Institutionen för vattenbyggnad
Chalmers Tekniska Högskola

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SEDIMENT TRANSPORT IN PIPE CHANNELS

Postdoctoral experimental studies

December 1991 - April 1992

Gustavo Perrusquía

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ABSTRACT

In a previous publication the author reported on an experimental study of the transport of sediment in a part-full pipe with a permanent deposit. Relationships to estimate both flow resistance and bedload transport were then proposed and further experimental work was recommended, specially to cover those cases when the water depth exceeds the half-full condition. A new experimental series has been carried out for the cases when both water discharge and sediment transport rates are considerably larger than in previous experimental studies. It was found that the trajectories of the original curves remain practically unchanged and that both of the aformentioned relationships do not change significantly after adding the new experimental points. The new relationships can be applied even for the increased discharge-transport values.

KEYWORDS

Bedforms; Bedload; Flow resistance; Pipe channels; Sediment transport; Storm sewers; Stream traction.

PREFACE

In the Fall 1991, I presented the defense of my doctoral thesis whose title is: "Bedload Transport in Storm Sewers". The project was finansed by The Swedish Council for Building Research and Chalmers University of Technology supported me through a graduate research assistanship.

In my doctoral thesis, I proposed relationships for flow resistance and bedload transport computation in sewers with a sediment bed under steady flow conditions. I also emphasized the need for further experimental work, specially to cover those cases when the water depth exceeds the half-full condition, i.e. when the hydraulic section is not "trapezoidal" but adopts a "concave" form. In order to improve the aforementioned relationships to be applicable for a wider validity range, I carried out a new series of experiments during the spring 1992. Funds have been provided by The Swedish Council for Building Research and I gratefully acknowledge its support.

The analysis of sediment transport in sewer networks demands a dynamic approach similar to that used in flow analysis. MOUSE is a program system for the computation and analysis of sewer and drainage systems. It was developed by the Danish Hydraulic Institute and is widely used in Sweden. However, it does not have a sediment transport model to describe the effects of sediment in sewers. It is therefore desirable to implement a computer model that takes into account fluctuations in both flow and sediment conditions. A new project has been started at the Department of Civil Engineering at the University of Aalborg in Denmark, to develop such a model. I participate in the project and one of my tasks is to do the experimental work for the verification of the model. The results from the present study are to be used for that purpose, in addition to the objective mentioned above regarding the improvement of my own relationships.

The measurements at the laboratory could not have been possible without the help from my colleagues Bengt Carlsson, Karl-Oskar Djärv and Lars-Ove Sörman. Professor Lars Bergdahl and Dr. Sven Lyngfelt have given me invaluable support for the continuation of my research activities.

Göteborg, September 1992 Gustavo Perrusquía

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1 INTRODUCTION

The erosion and sedimentation of sediment in sewers, though a relatively new subject, has been widely studied in both the field and the laboratory, mainly in Western Europe. Field studies are quite useful since they provide a real-world picture of what actually happens underground. However, the information that comes out of such studies becomes too complicated to handle in a simulation model since the variety of data is only good for the records but not for a detailed description of the process.

It is then we discover that laboratory studies are still necessary to identify the different elements that are involved in the process. A partial list of the activity in the laboratory that is currently going on in this area at universities and research institutes is presented in Table 1.

TABLE 1 Research on Sediment in Sewers in the laboratory. (Partial list)

Country and Institution	Type of Research
Belgium	
State University of Gent	Cohesive and non-cohesive sediments in a cylindrical flume
University of Liège	Behaviour of sediments in manholes
Catholique Univ. of Leuven	Cohesive and non-cohesive sediment transport in unsteady flow
Denmark	
Aalborg University	Cohesive sediment transport
Holland	
Delft Univ. of Technology	Sediment transport in circular sewers with non-cohesive deposits
Sweden	
Chalmers Univ. of Technol.	Bedload transport in storm sewers
United Kingdom	
University of Newcastle	The influence of cohesion on sediment movement in pipe channels
Hydraulics Research Ltd.	Non-cohesive flume traction in sewers

In previous publications, the author has reported on experimental studies of: 1) flow capacity of sewers with plane, stable sediment beds (Perrusquía *et al.*, 1987), 2) flow resistance in sewers with erodible sediment beds (Perrusquía, 1990A) and 3) sediment transport in sewers with a permanent deposit (Perrusquía, 1991). The results of this work was the first known relationship for sediment transport for an alluvial bed in a sewer. However, most of the experiments were done for water levels up to the half-full condition ("trapezoidal" hydraulic section). To verify the validity of this relationship for higher water levels ("concave" hydraulic section), a new series of experiments was carried out. Both the water discharge and the sediment transport rates were considerably larger than in previous experimental studies.

The purpose of this report is to present the results of the experiments and to investigate whether the transition from "trapezoidal" to "concave" hydraulic section produces shape effects that may modify the form of the original relationship.

2 DESCRIPTION OF THE EXPERIMENTAL STUDIES

The experiments were carried out at the Department of Hydraulics, Chalmers University of Technology, Göteborg, Sweden, during the spring 1992. They were conducted in a concrete pipe 225 mm in diameter and 23 m long. Two sand sizes, 0.9 mm and 2.5 mm, were used. Two sediment bed thicknesses, 45 mm and 90 mm, were tested. Pipe slopes ranged from 0.002 to 0.006. The sediment bed was permanently deposited (not fixed) and the type of transport observed and measured was bedload transport exclusively. A complete description of the apparatus, the instruments and the experimental procedures is published elsewhere (Perrusquía, 1991). The experiments were run under uniform flow conditions. Flow depths, flow discharge rates, flow velocities, sediment supply rates, sediment transport rates and bedform dimensions were measured. The reproducibility of the runs was tested in a few cases and was found satisfactory.

3 ANALYSIS OF THE EXPERIMENTAL RESULTS

The majority of studies on sediment transport have been done in alluvial channels. However, the hydraulic principles upon which they are based can still be applied to the case of part-full pipes with a sediment bed subject to stream traction. Two basic concepts are treated in this report: 1) flow resistance and sediment transport. Both are discussed below together with the main results from the present study.

3.1 New Results Compared With Previous Studies

The experimental data range is summarized in Table 1. A more detailed description is included in Appendix I. The parameters used in the computations were found from the expressions listed in Appendix II.

TABLE 1 Range of the Experimental Data

Run No.	Pipe Slope S	Sand Size D_{50} (mm)	Sand Bed Thickness t (mm)	Flow Depth Y (mm)	Flow + Sediment Depth / Pipe Diameter (Y+t)/D‡
1	$2x10^{-3}$	0.90	45	67.5	0.50
2	"	"	"	113	0.70
3	$3x10^{-3}$	"	"	75.0	0.53
4	"	"	"	85.5	0.58
5	"	2.50	"	90.0	0.60
6	"	"	"	111	0.70
7	"	"	"	132.5	0.79
8	$4x10^{-3}$	"	"	90.0	0.60
9	"	"	"	106	0.67
10	"	"	"	122	0.74

‡Pipe Diameter, D = 225 mm

The experiments carried out between January 1989 and June 1990 are referred to as *PhD Thesis series* while those carried out during the spring 1992 are referred to as *Postdoctoral series*. The experiments corresponding to the latter series were identified, except for run 1, in the hydraulically rough flow regime. This is illustrated in Fig. 1 where the former series was also included.

