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LOCAL SCOUR AT SINGLE PIERS REVISITED

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Abstract

The paper summarizes recent contributions of the authors on the effects of relative flow depth, relative sand size, time and fluid viscosity, on the scour depth at single piers. These contributions rely on unique experiments in the sense that they are systematically longer than the vast majority of those found in the literature. The characterization of the effects of relative sand size and time is further improved as compared with existing literature while the effect of the relative flow depth confirms previous findings. New predictors are suggested. Viscous effects conveyed by the approach flow seem non-negligible; this is a new contribution that deserves further research.

Keywords: scouring; single piers; sediment size factor; time factor; effect of viscosity.

1. Introduction

Local scour around bridge piers and abutments is a frequent cause of partial failure or collapse of bridges. The costs of reconstruction/rehabilitation of destroyed/damaged bridges frequently amounts to several hundred thousand million Euro; above all, the priceless human loses that occasionally occur in these disasters are a matter of public concern. The societal claim for security imposes failure prevention, which in turn requires the accurate prediction of the scour depth or the proper mitigation of scouring. In view of the large number of variables involved in the scouring processes and the inherent complexity of their phenomenological interactions, scouring remains an unsolved problem, in spite of the remarkable progresses registered in the last few decades.

Single piers are characterized by a unique geometrical pattern along their vertical axes. In the last six decades, local scouring at single piers has been extensively studied. Research has been made mostly through experimentation. Early contributions of Chabert and Engeldinger (1956), Laursen and Toch (1956), Laursen (1963) or Shen *et al.* (1966) deserve to be mentioned. More recently, several comprehensive summaries of up-to-date knowledge on local scour around bridge piers and abutments have been published by authors such as Breusers and Raudkivi (1991) or Melville and Coleman (2000).

For uniform flows in straight open channels, the maximum scour depth, d_s, was shown to be described through the following parametric equation (*cf*. Fael (2007)):

$$\Pi_{d_s} = \phi\left(\Pi_d ; \Pi_U ; \Pi_{D_{50}} ; \sigma_D ; s ; \Pi_\nu ; \Pi_f ; \Pi_\theta ; \Pi_B ; \Pi_G ; \Pi_t \right) \quad [1]$$

where Π stands for non-dimensional parameter and ϕ stands for "function of", while the indices represent the variables influencing scouring. These are, notably, d = flow depth; U = average approach flow velocity; D_{50} = median grain size of the bed sediment; ν = water kinematic viscosity; f = pier shape; θ = pier alignment angle; B = channel width; G = geometry of the channel cross section. Non-dimensional parameters σ_D and s stand for gradation coefficient and specific gravity of the bed sediment, respectively. The basic variables used to derive Eq. [1] are the characteristic length of the pier cross section, D_p, the gravitational acceleration, g, and the water density, ρ.

For wide rectangular sand bed channels, Eq. [1] reads

$$\Pi_{d_s} = \phi\left(\Pi_d ; \Pi_U ; \Pi_{D_{50}} ; \sigma_D ; \Pi_\nu ; \Pi_f ; \Pi_\theta ; \Pi_G ; \Pi_t \right) \quad [2]$$

In this equation, it is assumed that the effect of flow contraction on scouring at single piers vanishes in wide channels and that the specific sediment gravity is practically invariant for sand. It is also assumed that the rectangular cross section is the reference shape of open channels.

According to Melville and Coleman (2000), the previous equation can be materialized as follows:

$$\Pi_{d_s} = \frac{d_s}{D_p} = K_d K_U K_{D_{50}} K_{\sigma_D} K_\nu K_f K_\theta K_t \quad [3]$$

It should be noted here that K_d refers to the effect of the relative flow depth or flow shallowness, $\Pi_d = d/D_p$; K_U accounts for the effect of flow intensity, $\Pi_U = U/U_c$ (U_c = critical velocity of beginning of sediment motion); K_{D50} reflects the effect of relative sediment size or sediment coarseness, $\Pi_{D50} = D_p/D_{50}$; $K_{\sigma D}$ refers to the effect of armoring (which depends on σ_D); K_ν accounts for the effect of water viscosity as conveyed through any form of Reynolds number, *e.g.*, $\Pi_\nu = u_* D_{50}/\nu$ (u_* = friction velocity); K_f and K_θ attend, respectively, to the effects of shape and alignment of the pier; and K_t varies with the non-dimensional time, $\Pi_t = Ut/D_p$.

