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Temporal Evolution of Clear-Water Local Scour at Bridge Piers with Flow-Dependent Debris Accumulations

Francisco Nicolás Cantero-Chinchilla¹; Gustavo Adolfo Mazza de Almeida²; and Costantino Manes³

Abstract: Previous research has shown that local scour at bridge piers is severely increased by the accumulation of woody debris around piers. However, due to the unavailability of accurate information regarding the characteristics of formed debris jams, the shape and dimensions of accumulations tested in previous laboratory experiments had to be assumed. This article provides an assessment of debris-induced scour based on recently available knowledge about the relation between the potential dimensions of debris accumulations, the characteristics of flow and debris elements. Clear-water scour experiments (with and without debris accumulation) were conducted using debris models with shape and size that correspond to the particular flow characteristics of each experiment. The results showed that scour depths obtained with flow-dependent debris accumulations were larger than without accumulations by a factor ranging from 1.18–2.19. The analysis of the scour depths affected by the accumulations suggested similarity characteristics as well as dependence on the flow intensity, blockage area ratio and depth ratio.

Author keywords: Woody-debris; Bridge pier; Bridge scour; Temporal scour evolution.

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20 Introduction

21 During flood events in river basins characterized by large wooded lands, floating woody debris
22 may accumulate at the pier front leading to further alterations of the flow velocity, turbulence
23 and pier loadings (Diehl 1997; Parola et al. 2000; Bradley et al. 2005; Lagasse et al. 2010).
24 Investigations on the potential cause of bridge failures indicate that debris contributes to
25 approximately one-third of all failures of fluvial bridges in the US, UK and Ireland (Diehl 1997;
26 Benn 2013).

27 The effect of large woody debris (LWD) accumulations on bridge pier scour has been studied
28 over the past decades by means of simplified laboratory models of debris jams (Melville and
29 Dongol 1992; Pagliara et al. 2010; Pagliara and Carnacina 2013; Najafzadeh et al. 2017; Rahimi
30 et al. 2017) having impermeable, cylindrical or prismatic shapes (Melville and Dongol 1992;
31 Pagliara and Carnacina 2010a; Rahimi et al. 2017). However, the shape of LWD accumulations
32 observed in the real-world is far from prismatic and solid, nor is it independent on the flow
33 conditions, channel geometry and the characteristics of the transported debris (Melville and
34 Coleman 2000; Schmocker and Hager 2013). Only a few works have been conducted using
35 models with a shape, porosity and roughness that resemble the characteristics of accumulations
36 formed in rivers (Laursen and Toch 1956; Lagasse et al. 2010) even though the dimensions of
37 the debris jams used, which has an important effect on scour (Pagliara and Carnacina 2011,
38 2013), had to be assumed. Recently, Panici and de Almeida (2017, 2018, 2020) defined
39 empirical relations between the maximum dimensions of debris jams (made of rigid elements)
40 and the characteristics of flow and debris elements for single, isolated piers under steady flow
41 and a constant supply of debris over a fixed bed (clear-water conditions). That investigation
42 found that the maximum dimensions and shape of jams that are likely to be formed by a natural
43 process of self-assembly of individual pieces can be accurately modelled as inverted half-cones
44 defined by three reference lengths (H , W , K , as shown in Fig. 1a, which are the submerged
45 height, width, and length of the debris accumulation, respectively) as follows:

$$46 \quad D_i = A_i + B_i \exp[-C_i Fr_L], \quad (1)$$

47 where $\mathbf{D} = [W/l_{log}, H/l_{log}, K/l_{log}]$; $\mathbf{A}=[0.99, 0.7, 0.47]$; $\mathbf{B}=[3.24, -0.89, 3.72]$; $\mathbf{C}=[4.63, 3, 9.94]$;
48 and $Fr_L = \log$ Froude number $[= U/(gl_{log})^{1/2}]$, where U = depth-averaged streamwise velocity; g =
49 gravitational acceleration; and l_{log} = longest length of logs within the accumulation (which for

50 accumulations made of uniform length logs coincides with the constant length). The subscript i
51 ($= 1, 2, 3$) is used to denote the component of the vectors. Even though live-bed conditions often
52 prevail in pier scour, Eq. (1) was originally developed under fixed bed conditions as a first
53 attempt to model the debris accumulation formation and, to that purpose, it is adopted in this
54 study. Implicit to this approach is the assumption that the presence of the scour hole has a
55 negligible influence on the formation of debris accumulations, which is primarily governed by
56 the advection of floating debris by the near free-surface flow. Although experiments under a
57 constant debris supply showed that debris accumulations build up gradually (Panici and de
58 Almeida, 2018), the evolution of accumulations in rivers is unpredictable due to the randomness
59 of debris transport. For this reason, Eq. (1) is used here to define the dimensions of debris models
60 corresponding to the critical condition observed in Panici and de Almeida (2018) (i.e. maximum
61 dimensions). This condition is assumed to represent the worst-case scenario, whereby the flow
62 obstruction produces the maximum effect on scour.