To compare the new findings with the results from previous studies, the bed mobility number, Θ_b, was plotted against the transport parameter, Φ_b. This type of representation (Θ_b vs. Φ_b) was chosen because it is well known that shear stress (the bed mobility number is a dimensionless shear stress parameter) plays an important role in the mechanics of sediment transport. The plots of Θ_b vs. Φ_b are shown in Figs. 2 to 9 and are classified according to pipe slope, sand size, sediment thickness as well as hydraulic section.

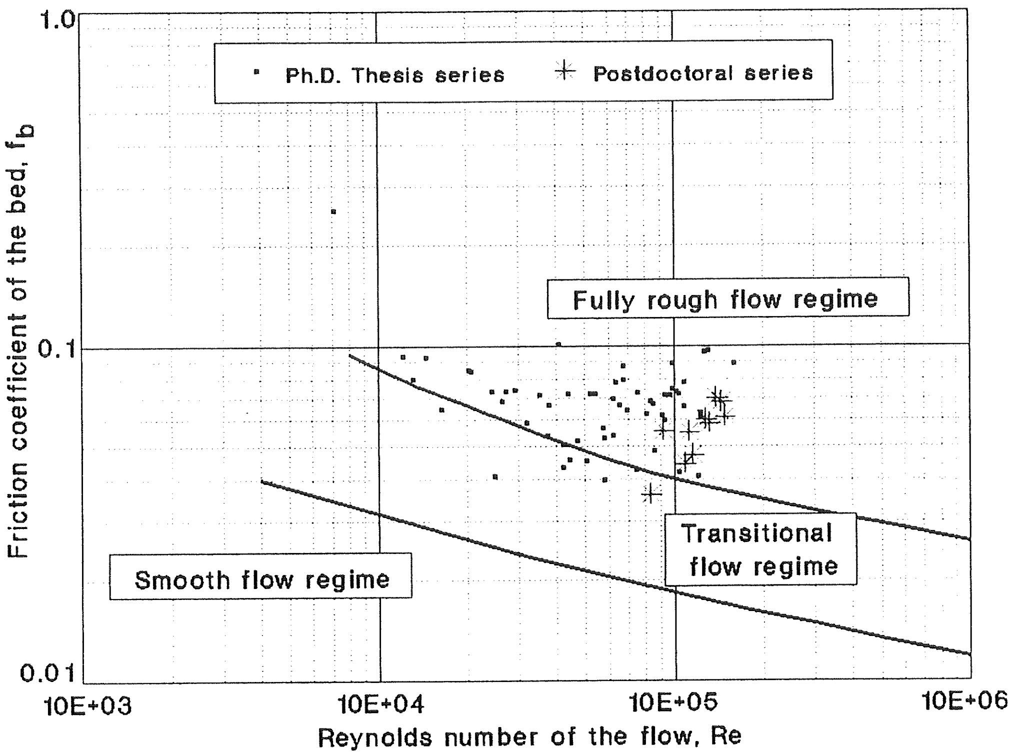
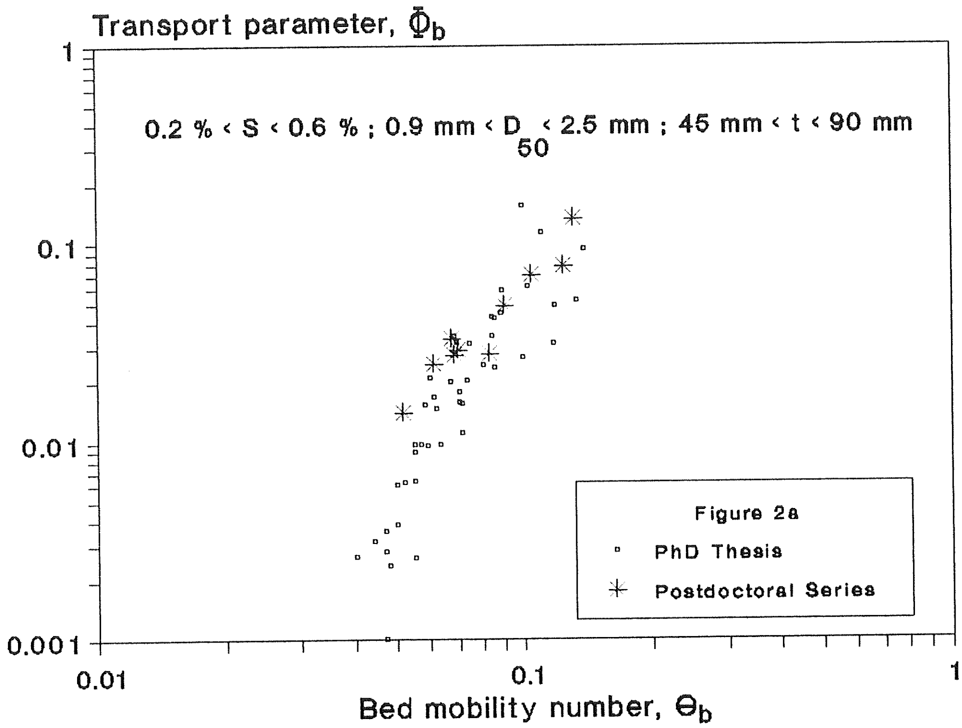


Fig. 1 Location of experiments according to flow regime

The total experimental range was $0.2\% < S < 0.6\%$, for pipe slope; 0.9 mm $< D_{50} < 2.5$ mm, for sand size; and 45 mm $< t < 90$ mm, for sediment thickness. A summary (for the total experimental range) of both the PhD and Postdoctoral series is shown in Fig. 2a, while in Fig. 2b the runs were classified in groups according to their hydraulic section being trapezoidal $[(Y+t) \leq D/2]$ or concave $[(Y+t) > D/2]$. The runs were separated into trapezoidal and concave hydraulic sections in Figs. 3a and 3b respectively, to better appreciate whether different paths could be detected depending on the shape of the hydraulic section. The sediment thickness, $t = 45$ mm was chosen as a common parameter in Figs. 4a and 4b, where the runs were classified according to sand size and pipe slope. In Fig. 5a the runs were divided according to the shape of the hydraulic section, while in Fig. 5b they were grouped using a common symbol. No figures for $t = 90$ mm are shown since the Postdoctoral series did not include experiments with that sediment thickness. Fig. 2a was redrawn as Fig. 6a using a common symbol and the results from the Newcastle studies (Perrusquía, 1990B) were included in Fig. 6b for comparison.

In summary, no apparent path or trend in the Θ_b vs. Φ_b plots was detected as far as the shape of the hydraulic section is concerned. However, these plots form the basis for the transport formula which is presented later in this report.



