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INFLUENCE OF BED MATERIAL DENSITY ON LOCAL SCOUR AROUND SPUR DIKES

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ABSTRACT

An experimental study on local scour has recently started in a laboratory flume at the National Laboratory of Civil Engineering (LNEC) in Lisbon. The main objective of this study is the investigation of the influence of the sediment specific density on the final scour hole around a spill-through spur dike placed perpendicular to the flow, in order to improve knowledge for the use of light-weight bed materials in physical modelling. The results of three sets of runs under regime conditions, corresponding to two different mixtures of river sand and a light weight bed material, are discussed. Experiments were made under live-bed and with clear-water conditions, for which different equations, obtained by multiple regression analysis, are suggested, allowing the prediction of the maximum scour depth. The paper presents the results already obtained and the discussion on maximum scour depth and geometric characterisation of the scour holes in the framework of existing literature.

INTRODUCTION

Spur dikes are among the hydraulic structures used in environmentally acceptable river training schemes. Thus, the evaluation of their performance and design criteria became again, recently, a topic of interest. The efficiency of river training schemes is frequently evaluated and improved by running physical models where the loose boundary is simulated by light-weight grains, i.e., materials with lower density than the standard value for sand. The role of the sediment specific density in the local scour phenomenon associated with the spur dikes incorporated in river training schemes is not clear in the available literature, which poses serious problems to the interpretation of models results. Hence, an experimental study on this topic has recently started in a laboratory flume of the National Laboratory of Civil Engineering (LNEC) in Lisbon.

Three series of tests were already made. Two of them were carried out over two different natural sands; in the third one, pumice was used as bed material. The most important results concerning the two "sand series" were presented and discussed in COUTO and CARDOSO (1994). The purpose of the present paper is the presentation of results concerning the third series and the discussion of the influence of specific density on the geometry of scour holes around spur dikes.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experiments were carried out in a flume 18 m long (the test reach being 10 m long), 2 m wide and 0.6 m deep. The inlet system includes a constant head tank leading to a Bazin spillway used to measure the discharge. The maximum available discharge is 0.16 m^3/s. The experiments were run with a 0.15 m thick movable bed. The flume is prepared for the study of localised river problems since a deeper bottom exists in the central reach, allowing an additional sand thickness of 0.4 m. The initial bed slope is adjustable to a pre-fixed value for each run, with the help of a carriage system. At the upstream section of the flume, a sediment feed device may be used that can be operated at adjustable rates. At the downstream end, a tailgate allows the regulation of the flow depth in the flume.

The measuring equipment includes an electronic water level gauge and a bed follower, installed in the carriage system. The water elevations can also be measured by two point gauges installed in side wells close to the upstream and the downstream sections respectively. The level gauge is fixed in the carriage at the central longitudinal axis of the flume. The bed follower is allowed to travel in the transverse direction at almost all the flume width, recording the cross sectional deformations of the bed. These two electronic instruments are integrated in an automatic data acquisition system.

The spur dike used in these experiments is represented in Fig. 1 and was placed perpendicular to the flow, 5 m downstream of the flume entrance. The spill-trough part of the spur is exposed to the flow before the scour develops, since the moveable bed is levelled just at the plan that contains the edge separator to the lower semi-circular geometry.