63 The present technical note reports results from three sets of experiments, the rationale of
64 which introduces the objectives of the study. The first set consists of 34 local scour experiments
65 that were conducted with and without the twigs-made debris-models resembling dimensions
66 proposed by Panici and De Almeida (2018). This set of experiments intends to quantify the
67 relative increase of the local scour depth and to derive a predictive equation to quantify the
68 worsening effect of debris on scour. A second set involved three pairs of experiments using
69 debris models with dimensions corresponding to the adopted flow and twig characteristics [i.e.
70 defined following Eq. (1)] as well as three tests with a debris model with size different from that
71 predicted by Eq. (1). These experiments helped assessing the potential impact of adopting
72 arbitrary debris models on predicted scour depths. Finally, the third set involved the comparison
73 between two experiments: one with a debris model used in the first set and another one with a
74 replica of the same model made of impermeable foam instead of twigs. This set was conducted
75 in order to investigate the effects of debris permeability on local scour, which was originally
76 investigated by Lagasse et al. (2010) and Pagliara and Carnacina (2010b) however using
77 arbitrary shapes and dimensions for the debris models.

78

79 **Experiments**

80 Consider the idealized case of an open channel flow over an erodible bed with uniform sediment
81 diameter (and fixed density ρ_s) and within a rectangular channel of width b and depth h . In such
82 a case, Fig. 1b depicts the main flow features in pier scour affected by woody debris
83 accumulations (Pagliara and Carnacina 2013, Dey 2014), including the expected flow diversion
84 likely to affect scour. Debris accumulations are also known to produce energy losses leading to
85 backwater effects, such as the afflux, the study of which is however out of the scope of this
86 work. In order to quantify the implications of such flow alterations on local scour (d_s), the
87 approach proposed by Pagliara and Carnacina (2010a, 2010b) is followed. Within the context of
88 the idealized conditions considered herein, these authors argued that the main parameters
89 influencing the non-dimensional temporal evolution of scour (d_s/D) are the relative depth h/D ,
90 the sediment coarseness d_{50}/D , the flow intensity U/U_c and the non-dimensional time $T = Ut/D$,
91 where D = pier width; d_{50} = median (50 percentile) sediment diameter; U_c = mean critical
92 velocity [herein estimated by Lavy's (1956) expression (Dey 2014)]; and t = time. When debris
93 effects are taken into consideration, this pool of non-dimensional parameters must be
94 complemented with others describing the properties of the debris accumulation. Pagliara and
95 Carnacina (2010a, 2010b) argued that such non-dimensional parameters should be obtained out
96 of the following: a set of length scales describing the size and shape of the accumulation L_i (in
97 the present case, H , W and K), the characteristic length scale describing the logs composing the
98 debris l_{log} , the porosity of the accumulation n_d and a parameter accounting for the whole
99 obstruction caused by the coupled pier-debris accumulation, which, especially within the context
100 of laboratory experiments where flumes are of limited width, can play a significant role on scour.
101 They called this parameter the blockage area ratio A^* , which for the debris accumulation
102 geometries considered herein might be defined as $A^* = A_b/(hb)$, where $A_b = HW/2 + D(h-H)$.
103 Pagliara and Carnacina (2010b) also argued that the parameter T should be altered to account for
104 the effective increase of the pier-size due to the presence of debris accumulations, defining a new
105 non dimensional time as $T^* = hUt/A_b$. On top of this, it is argued in this work that the main effect
106 of W on scour is to dictate the blockage area ratio A^* and, therefore, can be considered redundant.
107 Moreover, while the density of debris ρ_L may play an important role in the formation –thus on
108 the dimensions— of debris accumulations (Panici and de Almeida 2018), is not expected to
109 influence scour directly and, thus, it is not herein considered. In addition, Pagliara and Carnacina
110 (2010b) and Lagasse et al. (2010), indicated that the dependency of d_s on n_d is minimal and

111 hence n_d can also be neglected. Therefore, using the pier diameter D as the repeating variable, it
112 is possible to link the non-dimensional local scour with the following set of non-dimensional
113 parameters

$$114 \quad \frac{d_s}{D} = f\left(\frac{h}{D}, U^*, T^*, \frac{d_{50}}{D}, A^*, \frac{H}{h}, \frac{K}{D}, \frac{l_{log}}{D}\right). \quad (2)$$

115 Note that H/h in Eq. (2) was obtained by combining H/D with h/D . In agreement with Pagliara
116 and Carnacina (2010b), this parameter was preferred to H/D as it is more effective to quantify
117 the acceleration of the flow occurring beneath the debris, which is presumably an important
118 scour-worsening mechanism.

119 According to Oliveto and Hager (2002, 2005), the temporal development of the local scour
120 without debris accumulation in clear water conditions follows the logarithmic law (Pagliara and
121 Carnacina 2010b)

$$122 \quad \frac{d_s}{D} = \varepsilon \ln\left(\frac{T^*}{10}\right), \quad (3)$$

123 where ε is the scour evolution rate, which can depend on all the non-dimensional parameters on
124 the right-hand side of Eq. (2) with obvious exception of T^* . In the work presented herein ε will be
125 used to quantify and compare the severity of scour for all experimental conditions.

