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Experimental investigation of local scour around circular bridge piers under steady state flow conditions

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Local scour around bridge piers is one of the main causes of bridge failures. In this study, scour depths and scour hole geometries around circular bridge piers were investigated under clear water scour conditions for various flow rates. The experiments were carried out in a rectangular flume 80 cm wide, 18.6 m long and 75 cm high by using uniform sediment with a median diameter of 1.63 mm and geometric standard deviation of 1.3. The flow rates and approach flow depths were measured with an electromagnetic flow meter and ultrasonic level sensors, respectively. A new empirical equation for the determination of scour depth is proposed based on the experimental findings of the present study and on experimental data available in the literature. The experimental results were also compared with those calculated using several empirical equations developed by previous studies. The proposed new equation to predict scour depth around a circular bridge pier was evaluated in terms of determination coefficient (R^2) and scatter index (SI). The Fisher (f) test was also applied to test the statistical significance of the proposed equation.

INTRODUCTION

It has been estimated that 60% of all bridge failures result from scour and other hydraulically related causes (Landers 1992). One of the most important steps in bridge design is to estimate the maximum local scour depths around bridge piers. Since the scour process is complex, the maximum scour depth cannot be determined analytically, and this has led many engineers to perform experiments to investigate local scour processes.

The effective variables affecting the local scour process are flow parameters, bed material characteristics, pier geometry and time. By means of dimensional analysis the following dimensionless parameters can be determined:

$$\frac{d_s}{D} = f\left(Fr, F_d, \frac{y}{D}, \frac{V}{V_c}, \frac{D}{d_{50}}, \frac{Vt}{D}, \sigma_g, K_s, K_\alpha\right) \quad (1)$$

where Fr is the Froude number, F_d is the densimetric Froude particle number, y is the approach flow depth, D is the pier diameter, V is the approach flow velocity, V_c is the critical velocity, d_{50} is the median particle size of the bed material, σ_g is the geometric standard deviation of the particle size distribution, K_s is the pier shape factor and K_α is the alignment factor.

Many experiments have been carried out by many researchers, and various empirical equations have been proposed to estimate maximum scour depth. Laursen (1958), Breusers *et al* (1977), Gunyakti (1988) and Yanmaz (1989) proposed respective equations which are a function of approach flow depth (y/D). Hancu (1971) proposed an equation based on the dimensionless approach flow depth (y/D) and the Froude number (Fr). The empirical relation proposed by Melville (1997) involved flow intensity (V/V_c), particle size factor (K_d), pier shape factor (K_s), alignment factor (K_α) and channel geometry factor (K_G). Richardson and Davis (2001) proposed an equation based on the pier shape factor (K_s), alignment factor (K_α), bed condition factor (K_b), armouring factor (K_z), approach flow depth (y/D) and Froude number (Fr).

The temporal variation of the scour depth has also been investigated by researchers, and numerous empirical relationships have been determined based on experimental findings (Yanmaz & Altinbilek 1991; Kothyari *et al* 1992; Melville & Chiew 1999; Oliveto & Hager 2002; Mia & Nago 2003; Chang *et al* 2004; Kothyari *et al* 2007).

The range of conditions to which an empirical equation applies is very important. Therefore the aim of this study was to propose a widely applicable empirical equation based on a wide range of experimental data obtained from the present study and from

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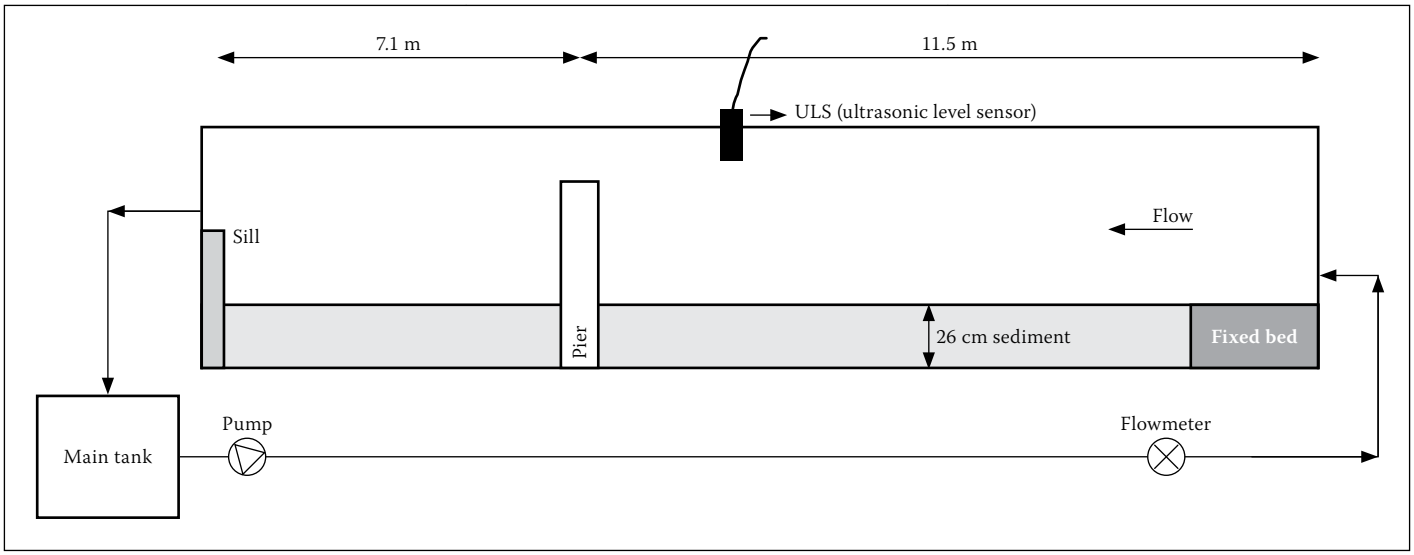