In recent years, we have revisited local scouring at cylindrical piers (where $K_f = K_\theta = 1$) inserted in channel beds composed of practically uniform non-ripple forming sand (D_{50} > 0.6 mm; $K_{\sigma D} \approx 1$). The studies were mostly undertaken for approach flow velocities close to the condition of beginning of sediment motion, where the equilibrium scour depth is widely reported to reach a maximum (K_U = 1) if the remaining non-dimensional parameters are kept constant. In these circumstances, we have indeed contributed to an enhanced characterization of the following equation:

$$\Pi_{d_s} = K_d K_{D_{50}} K_\nu K_t \quad [4]$$

The most valuable contributions refer to the effects of relative sand size, K_{D50}, time, K_t, and fluid viscosity, K_ν, while the studies essentially confirm the existing literature on the effect of relative flow depth, K_d. This paper reviews those contributions, summarizing mostly Lança *et al*. (2010), Simarro *et al*. (2011), Lança (2013) and Lança *et al*. (2013).

Prior to addressing those key contributions, the paper includes a short description of the flumes and the characterization sands used in the studies; it also assesses the scour depth time evolution and the equilibrium scour depth in experimental studies.

2. Experimental facilities and granular materials

The tests were carried out in the University of Beira Interior (UBI) and the Faculty of Engineering of the University of Porto (FEUP). Three horizontal-bed flumes were used in the studies. Each flume included a central reach containing a rectangular recess box in the bed (Figure 1), where the piers were installed at ≈ 1.0m from the upstream boundary of the box. The main features of the flumes are shown in Table 1, where B = flume width, Λ = flume length, λ = distance from flume entrance to the recess box, Γ = length of bed recess box and δ = its depth (Figure 1).

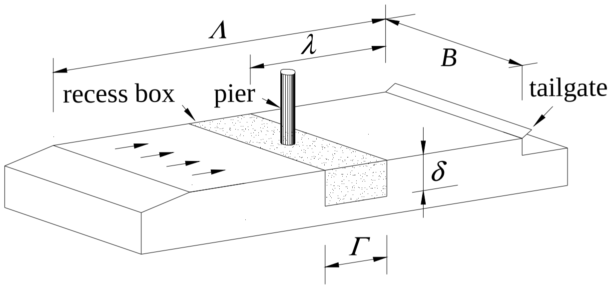

Figure 1. Sketch of used flumes.

Table 1. Main features of the flumes.

Flume	B (m)	Λ (m)	λ (m)	Γ (m)	δ (m)
UBI_1	4.00	28.00	13.90	3.00	0.60
UBI_2	0.83	12.70	5.00	3.10	0.35
FEUP	1.00	33.20	16.00	3.20	0.35

Three natural quartz sands were used in the studies summarized herein. They are characterized in Table 2, where D_n = sand particle sieving diameter for which n% are finer by weight. The table also includes the values of the gradation coefficient, $\sigma_D = (D_{84.1}/D_{50} + D_{50}/D_{15.9})/2$. All sands can be considered as uniform, since $\sigma_D < 1.5$. The specific gravity was verified to be $s \approx 2.65$ in all cases.

Table 2. Diameters and gradation coefficient of used sands.

Sand	$D_{15.9}$ (mm)	D_{50} (mm)	$D_{84.1}$ (mm)	σ_D (–)
S_1	0.87	1.28	1.87	1.46
S_2	0.64	0.86	1.17	1.35
S_3	2.34	3.00	3.67	1.25

The detailed description of the experimental facilities and procedures may be found, for instance, in Lança (2013) or Lança *et al*. (2013). Distinctive characteristics of the experiments informing the results reported herein are the absence of contraction scour and wall effects and, above all, the long duration of the experiments, typically exceeding 7 days and reaching up to 45.6 days, this way allowing for the proper assessment of equilibrium scour depth, as described in the next section. Other remarkable characteristics of the studies are a large number of experiments covering uncommon ranges of the relative sediment size, $\Pi_{D50} = D_p/D_{50}$, and three experiments specially designed to assess the effect of viscosity on scouring.