126 A set of experiments were, thus, conducted to investigate the effects on ε of only those
127 dimensionless groups in Eq. (2) related to the debris dimensions. 17 pairs of local scour
128 experiments were carried out with and without debris accumulation for various sediment and
129 flow conditions, but all under clear-water conditions, in a large flume at the University of
130 Southampton. The experiments were conducted in a 23 m long, 1.38 m wide, and 0.6 m deep
131 flume, while debris models were attached to a circular pier (cylinder) of 0.1 m diameter. A
132 complete description of the experimental campaign is available online as supplemental material
133 (supplemental Appendix I) in the ASCE Library (ascelibrary.org), including a sketch of the
134 experimental setup (Fig. S1), debris model photographs (Fig. S2) and a table with characteristics
135 of the paired experiments (Table S1). As debris models, rigid twigs were selected to resemble
136 conditions under which Eq. (1) was originally developed by Panici and de Almeida (2018).
137 While a comprehensive description of the influence of debris on scour would require tests under

138 both clear-water and live bed conditions, in this first comparative study the focus is exclusively
139 on the simplest scenario of clear-water scour.

140

141 **General Debris Effects on Local Scour**

142 Figs. 2a and 2b present d_s/D vs T^* graphs obtained from the first set of experiments (described in
143 the supplemental Appendix I). It is reassuring to observe that all the results resemble straight
144 lines when plotted in semilogarithmic coordinates. This means that Eq. (3) represents an
145 acceptable model to describe the scour evolution in time for all experimental conditions and,
146 more importantly, ε (which represents the slope of the straight lines) can be taken as an effective
147 parameter to quantify scour severity.

148 The difference between Figs. 2a (experiments with debris) and 2b (experiments without
149 debris) is striking. It is evident that debris leads to much steeper curves, which ultimately lead to
150 more severe scour. In particular, the comparison between the experimental data with and without
151 debris accumulation reported in Fig. 2c reveals an average increase of the local scour depth of
152 50% [based on the so-called debris effect parameter $K_d = \varepsilon/\varepsilon_{nd}$ (Table S1, supplemental
153 Appendix I), where ε_{nd} is the scour evolution rate without debris] and a maximum of 100%
154 (Tests T03 and T06), approximately. These results contrast with former studies where the
155 dimensions of debris accumulations were assumed *a priori* and not linked to the appropriate
156 value of Fr_L . Such studies reported that debris jams increase the depth of scour by a factor of up
157 to 1.5 to 3.0 times the scour depth observed without accumulation (Melville and Dongol 1992;
158 Pagliara and Carnacina 2010b). This aspect is further discussed and clarified in section “size
159 effects” of the supplemental material where results from the second set of experiments are
160 presented and commented.

161 Values of ε in Eq. (3) were determined by linear regression for each experiment using the
162 monitored scour depths in semi-log-form as presented in Fig. 2 (Table 1). A multivariable
163 nonlinear regression was then performed to determine a relation between the dependent
164 parameter ε and three non-dimensional groups, namely U^* , H/h and A^* , which are assumed to be
165 the most influential on ε (Pagliara and Carnacina 2010b). The analysis of the data in Fig. 3a led
166 to the following power law relation

167

$$\varepsilon = \alpha U^{*\beta} \left(\frac{H}{h} \right)^\chi A^{*\delta}, \quad (4)$$

168 where $\alpha = 1.72$, $\beta = 1.31$, $\chi = 0.65$, $\delta = 0.13$ and led to the best coefficient of determination after
 169 linearization ($R^2 = 0.78$ in Fig. 3a). The interdependency between H/h and A^* is analyzed in the
 170 supplemental Appendix II.

171 Due to length restrictions, the analyses of the size and permeability effects are available
 172 online as supplemental material in the supplemental Appendix III. From Fig. S3 (supplemental
 173 Appendix III), it can be drawn that a precise representation of the debris geometry under given
 174 flow conditions is important for an accurate assessment of the local scour, which is in line with
 175 the findings by Lagasse et al. (2010). Further, from Fig. S4 (supplemental Appendix III), it is
 176 suggested that the permeability effect much smaller than the effect of the accumulation itself to a
 177 value $\sim 10\%$.

178

179 Discussion and Conclusions

180 Eq. (4), which relates the scour evolution rate to the debris geometry and flow conditions, can be
 181 found of high practical importance for the risk assessment and design of bridge piers subject to
 182 the potential accumulation of woody debris. Since Eq. (3) is differentiable, dd_s/dt can be
 183 integrated using the results from hydraulic simulations providing values of $U(t)$ and $h(t)$ to be
 184 used in Eq. (4) and, therefore, $d_s(t)$ can be obtained from any initial condition (e.g. pre-event
 185 depth of scour). The combination of this approach with the method proposed here to determine
 186 the effects of debris on scour (which are based on the actual potential size of accumulations that
 187 can be formed under particular conditions and not arbitrarily defined) will lead to a more
 188 accurate assessment of scour and therefore cost-effective design.