Figure 1 Sketch of the experimental set-up

Table 1 The details of the experiments

Experiment reference	D (cm)	Q (ℓ/s)	y (cm)	V/V_c
AE1	8	43	19.5	0.49
AE2	8	47	20.2	0.51
AE3	8	53	20.7	0.56
AE4	8	57	21.3	0.58
AE5	8	62	22.3	0.60
AE6	8	66	22.7	0.63
AE7	8	71	23.4	0.65
AE8	11	43	19.5	0.49
AE9	11	47	20.2	0.51
AE10	11	53	20.7	0.56
AE11	11	57	21.3	0.58
AE12	11	62	22.3	0.60
AE13	11	66	22.7	0.63
AE14	11	71	23.4	0.65
AE15	15	43	19.5	0.49
AE16	15	47	20.2	0.51
AE17	15	53	20.7	0.56
AE18	15	57	21.3	0.58
AE19	15	62	22.3	0.60
AE20	15	66	22.7	0.63
AE21	15	71	23.4	0.65
AE22	20	43	19.5	0.49
AE23	20	47	20.2	0.51
AE24	20	53	20.7	0.56
AE25	20	57	21.3	0.58
AE26	20	62	22.3	0.60
AE27	20	66	22.7	0.63
AE28	20	71	23.4	0.65

Table 2 The experimental findings

Experiment reference	D (cm)	d_s (cm)	L_s (cm)
AE1	8	3.0	6.0
AE2	8	5.5	9.0
AE3	8	8.0	13.0
AE4	8	9.0	13.0
AE5	8	10.0	15.0
AE6	8	10.2	15.0
AE7	8	11.2	19.0
AE8	11	4.7	7.5
AE9	11	6.7	9.5
AE10	11	10.4	15.5
AE11	11	11.3	15.5
AE12	11	12.8	19.5
AE13	11	13.7	21.5
AE14	11	14.6	21.5
AE15	15	4.4	11.5
AE16	15	6.8	11.5
AE17	15	11.9	17.5
AE18	15	13.3	21.5
AE19	15	15.9	25.5
AE20	15	16.6	25.5
AE21	15	18.4	29.5
AE22	20	7.2	11.0
AE23	20	8.7	13.0
AE24	20	10.2	15.0
AE25	20	13.8	21.0
AE26	20	16.1	25.0
AE27	20	19.2	29.0
AE28	20	20.6	31.0

available literature. One hundred and eighty two experimental results were used and the relevance of the proposed equation was tested statistically. The geometries of the scour holes obtained after each experiment were determined and are also presented to provide an indication of likely scour hole geometries.

EXPERIMENTAL SETUP AND EXPERIMENTAL RESULTS

The experiments were carried out in a rectangular flume 80 cm wide, 18.6 m long and 75 cm deep. Uniform granular sediment with median diameter d_{50} of 1.63 mm and geometric standard deviation of 1.3 were used in the model. The flow rates and approach flow depths were measured by using electromagnetic flow meter and ultrasonic level sensors, respectively. The slope of the flume was 0.6%. A sketch of the experimental set-up is given in Figure 1. The bridge piers were located at 11.5 m from the upstream end of the flume.

Circular bridge piers of 8 cm, 11 cm, 15 cm and 20 cm diameter were tested. The experiments were carried out using seven different steady flow rates of 43 ℓ/s, 47 ℓ/s, 53 ℓ/s, 57 ℓ/s, 62 ℓ/s, 66 ℓ/s and 71 ℓ/s. The reference of each experiment, pier diameter (D), flow rate (Q), approach flow depth (y) and flow intensity (V/V_c) is given in Table 1. The observed scour depth did not change after 320 minutes in the case of the largest pier diameter and flow rate. Since the duration of each experiment was 480 minutes, it was found that the change in the scour depth after this duration was negligible. Therefore the duration of the experiments was deemed to be sufficient to reach the equilibrium scour depth.

The critical velocity V_c was determined from Equation 2 (Melville & Sutherland 1988).

$$\frac{V_c}{u_{*_c}} = 5.75 \log\left(5.53 \frac{y}{d_{50}}\right) \quad (2)$$

where u_{*_c} is the critical shear velocity which can be calculated using the following relationship (Melville 1997):

$$u_{*_c} = 0.0115 + 0.0125\, d_{50}^{1.4} \quad (3)$$
for 0.1 mm < d_{50} < 1 mm

$$u_{*_c} = 0.0305\, d_{50}^{0.5} - 0.0065\, d_{50}^{-1} \quad (4)$$
for 1 mm < d_{50} < 100 mm

In these relationships u_{*_c} is in m/s and sediment size is d_{50} in mm.

