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On the accuracy of equivalent roughness height formulas in practical applications

Benoît Camenen*†and Magnus Larson‡

Abstract

This paper presents a discussion on the application and accuracy of roughness height formulas from a practical point of view. Such formulas have been proposed to describe the equivalent roughness height for plane bed conditions based on the Shields parameter. The application of these relationships requires an iterative solution technique. However, as this note demonstrates, the roughness estimates are not always reliable since the application of the formulas yield large discrepancies in the results.

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Keywords

Roughness height, friction factor, plane bed, sheet flow, experimental data, predictive formula, iterative formula.

Introduction

Estimating bedload transport is of great importance for engineering design and morphodynamic modelling; yet bedload transport rate predictions are based on insufficient understanding of the resistance to flow in alluvial channels. Although the roughness height or resistance coefficient are quite difficult to estimate, they remain fundamental parameters in bed shear stress and sediment transport calculations. Total resistance to the flow in a river includes grain resistance, bedform resistance, resistance due to lateral and vertical channel irregularities, as well as dissipation due to the solid transport (Recking et al., 2008). Meyer-Peter and Müller (1948) introduced a linear decomposition of the total resistance coefficient, which may be rewritten as a linear decomposition of the total bed roughness (Soulsby, 1997; Camenen et al., 2006).

Excluding form drag, the value of the equivalent roughness height k_s still varies considerably depending on the configuration of the grains forming the bed roughness or the dissipation due to sediment transport. If k_s is generally assumed to be proportional to a characteristic bed grain size (Bathurst,

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1985), several authors showed a significant increase in k_s when bedload transport occurs, even for coarse sediments (Campbell et al., 2005; Recking et al., 2008). This increase in roughness is often explained for fine sediments by the dissipation of energy in the sheet flow layer that appears for large Shields parameter values (dimensionless bed shear stress defined such as $\theta = RI/[(s-1)d_{50}]$, with R: hydraulic radius, I: energy slope, s: relative density of the sediment to the fluid, and d: grain size). Sediments move collectively along the bottom mainly in a layer and $k_s \approx \delta_s$, where δ_s is the thickness of the sheet flow layer (Wilson, 1989). This movement induces an effective roughness ratio k_s/d, where d is the grain size diameter, up to 50 (Wilson, 1966; Nnadi and Wilson, 1992; Sumer et al., 1996). Based on a large data set, Recking et al. (2008) found a significant difference in the fit of a logarithmic law for the friction coefficient depending on the presence of sediment movement, which can be described in terms of a roughness, such as the k_s/d-ratio, that varies from approximately 1 for a fixed bed to 3 for a moderate sediment transport rate.

Generally, this phenomenon was expressed using a Shields parameter value θ over a critical value for the upper plane bed regime, where k_s is not only a function of the median grain size d_{50} but also of θ (Wilson, 1966; Nnadi and Wilson, 1992; Yalin, 1992; van Rijn, 1993; Sumer et al., 1996; Bayram et al., 2003; Camenen et al., 2006) or of bedload transport rate, if the latter is assumed to be directly related to the Shields parameter (Meyer-Peter

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and Müller, 1948). Most of the formulas were validated for fine sediments and high shear stresses. Sumer et al. (1996) observed that the roughness height may be a function of a dimensionless settling velocity $\varpi_s = W_s/u_*$ (where W_s is the settling velocity and u_* the shear velocity). Camenen et al. (2006) also showed that large values on the effective roughness ratio k_s/d_{50} can be observed for lower values of the Shields parameter. They proposed a new relationship for the critical Shields parameter for the upper plane regime, which is a function of a dimensionless settling velocity $W_{s*} = [(s-1)^2/(g\nu)]^{1/3}W_s$ (where g the acceleration due to gravity, and ν the kinematic viscosity of the fluid) and a Froude number $F_r = U_c/\sqrt{gh}$ (where U_c the steady current velocity and h the water depth). Then, for a low Froude number and coarse sediment, large effective roughness ratios are also observed. The flow seems to be affected by the bed load transport for these particular cases as much as in the sheet flow transport cases.

However, one important aspect of these previous studies is that all the equations presented in Camenen et al. (2006) have been fitted knowing the total shear stress, since it is directly computed from energy slope measurements. Therefore, in practical applications, as the total Shields parameter is an unknown, these relationships induce an iterative method for the computation of the roughness height and the total Shields parameter. Two main problems may occur: (1) a solution does not always exist depending on the proposed equation (or more than one solution exist), and (2) the

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iterative approach in itself induces a large discrepancy in the results. The main objective of the present study is to highlight these problems induced by the iterative method. Although similar problems occur for oscillatory flows (Camenen et al., 2009), this paper is dealing with unidirectional flows only. As a consequence, this paper corresponds to an extension to Camenen et al. (2006) dealing with the application of the previously proposed formulas.

Iterative calculation of the roughness height

Since experimental data implicate a relationship where roughness height is a function of the total shear stress, an iterative calculation is needed to compute the roughness. Indeed, from a practical point of view, the Shields parameter θ is an unknown.

Iterative procedure

The iterative solution can be expressed using the relationship for the friction coefficient (see Eq. 12 in Camenen et al., 2006) and the definition of the Shields parameter (see Eq. 2 in Camenen et al., 2006). Assuming the hydraulic radius R, median grain size d_{50}, relative density of sediments s, and depth averaged velocity U_c as input parameters, the only unknown parameter to estimate the Shields parameter is the roughness height k_s or roughness length $z_0 = k_s/30$. Thus, the Shields parameter can be expressed

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as a function of k_s/d_{50}:

$$\theta = F\left(\frac{k_s}{d_{50}}\right) = \left[\frac{\kappa}{(R+z_0)/R\ln\left((R+z_0)/z_0\right)-1}\right]^2 \frac{{U_c}^2}{(s-1)gd_{50}} \quad (1)$$

Employing the relationships proposed by different authors (Wilson, 1966; Yalin, 1992; van Rijn, 1993; Sumer et al., 1996; Bayram et al., 2003; Camenen et al., 2006), which can be expressed as $k_s/d_{50} = f(\theta)$, equation 1 can easily be solved using an iterative technique. The function f may often be written according to:

$$\frac{k_s}{d_{50}} = f(\theta) = a_1 + a_2\theta^b \quad (2)$$

where a_1, a_2 and b are constants ($0 \leq a_1 \leq 5$, $1 \leq b \leq 2.5$ and a_2 varies with b and authors; b can also be a function of the settling velocity, shear velocity or/and the Froude number).

The iterative procedure may be summarized as follows:

- fix a first value for k_s: $k_{s,p1} = \alpha d_{50}$ ($\alpha = 2$ may be used assuming skin roughness),
- compute θ_p using Eq. 1 with $k_s = k_{s,p1}$,
- compute a new value for k_s: $k_{s,p2}$ using Eq. 2 with $\theta = \theta_p$,
- while $|1 - k_{s,p1}/k_{s,p2}| > \epsilon$, fix $k_{s,p1} = k_{s,p2}$ and iterate the previous two operations

Of course, the choice of α and ϵ ($\epsilon = 0.01$ was used) may slightly influence the results.