189 The accuracy of the results derived from the methods proposed in this study are subjected,
 190 however, to the applicability of Eq. (1). Hence, strictly speaking the results apply to single,
 191 circular bridge piers subjected to the formation of half-conical woody debris accumulations
 192 within the range of conditions described by Panici and de Almeida (2018). However, new results
 193 by Panici and de Almeida (2020) show that the dimensions of accumulations formed at piers of
 194 different shape are not substantially influenced by the shape (except for square piers, which

195 results in accumulations that are approximately 15% wider than those formed at other pier
196 shapes). Therefore, the results presented in this paper may also provide a good approximation of
197 scour when applied to other pier shapes. Also, our analysis has only explored the range of flow
198 conditions achievable by the laboratory facilities, namely, $0.2 < H/h < 0.59$, $0.37 < U^* < 0.82$
199 and $0.10 < A^* < 0.24$ and needs to be extended by exploring a wider range of hydrodynamic and
200 debris conditions, which should involve, also, experiments in the live-bed regime.

201 In this paper, the woody debris accumulations experimentally tested had shape and
202 dimensions linked to the process of collection of individual floating debris elements under given
203 flow conditions at single, circular piers. The main conclusions are:

- 204 • When flow-dependent debris accumulations are tested, the local scour depth was found to be
205 within the range of 1.18–2.19 times the corresponding local scour without accumulations.
- 206 • The time evolution of local scour with and without debris followed the model proposed by
207 Oliveto and Hager (2002). This suggests that all the experiments could be considered similar
208 and comparable through the rate of scour parameter ε .
- 209 • A multi-variable regression analysis allowed us to identify the influence of flow intensity,
210 blockage area ratio, and depth ratio on the development of local scour with flow-dependent
211 debris accumulation.
- 212 • Local scour depth with debris accumulation displays a relatively modest dependency on the
213 debris permeability. An experiment using the extreme condition of zero-permeability debris
214 model resulted in only~10% increase in scour.

215 Future research in this line could be focused on aspects not fully explored in this work, e.g.,
216 the effect of the dimensionless flow depth or the rate at which the debris accumulation forms
217 relative to the rate at which scour develops.

218

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225 MSc student at the Politecnico di Torino, who contributed to the experimental campaigns.

226

227 **Data Availability Statement**

228 Some or all data, models, or code that support the findings of this study are available from the
229 corresponding author upon reasonable request. List of items:

230 - File with all scour depth measurements per experiment.

231

232 **Supplemental Materials**

233 The following appendixes, table and figures are available online in the ASCE Library
234 (ascelibrary.org) in a unique supplemental appendixes document:

235 - Appendix I: Description of the Experimental Campaign,

236 - Appendix II: Interdependency between relative blockage variables,

237 - Appendix III: Secondary Debris Effects on Local Scour, including the subsections *Size*
238 *effects* and *Permeability effects*,

239 - Table S1,

240 - Figs. S1–S4.

241

242 **References**

243 Benn, J. (2013). “Railway bridge failure during flooding in the UK and Ireland.” *Proc. Inst. Civ.*
244 *Eng. Forensic Eng.*, 166(4), 163–170.

245 Bradley, J. B., Richards, D. L., and Bahner, C. D. (2005). “Debris control structures: Evaluation
246 and countermeasures.” U.S. Dept. of Transportation, Federal Highway Administration, *Rep.*
247 *FHWA-IF-04-016*, Washington, DC.

248 Dey, S. (2014). *Fluvial hydrodynamics: Hydrodynamic and sediment transport phenomena.*
249 Springer, Berlin.

250 Diehl, T. H. (1997). "Potential drift accumulation at bridges." U.S. Dept. of Transportation,
251 Federal Highway Administration, *Rep. FHWA-RD-97-028*, Washington, DC.

252 Lagasse, P. F., Clopper, P. E., Zevenbergen, L. W., Spitz, W. J., and Girard, L. G. (2010).
253 "Effects of debris on bridge pier scour." *National Cooperative Highway Research Program*
254 *(NCHRP) Rep. No. 653*, Transportation Research Board, Washington, DC.

255 Laursen, E. M., and Toch, A. (1956). *Scour around bridge piers and abutments*, Iowa Highway
256 Research Board, Ames, IA.

257 Lavy, E. E. (1956). *River mechanics*, National Energy Press, Moscow.

258 Melville, B. W., and Coleman, S. E. (2000). *Bridge scour*, Water Resources Publications,
259 Highlands Ranch, CO.

260 Melville, B., and Dongol, D. (1992). "Bridge pier scour with debris accumulation." *J. Hydraul.*
261 *Eng.*, 10.1061/(ASCE)0733-9429(1992)118:9(1306), 1306–1310.