3. Assessing the scour depth time evolution and the equilibrium scour depth

Time plays an important role in scouring. Ettema (1980) identified three phases of the scouring process: the initial phase, the principal phase and the equilibrium phase. It is well established that, under live-bed conditions ($U > U_c$), scour depth tends to equilibrium very quickly while, under clear-water conditions ($U \leq U_c$), scour evolves much slower: the principal phase lasts for a long time and the equilibrium scour depth is approached asymptotically.

According to Ettema (1980), in the equilibrium phase, the scour depth "practically" does not increase anymore. Coleman *et al*. (2003) – for instance – state that an equilibrium scour hole may continue to deepen at a "relatively slow rate". Each author has a different interpretation of the meaning of concepts like "practically" or "relatively slow rate". Some investigators state that equilibrium cannot be achieved in finite time (Franzetti *et al.* (1982)), or even that the scour hole never stops developing. The reported subjectivity has important implications on the design of scour experiments.

Assuming that equilibrium scour exists but that it is not reached in a finite time, the question is "how long should experiments be until the scouring rate becomes insignificant or practically null and scour depth is close enough to its ultimate value" (Simarro *et al.* (2011)). On this question, Lança *et al*. (2010) reported five long lasting experiments run in flume UBI_1, sand S_1, for $U/U_c \approx 0.8$. Tests lasted 24.9 days $\leq T_d \leq$ 45.6 days (T_d = test duration), *i.e.*, much longer than common experiments. The relative flow depth, $\Pi_d = d/D_p$, was kept reasonably constant and ≈2, rendering the effect of this parameter on the equilibrium scour depth negligibly small; relative sediment size, $\Pi_{D50} = D_p/D_{50}$, varied in the range $49.2 \leq \Pi_{D50} \leq 93.0$, which maximizes the scour depth, as shown in Section 4.

According to Lança *et al.* (2010), the equilibrium phase is not unambiguously identifiable; they observed that the scour depth continues to evolve after several weeks (see Figure 2).

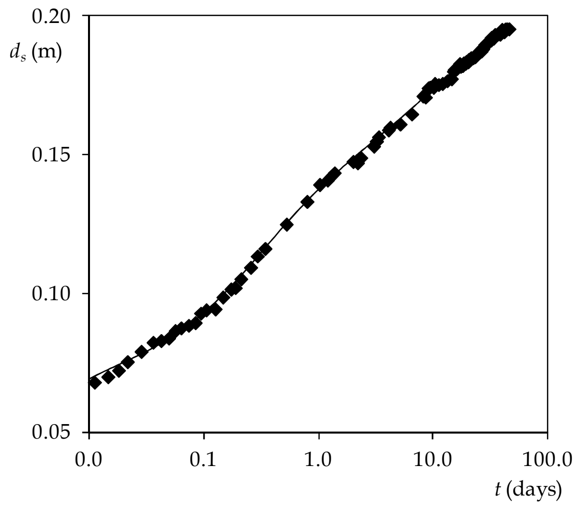

Figure 2. Time evolution of the scour depth for a test defined by T_d = 45.6 days.

Lança *et al.* (2010) tested several methods to fit the data of their long experiments and concluded that the equilibrium scour depth, d_{se}, may be obtained by fitting the 6-parameters polynomial equation,

$$d_s = p_1\left(1-\frac{1}{1+p_1p_2t}\right)+p_3\left(1-\frac{1}{1+p_3p_4t}\right)+p_5\left(1-\frac{1}{1+p_5p_6t}\right) \quad [5]$$

to scour depth measurements acquired for at least 7 days and extrapolating the fitted equation to $t = \infty$. The equilibrium scour depth is given by, $d_{se} = p_1 + p_3 + p_5$.