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Graphical interpretation of the iterative procedure

It is also possible to graphically represent this iterative procedure. Fig. 1 presents curves of the effective roughness ratio plotted against the total Shields parameter obtained from various equations $k_s/d_{50} = f(\theta)$ and the equation $k_s/d_{50} = F^{-1}(\theta)$ (represents calculation of k_s/d_{50} from the total Shields parameter, see Eq. 1) for two particular cases: figure (a) corresponds to an experimental case from Smart (1984); figure (b) corresponds to an experimental case from Nnadi and Wilson (1992).

Fig. 1 here

In Fig. 1, it can be seen that both functions $f(\theta)$ and $F^{-1}(\theta)$ are increasing functions of θ, but $f(\theta)$ is a convex function, whereas $F^{-1}(\theta)$ is a concave function. In general, this means that either two solutions coexist (*cf.* Fig. 1(a)) or no solution exists (*cf.* Fig. 1(b) for the Sumer *et al.* formula). Another observation is that the similar slopes of these curves ($f(\theta)$ and $F^{-1}(\theta)$) close to the intersection points induces large uncertainties (*cf.* Fig. 1(a) for the formula proposed by Camenen *et al.* or (b) for all formulas). This effect is not as strong for the Wilson formula since the power on θ is not as large as for the other equations (1 compared to 1.5 or 2.5). The iterative method will never induce a better result compared to the fitted curve because the two curves f and F^{-1} are increasing functions of θ. In Fig. 2 are two different situations presented that illustrates this point:

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1. A slight underestimation is observed using the fitted curve. The experimental point is E_1 with the coordinates (θ_1,$(k_s/d_{50})_{1e}$). The estimated value of (k_s/d_{50}) from the fitted curve is such that $(k_s/d_{50})_{1p} < (k_s/d_{50})_{1e}$ (point P_1). From the iterative method (point I_1), the predicted value of θ is necessarily smaller ($\theta_{1i} < \theta_1$). Thus, $(k_s/d_{50})_{1i} < (k_s/d_{50})_{1p} < (k_s/d_{50})_{1e}$.

2. A slight overestimation is observed using the fitted curve. The experimental point is E_2 with the coordinates (θ_2,$(k_s/d_{50})_{2e}$). The estimated value of (k_s/d_{50}) from the fitted curve is such that $(k_s/d_{50})_{2p} > (k_s/d_{50})_{2e}$ (point P_2). From the iterative method, the predicted value of θ is necessarily larger ($\theta_{2i} > \theta_2$). Thus, $(k_s/d_{50})_{2i} > (k_s/d_{50})_{2p} > (k_s/d_{50})_{2e}$.

Fig. 2 here

In conclusion, it appears that the iterative method is not very accurate from a practical point of view. A solution does not always exist, and most of the time, two solutions coexist. If there is an error between the data and the fitted curve, it will necessarily be larger after employing the iterative method.

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Results obtained from the iterative methods

Prediction of the roughness height

In order to discuss the iterative method, several empirical formulas for Eq. 2 presented in Camenen et al. (2006) were tested using the same data set for plane bed conditions also introduced in Camenen et al. (2006). In Table 1 are the predictions of equivalent roughness height within a factor of 2 ($P2$ in %) and 5 ($P5$ in %) of the measured values presented for the different formulas, as well as the mean value (mr) and standard deviation (sr) of the ratio $r = k_{s,pred}/k_{s,expe}$. The term "$Er_{log}$" (logarithmic error index, in %) is defined as,

$$Er_{log} = \frac{100}{n} \sum_{1}^{n} \left| \log \left[\frac{(k_s/d_{50})_{pred}}{(k_s/d_{50})_{expe}} \right] \right| \tag{3}$$

in which n denotes the number of observations. When no solution existed, a value $k_s/d_{50} = 250$ (maximum roughness height ratio observed experimentally) was chosen, and when several solutions coexisted, the smallest value was chosen. As a comparison, results using the grain related roughness ($k_s = 2d_{50}$) and a recently published formula by Rickenmann and Recking (2011) are also presented ($U_c/u_* = 4.416(R/d_{84})^{1.904}\{1 + [R/(1.283d_{84})]^{1.618}\}^{-1.083}$).

Tab. 1 here

Although good agreement is found towards the data using the experimental total shear stress values, the iterative solution for a pair (k_s, θ)

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induces large discrepancies in the results. As a matter of fact, the accuracy of the results ($P2$) drops with 10% to 30% depending on the formula used (*cf.* table 1 and Fig. 3). A large increase in Er_{log} and sr is also observed for all the formulas. It clearly appears that the discrepancy of the iterative methods depends mainly on the value of the coefficient b proposed in each formula ($b = 1.0$ for the Wilson formula, $b = 2.5$ for the Sumer *et al.* formula and $b = 1.7$ for the Bayram *et al.* and Camenen *et al.* formulas). Indeed, the larger the coefficient b is, the closer are the two slopes of the functions $F^{-1}(\theta)$ and $f(\theta)$, and the larger the uncertainties induced by the iterative solution. As a result, the obtained k_s/d_{50} values often correspond to the minimum value imposed by the formula (skin roughness). This observation is clearly confirmed by the graphs in Fig. 3. It also explains the relatively better results observed for the Sumer *et al.* formula since there is a higher minimum value ($k_s/d_{50} = 4.5$) when $\varpi = W_s/u_* \leq 0.9$ ($u_* = \sqrt{\tau/\rho}$ is the shear velocity, where τ is the bottom shear stress and ρ the density of the fluid). In Fig. 3, it appears that the Sumer *et al.* and Bayram *et al.* formulas yield unrealistic results corresponding to their minimum value (2 or 4.5 for the Sumer *et al.* formula depending on ϖ) for most of the cases. If the Camenen *et al.* formula yields the best result using the measured Shields parameter, the obtained result from the iterative solution is quite poor and it yields large uncertainties. As many of the experimental cases correspond to a roughness height close to the skin roughness height

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($k_s \approx 2d_{50}$), to use the skin roughness height yields nearly as good result as the more complex formulas. The Rickenmann and Recking formula yields slightly better results but very similar as for the skin roughness. No formula gives good predictions for the roughness height when $k_s > 10d_{50}$, but the Wilson formula yields much better results than the other formulas. Finally, the Wilson formula (with a minimum value k_s/d_{50}) produces the best results among the studied formulas, although the scatter is significant.

Fig. 3 here

Prediction of the total Shields parameter

A comparison between the predicted and the observed value of the Shields parameter shows similar results. A quite large discrepancy is observed for the prediction of the total Shields parameter whatever formula used. Even the Wilson formula, which seems to yield slightly better results for the estimation of the roughness height, does not produce any improvement for the estimation of the total Shields parameter. The Wilson, Bayram *et al.*, and Camenen *et al.* formulas yield overestimations with relatively large dispersion in the predictions. The Sumer *et al.* formula, since it gives values for k_s/d_{50} between 2 and 5, presents slightly better results compared to the other formulas. Finally, it appears that using the skin Shields parameter (or the Rickenmann and Recking formula) yields predictions, which are as good as using the other studied formulas, apart for the large values on the

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Shields parameter, which are underestimated.

