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EXPERIMENTS ON ALLUVIAL FRICTION

By

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ABSTRACT

During the design of engineering works on rivers or canals it is frequently necessary to calculate the flow or sediment transport. To calculate these quantities the frictional energy-losses on the boundary of the channel must be determined. This is particularly difficult for alluvial channels as the frictional losses are related to the size and shape of the bed features such as dunes or ripples that are developed on the bed of the channel and these features vary as the flow varies. Frequently the flow and bed features are categorised as being in lower or upper regime, depending upon the nature of the bed features. Earlier work at HR resulted in the development of a method for predicting alluvial friction. This method, however, was not universally applicable to all flows since it could only be applied to flows in lower regime, that is, with plane bed, ripples or dunes.

Laboratory experiments are described in this report in which alluvial friction was measured for steady-state flows over sand beds. The observed bed forms are correlated with values of the dimensionless unit stream power. It is shown that the value of the dimensionless unit stream power can be used to determine the nature of the bed form and in particular whether the flow corresponds to upper or lower regime. The friction is analysed in terms of the White et al (1980) method for predicting alluvial friction and an extension of this method is suggested for flows in upper regime. This new method enables predictions to be made of alluvial friction for a much wider range of flows than previously. This greatly extends the range of conditions for which accurate calculations can be made of flow and sediment transport in alluvial channels.

CONTENTS

SYMBOLS

D	(m)	Grain diameter for uniform sediments
D_n	(m)	Grain diameter for which n% of the sample is finer
D_{gr}		Dimensionless grain size
d	(m)	Average depth of flow
F_{cg}		Dimensionless sediment mobility (coarse grains)
F_{gr}		Dimensionless sediment mobility
F_{fg}		Dimensionless sediment mobility (fine grains)
g	(ms^{-2})	Acceleration due to gravity
S		Water surface slope
s		Specific gravity of sediments (ρ_s/ρ)
U_E		Dimensionless unit stream power
V	(ms^{-1})	Velocity of flow
v_*	(ms^{-1})	Shear velocity $\sqrt{(gdS)}$
ν	(m^2s^{-1})	Kinematic viscosity of water
ρ	(kg m^{-3})	Density of water
ρ_s	(kg m^{-3})	Density of sediment

1 INTRODUCTION

To calculate the flow or sediment transport in an alluvial channel the frictional losses on the boundary of the channel must be determined. In response to this need a number of theories for predicting the frictional losses in alluvial channels have been developed (Einstein and Barbarossa, 1952; Engelund, 1966; Raudkivi, 1967 and White et al, 1980). Most of these theories are based on laboratory data. These laboratory experiments are almost invariably characterised by the use of narrow-graded clean sand, that is, sand with a small range of sizes from which both the larger sizes and any smaller silt or clay material has been removed. The finer silts and clays frequently show very different properties to those of sand since these materials demonstrate cohesive properties whereas sands are non-cohesive. In practical problems, however, it is rare that the sediments which are encountered are similar to the narrowly graded sands used in laboratory experiments. Much more frequently sediments are widely graded and contain varying quantities of silts and clays.

Recently laboratory experiments were carried out at HR to investigate the impact of introducing a proportion of fine silt and clay material into a sand bed (Bassi, 1985). The alluvial friction due to a sand bed was measured and then the experiment was repeated after the introduction of varying quantities of fine material. The results were analysed using an approach suggested by the work of White et al (1980) for sand beds. No discernible change was observed in the alluvial friction of the sand bed upon the introduction of the fine material, but somewhat more disturbingly, there was a discrepancy between the results for just the sand bed and the predictions of the White et al theory. The investigation of variations in friction caused by the introduction of silt and clay material is of doubtful value if there are still uncertainties as to the friction due to a uniform sand bed. It was therefore decided to carry out experiments to investigate further the friction due to a sand bed. The experiments described in this report were designed to provide more information on the alluvial friction due to sand beds and so act as a basis for comparison with experiments performed with sediments containing a mixture of sand and silt.

2 EXPERIMENTAL APPARATUS AND PROCEDURE

The experiments were performed in a 2.44m wide, 24m long, recirculating, tilting flume. The sediment bed was 16m in length. At the downstream end of the flume a tailgate was used to control the depth of flow.

A flat-V Crump Weir located 3m downstream of the tailgate was used to measure the discharge. The tapping point for measuring the head over the weir was 0.6m upstream from the weir crest.