262 Najafzadeh, M., Saberi-Movahed, F. and Sarkamaryan, S., (2017). "NF-GMDH-Based self-
263 organized systems to predict bridge pier scour depth under debris flow effects." *Mar.*
264 *Georesour. Geotech.*, 1–14.

265 Oliveto, G., and Hager, W. (2002). "Temporal evolution of clear-water pier and abutment scour."
266 *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(2002)128:9(811), 811–820.

267 Oliveto, G., and Hager, W. (2005). "Further results to time-dependent local scour at bridge
268 elements." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(2005)131:2(97), 97–105.

269 Pagliara, S. and Carnacina, I., (2010a). "Influence of wood debris accumulation on bridge pier
270 scour." *J. Hydraul. Eng.*, 10.1061/(ASCE)HY.1943-7900.0000289, 254–261.

271 Pagliara, S., and Carnacina, I. (2010b). "Temporal scour evolution at bridge piers: Effect of
272 wood debris roughness and porosity." *J. Hydraul. Res.*, 48(1), 3–13.

273 Pagliara, S., and Carnacina, I. (2011). "Influence of large woody debris on sediment scour at
274 bridge piers." *Int. J. Sediment Res.*, 26(2), 121–136.

275 Pagliara, S., and Carnacina, I. (2013). "Bridge pier flow field in the presence of debris
276 accumulation." *Proc. Inst. Civ. Eng. Water Manag.* 187–198.

277 Pagliara, S., Carnacina, I., and Cigni, F. (2010). "Sills and gabions as countermeasures at bridge
278 pier in presence of debris accumulations." *J. Hydraul. Res.*, 48(6), 764–774.

279 Panici, D. and de Almeida, G. A. (2017). "Understanding the formation of woody debris jams at
280 bridge piers." *Proc. 37th IAHR Congress*, Kuala Lumpur, Malaysia.

281 Panici, D. and de Almeida, G. A., (2018). "Formation, growth and failure of debris jams at
282 bridge piers." *Water Resour. Res.*, 54(9), 6226–6241.

283 Panici, D. and de Almeida, G. A., (2020). "The influence of pier geometry and debris
284 characteristics on the accumulation of woody debris at bridge piers" *J. Hydraul. Eng.*,
285 10.1061/(ASCE)HY.1943-7900.0001757, 04020041.

286 Parola, A. C., Apeldt, C. J., and Jempson, M. A. (2000). "Debris forces on highway bridges."
287 *National Cooperative Highway Research Program (NCHRP) Rep. No. 445*, Transportation
288 Research Board, National Research Council, Washington, DC.

289 Rahimi, E., Qaderi, K., Rahimpour, M., and Ahmadi, M. M. (2017). "Effect of debris on piers
290 group scour: An experimental study." *KSCE J. Civ. Eng.*, 1–10.

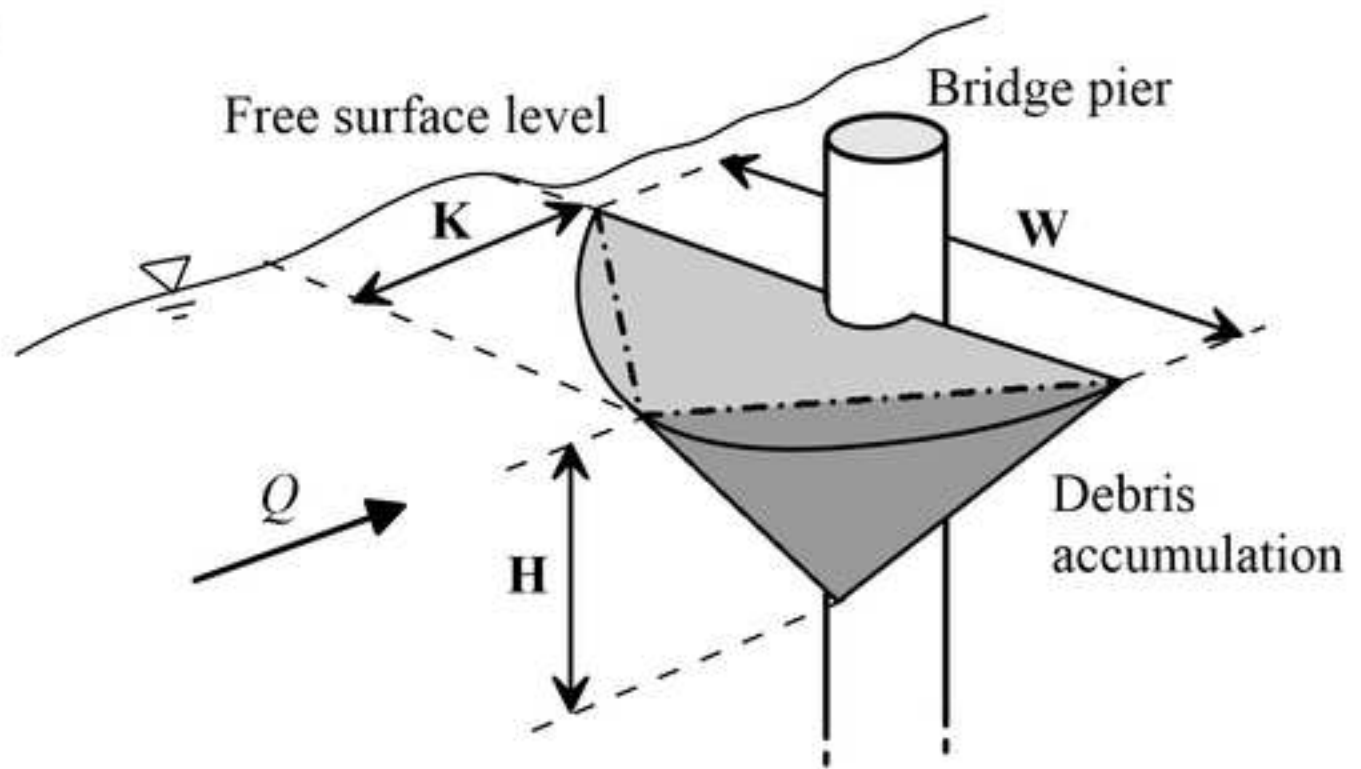
291 Schmocker, L., and Hager, W.H. (2013). "Scale modelling of wooden debris accumulation at a
292 debris rack." *J. Hydraul. Eng.*, 10.1061/(ASCE)HY.1943-7900.0000714, 827–836.