Tab. 2 here

Conclusions

Many formulas have been proposed to estimate the roughness height in the case of plane beds. All the previous authors proposed equations assuming that the total Shields parameter is already known. Although these formulas present interesting results for the understanding of the physics, and reveal the main factors governing roughness, they are not applicable from an engineering point the view. The iterative formulas resulting from these equations yields very large scatter in the results. Finally, the use of the skin Shields parameter produces nearly as good results, apart for large values of the total Shields parameter, which are underestimated. There is thus a strong need for a new method to correctly predict the total Shields parameter for the upper regime where the roughness height is no more a function of the grain size only ($k_s/d_{50} > 5$).

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Notation

The following symbols and subscripts are used in this paper:

a_1, a_2, b	:	constants depending on authors for the function f,
d, d_{50}, d_{84}	:	sand diameter, median sand diameter and diameter for which 84% of sediment by weight is smaller, respectively,
Er_{log}	:	logarithm error index (in %),
f	:	empirical functions used to estimate k_s/d_{50},
F	:	function of k_s/d_{50} used to calculate the Shields parameter,
Fr	:	Froude number,
g	:	acceleration due to gravity ($g = 9.81$ m/s),
h	:	water depth,
I	:	energy slope,
k_s	:	roughness height,
mr, sr	:	mean value and standart deviation ,
$P_{1.2}$, P_2, P_5	:	predictions within a factor of 1.2, 2 and 5, respectively (in %) of the measured values,
R	:	hydraulic radius,
s	:	relative density of the sediment to the fluid ($s = 2.65$ for silica in water),

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u_* : friction velocity,

U_c : depth-averaged velocity,

W_s : settling velocity,

W_{s*} : nondimensionnal settling velocity ($W_* = (s-1)^{2/3}/(g\nu)^{1/3}\ W_s$).

z_0 : roughness lenght ($z_0 = k_s/30$),

α : constant used for the first estimation of k_s in the iterative procedure,

κ : von Karman constant ($\kappa = 0.41$),

ν : kinematic water viscosity ($\nu = 10^{-6}\ \mathrm{m}^2/s$),

θ : total Shields parameter due to steady current,

ϖ_s : suspension parameter ($\varpi_s = W_s/u_*$).

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Table 1: Prediction of the equivalent roughness height within a factor of 2 and 5 of the measured values together with a logarithmic error index, and the mean value and standard deviation of the ratio $r = k_{s,pred}/k_{s,expe}$ for the studied formulas (R. & R.: Rickenmann & Recking) and all data, and data where $(k_s/d_{50})_{expe} > 10$ (influence of the iterative method on the results).

	all data									
	experimental value of θ					iterative method				
Author(s)	$P2$	$P5$	Er_{log}	mr	sr	$P2$	$P5$	Er_{log}	mr	sr
$k_s = 2d_{50}$	41	73	49	-0.3	0.57			–		
R. & R.	41	81	44	-0.03	0.55			–		
Wilson	57	90	33	0.01	0.45	44	76	50	0.08	0.67
Sumer *et al.*	54	87	34	-0.09	0.50	45	79	46	-0.09	0.62
Bayram *et al.*	57	88	34	-0.02	0.47	39	74	53	0.09	0.72
Camenen *et al.*	74	97	23	-0.01	0.30	36	66	61	-0.01	0.81
	data where $(k_s/d_{50})_{expe} > 10$									
	experimental value of θ					iterative method				
Author(s)	$P2$	$P5$	Er_{log}	mr	sr	$P2$	$P5$	Er_{log}	mr	sr
$k_s = 2d_{50}$	0	0	120	-1.2	0.23			–		
R. & R.	0	2	80	-0.8	0.25			–		
Wilson	52	70	47	-0.4	0.55	33	53	69	-0.5	0.71
Sumer *et al.*	29	60	64	-0.6	0.57	4	36	85	-0.8	0.57
Bayram *et al.*	46	67	52	-0.5	0.54	9	31	91	-0.4	0.54
Camenen *et al.*	68	96	27	-0.2	0.29	11	30	93	-0.6	0.83

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Table 2: Prediction of total Shields parameter within a factor of 1.2 and 2 of the measured values together with a logarithmic error index, and the mean value and standard deviation of the ratio $r = \theta_{pred}/\theta_{expe}$ for the studied formulas (and the skin Shields parameter, as well as the Rickenmann & Recking formula) and all data.

Author(s)	$P1.2$	$P2$	Er_{log}	mr	sr
skin Shields parameter	30	75	22	-0.14	0.28
Rickenmann & Recking	28	80	20	-0.04	0.27
Wilson	31	75	31	0.08	0.68
Sumer *et al.*	32	78	27	-0.01	0.59
Bayram *et al.*	30	73	38	0.14	0.77
Camenen *et al.*	27	67	41	0.07	0.83

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(a)	(b)
Fig. 1a	Fig. 1b

Figure 1: Graphical illustration of the iterative method for two specific cases (experimental data from Smart (a) and Nnadi & Wilson (b)).

Figure 2: Graphical illustration of the iterative method for the two main situations.

	experimental value of θ	iterative method
(a)	Fig. 3a1	Fig. 3a2
(b)	Fig. 3b1	Fig. 3b2
(c)	Fig. 3c1	Fig. 3c2

Figure 3: Effect on the results using an iterative method for the Wilson (a) (with a minimum value of $k_s/d_{50} = 2$), Sumer *et al.* (b), and Camenen *et al.* (c) formulas.