The recirculating system consisted of two $0.113m^3s^{-1}$ and one $0.028m^3s^{-1}$ pumps. The entrances where the recirculating system returned the flow to the upstream end of the flume were proportioned to ensure the uniformity of the velocity distribution across the flume.

Water surface slope was measured using five tapping points located at 2.5m intervals along the flume. 8mm diameter plastic tubing connected the tapping points to 60mm diameter stilling pots. The gauged heads in the stilling pots were measured using vernier point gauges reading to 0.02mm. A similar arrangement was used to measure the head above the crest of the Crump weir.

A section of the flume had glass walls, this transparent section covering the central part of the sediment bed. The flow depth was measured at 6 points along this length on both sides of the flume. At each location the average bed level and water level were measured using a ruler attached to the wall.

The bed forms and their size were observed for each test. The velocity of the bed forms was measured for selected tests.

The grading curve of the sand used is shown in Fig 1. The D_{35} and D_{50} sizes were 0.21mm and 0.23mm, respectively.

A total of 31 tests were performed, the results of which are summarised in Table 1.

3 DATA SUMMARY

The average water surface slope was calculated from the measured water levels by using a least-squares linear regression. Two values of the slope were determined, the first from the three central levels only, the second using all 5 points. The second value was used for all calculations.

The average flow depth was calculated by averaging the six depths measured in the central part of the flume.

A summary of the measured data for the 31 tests is given in Table 1. For each test the following data is provided:

- flume slope
- average water surface slope, calculated using the 3 central water levels
- average water surface slope, calculated using all 5 measured levels

- average flow depth, in metres
- discharge, in litres per second
- average flow velocity, calculated from the measured discharge and mean cross section
- bed features
- temperature

4 DISCUSSION OF RESULTS

Following the work of White et al (1980) and Bassi (1985) the results were analysed in terms of the sediment mobility, F_{gr}, the ratio of the effective shear forces to the immersed weight of the particles. The mobility number was defined in such a way that only the relevant shear forces were used, that is, total shear for fine sediments, grain shear for coarse sediments and an intermediate value depending upon the dimensionless grain size for the transitional sediments.

The dimensionless grain size D_{gr} was defined by

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

where g is acceleration due to gravity
s is specific gravity of the sediment
ν is kinematic viscosity
and D is sediment diameter

The dimensionless sediment mobility was defined by

$$F_{gr} = \frac{v_*^{\,n}}{\sqrt{gD(s-1)}}\left[\frac{V}{\sqrt{(32)}\log_{10}(10d/D)}\right]^{1-n}$$

where v_* is the shear velocity
V is the average flow velocity
d is the depth
and n is an exponent which varies from 1.0 for fine sediments (D_{gr} = 1.0) to 0.0 for coarse sediments

(D_{gr} = 60). Thus for fine sediments

$$F_{fg} = \frac{v_*}{\sqrt{(gD(s-1))}}$$

and for coarse sediments

$$F_{cg} = \frac{V}{\sqrt{(gD(s-1))}\sqrt{(32)}\log_{10}(10d/D)}$$

Values of F_{fg} and F_{gr} are shown plotted in Figure 2, together with the equation given by White et al (1980). It can be seen that there are two distinct relationships, one for a flat bed, ripples and dunes, termed lower regime, and another relationship for the upper regime of plane bed and anti-dunes with a transition between the two curves. This leads to the postulation that the method for predicting alluvial friction described by White et al (1980) applies to the lower regime case and that the method could be extended to predict flows in the upper regime by the inclusion of a new relationship for the upper regime case.

The use of two different relationships, one for lower regime and one for upper regime was first suggested by Engelund (1966). Engelund plotted the dimensionless bed shear due to skin friction against the total dimensionless bed shear for a sequence of flume data, see Figure 3. He postulated two relationships, the lower regime curve for dunes, ripples being excluded from Engelund's analysis, while the upper regime curve applies to flat beds, standing waves and anti-dunes.

The development of equations to extend the White et al analysis to the upper regime case is explained in greater detail in White et al (in preparation).

A comparison of the present results with those from Bassi (1985) and Guy et al (1966) are shown in Figure

4. It can be seen that the present results and those of Bassi (1985) are close to each other but that they are both above those of Guy et al (1966) and the theoretical relationship of White et al (1980). In the upper regime the present data is also above that of Guy et al (1966).

The postulation of two different relationships for alluvial friction leads to the problem of determining, which is the appropriate relationship to use in particular circumstances. We have so far distinguished the lower and upper flow regimes by describing the bed features associated with them. It, therefore, seems reasonable that the method of determining the appropriate regime should be related to a method of determining the dominant bed features. Following the work of Simons and Richardson (1963) we were lead to the consideration of a non-dimensional unit stream power U_E, where U_E is defined by:

$$U_E = \frac{VS}{(g\nu)^{1/3} D_{gr}} .$$

Figure 5 shows data from the present study and from Guy et al (1966).