The scour holes measured after each experiment along the centre line of the flume are shown in Figure 2.

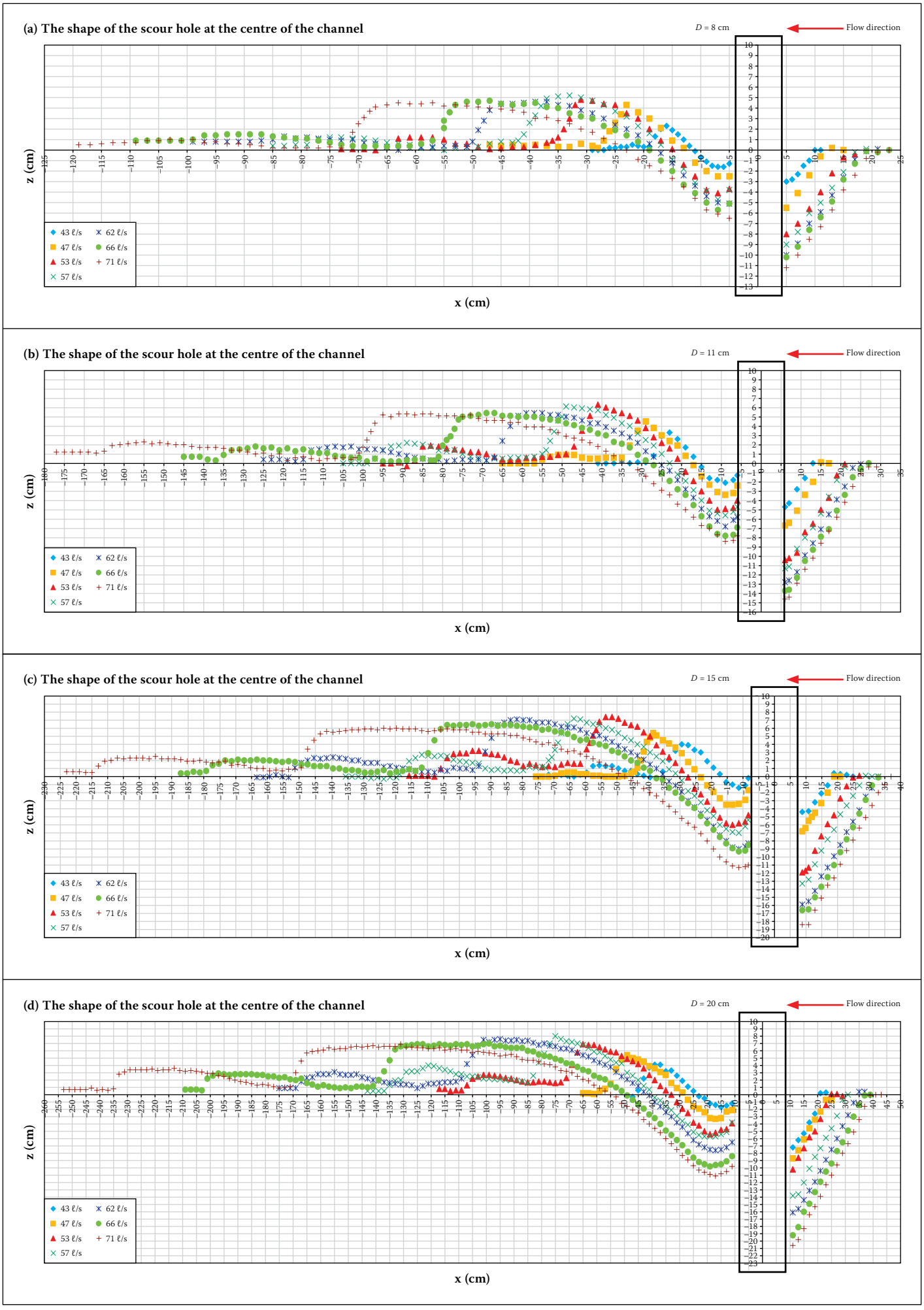

Figure 2 Measured scour hole along the centre line of the flume length

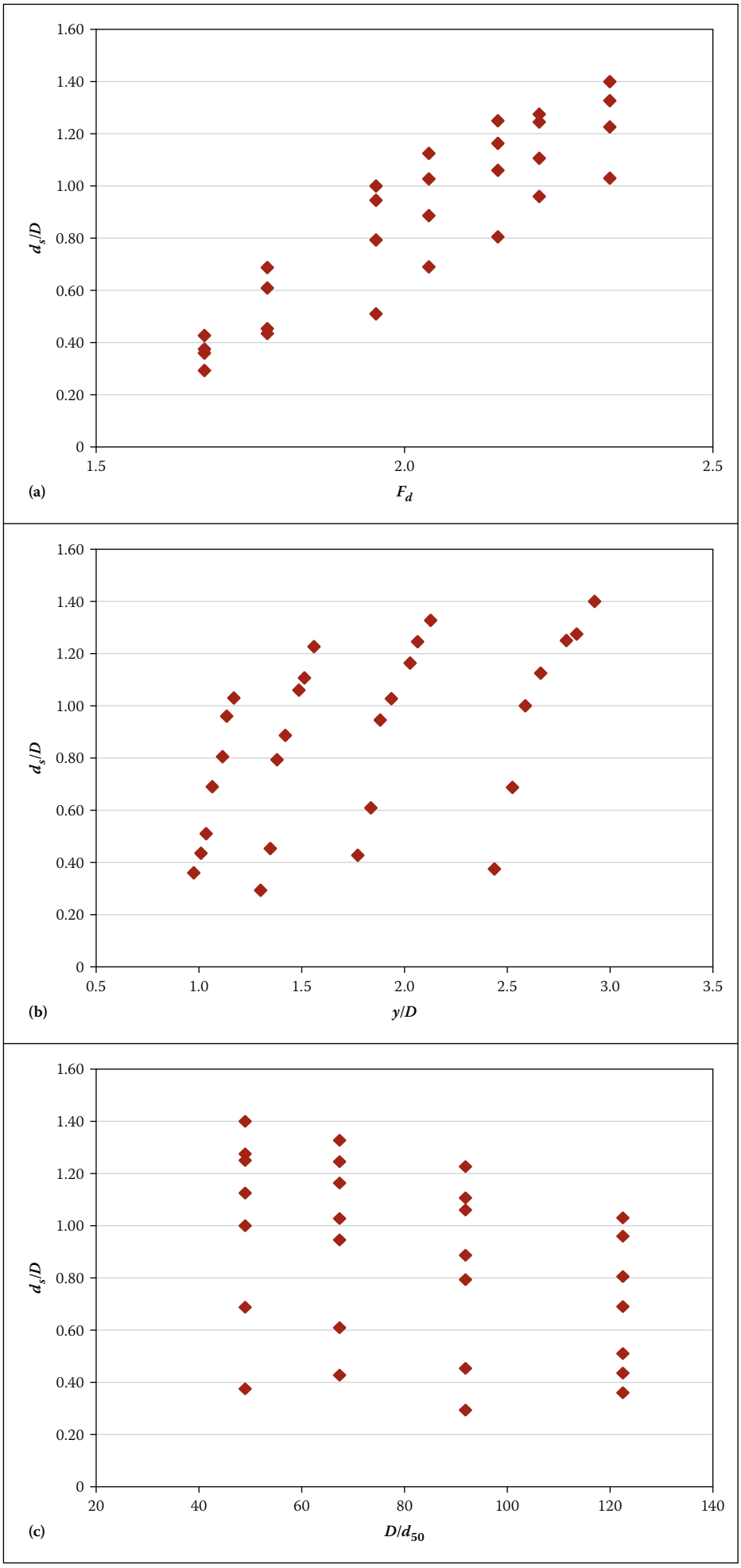

Figure 3 Variations of the dimensionless final scour depth versus (a) densimetric Froude particle number (F_d), (b) dimensionless approach flow depth (y/D), (c) relative sediment size (D/d_{50})

The experimental findings are given in Table 2, where d_s is the flume centre line maximum scour depth measured after each experiment, and L_s is the maximum extent of the scour hole upstream of the pier.

The experimental results showed the following:

- The maximum scour depths occurred at the upstream face of the pier.
- Scour depth increased with flow velocity and pier diameter.
- The length of the deposit downstream of the pier and the length of the scour hole increased with flow velocity and pier diameter.

Figures 3(a), (b) and (c) show the variation in the dimensionless scour depth (d_s/D) with densimetric Froude particle number (F_d), dimensionless approach flow depth (y/D) and relative sediment size (D/d_{50}), respectively. The dimensionless scour depths increase with densimetric Froude particle number and dimensionless approach flow depth, as is clearly shown in Figure 3.

Densimetric Froude particle number (F_d), can be calculated by using Equations 5 and 6 (Oliveyo & Hager 2002):

$$F_d = \frac{V}{(g'd_{50})^{0.5}} \tag{5}$$

$$g' = \left[\frac{\rho_s - \rho}{\rho}\right] g \tag{6}$$

where ρ_s and ρ are the mass density of the sediment and water, respectively, and g is the gravitational acceleration.