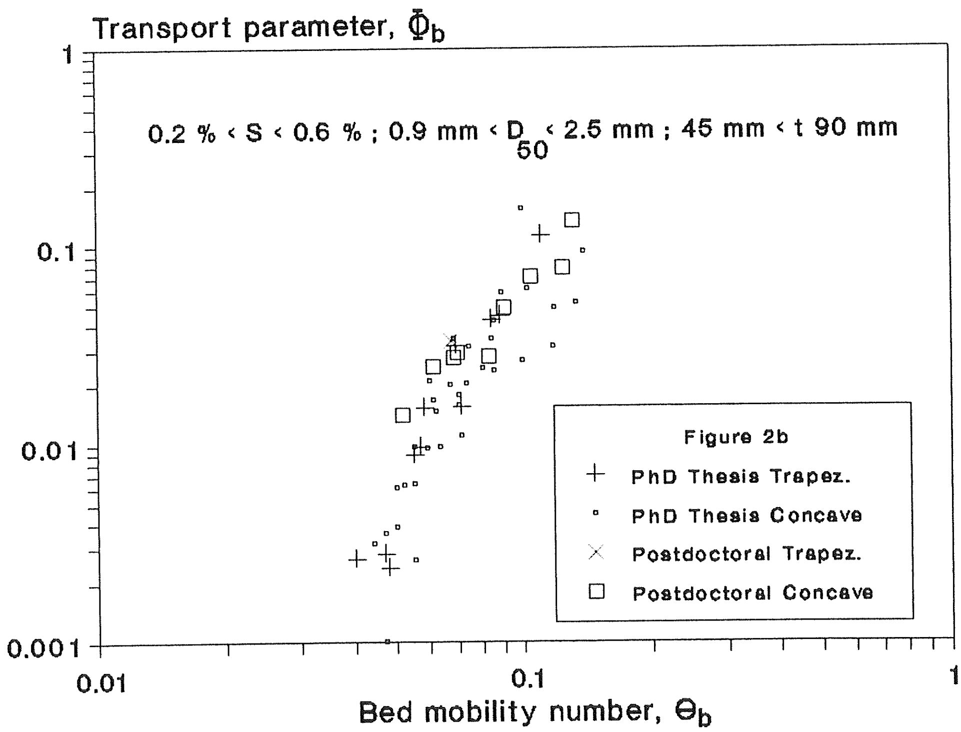
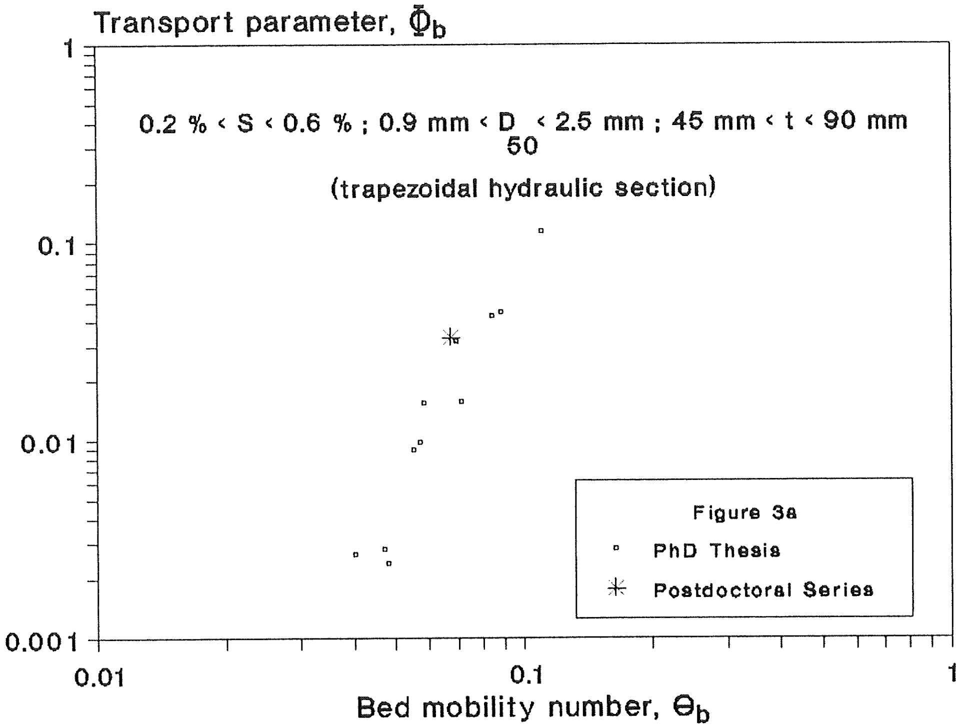


Fig. 2 Plot of Θ_b vs. Φ_b: (a) by series; and (b) by hydraulic section



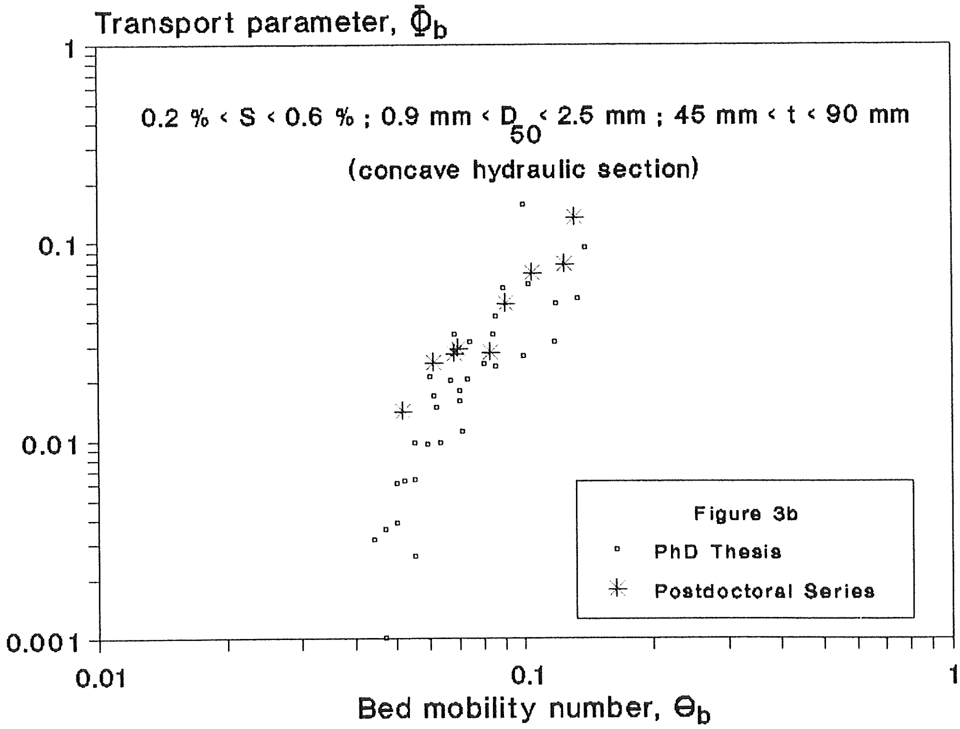
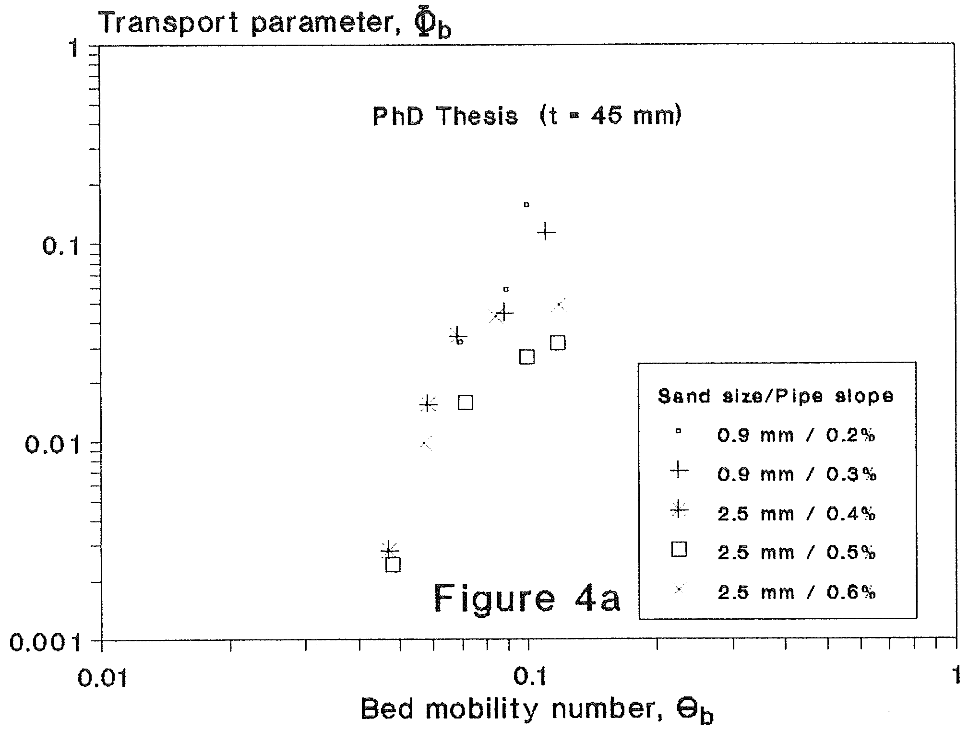