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Fig. 1a

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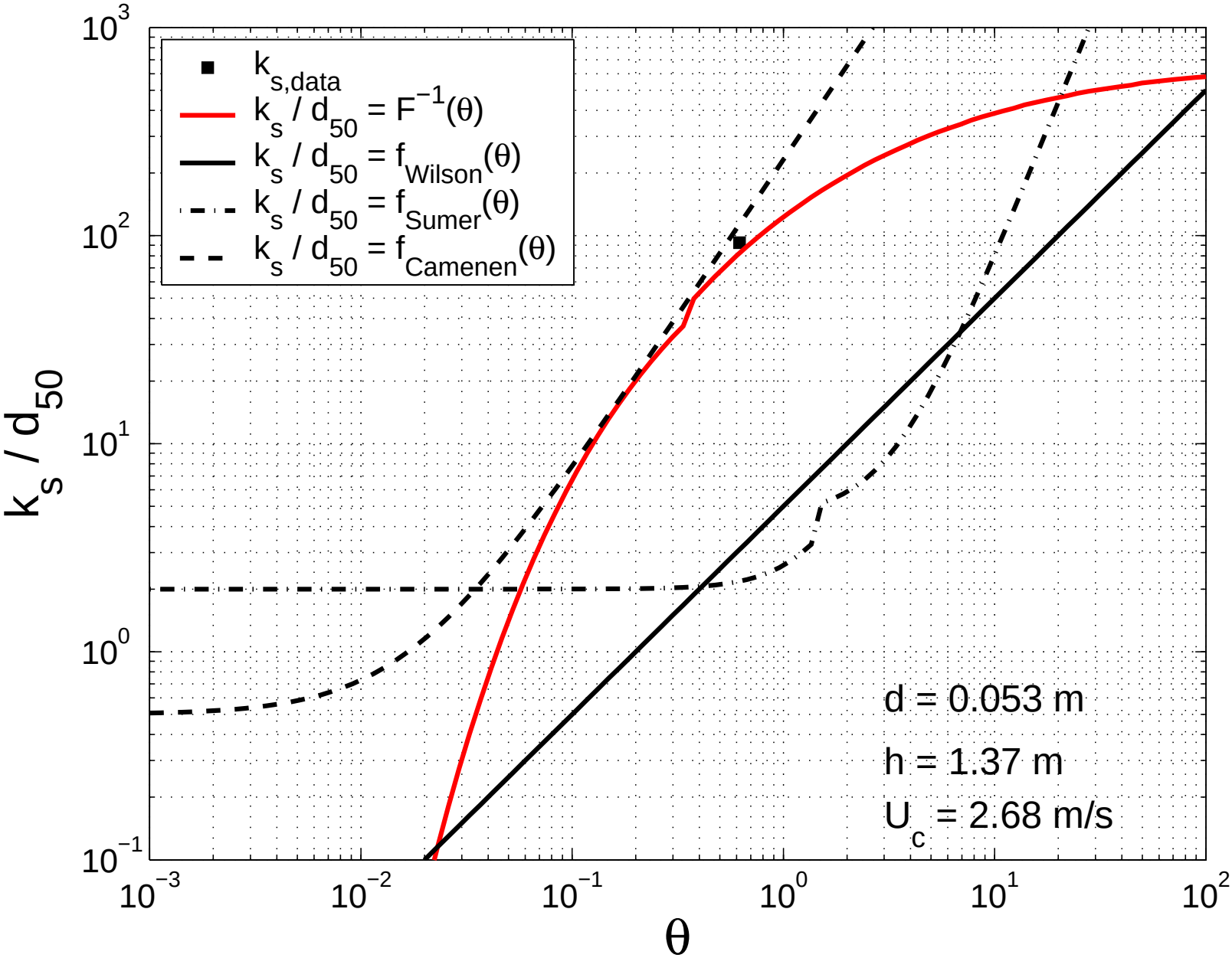

Fig. 1b

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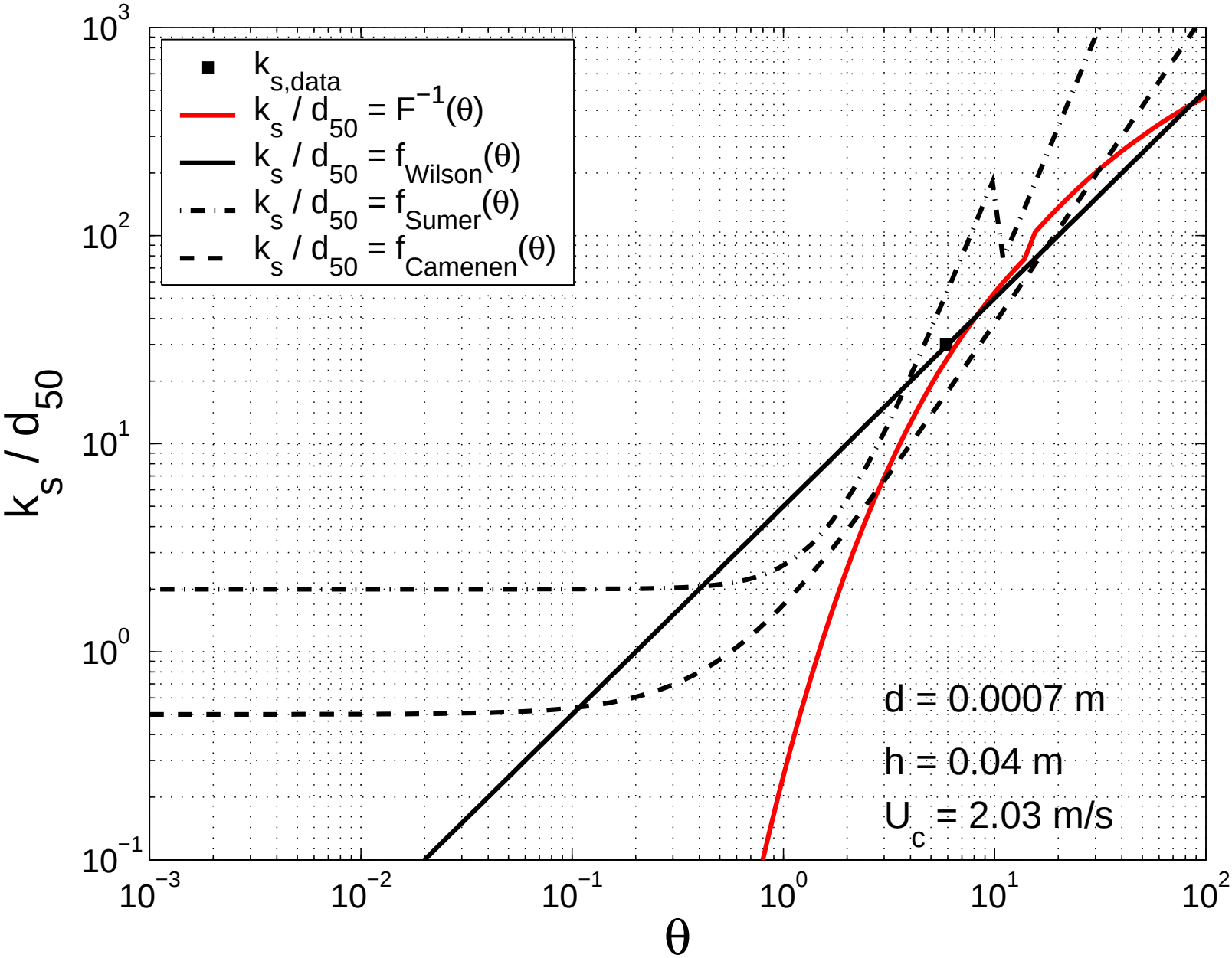

