as "pressure scour"

at submerged bridges from recent research by Abed (1991), Jones *et al.* (1993), Umbrell *et al.* (1998), Arneson (1997), Arneson and Abt (1998) and Lyn (2008). The scour that develops can be considered to comprise two components:

- local scour, which can be estimated by neglecting the effects of submergence; and
- scour due to bridge superstructure submergence, termed ***pressure scour*** in the United States because the flow through the bridge opening does not have a free surface. The pressure scour component can also be considered to be a form of vertical contraction scour.

The HEC-18 equation, given in Richardson and Davis (1995) and based on Arneson (1997), is

$$\frac{d_s}{y} = -5.08 + 1.27\left(\frac{y}{H_b}\right) + 4.44\left(\frac{H_b}{y}\right) + 0.19\left(\frac{V_a}{V_c}\right) \qquad (3)$$

where H_b = height from undisturbed bed level to the "low steel" elevation of the bridge superstructure and V_a = average velocity of the flow through the bridge opening before scour occurs.

Lyn (2008) showed that (3) has unsatisfactory features. For example, as H_b increases, i.e. as the degree of contraction is reduced, d_s/y remains substantial (>0.5) even when V_a/V_c is small (i.e. when $V_a/V_c < 0.5$). After re-analysing Arneson's (1997) data, Lyn (2008) proposed the following alternative equation for design

$$\frac{d_s}{y} = \min\left[0.18\left(\frac{V_a}{V_c}\right)^{2.95}, 0.6\right] \qquad (4)$$

Equation (4) is limited to the range $0.3 < H_b/y < 0.95$. It is plotted in Figure 12 for $H_b/y = 0.7$. Lyn (2008) showed also that (4) compares well with data from the other major experimental study of pressure scour so far reported, that of Umbrell *et al.* (1998).

3. SUMMARY

The relation between the depth of local scour at a bridge pier and its dependent parameters is discussed. The dependent parameters described are flow intensity (V/V_c), flow shallowness (y/b), Euler number (V^2/gb), Reynolds number (Vb/ν), sediment coarseness (b/d_{50}), sediment nonuniformity (σ_g), time (t), pier shape (for simple and complex piers, and for floating debris effects), pier alignment, and superstructure submergence.

Emphasis is given to the underlying physics of the process of local scour. Knowledge gaps are noted. Recent research findings are included. In particular, Ettema *et al.* (2006) noted that it is impossible to currently scale pier size, flow depth and sediment size in flume experiments. A practical implication of this is inadequate similitude of large-scale turbulence generated by flow around piers. Also, recent data by Sheppard *et al.* (2004) demonstrate significant scour depth reductions for increasing b/d_{50} when $b/d_{50} > 50$. Thus, local scour depths at field scale may be significantly reduced from those observed in the laboratory.

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