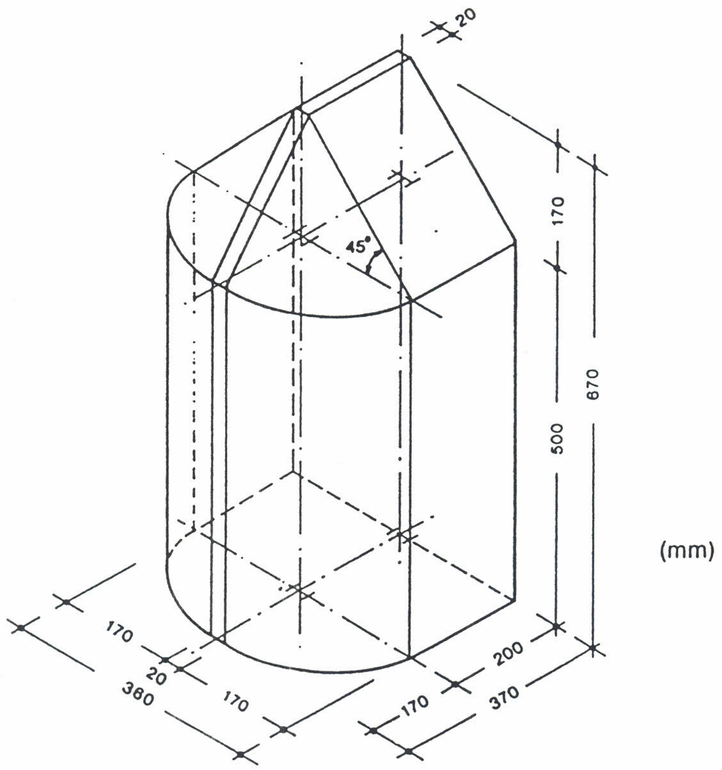
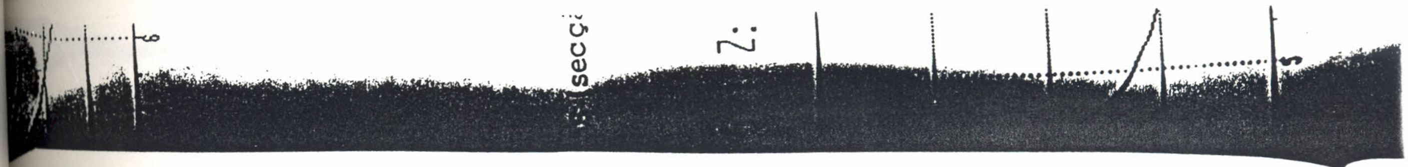


Fig. 1 - Spur dike

According to the experimental procedure followed in this study, the discharge, Q, was set constant for each run; a tentative water depth, h_0, was also set. Searching the regime conditions, the corresponding values of the bed slope, i_b, and the sediment discharge, Q_s, were estimated on the basis of a resistance relation and a sediment transport formula.



Prior to each run, the bed was levelled with the calculated slope. When this slope was estimated to be below 2.1×10^{-4} the bed was set horizontal for practical reasons. The tailgate was regulated such that an approximate value of selected h_0 was reached after the flow discharge being imposed. Finally, the flow itself could adjust the bed slope and the water depth. The flow response was monitored and attempts were made to reach the regime conditions, by acting in the rate of sediment feeding and in the water depth. The bottom profile was estimated by means of linear regression applied to a sample of bed levels, being those bed levels obtained by averaging the corresponding cross section bed measurements. The evolution of the scour hole in time was monitored by the bed follower probe. The test was stopped when the evolution of the scour hole was negligible or oscillating around an equilibrium value. After the flow stopped, 29 cross section profiles were measured, in the zone of the local scour, in order to represent its final topography.

RESULTS AND DISCUSSION

As stated before, three series of runs, corresponding to two different river sands and to pumice, were carried out: series A1, with median grain size D_{50}= 0.37 mm and gradation coefficient σ_g= 1.58; series A2, with D_{50}= 0.96 mm and σ_g= 1.29 (in both river sands the specific density was $W = \gamma_s/\gamma = 2.65$); and series P1, with D_{50}= 1.75 mm and σ_g= 1.17 (pumice, $W = \gamma_s/\gamma = 1.44$).

The most relevant variables measured for each run over the pumice bed are presented in Table 1 for the final (equilibrium) stage, where the bed slope and the water surface slope, i_s, were accepted as similar. The table includes the values of the water depth, followed by the values of the imposed discharge, Q, the corresponding hydraulic radius, R, mean velocity, U_0, and i_b, i_s, and Q_s, for the undisturbed flow (free of disturbance induced by the spur dike). Equivalent data can be found in COUTO and CARDOSO (1994) for the "sand series" runs (A1 and A2).