For the lowest values of U_E the bed was plane. As U_E increased the bed form changed from plane to ripples, this is for values of U_E larger than 0.00035. Initially, the ripples were small and regular, for example, the ripples formed in Run 17 were approximately 10cms long with a height of 1.2cms. The value of U_E was 0.0015. As the value of U_E increased the ripples increased in size. In run 16, with a U_E value of 0.0028, the ripple length was 19cms and the height was between 2 and 4.5cms. For larger values of U_E dunes were formed, the length of the dunes being between 80 and 100cms for a value of U_E of 0.0067. The dunes disappear for U_E values larger than 0.011. There is then a transition to a flat bed regime. For larger values of U_E anti-dunes are formed, then chute and pools.

Using a criterion based on the value of U_E White et al (to appear) developed an algorithm for the calculation of alluvial friction. There are still, however, unresolved problems in connection with the transition from one regime to the other. It is unclear whether there are stable states lying between the two regimes and whether the transition displays hysteresis. These problems can only be resolved by further careful experiments.

The development of a method of determining the dominant bed features together with the recognition that the White et al (1980) analysis can be extended to upper regime flows has enabled the development of a comprehensive theory to predict alluvial friction. It is hoped that the theory that has been developed will act as a basis for future work to elucidate further problems of alluvial friction such as the effect of the introduction of cohesive material, alluded to in the introduction, and the impact of unsteady flows.

5 CONCLUSIONS

A set of experiments carefully measuring the alluvial friction due to a sand bed have been performed.

The type of bed features developed has been related to the dimensionless unit stream power U_E.

Two distinct relationships have been observed describing the alluvial friction, one for lower regime and one for upper regime. This is the basis for an extension, proposed by White et al (to appear), to the method of predicting alluvial friction described by White et al (1980).

The observations in the lower regime are similar to those of Bassi (1985) but both sets of results differ from those of Guy et al (1966) and the theoretical relationship of White et al (1980).

The details of the transition from one regime to the other are unknown and further experiments are required to elucidate them.