Fig. 2
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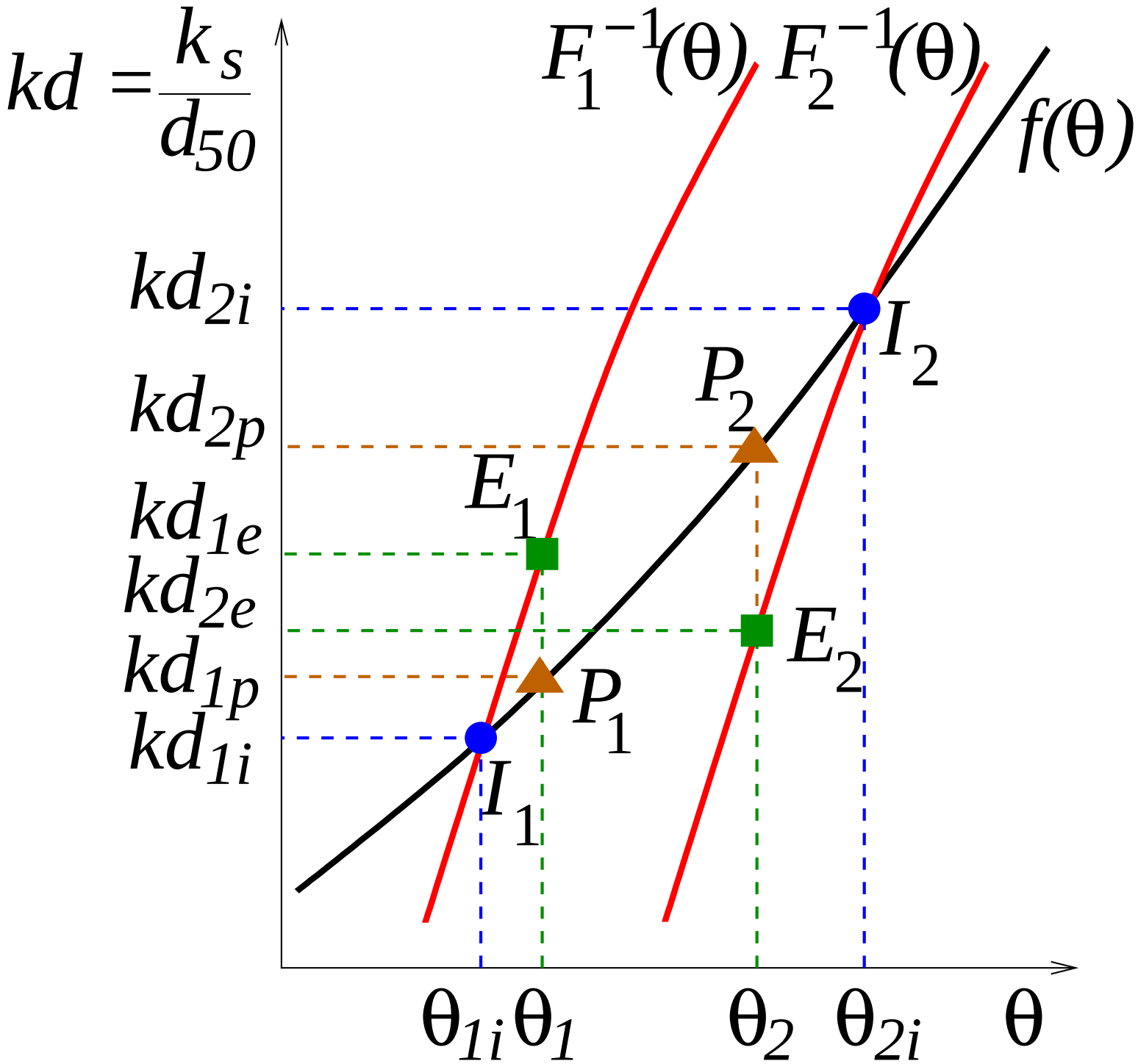

Fig. 3a1
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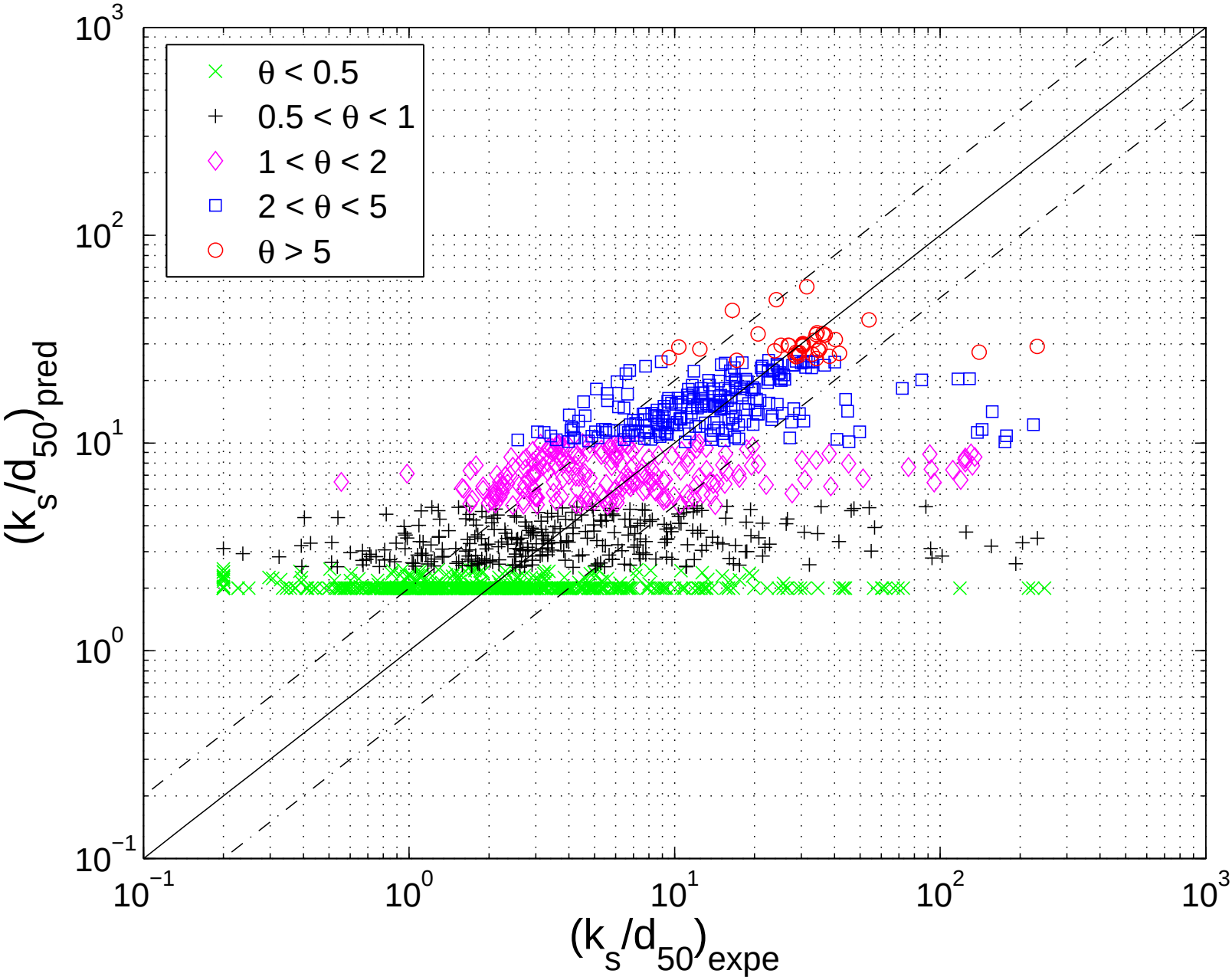