Table 1

Run	h_0 (m)	Q $\times 10^3$ (m^3/s)	R (m)	U_0 (m/s)	i_b $\times 10^3$	i_s $\times 10^3$	Q_s $\times 10^6$ (m^3/s)	Fr	J $\times 10^3$	Re $\times 10^{-3}$	Z	U_0/U_c
P1.01	0.049	18.4	0.047	0.19	0.23	0.50	0.32	0.28	0.48	34	28	0.88
P1.02	0.053	24.0	0.050	0.23	0.99	1.04	2.02	0.32	1.03	44	30	1.05
P1.03	0.053	29.6	0.050	0.28	1.88	1.67	21.34	0.40	1.70	55	30	1.29
P1.04	0.056	27.6	0.053	0.25	0.99	0.74	1.48	0.34	0.77	50	32	1.13
P1.05	0.065	36.0	0.061	0.28	1.37	1.06	6.90	0.36	1.10	68	37	1.24
P1.06	0.060	44.4	0.057	0.37	1.26	1.47	17.80	0.50	1.42	84	34	1.68
P1.07	0.090	41.4	0.083	0.23	0.76	0.46	0	0.26	0.48	67	51	0.99
P1.08	0.091	54.0	0.083	0.30	0.00	0.76	8.90	0.33	0.68	96	52	1.27
P1.09	0.105	66.6	0.095	0.32	1.78	1.26	16.58	0.33	1.32	120	60	1.33
P1.10	0.135	55.2	0.119	0.20	0.11	0.48	0	0.19	0.47	84	77	0.83
P1.11	0.117	72.0	0.105	0.31	0.57	0.52	2.23	0.30	0.52	120	67	1.27
P1.12	0.132	88.8	0.117	0.34	0.77	0.96	7.73	0.31	0.94	158	75	1.37
P1.17	0.033	9.6	0.032	0.15	0.21	0.86	0	0.26	0.82	15	19	0.72
P1.18	0.052	16.0	0.049	0.15	0.00	0.47	0	0.22	0.45	26	30	0.71
P1.19	0.072	19.6	0.067	0.14	0.00	0.38	0	0.17	0.37	32	41	0.60
P1.20	0.075	25.2	0.070	0.17	0.00	0.45	0	0.20	0.43	40	43	0.74
P1.21	0.093	37.8	0.085	0.20	0.00	0.35	0	0.22	0.33	60	53	0.87
P1.22	0.096	32.4	0.088	0.17	0.00	0.41	0	0.18	0.40	50	55	0.72

The Froude number was evaluated as $Fr = U_0/\sqrt{gR}$; it covers values between 0.17 and 0.50 in the lower flow regime, while for series A1 and A2 Fr covered values between 0.23 and 0.64. The slope of the energy line, J, was calculated as a function of the bed and water surface slopes as $J = Fr^2\, i_b + \left(1 - Fr^2\right) i_s$. From Table 1, it can be seen that, with a few exceptions, J and i_b are reasonably similar, which means that uniform flow was satisfactorily achieved. Reynolds number, $Re = 4RU_0/\nu$, varies between 0.15×10^5 and 1.58×10^5

showing that the flow is turbulent. In the previous series this parameter varied between 0.35×10^5 and 1.87×10^5. For the calculation of Re, the kinematic viscosity, ν, was evaluated in function of the water temperature which varied between 12.9 °C and 20.4 °C during the tests. The relative submergence, $Z = h_0/D_{50}$, varies between about 19 and 77, while in tests A1 and A2 varied between 37 and 336. It should be pointed out that series P1 extended the study to lower values of Fr, Re and Z.

In the last column of Table 1, the relative flow intensity parameter U_0/U_c is included, where U_c is the mean velocity corresponding to the initiation of sediment motion, i.e., the critical mean velocity. This variable was defined for each run, as a function of h_0 and the sediment characteristics (D_{50} and γ_s), following the formulations of Goncharov, Neill, and Garde, as presented in GARDE and RAJU (1985), p. 58.

The values of the most pertinent variables characterising the scour hole, namely its maximum width, L_s, its area, A_s, the excavated volume, V_s, and the maximum scour depth, h_s, are given, for the tests over the pumice bed, in Table 2. The duration of each run, t_f, and the spur length, L, are also given. The referred geometric parameters were obtained from the representation of the scour topography by contour lines drawn at 1 cm intervals. The length L was measured perpendicularly to the flow direction in the horizontal plan located at half depth between the initial bed and the water surface, as suggested by MELVILLE (1992). Equivalent data for series A1 and A2 can be found in COUTO and CARDOSO (1994). The duration of each run varies between 2 and 42 hours, while in series A2 the maximum duration was up to 56 hours. The tests in which the bed movement was non-existent or incipient were run for longer periods.