6 ACKNOWLEDGEMENTS

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TABLES

TABLE 1 - EXPERIMENTAL RESULTS

Run	Flume slope (10^{-3})	Discharge (L/s)	Water surface slope s 5 points x10^3	3 points	Depth (m)	Bed features Length (cm)	Height (cm)	Speed (cm/s)	Temperature °C	Duration of test hr	Bed forms
1a	0.924	107	0.695	0.706	0.153	21.5	3.5	-	-	3.5	Ripples
1b	0.924	107	0.746	0.748	0.156	21.5	3.5	-	-	5.5	Ripples
1c	0.924	107	0.860	0.872	0.160	19.0	3.8	10	16.8	23.0	Ripples
1d	0.924	107	0.882	0.808	0.156	17.0	4.0	10	17.0	28.0	Ripples
2a	0.924	184	1.200	1.040	0.174	-	-	-	-	2.0	Ripples
2b	0.924	184	1.298	1.360	0.176	22.0	4.2	126	-	4.0	Ripples
2c	0.924	178	1.158	1.222	0.196	23.0	4.0	36	19.9	21	Ripples
2d	0.924	178	1.039	1.122	0.197	-	-	-	19.9	22	Ripples
2e	0.924	178	0.992	0.992	0.203	-	-	-	19.9	23	Ripples
2f	0.924	178	0.843	0.800	0.214	-	-	-	19.9	25	Ripples
2g	0.924	178	0.589	0.594	0.231	19.2	-	-	19.9	25.6	Ripples
3a	1.272	110	1.308	-	0.134	25	4	30	13.0	4.0	Ripples
3b	1.272	98	0.779	-	0.156	15	2.5	9.2	13.0	5.50	Ripples
4	1.272	100	0.719	-	0.154	15	2.5	-	16.0	1.0	Ripples
5	0.924	170	1.462	-	0.160	23	4.2	-	-	3.5	Ripples
5'	0.924	203	1.812	-	0.125	-	-	-	19.8	4.0	Flat bed (upper)
6	0.924	205	1.461	-	0.160	Dunes 80	8.5	-	17.8	24	dunes with ripples
				-		With ripples 24	3.5	60			
7'	0.924	150	1.655	-	0.125	Dunes 100	6.0-8.5	-	19.4	18.6	dunes with ripples
				-		With ripples 27	4.0				
8'	2.665	182	2.230	-	0.101	-	-	-	21.0	4.5	Flat bed (upper)
9	4.874	168	3.379	-	0.092	-	-	-	19.6	1.3	Flat bed (upper)
9'	4.874	160	3.33	-	0.093	-	-	-	21.2	18.3	Flat bed (upper)
10a	8.038	143	4.796	-	0.085	-	-	-	19.7	1.0	Flat bed (upper)
10b	8.038	150	5.113	-	0.085	50-80	1.2-2.5	-	20.0	3.5	Standing wave and flat (upper)
11	9.038	223	6.584	-	0.086	70-100	1-3	-	16.1	3.0	Anti-dunes and flat (upper)
12	4.058	110	2.347	-	0.094	Ripples 20	2	-	16.5	19.0	Dunes with ripples
				-		Dunes 80	6				
13	2.068	109	1.950	-	0.110	-	-	-	16.8	4.5	Ripples
14	0.924	113	1.846	-	0.117	18	3	300	13.4	5.3	Ripples
15	0.775	108	1.887	-	0.123	-	-	-	15.5	18	Ripples
16	0.277	70	1.502	-	0.100	19	2-4.5	65	16.8	18	Ripples
17	0.476	85	0.690	-	0.140	10	1.2	-	16.1	3.5	Small ripples
18	0.476	90	1.593	-	0.113	18.5	3.5	60	17.2	18	Ripples
19	5.919	110	5.097	-	0.066	-	-	-	15.3	1	Flat bed (upper)
20	0.178	77	0.072	-	0.189	-	-	-	15.3	4	Flat bed (lower)
21	0.178	77	0.093	-	0.176	-	-	-	15.3	4.5	Flat bed (lower)
22	0.178	77	0.147	-	0.163	-	-	-	15.3	5.0	Flat bed (lower)
23	0.178	77	0.253	-	0.152	11	1.3	-	17.2	17	Flat with some small ripples (lower)
24	0.476	113	0.556	-	0.168	15	2.5	3.0	17.6	5	Ripples
25	5.774	210	4.945	-	0.100	-	-	-	12.5	1	Flat with some anti-dunes (upper)
26	0.476	80	0.166	-	0.176	-	-	-	12.5	1	Flat (lower)
27	0.476	80	0.170	-	0.166	-	-	-	12.5	0.5	Flat (lower)
28	0.476	80	0.340	-	0.149	-	-	-	12.5	0.5	Flat (lower
29	0.476	110	0.806	-	0.158	13	1.5	-	13.5	3.5	Small ripples (lower)
30	0.874	113	1.560	-	0.134	16	2.5	60	16.5	18	Ripples
31	5.774	210	4.539	-	0.099	-	-	-	16.5	1.0	Flat bed and anti-dunes (upper)