1 **Table 1.** Scour experiments results

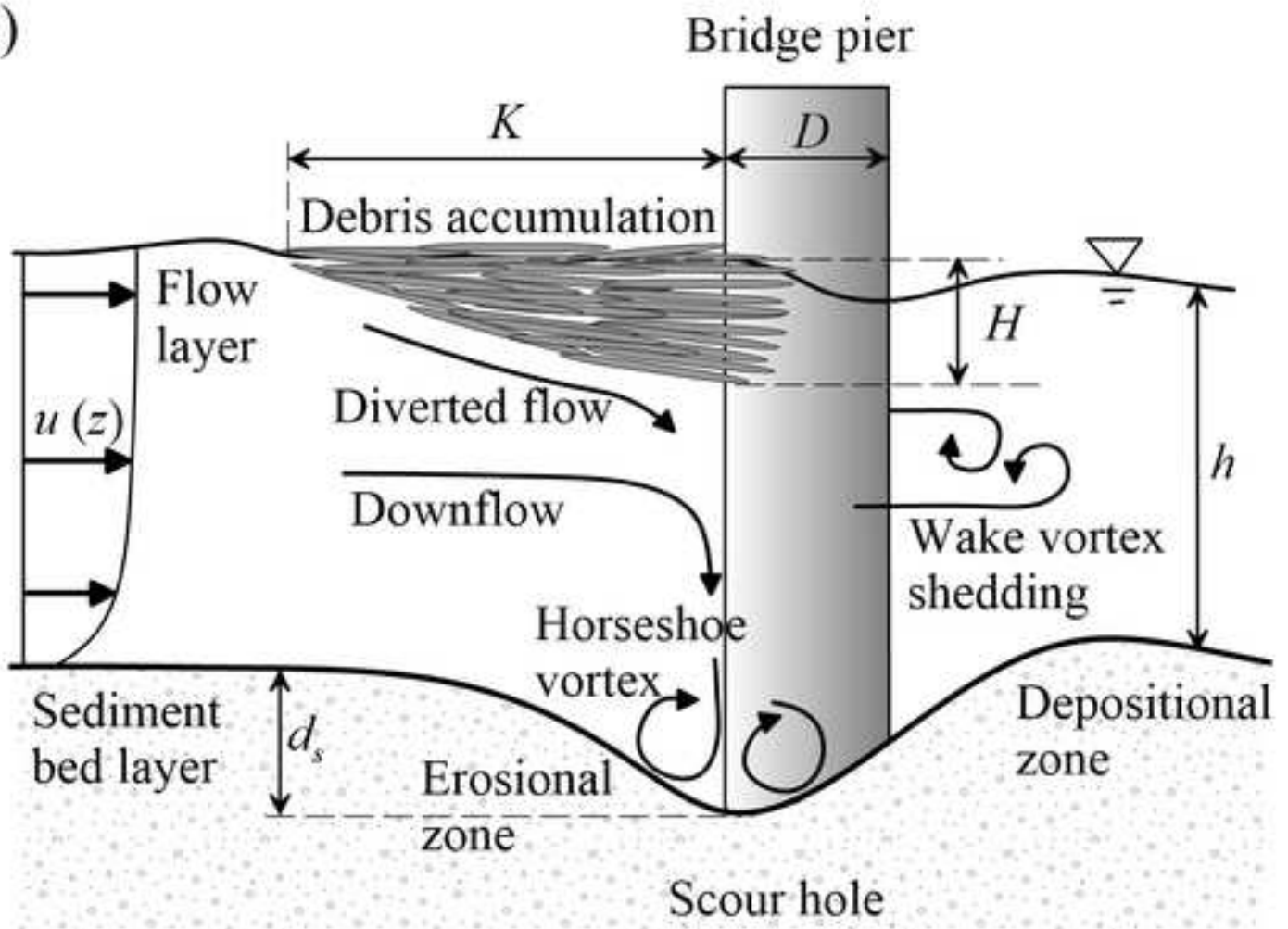
Tests	U_c	U/U_c	ε	ε_{nd}	K_d
T01	0.6	0.48	0.12	0.085	1.41
T02	0.61	0.63	0.27	0.16	1.69
T03	0.58	0.86	0.73	0.36	2.03
T04	0.59	0.57	0.29	0.18	1.61
T05	0.51	0.37	0.09	0.045	2.00
T06	0.54	0.44	0.285	0.13	2.19
T07	0.57	0.5	0.245	0.15	1.63
T08	0.62	0.53	0.2	0.17	1.18
T09	0.62	0.59	0.34	0.24	1.42
T10	0.6	0.62	0.34	0.24	1.43
T11	0.54	0.68	0.48	0.335	1.39
T12	0.6	0.68	0.32	0.23	1.18
T13	0.55	0.52	0.385	0.27	1.43
T14	0.57	0.59	0.52	0.355	1.46
T15	0.59	0.65	0.57	0.39	1.46
T16	0.57	0.65	0.49	0.37	1.32
T17	0.55	0.69	0.39	0.25	1.56