Table 2

Run	t_f (h)	L (m)	L_s (m)	A_s (m^2)	V_s $\times 10^2$ (m^3)	h_s (m)
P1.01	14.83	0.346	0.16	0.15	0.26	0.066
P1.02	7.30	0.344	0.25	0.27	0.90	0.110
P1.03	6.50	0.344	0.36	0.36	1.45	0.144
P1.04	10.67	0.342	0.26	0.29	0.94	0.119
P1.05	6.00	0.338	0.37	0.57	2.41	0.202
P1.06	7.33	0.340	0.39	0.73	5.53	0.231
P1.07	15.75	0.325	0.29	0.33	1.25	0.126
P1.08	9.83	0.325	0.42	0.83	7.47	0.265
P1.09	9.00	0.318	0.35	0.92	8.66	0.303
P1.10	10.58	0.303	0.27	0.48	1.57	0.123
P1.11	41.97	0.312	0.56	1.49	16.59	0.301
P1.12	9.25	0.304	0.56	1.47	14.62	0.313
P1.17	9.67	0.354	0.15	0.15	0.07	0.012
P1.18	2.32	0.344	0.12	0.17	0.07	0.028
P1.19	8.00	0.334	0.17	0.13	0.07	0.035
P1.20	5.33	0.333	0.20	0.11	0.19	0.060
P1.21	6.83	0.324	0.21	0.17	0.44	0.074
P1.22	7.16	0.322	0.12	0.09	0.17	0.054

The maximum scour depth, h_s, is presented in Fig. 2 in function of the undisturbed flow depth, h_0, where both variables are made dimensionless by the spur length, L. The data plotted includes the three series of tests. In this picture, the data were separated in three groups. The runs with $U_0/U_c < 0.9$ (neat clear-water) were included in the first plot; the runs with $0.9 \leq U_0/U_c \leq 1.15$ were chosen for the representation at the threshold condition and included in the second plot; the runs with the values of $U_0/U_c > 1.15$ (neat live-bed) were represented in the third plot.

The scour depth values were divided by the shape coefficient K_s in order to remove the shape effect and make the results comparable with those obtained for a vertical plate obstacle, as suggested by MELVILLE (1992). A value of $K_s = 0.7$ was chosen in such a way that the envelope curve obtained by that author for threshold conditions also serves as an envelope curve for the present data obtained with sandy bed and close to the threshold condition. This value of K_s is between those recommended for semi-circular end ($K_s = 0.75$) and spill-through abutments with slope 1:1 ($K_s = 0.5$). $K_s = 0.7$ is close to the value of the semi-circular end spur, because, in this study, the spill-through spur presents a vertical wall bellow the initial bottom that shows up as scouring proceeds.