Fig. 3a2
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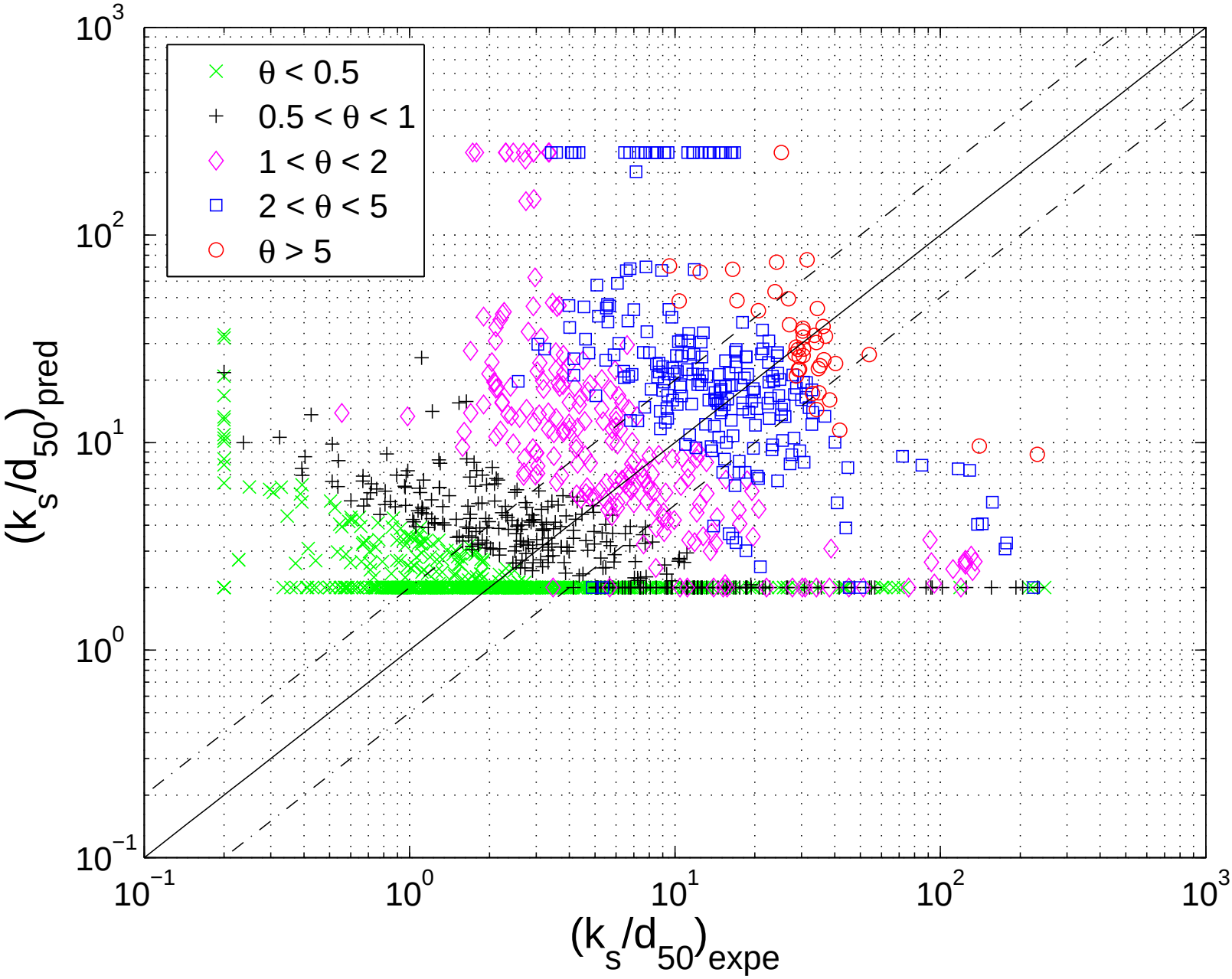

Fig. 3b1
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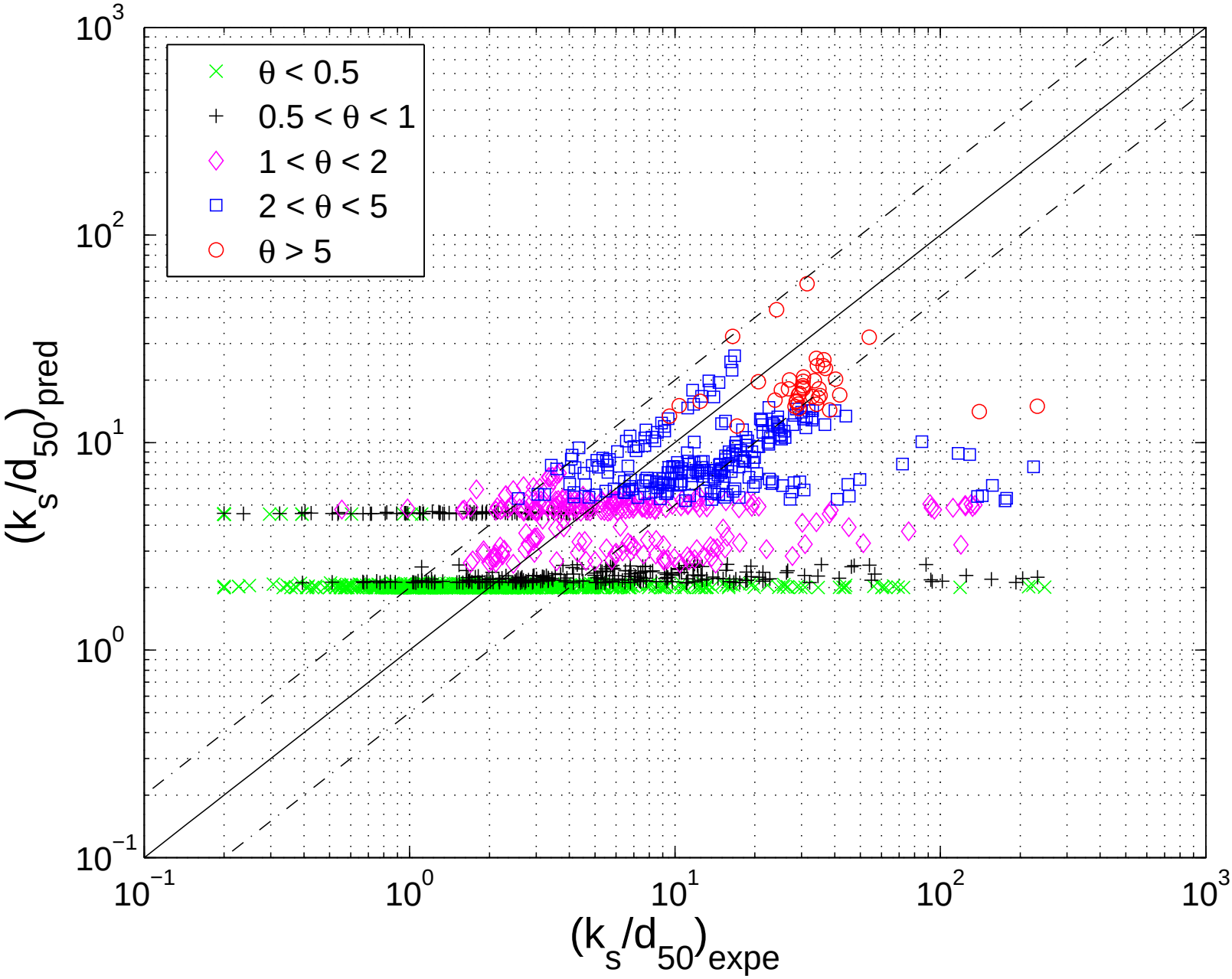