Since the number of experiments described above was not sufficient to derive an empirical equation, 154 additional experimental findings obtained by previous studies were taken into account to propose a more comprehensive and general equation. Equation 7 is proposed by using the experimental data obtained from the present study and experimental findings obtained by Ettema (1980), Graf (1995), Yanmaz and Altinbilek (1991), Melville and Chiew (1999), Mia and Nago (2003), Oliveto *et al* (2003) and Sheppard *et al* (2004). Details of these previous studies are summarised in the Appendix. The total number of experiments used to derive the proposed equation is 182.

$$\frac{d_s}{D} = 1.39(F_d)^{0.77}\left(\frac{y}{D}\right)^{0.036}\left(\frac{D}{d_{50}}\right)^{-0.194} \tag{7}$$

The comparison between the measured scour depths and those computed from Equation 7 are given in Figure 4. Equation 7 was evaluated in terms of determination coefficient (R^2) and scatter index (SI). These parameters are defined as follows:

$$R^2 = \left[\frac{\sum_{i=1}^{n}(d_{s,measured_i} - \overline{d_{s,measured}})}{\sqrt{\sum_{i=1}^{n}(d_{s,measured_i} - \overline{d_{s,measured}})^2}} \right.$$

$$\left. \frac{(d_{s,computed_i} - \overline{d_{s,computed}})}{\sqrt{\sum_{i=1}^{n}(d_{s,computed_i} - \overline{d_{s,computed}})^2}} \right]^2 \quad (8)$$

$$SI(\%) = \frac{\sqrt{\frac{\sum_{i=1}^{n}(d_{s,measured_i} - d_{s,computed_i})^2}{n}}}{\overline{d_{s,measured}}} \cdot 100 \quad (9)$$

Determination coefficient (R^2) and scatter index (SI) values are also shown in Figure 4. As shown in this figure, the measured and computed scour depths are in good agreement.

Measured scour depths were also compared with those calculated by using several equations given in the literature. The results are given in Figures 5(a) and 5(b). The maximum R^2 (coefficient of determination) value was obtained for each equation.

The Fisher (f) test was applied to check the statistical relevance of the proposed equation. The parameter f is defined as follows:

$$f = \frac{\left(\frac{SSR}{\vartheta_1}\right)}{\left(\frac{SSE}{\vartheta_2}\right)} \quad (10)$$

where SSR is the sum of squared residuals, SSE is the sum of squares for error, ϑ_1 is the number of the independent variables (k), and $\vartheta_2 = n - k - 1$, (n is the number of the data). SSR and SSE can be calculated from the following equations:

$$SSR = \sum_{i=1}^{n}(d_{si}^{computed} - \overline{d_{si}^{measured}})^2 \quad (10\text{-a})$$

$$SSE = \sum_{i=1}^{n}(d_{si}^{measured} - d_{si}^{computed})^2 \quad (10\text{-b})$$

where $\overline{d_{si}^{measured}}$ is the arithmetic mean of the observed and computed scour depth values.

The critical value of f is 3.78 for the selected 0.01 significance level. If the computed f value is greater than the critical value, then the proposed equation is significant. The f value was computed as 825 and therefore the proposed equation is significant.

The error between the measured scour depth and the scour depths estimated with Equation 7 were computed by means of the sum of errors squared (Sheppard *et al* 2011):

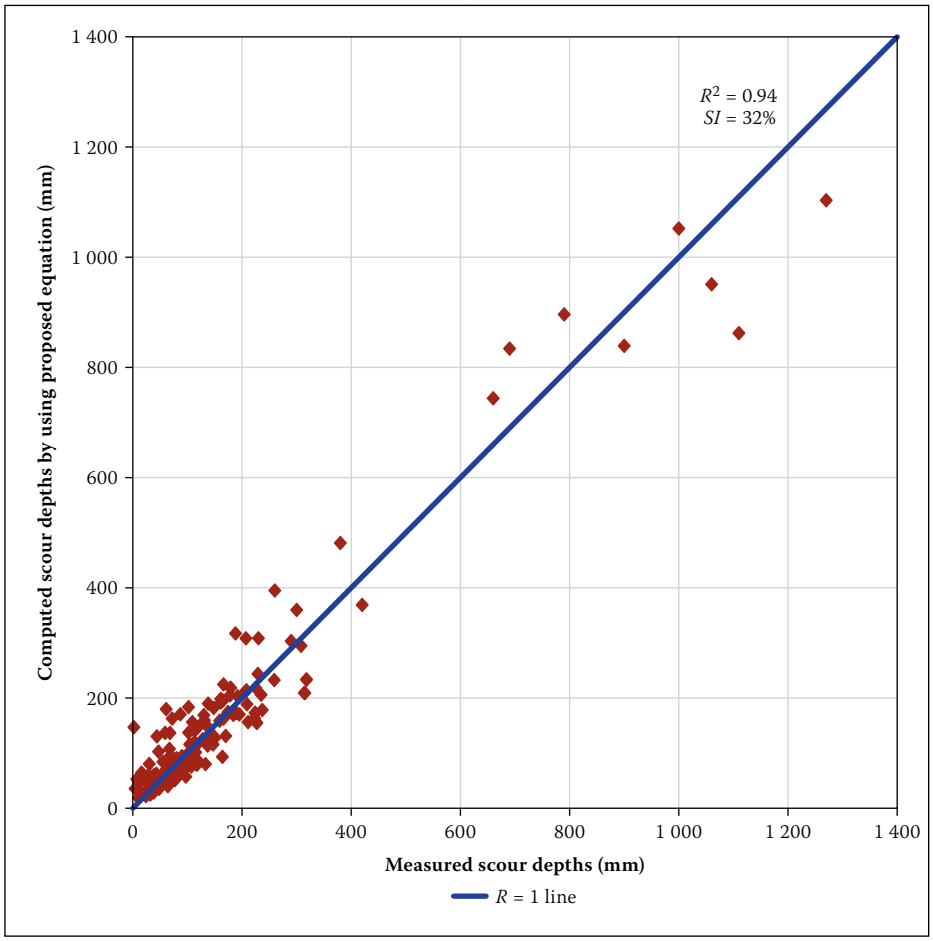

Figure 4 Measured scour depths versus computed scour depths by using proposed equation