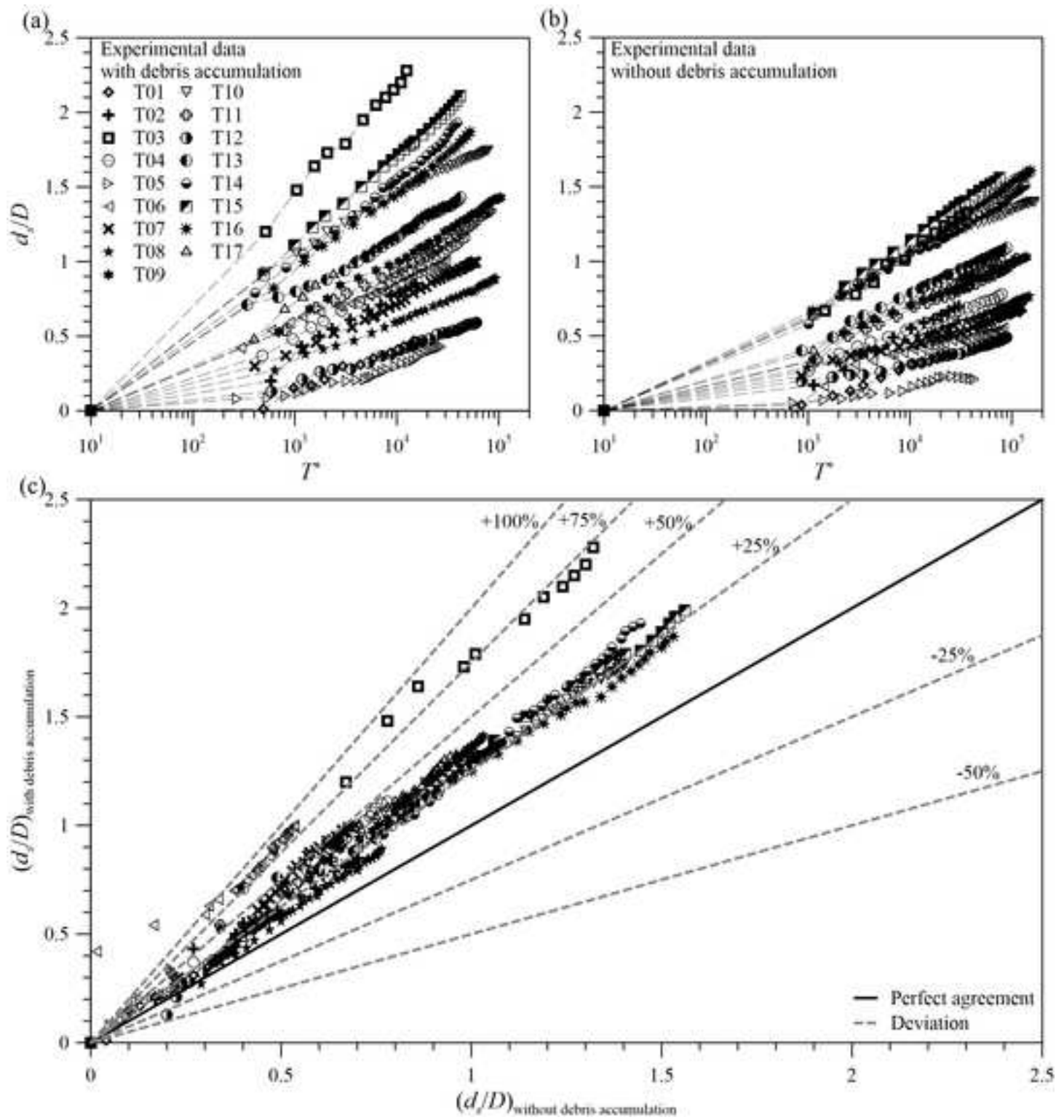
2 Note: U_c is computed following the mean critical velocity method as proposed by Lavy (1956).