Fig. 3 Plot of Θ_b vs. Φ_b by hydraulic section: (a) trapezoidal; and (b) concave



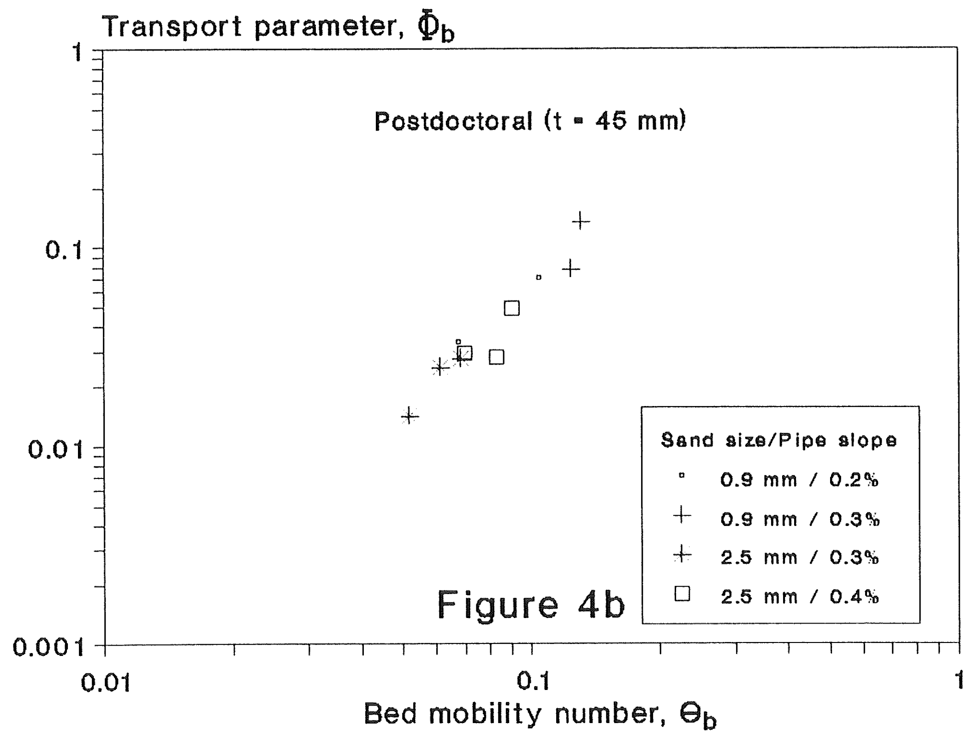


Fig. 4 Plot of Θ_b vs. Φ_b by sediment thickness: (a) PhD Thesis; and (b) Postdoctoral