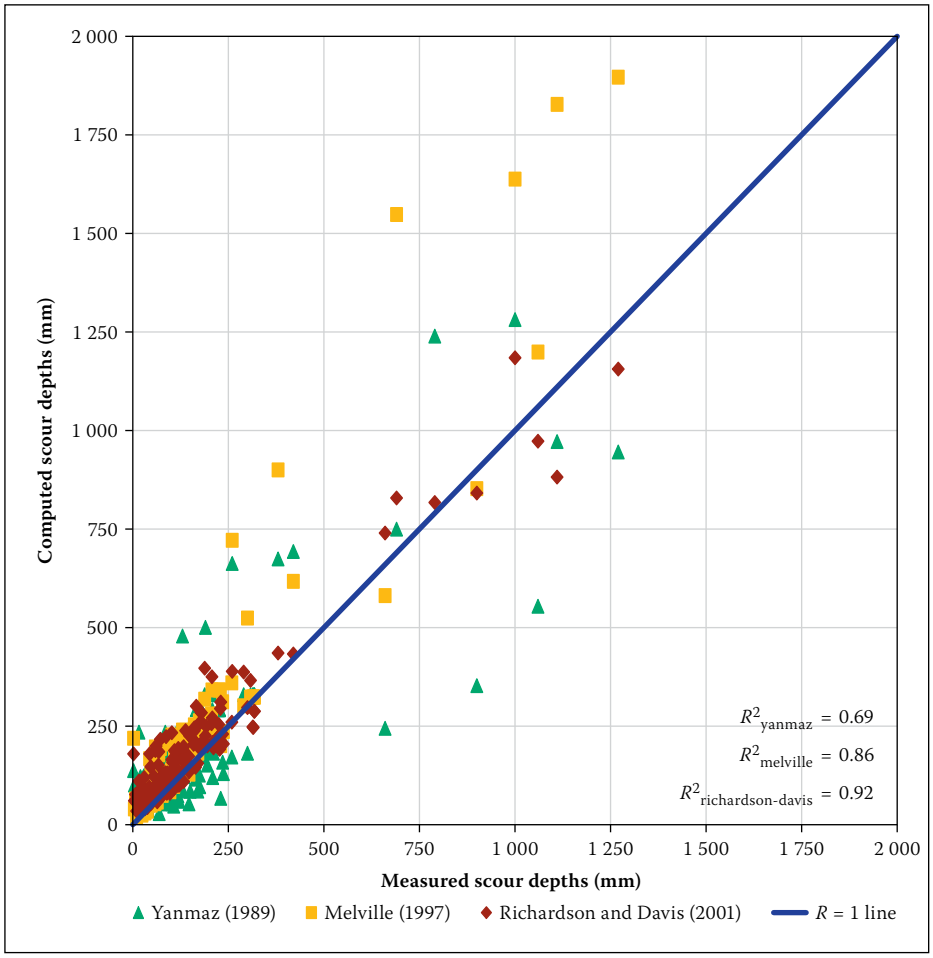

Figure 5(a) Measured scour depths versus computed scour depths by using equations given by Yanmaz (1989), Melville (1997), and Richardson and Davis (2001)