The data of Lança *et al*. (2010), complemented with one test from the literature, were reassessed by Simarro *et al.* (2011) who have shown that the exponential function by Franzetti *et al.* (1982),

$$K_t = \frac{d_s}{d_{se}} = 1-\exp\left[-a_1\,\Pi_t^{a_2}\right], \qquad \text{with} \qquad \Pi_t = \frac{Ut}{D_p} \quad [6]$$

precisely predicts the scour depth time evolution along the three scour phases. Remarkably, Eq. [6] only depends on a_1 and a_2 if d_{se} is estimated independently.

The technique suggested by Lança *et al.* (2010) was systematically applied to derive the values of the equilibrium scour depth reported herein; the exponential function will be further characterized in section 5.

4. Effects of flow depth and sediment size on the equilibrium scour depth

For a given value of $\Pi_\nu = u_*D_{50}/\nu$ as well as for values of $\Pi_\nu > \approx 100$, corresponding to rough turbulent approach flow, Eq. [4] may be simplified as

$$\Pi_{d_s} = K_d K_{D_{50}} K_t \quad [7]$$

In equilibrium, where $d_s = d_{se}$ and $\Pi_{ds} = \Pi_{dse}$, Eq. [7] reads

$$\Pi_{d_{se}} = K_d K_{D_{50}} \quad [8]$$

It is profusely recognized that the relative approach flow depth, $\Pi_d = d/D_p$, is one of the parameters that most influences the scour depth. On the contrary, important studies on scouring (*e.g.* Ettema (1980), Melville and Chiew (1999)) have successively assumed that the normalized equilibrium scour depth, $\Pi_{dse} = d_{se}/D_p$, does not depend on the relative sediment size, $\Pi_{D50} = D_p/D_{50}$, for $\Pi_{D50} > \sim 50$. This view has been disputed in the last decade by Sheppard *et al.* (2004). According to their studies, Π_{dse} decreases with increasing relative sediment sizes, for $\Pi_{D50} > \sim 50$.

In spite of these recent contributions, there is still a lack of information on scouring for comparatively high relative sediment sizes. The availability of two comparatively large flumes, UBI_1 and FEUP, rendered it possible for Lança *et al.* (2013) to generate additional high quality scour data for values of relative sediment size in the range $58 \le \Pi_{D50} \le 465$, while covering relative flow depth values, Π_d, in the range $0.5 \le \Pi_d \le 5.0$, for flow intensity close to the condition of initiation of motion ($0.93 \le \Pi_U \le 1.04$) and approximately constant – transitional – values of the sediment Reynolds number, $\Pi_\nu = u_*D_{50}/\nu$ (estimated as $12.8 < \Pi_\nu < 14.4$). Thirty eight tests with sand s_2, lasting between 7 and 14 days, were run for this purpose.

The aspect ratio, B/d, was guaranteed to be greater than 5.0, this way avoiding significant wall effects on the flow field. The ratio of channel width to pier diameter, B/D_p, was at least 5.0, being higher than 8.0 in 30 (out of 38) tests and higher than 10.0 in 27 tests. Contraction scour seemed absent since no bed degradation was observed over the contracted cross sections. The assembled data allowed the characterization of Eq. [8].

The values of $\Pi_{dse} = d_{se}/D_p$ are plotted against Π_{D50} in Figure 3. Data of six long duration clear-water experiments ($T_d \geq 6$ days) by Sheppard *et al.* (2004) for $\Pi_{D50} > 500$ and Π_U sufficiently close to 1.0 (0.85 to 1.21) are also included for completeness. Figure 3 separates the data – those of this study as well as those of Sheppard *et al.* (2004), where Π_{D50} goes up to 1260 – into six classes of Π_d. It is clear that the parameter Π_{D50} influences $\Pi_{dse} = d_{se}/D_p$, leading to decreasing normalized scour depths as Π_{D50} increases in the range of the study.