FIGURES

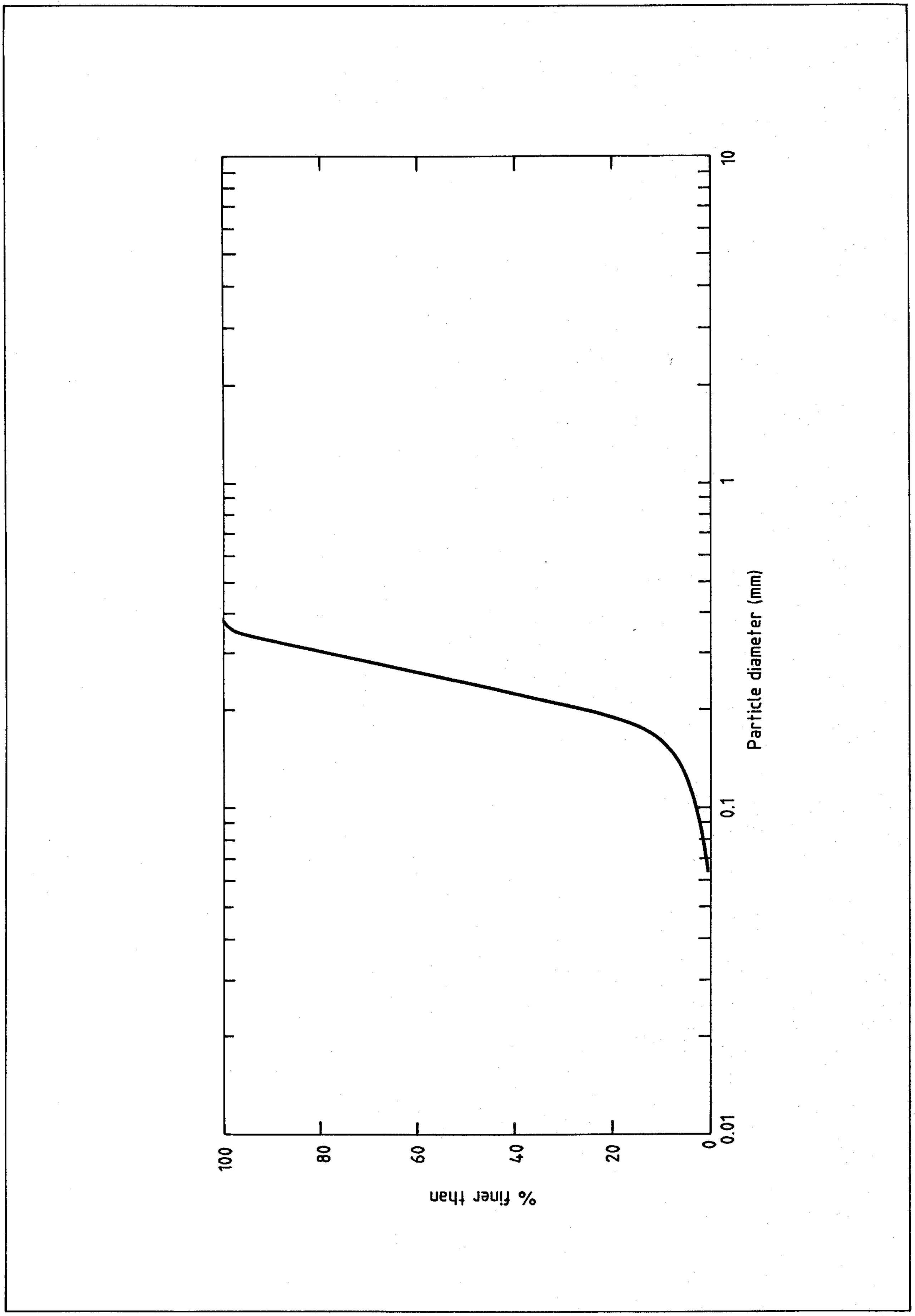

Fig 1 Grading curve of sand