Fig. 3b2
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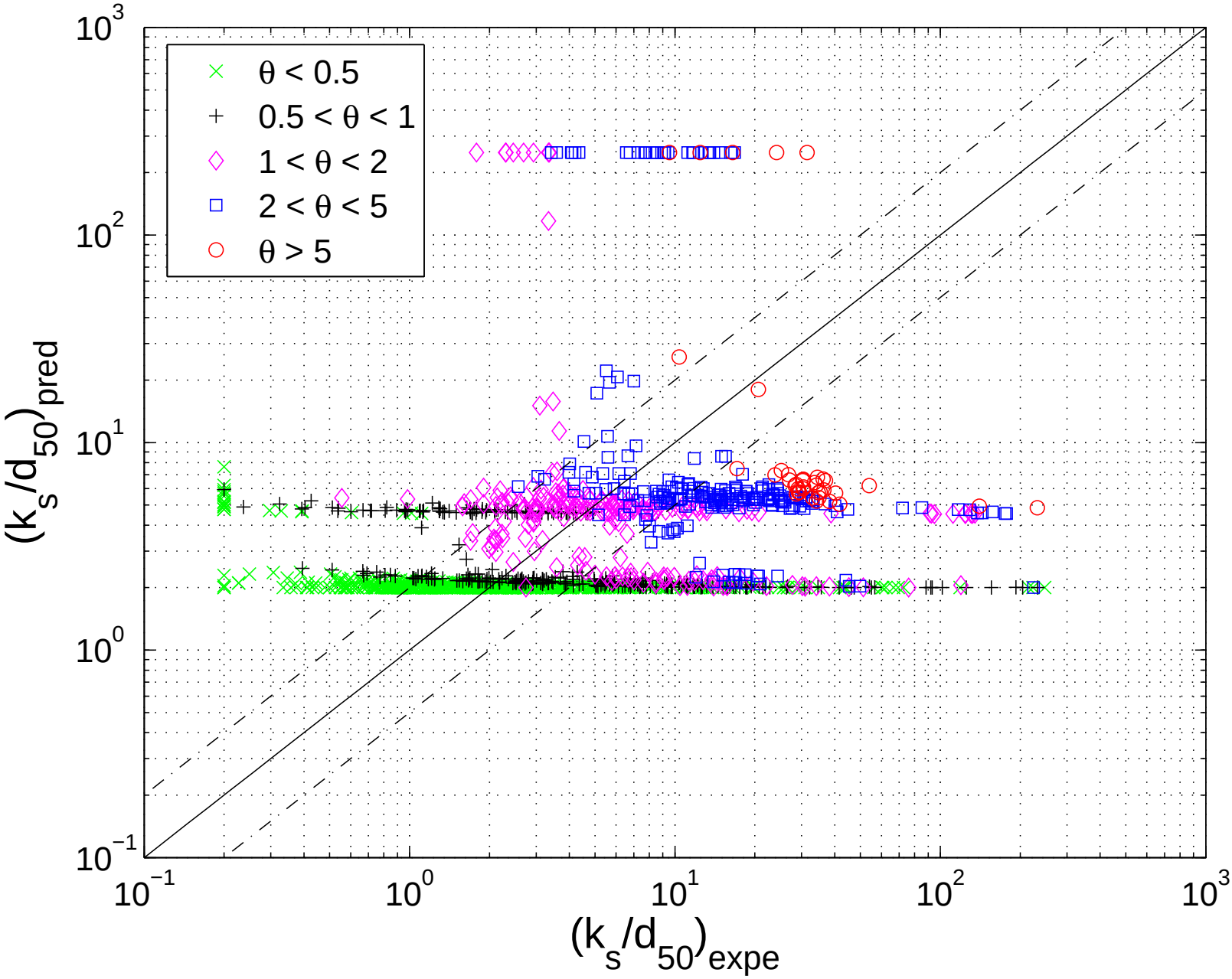

Fig. 3c1
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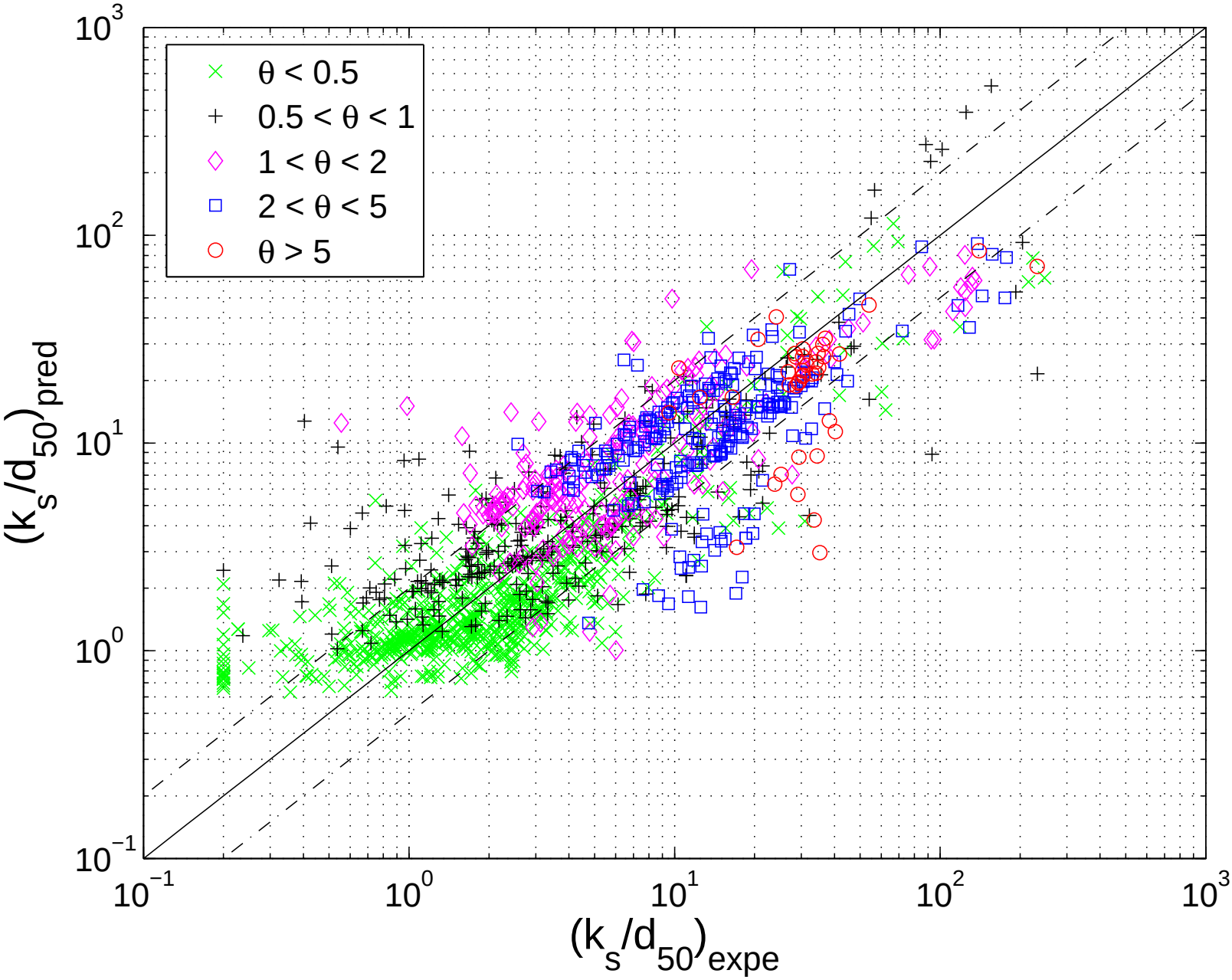