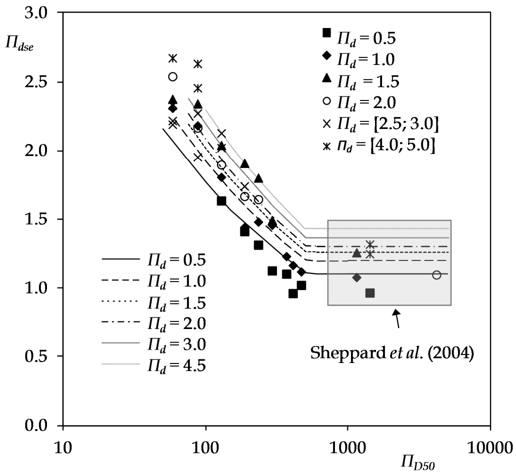

Figure 3. Effect of Π_{D50} and Π_d on Π_{dse}, Lança *et al.* (2013).

The double dependence of Π_{dse} on the relative flow depth, Π_d, and relative sediment size, Π_{D50}, is captured by the following regression equations suggested by Lança *et al.* (2013):

$$\Pi_{dse} = \begin{cases} 7.3(\Pi_{D50})^{-0.29}(\Pi_d)^{0.12} & 60 \leq \Pi_{D50} \leq 500 \\ 1.2(\Pi_d)^{0.12} & \Pi_{D50} > 500 \end{cases} \qquad [9]$$

Eq. [9] may be used to predict the equilibrium scour depth; however, for safety reasons, the following upper-bound predictor is suggested instead:

$$\Pi_{dse} = K_d K_{D50} \qquad [10]$$

where K_d is the predictor of Melville (1997) slightly modified to read:

$$K_d = \begin{cases} 2.3(\Pi_d)^{1/3} & 0.50 \leq \Pi_d \leq 1.45 \\ 2.6 & \Pi_d > 1.45 \end{cases} \qquad [11]$$

and K_{D50} is given by:

$$K_{D50} = \begin{cases} 1.0 & 60 < \Pi_{D50} \leq 100 \\ 5.8(\Pi_{D50})^{-0.38} & 100 < \Pi_{D50} \leq 500 \\ 0.55 & \Pi_{D50} > 500 \end{cases} \qquad [12]$$

Eq. [11] constitutes the envelope curve of the K_d data plotted in Fig. 4a. Likewise, Fig. 4b includes the envelop curve of K_{D50}. The values of K_{D50} were back calculated from the values of Π_{dse} by assuming K_d to be given by the modified predictor of Melville (1997), Eq. [11].

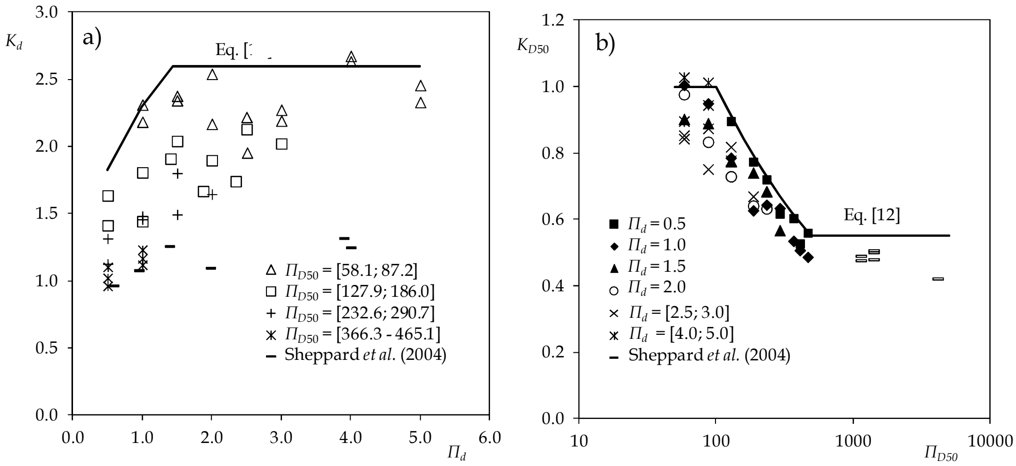

Figure 4. a) Variation of K_d with Π_d; b) Variation of K_{D50} with Π_{D50}.

In engineering practice, the use of Eq(s).[10] to [12] for safe upper bound scour depth prediction requires the use of appropriate multiplying factors – see Eq. [2] – to take into account the effects of flow intensity, water viscosity, pier shape, pier alignment, gradation coefficient of bed the material, flow contraction, cross-section shape, and time. Sections 5 and 6 assess the time factor and the viscosity effect, respectively.