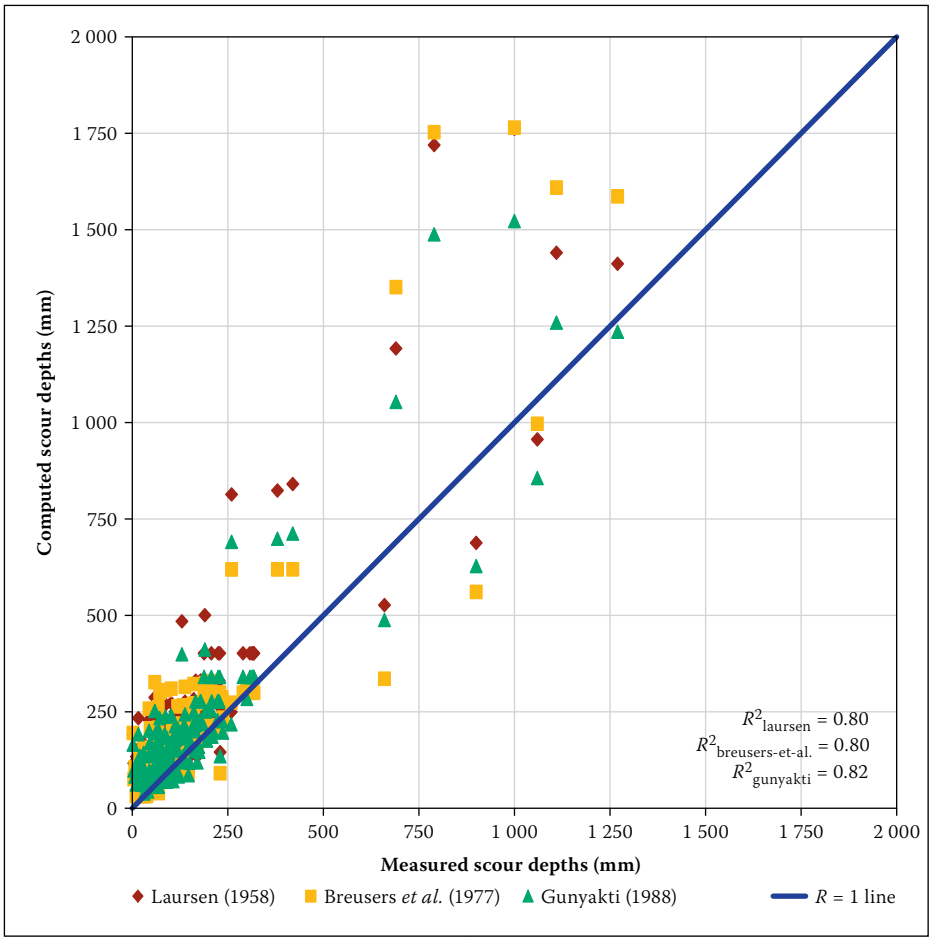

Figure 5(b) Measured scour depths versus computed scour depths by using equations given by Laursen (1958), Breusers *et al* (1977), Gunyakti (1988)

$$SSE(\%) = \frac{\sum(d_{s,measured} - d_{s,computed})^2}{\sum(d_{s,measured})^2} \cdot 100 \quad (11)$$

The *SSE* is calculated as 4.03%. Therefore the proposed equation is statistically consistent.

CONCLUSION

In this study the local scour around circular bridge piers was investigated experimentally. According to the experimental results, the scour depth increases with increasing pier diameter and flow velocity. It was observed that the length of the deposition downstream of the pier and the length of the scour hole also increase with flow velocity and pier diameter.

A new empirical relation to predict the maximum scour depth was proposed using the results of 182 experiments. Acceptable compatibility was obtained between the measured scour depths and the scour depths calculated by the proposed equation.

The significance of the proposed equation was demonstrated by applying the Fisher (f) test. The sum of squared errors (*SSE*) was calculated to be 4.03%, which indicates that the proposed equation is statistically consistent. The proposed equation was also evaluated in terms of determination coefficient (R^2) and scatter index (*SI*), which were calculated to be 0.94 and 32%, respectively. These values also demonstrate the reliability of the proposed equation.