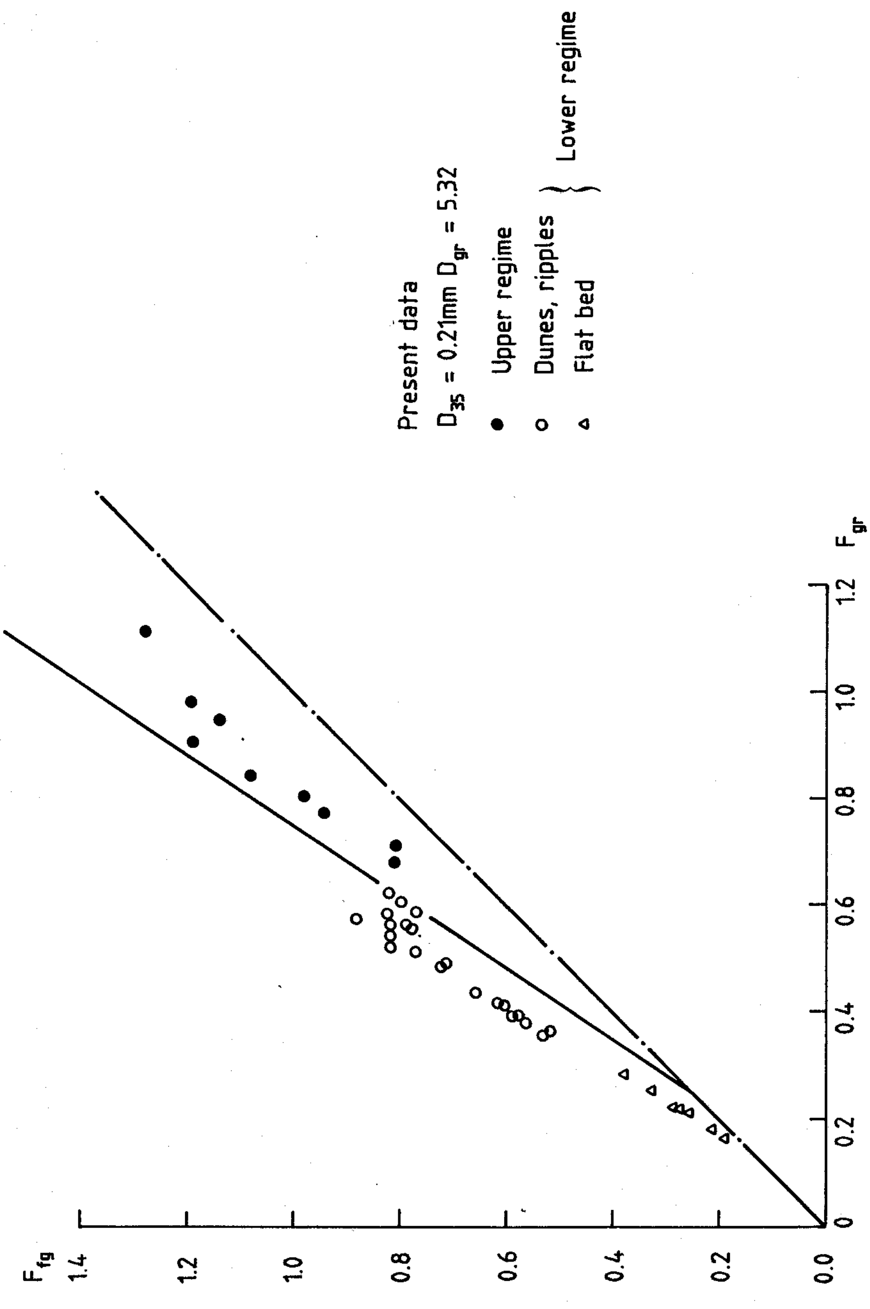

Fig 2 F_{gr} against F_{fg}, present results

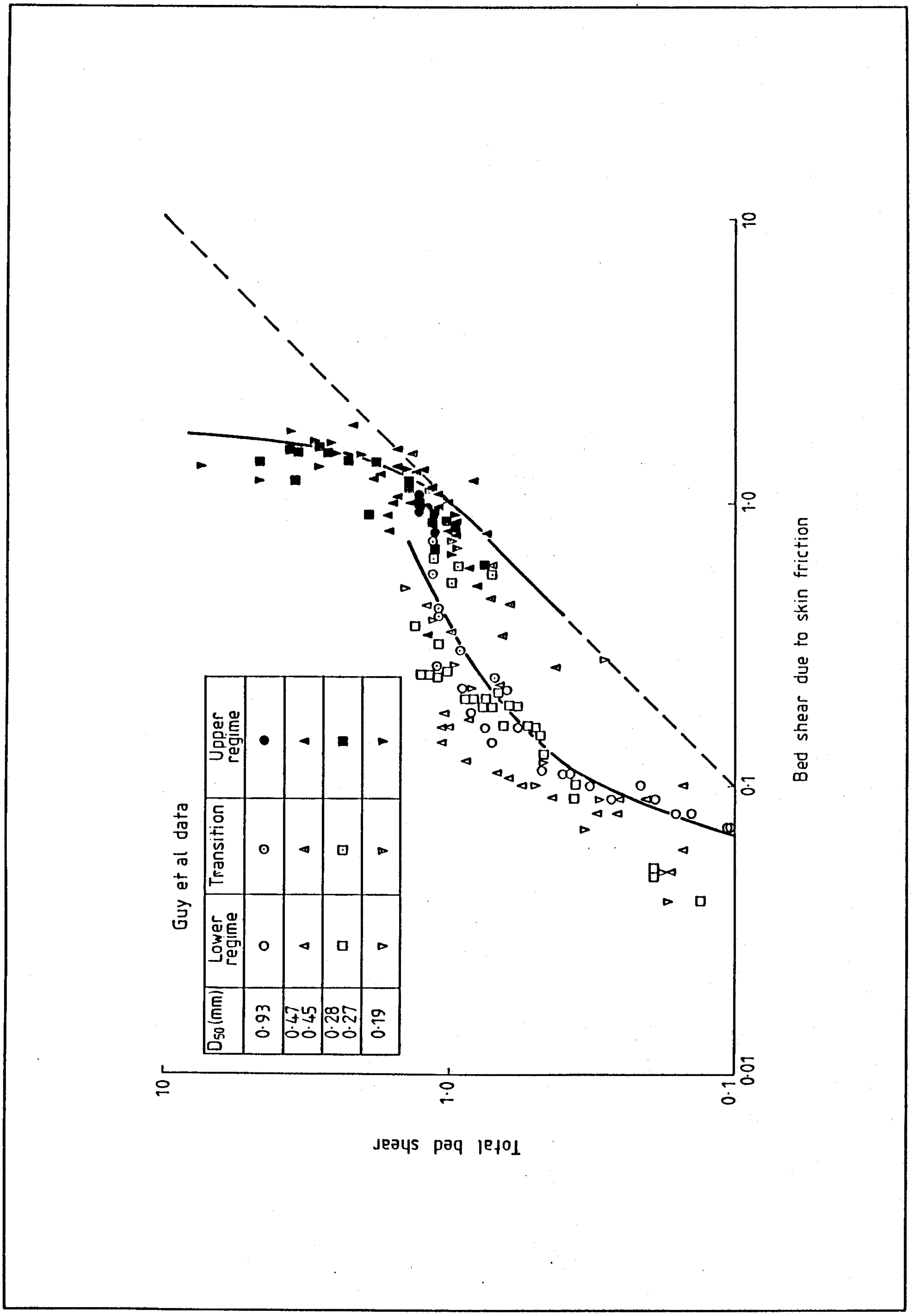