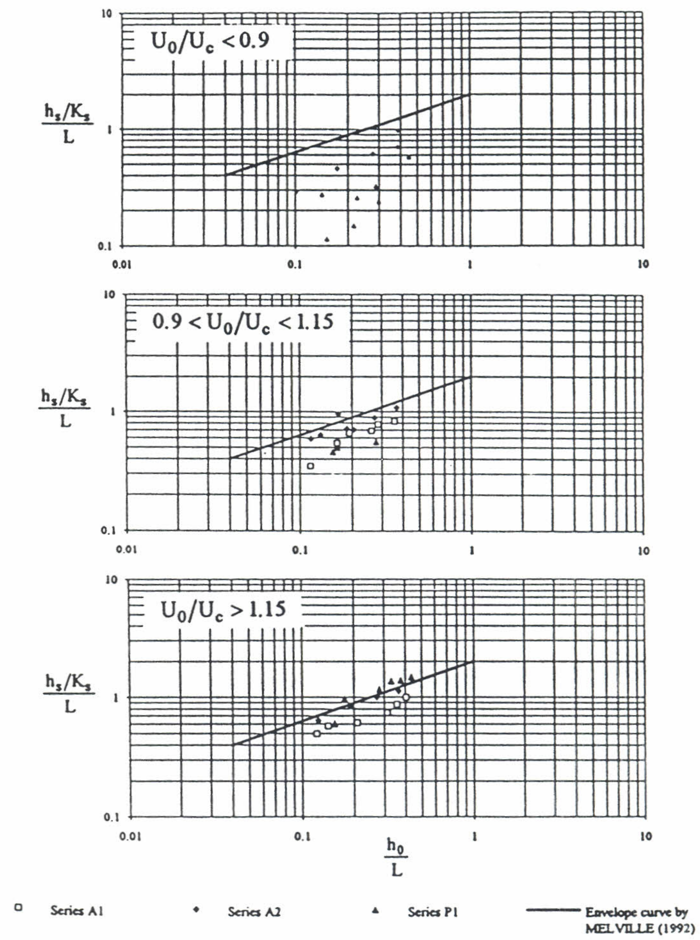


Fig. 2 - Maximum scour depth according to MELVILLE (1992)

Recent studies reported by BREUSERS and RAUDKIVI (1991) and MELVILLE (1992) state that the threshold condition leads to the largest scour depths and that the clear-water scour depths are considerably lower. This result can be confirmed, in some way, from the first plot in Fig. 2, where smaller scour depths are clearly observed. Such behaviour is more evident from the data corresponding to the light-weight material tests. The above mentioned authors state that, especially for bridge piers and under live bed conditions, scour depths tend to decrease for $U_0/U_c > 1$ and then increase again for $U_0/U_c \geq 3.5$, to about the threshold value. Comparing the second and third plots of Fig. 2, it can be concluded that this trend is not observed in the present study. In case of the sandy bed tests, the indiscriminate trend in the plots does not contradict the literature, since the upper relative flow intensity reached in this study is comparatively low ($U_0/U_c = 1.34$). However, the behaviour is totally the opposite in case of light-weight material tests. In fact, the plots show that the scour depths increase for $U_0/U_c \geq 1.15$, for which conditions the results are even above the envelope curve.

In what concerns the tests with sand, a slight influence of D_{50} on the maximum scour depth seems to exist. In fact, under threshold conditions, the data of series A2 (coarser sand) fall systematically above the data of series A1 (cf. Fig. 2). This result is in agreement with KANDASAMY (1989), p. 228, who mentioned that preliminary experiments indicate scour depth at abutments to be larger for coarser uniform sediment. This conclusion does not stand for the pumice. The use of this material, coarser than the sand of series A2, gave rise to less deeper scour holes.

In the following discussion, and for the sake of comparison with relevant literature, the data were split into two different groups: clear-water and live-bed data. Details on the separation of data corresponding to series A1 and A2 can be found in COUTO and CARDOSO (1994). For series P1 the set of clear-water runs corresponds to those with $Q_s = 0$ and test P1.01, with plain bed and incipient motion; in the remaining runs (classified as live-bed), sediment transport was observed, and formation of dunes took place in some of these.

Results on the maximum scour depth were analysed by regression techniques. According to the data analysis carried out for series A1 and A2, the best framework for the sand data was the following

$$\frac{h_s}{h_0} = f\left[(L/h_0), Z, Fr\right] \qquad (1)$$

The parameters in the right hand side of Eq. 1 reflect the influence of the main variables acting in the phenomena: the spur length, the sand diameter, the undisturbed flow velocity and depth, and gravity. All lengths are made dimensionless by h_0. With this framework, the results obtained for series A1 and A2 were

$$\frac{h_s}{h_0} = 38.3\,(L/h_0)^{-0.56} Z^{0.23} Fr^{2.76} \qquad \text{for clear-water} \qquad (2)$$

$$\frac{h_s}{h_0} = 4.30\,(L/h_0)^{0.29} Z^{-0.21} \qquad \text{for live-bed} \qquad (3)$$

These equations were obtained with correlation coefficients, r, of 0.96 and 0.93, respectively. The influence of Fr was seen to be negligible for live-bed, while it plays an important role for clear-water. Higher power coefficients for the Froude number in equations for clear-water than in equations for live-bed can be also found in other author's formulae (cf. comparison in rewritten formulae in WONG (1982)).