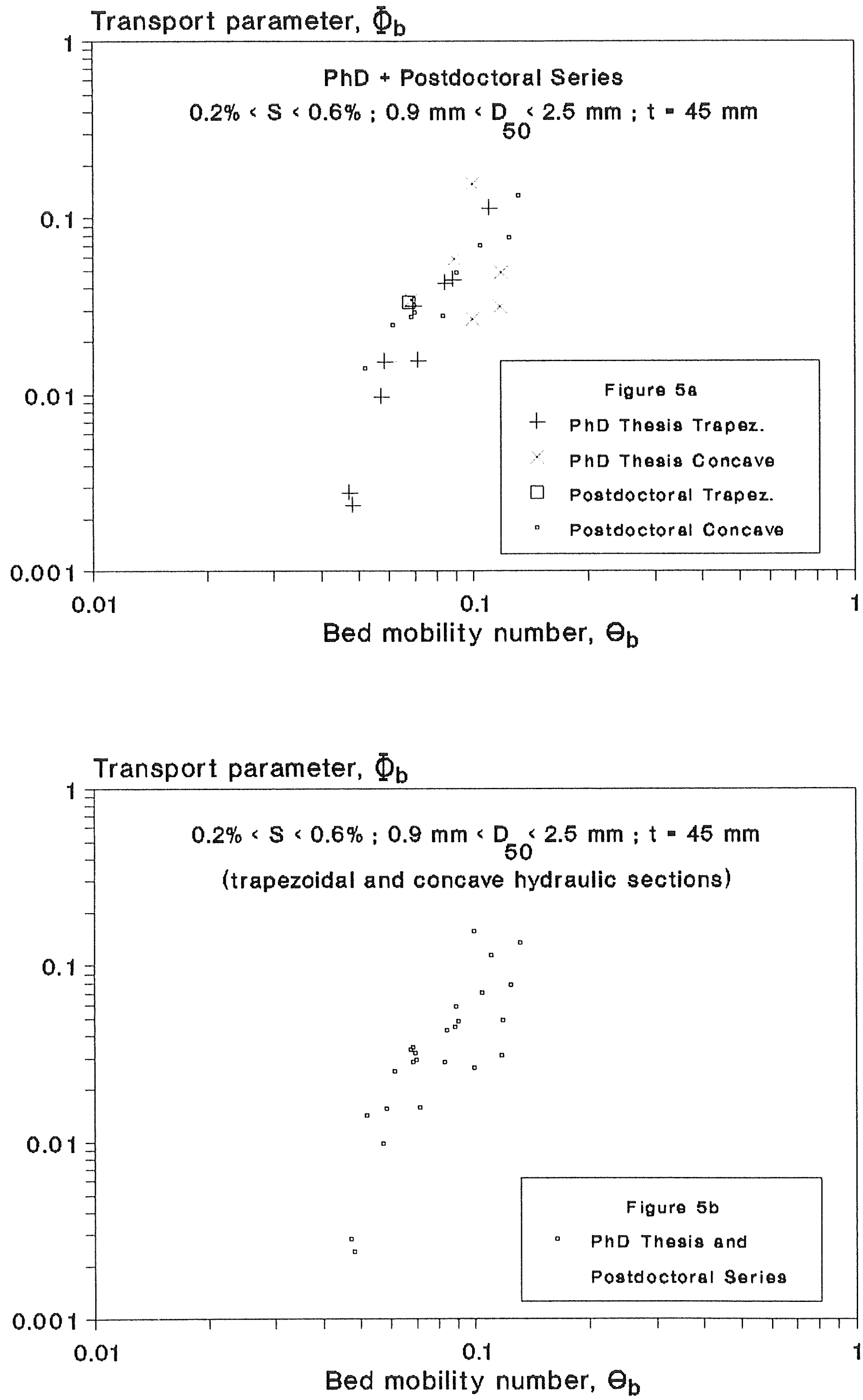
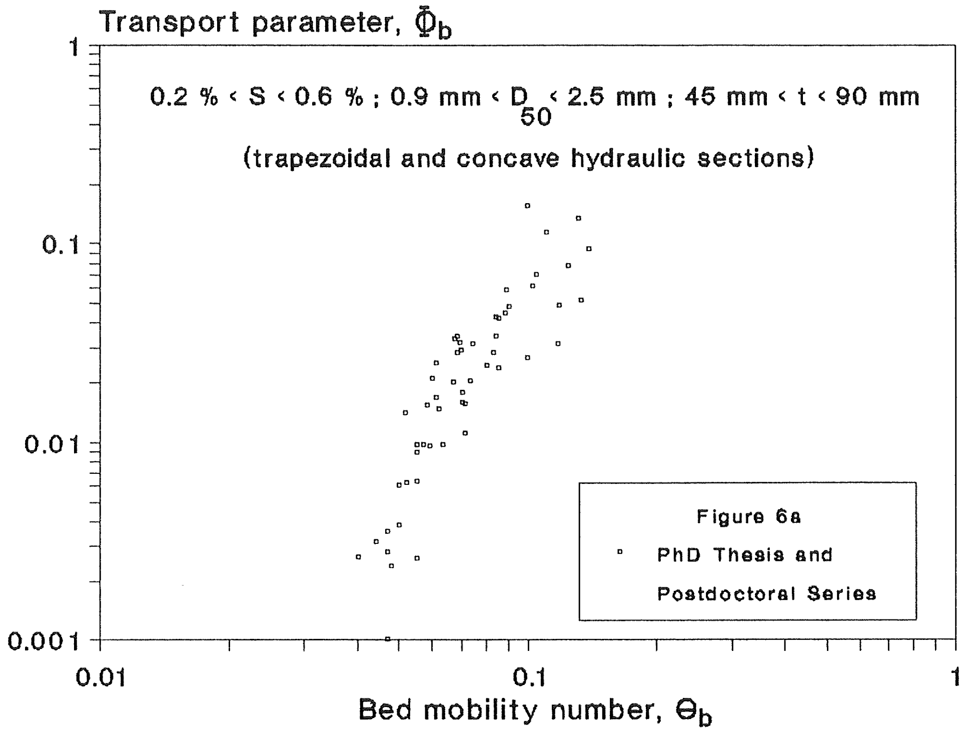


Fig. 5 Plot of Θ_b vs. Φ_b by sediment thickness: (a) hydraulic section; and (b) series



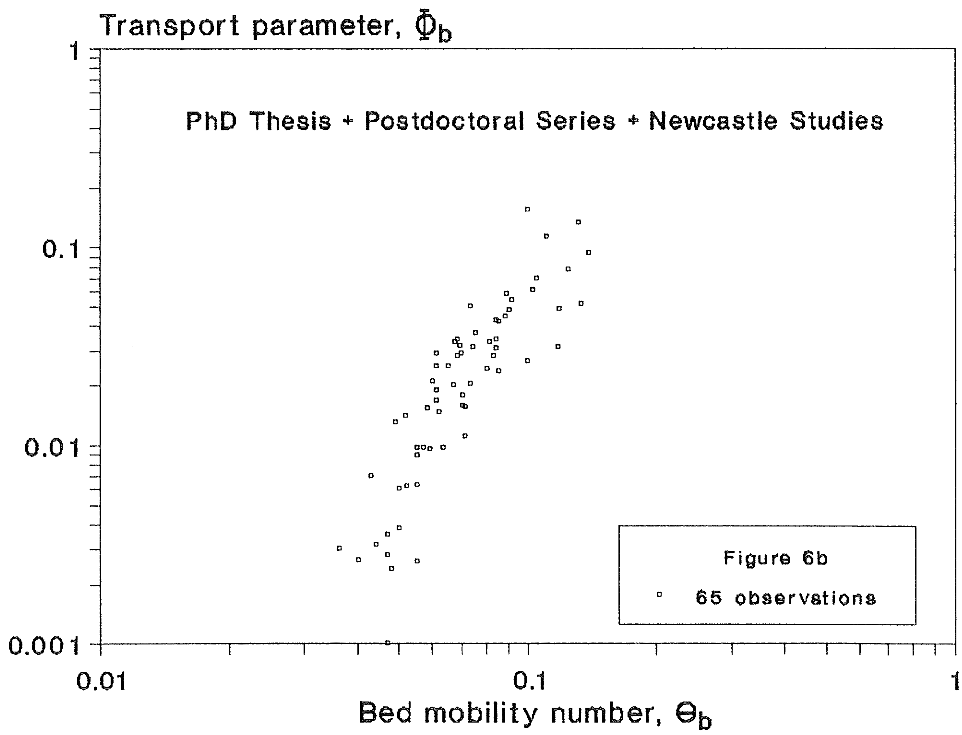


Fig. 6 Plot of Θ_b vs. Φ_b by series: (a) PhD + Postdoctoral; and (b) + Newcastle

3.2 Flow Resistance Estimation

A design method for flow resistance estimation was proposed by the author in a previous report (Perrusquía, 1991). The results from the present report were included in the analysis and it was found that the original expression does not change significantly. This is shown in Fig. 7 where Eq. (1) has the form:

$$\Theta_b/\Theta_c = 1.5 + 3.58\ \mathrm{Ln}\ (\Theta_b'/\Theta_c) \tag{1}$$

in which Θ_b' is the grain mobility number and Θ_c is the critical mobility number. Both parameters are thoroughly defined in Appendix II.

Seventy-seven percent of the observed Θ_b/Θ_c ratios are within ± 25% of the estimated Θ_b'/Θ_c ratios which shows that this is a fairly good way of estimating the grain mobility number, Θ_b'.