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APPENDIX

Details of the experimental results from previous studies

Experiment reference	D (cm)	y (cm)	d_{50} (mm)	V/V_c	d_s (mm)
E1	2.85	60	1.9	0.90	58
E2	2.85	20	1.9	0.90	57
E3	2.85	10	1.9	0.90	48
E4	2.85	5	1.9	0.90	41
E5	10.16	60	1.9	0.90	224
E6	10.16	40	1.9	0.90	223
E7	10.16	30	1.9	0.90	211
E8	10.16	20	1.9	0.90	1.98
E9	10.16	10	1.9	0.90	170
E10	10.16	5	1.9	0.90	147
E11	10.16	2	1.9	0.90	69
E12	10.16	60	5.35	0.90	179
E13	10.16	40	5.35	0.90	178
E14	10.16	30	5.35	0.90	165
E15	10.16	20	5.35	0.90	148
E16	10.16	10	5.35	0.90	131
E17	10.16	5	5.35	0.90	102
E18	15	60	1.9	0.90	318
E19	5.08	60	1.9	0.90	115
E20	5.08	60	1.9	0.75	85
E21	5.08	60	1.9	0.50	16
E22	15	60	0.84	0.95	225
E23	15	60	1.9	0.95	229
E24	15	60	5.35	0.95	207
E25	15	60	7.8	0.95	188
E26	10.16	60	0.8	0.90	227
E27	10.16	60	0.84	0.90	227
E28	10.16	60	1.9	0.90	224
E29	10.16	60	3.8	0.90	208
E30	10.16	60	5.35	0.90	179
E31	10.16	60	7.8	0.90	166
E32	15	60	0.8	0.90	315
E33	15	60	0.84	0.90	314
E34	15	60	1.9	0.90	318
E35	15	60	5.35	0.90	308
E36	15	60	7.8	0.90	290
G1	11	17	2.1	1.00	174
G2	10	23.2	2.1	1.00	195
G3	15	23.2	2.1	1.00	259
MC1	7	20	0.96	0.69	94
MC2	7	7	0.96	0.65	77
MC3	7	7	0.96	0.62	69
MC4	7	7	0.96	0.67	79
MC5	7	7	0.96	0.62	39
MC6	5	7	0.96	0.66	60
MC7	5	20	0.96	0.65	60
MC8	3.8	20	0.96	0.69	54
MC9	3.8	20	0.96	0.66	45
MC10	1.6	20	0.8	0.68	24
MC11	2.5	20	0.8	0.68	25
MC12	7	9.5	0.96	0.83	116
MC13	7	9.5	0.96	0.83	118
MC14	7	5	0.96	0.82	107
MC15	7	7	0.96	0.85	121
MC16	5	7	0.96	0.85	89
MC17	3.8	20	0.96	0.82	77
MC18	3.8	20	0.96	0.92	97
MC19	5	7	0.96	0.90	91
MC20	1.6	20	0.8	0.83	32
MC21	2.5	20	0.8	0.83	48
MC22	1.6	20	0.8	0.96	38
MC23	2.5	20	0.8	0.96	64
MC24	7	20	0.96	0.78	133
MC25	7	7.7	0.96	0.78	107
MC26	7	7	0.96	0.70	91
MC27	5	7	0.96	0.75	79
MC28	7	7	0.96	0.52	25
MC29	5	20	0.96	0.53	26
MC30	7	20	0.96	0.59	43
MC31	7	7	0.96	0.56	37
MC32	7	7	0.96	0.56	35
MC33	5	7	0.96	0.59	29
MC34	7	7	0.96	0.47	7
MC35	7	20	0.96	0.40	20
MC36	7	20	0.96	0.47	28
MC37	5	20	0.96	0.46	11
MC38	3.8	20	0.96	0.44	4
MC39	1.6	20	0.9	0.53	10
MC40	2.5	20	0.9	0.53	17
MC41	20	13.5	0.9	0.72	237
MC42	20	12	0.9	0.79	209
MC43	20	12	0.9	0.62	109
MC44	20	23	0.9	0.46	59
MC45	20	18.1	0.9	0.82	235
MN1	6	16	1.28	0.71	71
MN2	6	20	1.28	0.75	78
MN3	6	23.5	1.28	0.78	89
MN4	6	27	1.28	0.80	96
MN5	6	30	1.28	0.82	106
MN6	5	20	3	0.71	70
MN7	10	20	3	0.71	113
MN8	15	20	3	0.71	161
MN9	5	10	1.5	0.90	93
MN10	10	10	1.5	0.90	150
MN11	15	10	1.5	0.90	175
MN12	5	35	0.52	0.71	76
MN13	7.5	35	0.52	0.71	109
MN14	10	35	0.52	0.71	137
MN15	5	35	0.26	0.70	70
MN16	7.5	35	0.26	0.70	90
MN17	10	35	0.26	0.70	112
OH1	25.7	4.6	4.8	0.97	230
OH2	25.7	10	0.55	0.60	61
OH3	2.2	15	3.3	1.17	35
OH4	2.2	5.1	3.3	1.07	31
OH5	11	15	3.3	0.90	164
OH6	11	14.9	0.55	0.70	116
SH1	11	119	0.22	0.91	130
SH2	31	119	0.22	0.97	260
SH3	91	127	0.8	0.85	1 110
SH4	91	87	0.8	0.87	690
SH5	31	127	0.8	0.83	420
SH6	11	127	0.8	0.87	190
SH7	91	122	2.9	0.90	1 270
SH8	91	56	2.9	0.84	1 060
SH9	91	29	2.9	0.83	900
SH10	91	17	2.9	0.76	660
SH11	91	190	2.9	0.75	1 000
SH12	31	122	0.22	1.21	380
SH13	31	18	0.22	1.11	300
SH14	91	181	0.22	0.94	790
YA1	6.7	16.5	1.07	0.84	102
YA2	6.7	15.2	1.07	0.81	95
YA3	6.7	13.5	1.07	0.80	92
YA4	6.7	12.1	1.07	0.75	78
YA5	6.7	10.5	1.07	0.71	64
YA6	6.7	8.5	1.07	0.68	62
YA7	6.7	6.5	1.07	0.62	56
YA8	6.7	4.5	1.07	0.48	39
YA9	5.7	16.5	1.07	0.84	98
YA10	5.7	15.2	1.07	0.81	90
YA11	5.7	13.5	1.07	0.80	83
YA12	5.7	12.1	1.07	0.75	71
YA13	5.7	10.5	1.07	0.71	61
YA14	5.7	8.5	1.07	0.68	58
YA15	5.7	6.5	1.07	0.62	51
YA16	5.7	4.5	1.07	0.48	32
YA17	4.7	6.5	1.07	0.62	41
YA18	4.7	10.5	1.07	0.71	59
YA19	4.7	13.5	1.07	0.80	77
YA20	4.7	16.5	1.07	0.84	95
YA21	6.7	6.5	0.84	0.71	77
YA22	6.7	8.5	0.84	0.78	91
YA23	6.7	10.5	0.84	0.82	96
YA24	6.7	12.1	0.84	0.87	101
YA25	6.7	13.5	0.84	0.92	107
YA26	5.7	8.5	0.84	0.78	75
YA27	5.7	10.5	0.84	0.82	83
YA28	5.7	12.1	0.84	0.87	88
YA29	5.7	13.5	0.84	0.92	95
YA30	4.7	8.5	0.84	0.78	70
YA31	4.7	10.5	0.84	0.82	68
YA32	4.7	12.1	0.84	0.87	77
YA33	4.7	13.5	0.84	0.92	85