Adding the data from series P1 to the previous sample and using Eq. 1, the following model was obtained, with r = 0.95, for the clear-water set

$$\frac{h_s}{h_0} = 41.2\,(L/h_0)^{-0.61} Z^{0.14} Fr^{2.38} \qquad \text{for clear-water} \qquad (4)$$

The parameter combination in Eq. 1 could not explain the results in the case of the data from the live-bed condition, being r= 0.59 for the sample with the three series. Several tests have been performed and scatter introduced with live-bed data from series P1 was systematically observed. The following dimensionless framework, allowing the use of the bed material specific density ($W=\gamma_s/\gamma$) and the modified Froude number $F_G = U_0/\sqrt{h_0(\gamma_s-\gamma)/\rho}$ (defined in TYAGI (1967), p. 49), seems to be adequate

$$\frac{h_s}{h_0} = f\left[(L/h_0), Z, F_G, W\right] \qquad (5)$$

The results of using Eq. 5 to the live-bed set of data (series A1, A2 and P1), with r = 0.88, led to the following

$$\frac{h_s}{h_0} = 0.55\,(L/h_0)^{0.14} Z^{-0.18} F_G^{0.40} W^{2.66} \qquad \text{for live-bed} \qquad (6)$$

It can be observed that all coefficients are of the same order of magnitude between Eq. 2 and Eq. 4. Hence, the final scour depth depends on the Froude number when there is no sediment motion in the undisturbed flow and, in this case, the influence of the bed material specific density is negligible. The power coefficients for the parameters L/h_0 and Z are the of the same order of magnitude in Eqs. 3 and 6. Although the prediction of the experimental observations of the live-bed set presents some scatter, the above discussed trend to lower coefficients associated with Fr in this new data sample, in this case with the parameter F_G, is confirmed. The use of the parameter W and the coefficient obtained in Eq. 6 emphasise the influence of the bed material density in the final scour depth due to continuous sediment motion flow.

Attempts were made to include other pertinent combinations of parameters in a regression model for the data available in the present study. The analysis of VEIGA DA CUNHA (1973), suggesting the ratio u_*/w to represent the influence of the sediment characteristics, together with L/h_0 as independent variables in Eq. 1, was applied to data corresponding to the series of tests run with sand with reasonable results; when including data from tests run with pumice, that combination of parameters was no longer suitable. Similarly, results were inappropriate when including the sediment number, $N_s = U_0/\sqrt{(\gamma_s/\gamma - 1)gD_{50}}$ defined by CARSTENS (1966), or the combination of N_s, W and U_0/w as studied by TYAGI (1967). Hence, it is required some additional data analysis and it is expected that an extension of the present study using other light weight bed materials will improve the knowledge on the specific density effect.

The extension of the bed deformation due to local scour (including the downstream deposition of the eroded material) presents higher lengths for the case of the light weight sediment and the slope of the scour hole (or its angle, β, with the horizontal plan) is smaller. Both conclusions were discussed by EISENHAUER and KLEY (1988). It was also found that the ratios between the scour width and the scour depth are approximately constant for each series, being equal to 2.3 ($\beta \approx 24°$) and 2.0 ($\beta \approx 27°$) in series A1 and A2, and equal to 2.5 ($\beta \approx 22°$) in series P1. This result fits the conclusions of Izzard and Bradley (in TYAGI (1967), p. 55) who state that β is a function of the spur geometry and of the sediment characteristics and vary between 20° and 30°. In the present case it shows up that β increases for coarser sediment and decreases when a lighter weight sediment is used.

According to VEIGA DA CUNHA (1973), the geometry of the scour holes preserves similarity, meaning that A_S and V_S depend only on h_S. The logarithmic plot of the variation of V_S with h_S, obtained for series A1, A2 and P1 is included in Fig. 3.