5. Time factor

In the sequence of the assessment performed by Simarro *et al*. (2011), Lança *et al*. (2013) revisited the proposal of Franzetti *et al.* (1982), Eq. [6], as a candidate predictor of scour depth time evolution.

As the equilibrium scour depth, d_{se}, was known for each experiment, Lança *et al.* (2013) estimated the parameters a_1 and a_2 by the fitting Eq. [6] to the observed scour depth time evolution data.

They have concluded that a_1 varies in the range $0.005 \le a_1 \le 0.080$, with an average value of 0.031, while a_2 varies within the range $0.212 \le a_2 \le 0.458$, with an average value of 0.311. These intervals of a_1 and a_2 contain the values proposed by Franzetti *et al.* (1982), *i.e.*, $a_1 = 0.028$ and $a_2 = 1/3$.

Lança *et al.* (2013) have also shown for the first time that a_1 and a_2 depend on Π_{D50} (Figure 5), while no obvious variation of a_1 or a_2 with Π_d was identified. The coefficients a_1 and a_2 relate with Π_{D50} as follows:

$$a_1 = 1.22(\Pi_{D50})^{-0.764} \qquad a_2 = 0.09(\Pi_{D50})^{0.244} \qquad [13]$$

From the above, the model of Franzetti *et al.* (1982) for the prediction of scour depth time evolution, Eq. [6], can be applied. The time factor, K_t, reads as follows:

$$K_t = 1 - \exp\left\{-1.22(\Pi_{D50})^{-0.764}[\Pi_t]^{0.09(\Pi_{D50})^{0.244}}\right\} \qquad [14]$$

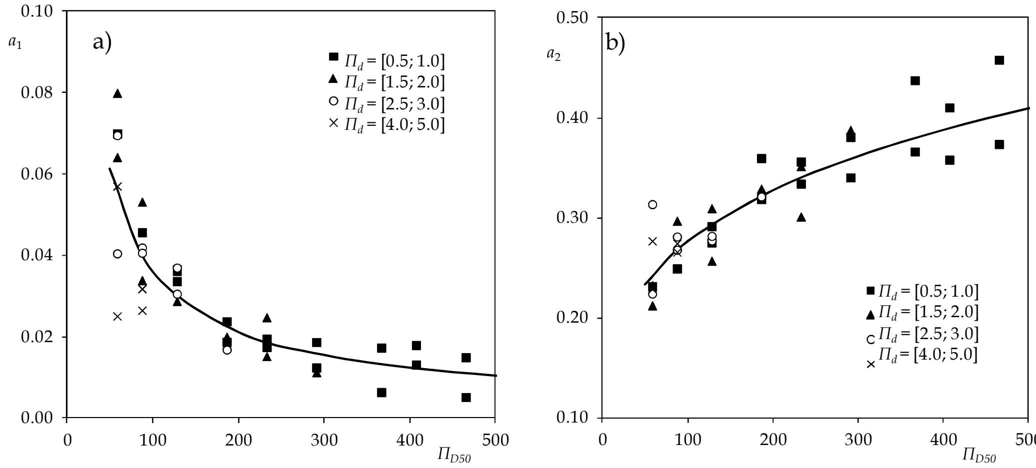

Figure 5. Dependence of a_1 and a_2 from Π_{D50}, Lança *et al.* (2013).

The simultaneous use of Eq(s). [9] and [14] is suggested for the central prediction of the scour depth at cylindrical piers in wide channels whose bed is composed of non-ripple forming uniform sand whenever the approach flow velocity is close to the critical velocity of beginning of motion, $\Pi_U \approx 1.0$. Further research is needed for different values of Π_U.

6. Effect of viscosity on the equilibrium scour depth

Eq. [1] may be materialized as

$$\Pi_{dse} = K_d K_\nu \qquad [15]$$

for equilibrium scour depth at cylindrical piers inserted in wide, rectangular channels, whose bed is composed of uniform non-ripple forming sand, if Π_U = const. and Π_{D50} = const..