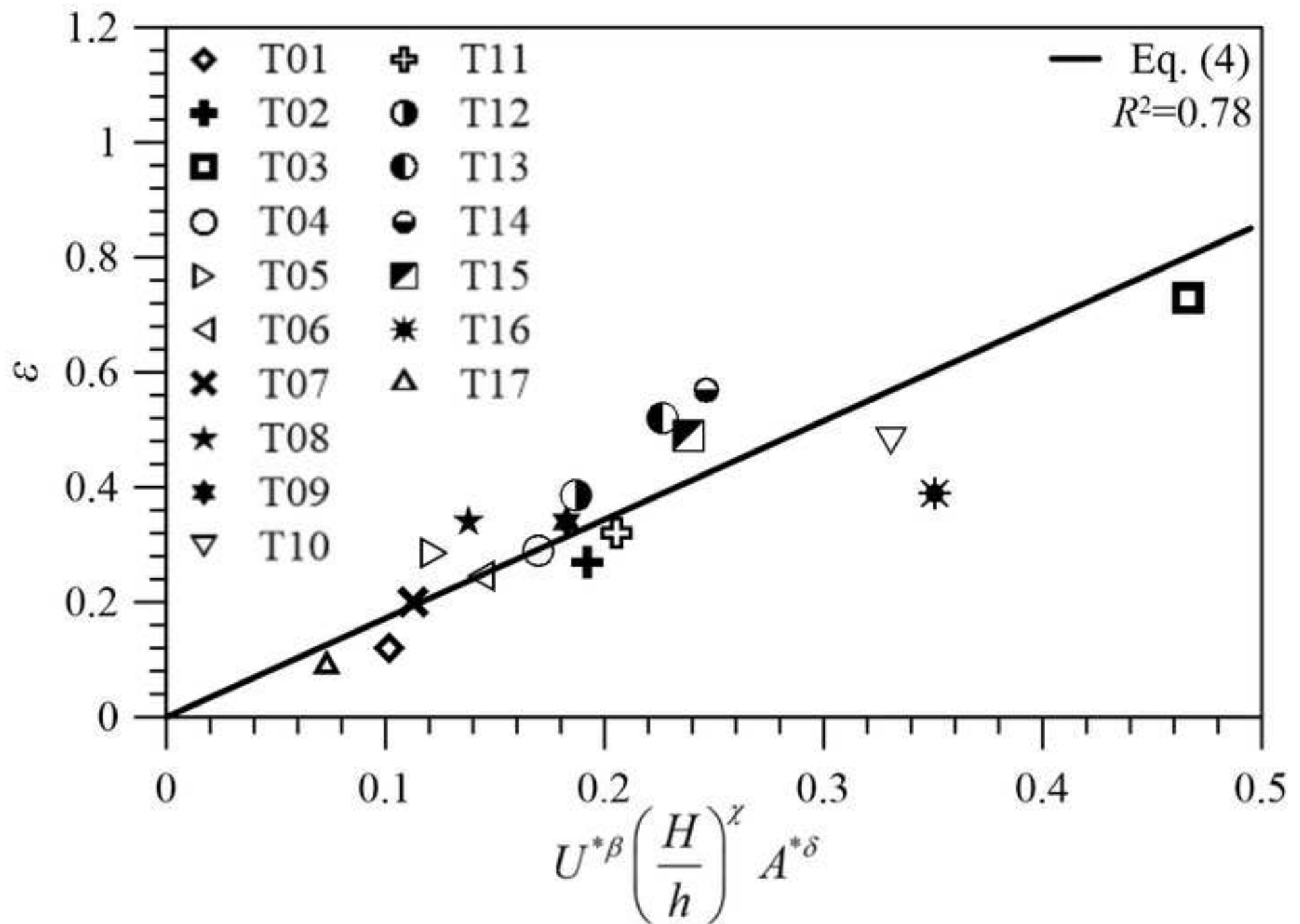
(a)



(b)







1 **Figure Captions List**

2

3 **Fig. 1.** Definition sketches of a permeable woody debris accumulation at the front of a bridge
4 pier in a river flow of discharge Q : (a) perspective and (b) lateral view

5 **Fig. 2.** Non-dimensional scour evolution data for tests T01-T17 being: (a) with debris
6 accumulation; and (b) without debris accumulation. (c) comparison between the local scour
7 depth data of tests T01-T17 with and without debris accumulation with deviation lines for $\pm 25\%$,
8 $\pm 50\%$, $+75\%$, and $+100\%$

9 **Fig. 3.** Power regression for experimental ε -data with debris accumulation for tests T01-T17 by
10 Eq. (4)