Fig. 3 Frictional relationship by Engelund

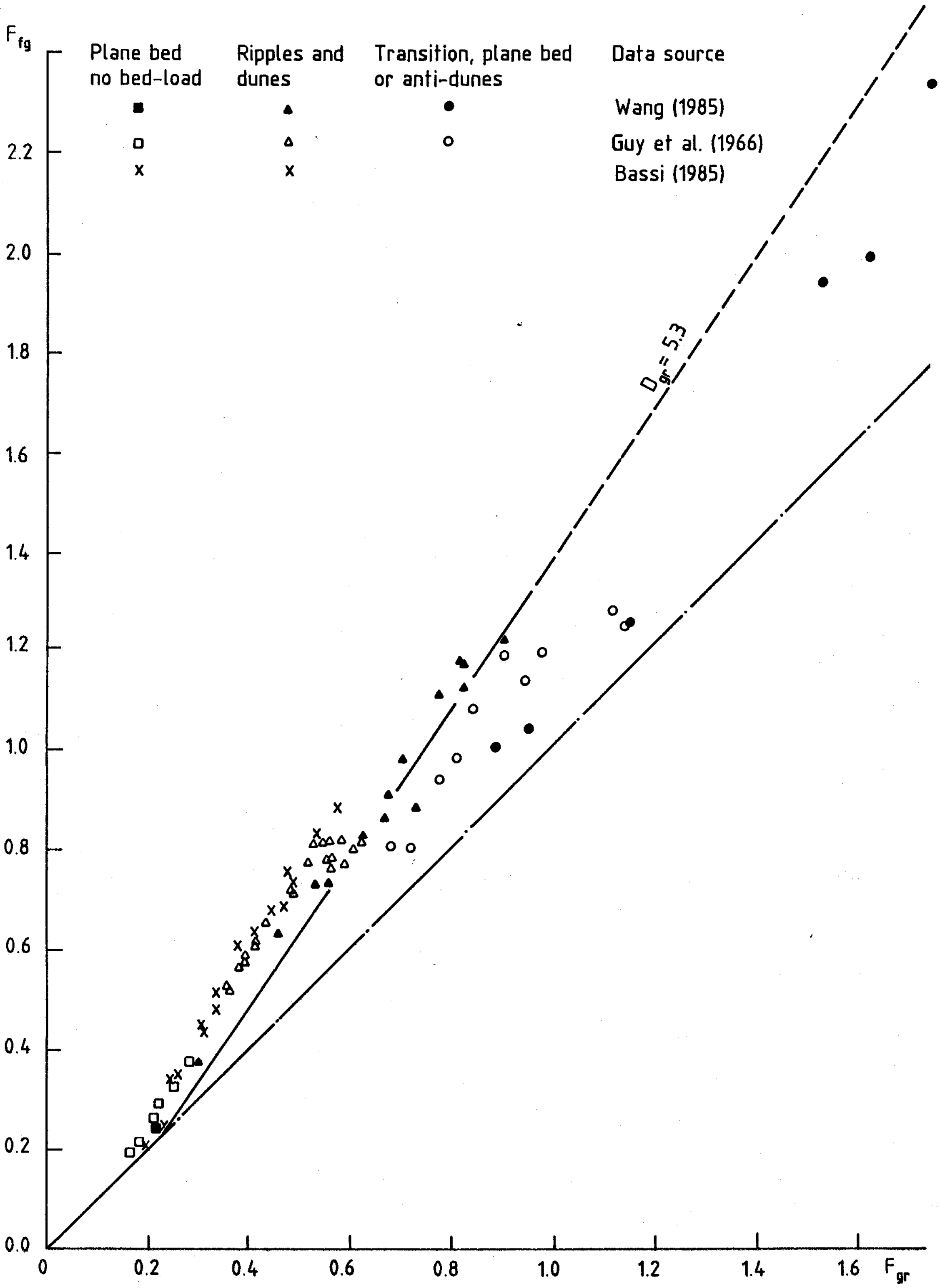