In spite of the pioneering works of Shen *et al*. (1966) and Nicollet and Ramette (1971) indicating that viscosity may affect the scouring process, important works on scouring (*e.g*., Melville and Coleman (2000), Oliveto and Hager (2002) or Sheppard *et al*. (2004)) may have overlooked the effect of viscosity.

The assumption seems to be that the flow is fully rough inside the scour hole, *i.e*., free of viscous effects, due to the presence of highly turbulent flow structures – down-flow, horseshow vortex and wake vortices – irrespective of the approach flow regime.

Lança (2013) reported a limited number of preliminary experiments to gain insight on the effect of viscosity. He has used flumes UBI_1 and FEUP and sands s_1, s_2 and s_3. He has run three experiments for cylindrical piers, by keeping $\Pi_{D50} \approx 58$ and $\Pi_d = 1$. Piers were simulated by PVC pipes defined by D_p = [50, 75, 175] mm.

The critical velocity of beginning of sand motion, U_c, was established through the equation of Neil (1967). The approach flow velocity, U, was fixed so as to guarantee $\Pi_U \approx 0.97$. For each experiment, the fiction velocity, u_*, was calculated through the equation

$$\frac{U}{u_*} = 5.75\log\left(\frac{12.27R\chi}{k}\right) \qquad [16]$$

valid for transitional rough flow. In the above equation, R = hydraulic radius, $k \approx 1.2D_{50}$ = sand roughness, χ = coefficient that varies with k/δ', and $\delta' = 11.6\nu/u_*$ = thickness of the viscous sub-layer.

Under the reported conditions, including Π_d = const., equation [15] reduces to

$$\Pi_{dse} = K_\nu \qquad [17]$$

The results of the experiments by Lança (2013) are plotted in Figure 6. The most important output is the apparent decrease of the equilibrium scour depth for increasing shear velocity Reynolds number, $\Pi_\nu = u_* D_{50}/\nu$.

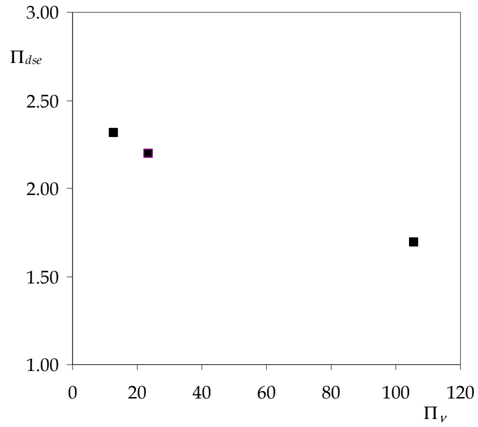

Figure 6. Effect of Π_ν on Π_{dse}, Lança (2013).

In view of the limited number and novelty of the experiments included in Figure 6, no predictor of K_ν is suggested yet. For the same reason, a systematic study of the effect of viscosity on the equilibrium scour depth is underway.

7. Conclusions

The most important conclusions of the works summarized herein are as follows:

i) The equilibrium scour depth decreases with Π_{D50}, for $\Pi_{D50} > \sim 100$, which implies refuting the classical assumption according to which the equilibrium scour depth would not depend on Π_{D50} for $\Pi_{D50} > \sim 25$. The sediment size factor, K_{D50}, may be obtained through Eq. [12].

ii) Safe upper-bound predictions of the equilibrium scour depth may be obtained through Eq. [10], valid for cylindrical piers inserted in uniform, fully-developed turbulent flows in wide rectangular channels with flat-bed composed of uniform, non-ripple-forming sand, flow intensity $\Pi_U \approx 1.0$, $\Pi_{D50} > \approx 60$ and $0.5 \leq \Pi_d \leq 5.0$.

iii) The exponential model of Franzetti *et al.* (1982), specified as Eq. [14], properly describes the time evolution of the scour depth. This contribution applies for $\Pi_U \approx 1.0$, $60 < \Pi_{D50} < 500$ and $0.5 \leq \Pi_d \leq 5.0$.

iv) The viscous effect conveyed by the approach flow seems non-negligible for transitional flow. This is a new contribution that deserves further research.

Acknowledgments

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