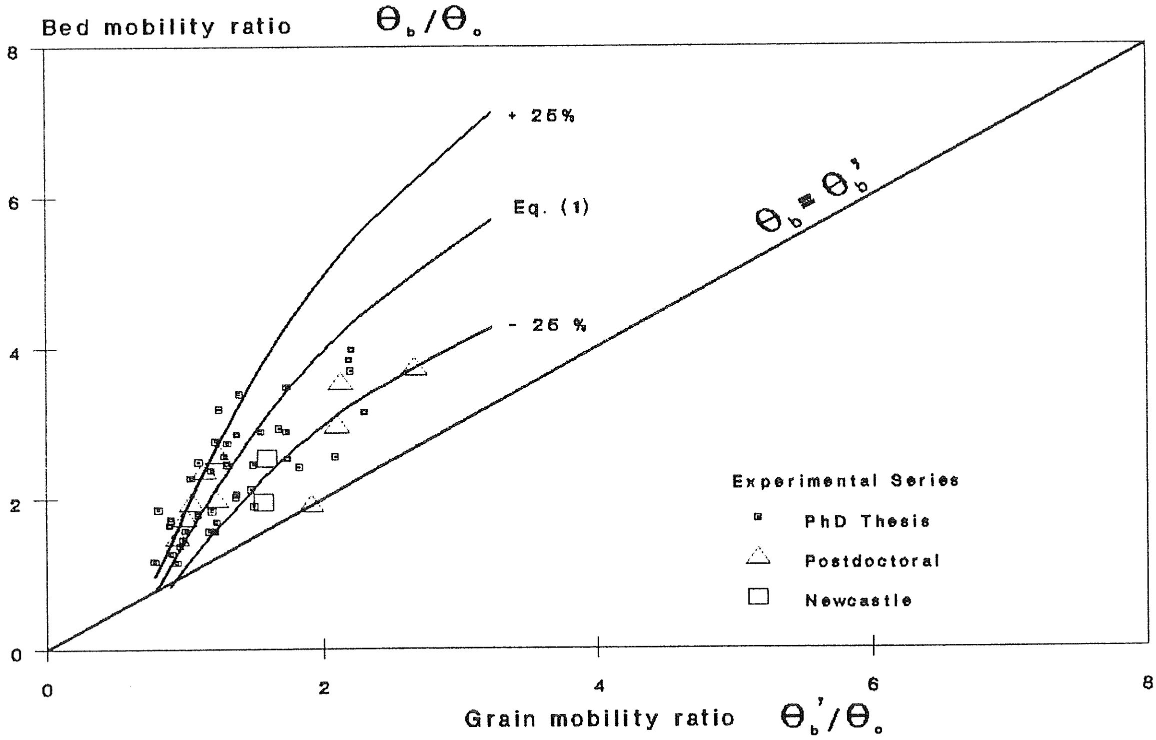


Fig. 7 Grain mobility as a function of bed mobility

3.3 Sediment Transport Formula

Likewise, the sediment transport formula, which was proposed by the author in a previous report (Perrusquía, 1991), was updated by including the results from the Postdoctoral series. Dimensional analysis was used to find functional relationships for bedload transport in pipe channels with a deposited bed. The experimental results were fitted to those relationships by using regression analysis.

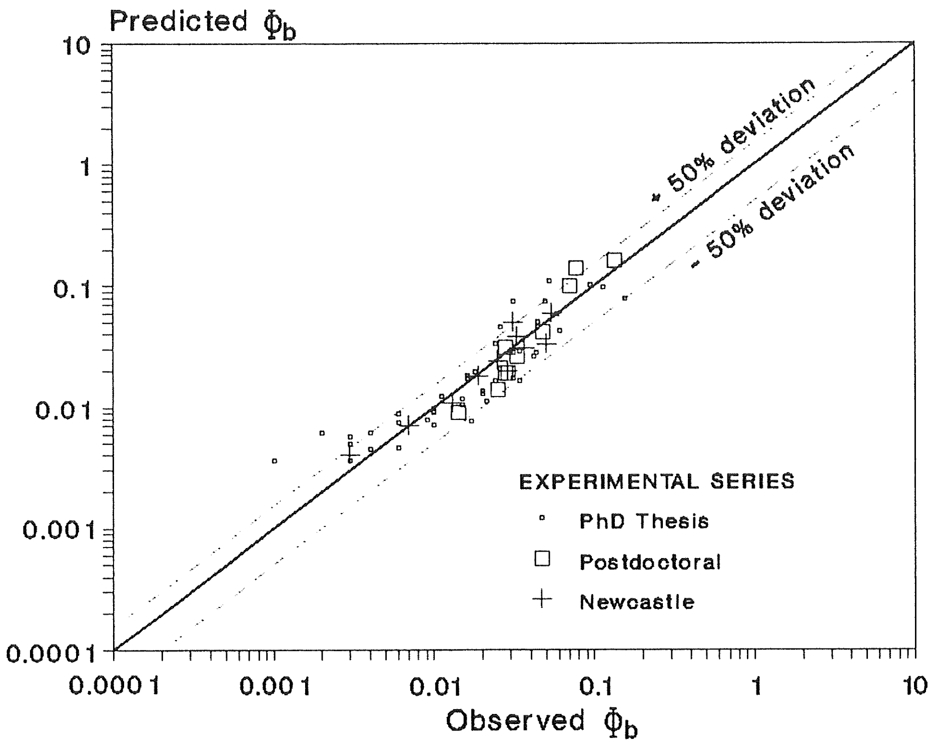


Fig. 8 Agreement of sediment transport formula

The new formula for the prediction of sediment transport has the form:

$$\Phi_b = 3.4x10^3 \, \Theta_b^{2.6} \, D_*^{-0.96} \, Z^{0.47} \, Y_r^{0.66} \, t_r^{-0.70} \qquad (2)$$

in which the dimensionless variables are: $Z = D_{50}/Y$, relative flow depth, $Y_r = Y/D$, relative bed thickness, $t_r = t/D$, and D_* is a particle number (Appendix II).

The value of the adjusted coefficient of determination was 0.85, which gives an idea of the accuracy in the prediction of sediment transport rates. This is illustrated in Fig. 8 where almost ninety percent of the predictions are within ± 50% of the observed values.

4 DISCUSSION AND CONCLUSIONS

The complementary series of experiments presented in this report was intended to check whether a "concave" hydraulic section, i.e. (Y+t)/D, affects the flow conditions so drastically that both the original flow resistance estimation and sediment transport formula need major changes. The significance of individual parameters such as sediment thickness, t, sand size, D_{50}, and pipe slope, S, was also investigated. Looking at Figs. 2 to 6, one can see that there is no apparent indication that any of these parameters have a decisive influence on transport.

Likewise, the bed mobility number, Θ_b, was selected as an appropriate parameter to describe the sediment transport process. This means that Θ_b is very significant but not sufficient even though several authors have used it (exclusively) in their equations to predict sediment transport rates.

This last asseveration is based on the fact that the aforementioned equations are all applicable to wide alluvial channels. Conditions are quite different in sewer pipes and geometric factors (including both relative flow and sediment depths) are also important.

The main conclusions can be listed as follows:

1) The original relationships to estimate flow resistance and sediment transport do not change significantly after adding the new experiments.
2) There is no indication that the sediment transport formula should be adjusted depending on the shape of the hydraulic section. However, both the flow depth and sediment thickness play an important role in the configuration of this formula.
3) The main contribution from these series of experiments is that both of the aforementioned relationships are the first attempt to provide engineers with a method that directly applies to the present case, namely bedload transport in storm sewers with a deposited sediment bed or "stream traction" in pipe channels.
4) Experimental data from other sources are needed to further develop the structure of the equations presented in this report. There is a lot more to say about this type of sediment motion. It took almost twenty years of research in the field of "flume traction" in pipes to develop formulas such as those proposed by Novak and Nalluri (1972 and 1975), based on a single parameter, May (1982 and 1989), based on a semi-theoretical approach, and Mayerle (1988), based on multiple regression.