Fig 4 F_{gr} against F_{fg}, all data

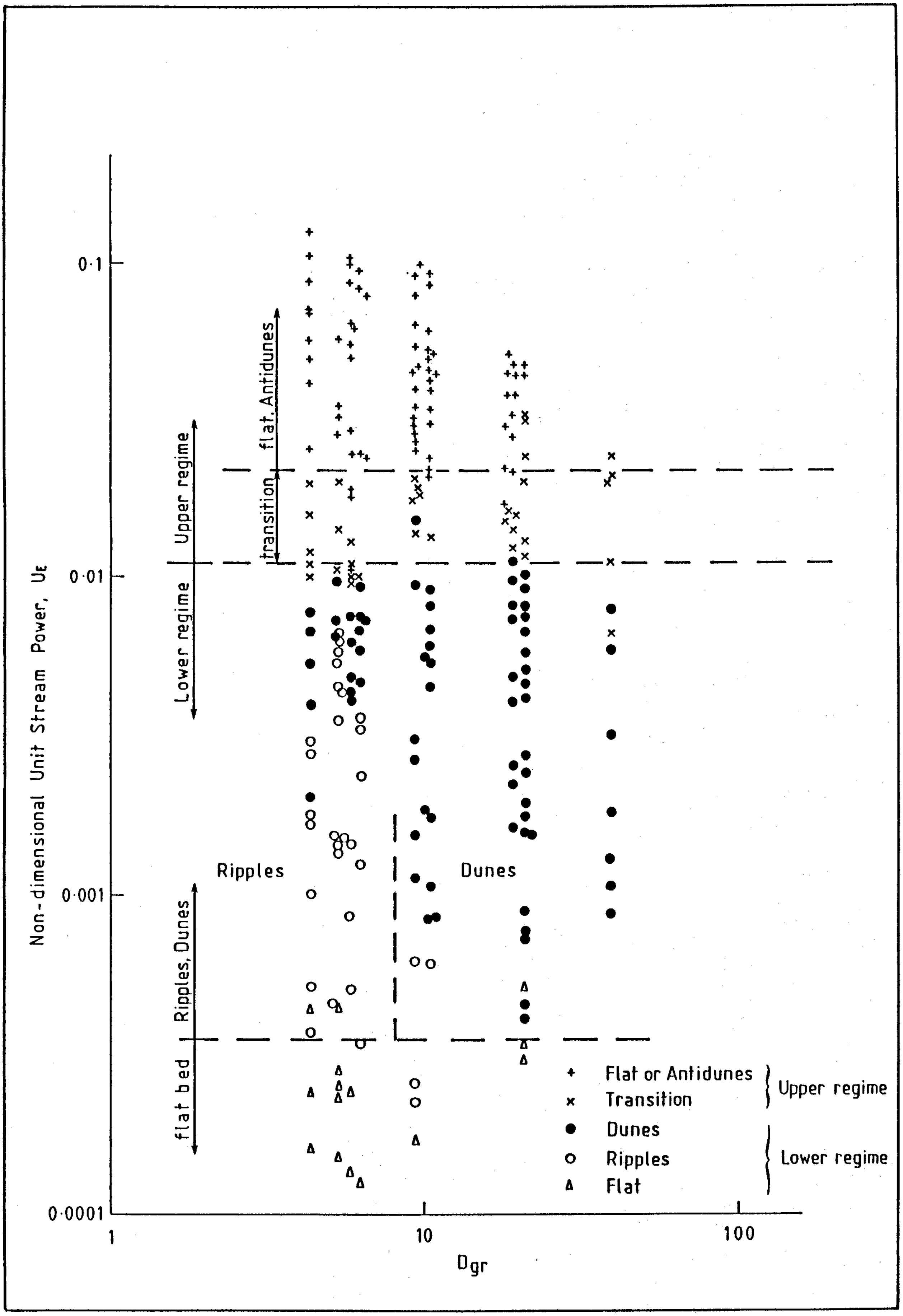

Fig 5 U_E against D_{gr}