Fig. 3c2
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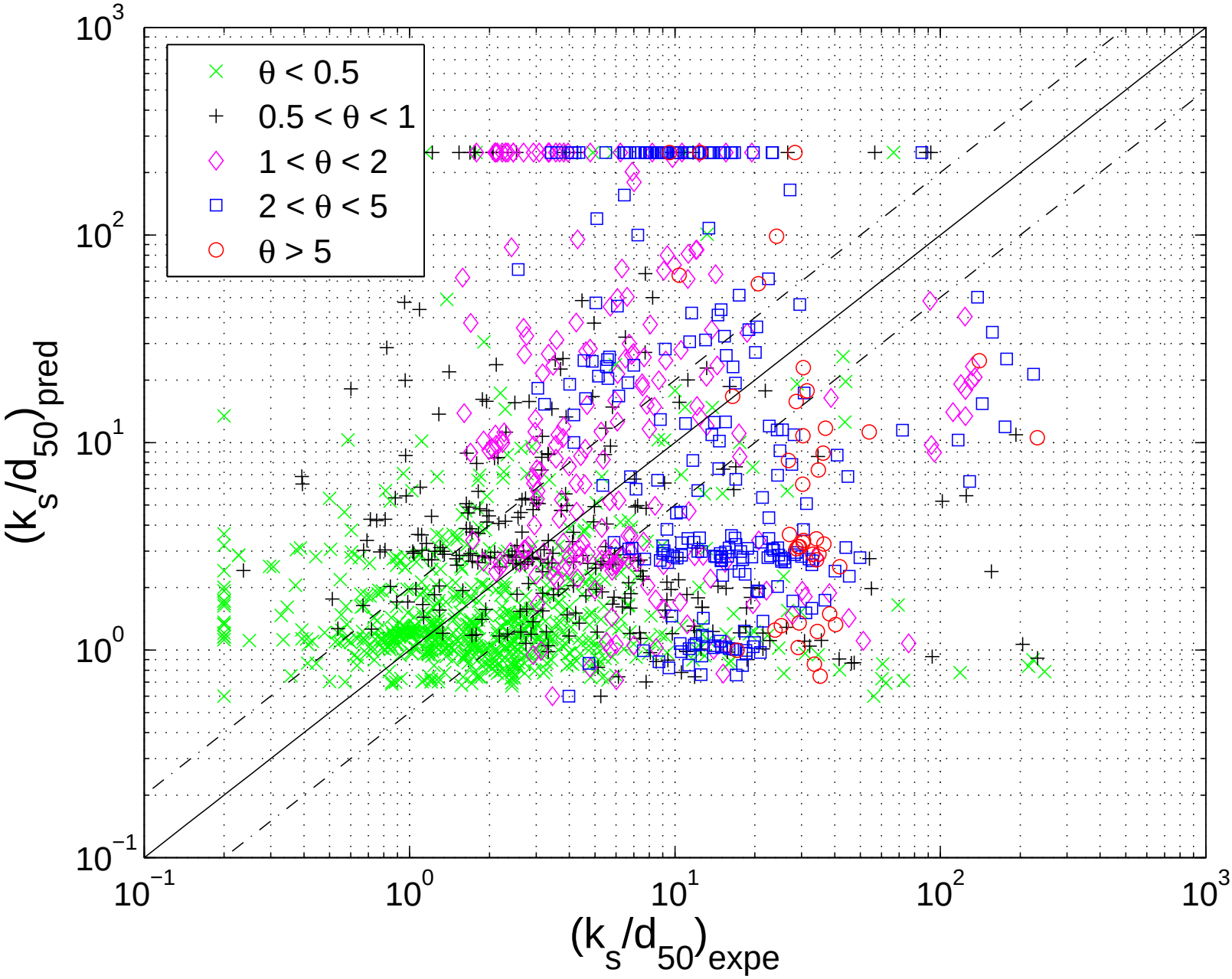

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Manuscript Authors: B. CAMENEN, M. LARSON

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Total # refs	0	0
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		249
		3059
		3

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1-column table = up to 60 characters wide by:	**2-column table = 61 to 120 characters wide by:**
17 lines (or less) = 158 word equiv.	17 lines (or less) = 315 word equiv.
up to 34 lines = 315 word equiv.	up to 34 lines = 630 word equiv.
up to 51 lines = 473 word equiv.	up to 51 lines = 945 word equiv.
up to 68 text lines = 630 word equiv.	up to 68 text lines = 1260 word equiv.

C. Total Characters wide by Total Text lines = word equiv. as shown in the table above. **Add word equivalents** for each table in the column labeled "**Word Equivalents.**"

Estimating Length of Tables &

Tables	Word Equivalents	**Figures**
Table 1	317	Figure 1
2	158	2
3	0	3
4	0	4
5	0	5
6	0	6
7	0	7
8	0	8
9	0	9
10	0	10
11	0	11
12	0	12
13	0	13
14	0	14
15	0	15
Please double-up tables/figures if additional space is needed (ex. 20+21).		16
		17
		18
		19
		20 and 21

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A. First reduce the figures to final size for publication.

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B. Use ruler and measure figure to fit 1 or 2 column wide format.

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C. Then use a ruler to check the height of each figure (including title & caption).

1-column fig. = up to 3.5 in.(88.9mm) wide by:	**2-column fig. = 3.5 to 7 in.(88.9 to 177.8 mm) wide by:**
up to 2.5 in.(63.5mm) high = 158 word equiv.	up to 2.5 in.(63.5mm) high = 315 word equiv.
up to 5 in.(127mm) high = 315 word equiv.	up to 5 in.(127mm) high = 630 word equiv.
up to 7 in.(177.8mm) high = 473 word equiv.	up to 7 in.(177.8mm) high = 945 word equiv.
up to 9 in.(228.6mm) high = 630 word equiv.	up to 9 in.(228.6mm) high = 1260 word equiv.

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Ref.: Ms. No. HYENG-7789
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