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APPENDIX I

Experimental Data

Postdoctoral Series   Experiments with a permanent deposit

Run number	Invert slope	Sand size	Sediment thickness	Sediment width	Flow Discharge	Flow depth	Total depth
		m	m	m	m3 / s	m	m
	S	D50	t	Pb	Q	y	Y = y + t
1	0.002	0.0009	0.045	0.180	0.00677	0.0675	0.1125
2	0.002	0.0009	0.045	0.180	0.01290	0.1130	0.1580
3	0.003	0.0009	0.045	0.180	0.00825	0.0750	0.1200
4	0.003	0.0009	0.045	0.180	0.01070	0.0855	0.1305
5	0.003	0.0025	0.045	0.180	0.01070	0.0900	0.1350
6	0.003	0.0025	0.045	0.180	0.01400	0.1110	0.1560
7	0.003	0.0025	0.045	0.180	0.01720	0.1325	0.1775
8	0.004	0.0025	0.045	0.180	0.01220	0.0900	0.1350
9	0.004	0.0025	0.045	0.180	0.01432	0.1060	0.1510
10	0.004	0.0025	0.045	0.180	0.01737	0.1220	0.1670

Postdoctoral Series Experiments with a permanent deposit

Run number	Transport rate samples	Mean transport rate	Mean rate of supply	Area water & sediment	Area sediment	Hydraulic area
	g / min	g / min	g / min	m2	m2	m2
	Tb	Tb				A
1	122, 106, 80.5	103	106	0.020	0.006	0.014
2	231, 160, 307, 166.5	216	206	0.030	0.006	0.024
3	211, 253, 237, 254	239	247	0.022	0.006	0.016
4	386, 440, 412, 554	413	412	0.024	0.006	0.018
5	202, 215, 187, 203	202	183	0.025	0.006	0.019
6	200, 413, 442	352	363	0.029	0.006	0.024
7	412, 340, 435	396	398	0.034	0.006	0.028
8	468, 451, 373, 411, 409	420	390	0.025	0.006	0.019
9	506, 329, 418, 314	400	396	0.028	0.006	0.023
10	718, 706, 685, 675	697	741	0.032	0.006	0.026

Postdoctoral Series   Experiments with a permanent deposit

Run number	Walls wetted perim	Bed wetted perim	Total Wetted perimeter	Water width	Hydraulic radius	Mean depth	Flow velocity
	m	m	m	m	m	m	m / s
	Pw	Pb	P	B	R	M	V
1	0.145	0.180	0.325	0.225	0.044	0.063	0.476
2	0.238	0.180	0.418	0.206	0.058	0.117	0.534
3	0.160	0.180	0.340	0.224	0.047	0.071	0.519
4	0.181	0.180	0.361	0.222	0.051	0.082	0.586
5	0.190	0.180	0.370	0.220	0.052	0.087	0.556
6	0.234	0.180	0.414	0.207	0.057	0.114	0.589
7	0.283	0.180	0.463	0.184	0.060	0.152	0.615
8	0.190	0.180	0.370	0.220	0.052	0.087	0.634
9	0.223	0.180	0.403	0.211	0.056	0.107	0.631
10	0.259	0.180	0.439	0.197	0.059	0.132	0.668

Postdoctoral Series Experiments with a permanent deposit

Run number	Froude number	Water temp	Kinematic viscosity	Reynolds number	Equiv Manning coeff	Einstein Manning coeff BED	Horton Manning coeff BED
		° C	m2 / s				
	Fr	Tw	v	Re	ne	nbE	nbH
1	0.60	20	1.00E-06	83378	0.0117	0.0127	0.0127
2	0.50	15	1.14E-06	108163	0.0125	0.0150	0.0152
3	0.62	18	1.06E-06	91619	0.0137	0.0162	0.0164
4	0.65	19	1.03E-06	115124	0.0128	0.0149	0.0150
5	0.60	19	1.03E-06	112278	0.0137	0.0166	0.0169
6	0.56	18	1.06E-06	127573	0.0138	0.0174	0.0178
7	0.50	20	1.00E-06	148472	0.0137	0.0178	0.0184
8	0.68	20	1.00E-06	131859	0.0139	0.0169	0.0173
9	0.61	19	1.03E-06	137866	0.0147	0.0188	0.0194
10	0.59	16	1.10E-06	144020	0.0144	0.0187	0.0194

Postdoctoral Series   Experiments with a permanent deposit

Run number	Hydraulic radius BED	Mobility number	Particle Reynolds number	Sediment transport rate	Volume sediment concent	Unit sediment transport rate	Sediment transport rate
	m			kg / s	ppm	g/min m	m3 / s
	Rb	Θb	Re *	Tb	Cv	qb	Qb
1	0.050	0.0671	28.1	0.0017	96	572	6.48E-07
2	0.077	0.1040	30.7	0.0036	105	1200	1.36E-06
3	0.061	0.1239	36.1	0.0040	182	1328	1.50E-06
4	0.065	0.1305	38.1	0.0069	243	2294	2.60E-06
5	0.071	0.0518	111.1	0.0034	119	1122	1.27E-06
6	0.084	0.0611	117.3	0.0059	158	1956	2.21E-06
7	0.094	0.0681	131.2	0.0066	145	2200	2.49E-06
8	0.072	0.0697	132.8	0.0070	217	2333	2.64E-06
9	0.085	0.0827	140.4	0.0067	176	2222	2.52E-06
10	0.093	0.0899	137.1	0.0116	252	3872	4.38E-06

Postdoctoral Series Experiments with a permanent deposit

Run number	Unit sediment transport rate m3/s m	Transport parameter	Bedform dimension Height mm	Length mm	Grain friction coeff Directly computed	Bedform friction coeff (fb - fb')	Bed friction coeff Sediment program
	qb	Φb	H	L	fb'	fb''	fb
1	3.60E-06	0.0331	8.7	430	0.0412	-0.0053	0.0359
2	7.55E-06	0.0695	13.0	367	0.0354	0.0091	0.0445
3	8.35E-06	0.0769	7.9	284	0.0383	0.0172	0.0555
4	1.44E-05	0.1328	13.0	357	0.0376	0.0097	0.0473
5	7.06E-06	0.0140	---	---	0.0530	0.0020	0.0550
6	1.23E-05	0.0245	6.5	642	0.0496	0.0108	0.0604
7	1.38E-05	0.0275	8.5	481	0.0476	0.0139	0.0615
8	1.47E-05	0.0292	6.7	500	0.0528	0.0058	0.0586
9	1.40E-05	0.0278	10.0	550	0.0493	0.0208	0.0701
10	2.44E-05	0.0484	10.6	605	0.0478	0.0205	0.0682