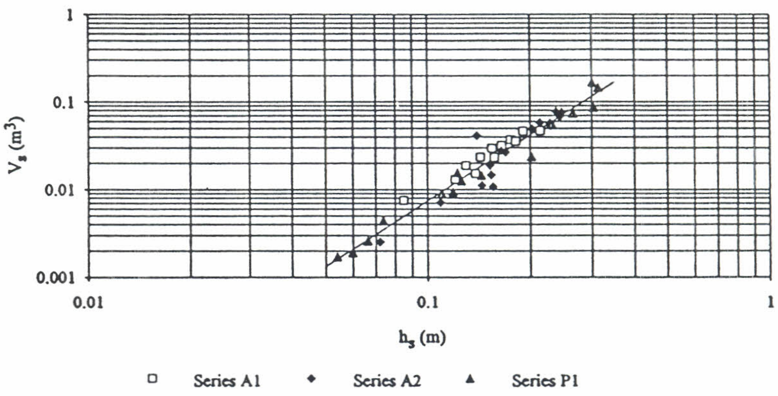


Fig. 3 - Excavated volume due to local scour

The plot shows that a straight line can be adjusted to the complete set of data, the higher deviations corresponding to the tests in neat clear-water condition. Distinction due to bed material used is not a clear evidence. The regression equation is

$$V_s = 2.3\, h_s^{2.49} \tag{7}$$

In equivalent conditions, using sand and a vertical wall spur, VEIGA DA CUNHA (1973) obtained similar results. His regression equation $V_s = 5.5\, h_s^{3.08}$ indicates that the multiplicative coefficient in Eq. 7 accounts for the spur shape effect. Similar plots were tried for A_s. Such plots have shown a considerable scatter, possibly due to the adopted measuring procedure, and some additional effort on data analysis is needed.

CONCLUSIONS

According to results and discussion presented, and for the range of experiments carried out, it can be stressed the influence of the bed material density on local scour due to flow under live-bed conditions. The regression analysis used for the prediction of maximum scour depth, showed that a dimensionless framework including the specific density is needed to explain the results of the three series of tests carried out under live-bed, Eq. 6. The clear-water tests results can be predicted by means of Eq. 4, using the dimensionless combination of parameters fitted for the clear-water sandy bed results, with evident influence of the Froude number. Additionally, the plot of the scour depth results for the light-weight material runs under neat live-bed conditions, scatter in the plot of the envelope curve obtained by MELVILLE (1992).

For the same spur, the ratio between the scour maximum width and the scour depth depends on the sediment size and density, where the slope of the scour hole was measured to be less steep for the light weight material. No distinction due to bed material used was observed in the plot of the excavated volumes with maximum scour depth and the results confirmed the similarity in the geometry of the scour holes.

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REFERENCES

BREUSERS, H.N.C. and RAUDKIVI, A.J. (1991), Scouring, A. A. Balkema, Rotterdam, Netherlands.

CARSTENS, M.R. (1966), "Similarity laws for localized scour", Journal of the Hydraulics Division, ASCE, Vol. 92, No. HY3, May, pp.13 - 36.

COUTO, L.T. and CARDOSO, A.H. (1994), "Experimental investigation on local scour around spill-through spur dikes", Proceedings, Internacional Symposium East-West, North-South on the State-of-the-Art in River Engineering Methods and Design Philosophies, St. Petersburg, Russia (accepted for publication; in print).

EISENHAUER, O. and KLEY, G.M. (1988), "Modelling local scour in light weight sediment", Proceedings, Modelling Soil-Water-Structure Interactions, Kolkman et al (eds), Balkema, Roterdam, pp.127-135.

GARDE, R.J. and RANGA RAJU, K.G. (1985), Mechanics of sediment transportation and alluvial stream problems, (second edition), Wiley Eastern Limited, New Delhi, India.

KANDASAMY, J.K. (1989), "Abutment scour", Report No. 458, Department of Civil Engineering, University of Auckland, Auckland, New Zealand.

MELVILLE, B.W. (1992), "Local scour at bridge abutments", Journal of Hydraulic Engineering, Vol. 118, No. 4, April, pp. 615 - 631.

TYAGI, A.K. (1967), "Effect of specific gravity of sediment on scour", M.Eng. Thesis, University of Roorkee, Roorkey, India.

VEIGA DA CUNHA, L. (1973), "Local scour at obstacles protruding from river bank", (in Portuguese, "Erosões localizadas junto de obstáculos salientes de margens"), Memória No. 428, Laboratório Nacional de Engenharia Civil, Lisboa, Portugal.

WONG, W.H. (1982), "Scour at bridge abutments", Report No. 275, Department of Civil Engineering, University of Auckland, Auckland, New Zealand.