Postdoctoral Series Experiments with a permanent deposit

Run number	Equiv grain rough Directly m	Equiv bedform rough (kb - kb') m	Equiv bed roughness Sediment program m	Grain shear stress Directly N / m2	Bedform shear stress (Tb - Tb') N / m2	Bed shear stress Directly N / m2	Grain mobility number Lau's
	kb' (2.5 D50)	kb"	kb	Tb'	Tb"	Tb	Θb'
1	0.0023	0.0000	0.0017	0.9798	0.0000	0.9768	0.0673
2	0.0023	0.0028	0.0050	1.0752	0.4391	1.5144	0.0738
3	0.0023	0.0048	0.0070	1.0875	0.7171	1.8046	0.0747
4	0.0023	0.0028	0.0050	1.3592	0.5421	1.9013	0.0933
5	0.0063	0.0018	0.0080	1.6420	0.4545	2.0965	0.0406
6	0.0063	0.0058	0.0120	1.7392	0.7330	2.4722	0.0430
7	0.0063	0.0078	0.0140	1.8225	0.9322	2.7547	0.0450
8	0.0063	0.0033	0.0095	2.1297	0.6920	2.8217	0.0526
9	0.0063	0.0108	0.0170	1.9815	1.3667	3.3482	0.0490
10	0.0063	0.0113	0.0175	2.1626	1.4769	3.6395	0.0534

Postdoctoral Series **Experiments with a permanent deposit**

Run number	Bedform mobility number (Ob - Ob')	Mobility number Directly	Bed shear stress ratio Directly	Effective shear stress ratio Lau's	Total excess shear Directly	Effective excess shear Lau's	Migration velocity m / s
	$\theta b''$	θb	$\theta b / \theta c$	$\theta b' / \theta c$	$\theta b - \theta c$	$\theta b' - \theta c$	
1	0.0000	0.0671	1.92	1.92	0.0321	0.0323	0.0170
2	0.0301	0.1040	2.97	2.11	0.0690	0.0388	---
3	0.0492	0.1239	3.54	2.13	0.0889	0.0397	---
4	0.0372	0.1305	3.73	2.67	0.0955	0.0583	0.0056
5	0.0112	0.0518	1.48	0.94	0.0088	0.0000	---
6	0.0181	0.0611	1.75	1.00	0.0181	0.0000	---
7	0.0230	0.0681	1.94	1.05	0.0251	0.0020	---
8	0.0171	0.0697	1.99	1.22	0.0267	0.0096	0.0021
9	0.0338	0.0827	2.36	1.14	0.0397	0.0060	---
10	0.0365	0.0899	2.57	1.24	0.0469	0.0104	---

Postdoctoral Series — Experiments with a permanent deposit

Run number	Trapezoidal or concave cross section	No transport or movable plane bed or movable bedforms	Transport and / or profile measurements	Date of run	Date of profile measure
1	Trapezoidal	Bed forms	Transport and profile	92-02-13	92-02-14
2	Concave	Bed forms	Transport and profile	92-02-18	92-02-21
3	Concave	Bed forms	Transport and profile	92-03-12	92-03-17
4	Concave	Bed forms	Transport and profile	92-03-19	92-03-20
5	Concave	Ondulated bed surface	Transport	92-03-25	---
6	Concave	Bed forms	Transport and profile	92-03-31	92-04-02
7	Concave	Bed forms	Transport and profile	92-04-03	92-04-07
8	Concave	Bed forms	Transport and profile	92-04-13	92-04-14
9	Concave	Bed forms	Transport and profile	92-04-15	92-04-15
10	Concave	Bed forms	Transport and profile	92-04-23	92-04-24

APPENDIX II

Calculation of Parameters

Grain Reynolds number:

$$Re_* = \frac{u_* \, D_{50}}{\nu}$$

in which $u_* = \sqrt{\tau_b/\rho}$ = shear velocity; τ_b = shear stress; ρ = density of water; D_{50} = particle diameter of bed material 50% being finer; and ν = kinematic viscosity of water.

Average velocity in a vertical profile:

$$\frac{V}{u_*} = 5.75 \log\left[10^{(B/5.75)}\left[\frac{R_b}{2.5\ k_b}\right]\right] \qquad \text{transitional flow}$$

$$\frac{V}{u_*} = 5.75 \log\left[12\,\frac{R_b}{k_b}\right] \qquad \text{rough flow}$$

in which V = mean flow velocity; B = roughness function in terms of Re_* which has a value of 8.5 for hydraulically rough flow ($Re_* > 70$); R_b = hydraulic radius corresponding to the sediment bed; and k_b = equivalent sand roughness of the bed.

Velocity-defect relationship:

$$\frac{u_{max} - u}{u_*} = 5.75 \log\left[\frac{y_{max}}{y}\right]$$

in which u = local flow velocity at a height y above the sediment bed.

Side wall elimination using Manning's equation. Manning's equation for both side walls and sediment bed:

$$V = \frac{1}{n_w} R_w^{\frac{2}{3}} S^{\frac{1}{2}} \qquad \text{side wall}$$

$$V = \frac{1}{n_b} R_b^{\frac{2}{3}} S^{\frac{1}{2}} \qquad \text{sediment bed}$$

in which A = total hydraulic area; n = Manning's roughness coefficient; P = wetted perimeter; R = hydraulic radius; S = energy slope; and subscripts w and b denote wall and bed components respectively.

Side wall elimination using Darcy-Weisbach's equation. Friction factor using the Colebrook-White equation:

$$f^{-\frac{1}{2}} = -2 \log\left[\frac{k_s}{14.8\ R} + \frac{2.51\ \nu}{R\sqrt{128\, g\, R\, S}}\right]$$

in which g = acceleration due to gravity; and k_s = equivalent sand roughness.

Bed shear stress:

$$\tau_b = \rho \, g \, R_b \, S$$

Volumetric concentration:

$$C_v = \frac{Q_b}{Q} \times 10^6$$

in which C_v = volumetric concentration in parts per million; Q = water discharge (the rate of fluid transport in volume per unit time).

Bed mobility number:

$$\Theta_b = \frac{\tau_b/\rho}{g(s-1)D_{50}} = \frac{R_b \, S}{(s-1)D_{50}}$$

in which Θ_b = dimensionless bed shear stress; and $s = \rho_s/\rho$ = relative density of the sediment; ρ_s being the density of sediment.

Bed mobility number as a total resistance:

$$\Theta_b = \Theta_b' + \Theta_b''$$

in which Θ_b' and Θ_b'' are the dimensionless shear stresses of the grain and bed-forms respectively.

Grain mobility number Θ_b':

$$\Theta_b' = \frac{(u_*')^2}{(s-1)g \, D_{50}}$$

in which u_*' = grain shear velocity.

Bedform mobility number:

$$\Theta_b'' = \frac{\tau_b''/\rho}{(s-1)g \, D_{50}}$$

in which τ_b'' = bedform shear stress.

Equivalent sand roughness of the bed:

$$k_b = k_b' + k_b''$$

in which the superscripts ' and " also relate to grain and bedform respectively.

Equivalent grain roughness:

$$k_b' = 2\ D_{50}$$

Dimensionless transport parameter:

$$\Phi_b = \frac{q_b}{\sqrt{g(s-1)D_{50}^3}}$$

in which q_b = sediment transport rate per unit width (Q_b/P_b).

Particle number:

$$D_* = D_{50}\left[\frac{(s-1)g}{\nu^2}\right]^{\frac{1}{3}}$$

Relative density:

$$s = \frac{\rho_s}{\rho}$$

Relative grain size:

$$Z = \frac{D_{50}}{Y}$$

Relative flow depth:

$$Y_r = \frac{Y}{D}$$

Relative bed thickness:

$$t_r = \frac{t}{D}$$

Relative pipe roughness:

$$k_r = \frac{D_{50}}{k_w}$$

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