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MEASUREMENT OF SEDIMENT TRANSPORT AND FRICTION FACTOR IN MOBILE BOUNDARY OPEN CHANNEL FLOW

by

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MANAGEMENT PERSPECTIVE

Because of the complex nature of the sediment transport phenomenon in river systems, it has become a common practice to investigate the phenomenon using laboratory flumes. But, even in laboratory flumes, there are difficulties with regard to the establishment of equilibrium and uniform flow conditions under which the measurements are to be carried out. In this paper, a new method has been proposed which ensures that the correct sediment feed rate is set up so that the conditions in the flume are uniform and steady. This new method involves monitoring the bed level and water surface elevations along the flume at regular intervals of time using sensitive probes and computer. Results of the experiments carried out using the new method show more consistency than the existing data sets that were obtained using methods that require human judgement on the part of the experimenter to decide whether the flow conditions are uniform or not.

PERSPECTIVE - GESTION

Etant donné la nature complexe du phénomène de transport des sédiments dans les cours d'eau, il est devenu pratique courante d'étudier le phénomène à l'aide des canaux d'essais. Mais même à l'aide des canaux d'essais, il est difficile d'établir les conditions d'équilibre et d'écoulement uniforme nécessaires pour prendre les mesures. Dans le présent article, nous proposons une nouvelle méthode qui permet d'obtenir un taux approprié d'alimentation en sédimentsde telle sorte que les conditions dans le canal d'essai sont uniformes et stables. Dans le cadre de cette nouvelle méthode, des sondes sensibles et un ordinateur contrôlent le niveau du lit et l'élévation de la surface de l'eau le long du canal à intervalles réguliers. Les résultats des expériences effectuées à l'aide de la nouvelle méthode sont plus uniformes que les données actuelles obtenues à l'aide de méthodes exigeant de la part de l'expérimentateur une certaine dose de jugement pour déterminer si les conditions de l'écoulement sont uniformes ou non.

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MESURE DU TRANSPORT DES SÉDIMENTS ET DU FACTEUR DE FRICTION DANS L'ÉTUDE DE L'ÉCOULEMENT DANS UN CANAL A SURFACE LIBRE ET A FOND MOBILE

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RÉSUMÉ : Dans cet article, nous avons mis à jour la difficulté pratique qui consiste à établir des conditions de débit quasi-uniforme dans les canaux de transport de sédiments, et nous proposons une nouvelle méthode pour surmonter cette difficulté. Des expériences effectuées à l'aide de la nouvelle méthode sont comparées aux mesures existantes ainsi qu'aux équations existantes sur la vitesse de transport des sédiments et sur le facteur de friction dans les écoulements à fond mobile.

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SUMMARY: In this paper, the practical difficulty of establishing quasi-uniform flow conditions in sediment transport flumes is elucidated and a new method to overcome this difficulty is put forward. Experiments conducted according to the new method are compared with existing measurements as well as existing equations of sediment transport rate and friction factor of mobile boundary flows.

INTRODUCTION

In conducting sediment transport experiments using laboratory flumes, one is faced with a number of practical difficulties. One major difficulty is the establishment of uniform or quasi-uniform flow conditions when the bed of the flume is covered with sand waves such as ripples, dunes and anti-dunes. A uniform or quasi-uniform flow is said to have been established when the average slope of the water surface is equal to the average slope of the sand bed and the rate of sediment entering the working section of the flume is equal to that leaving the working section. In this paper, the practical difficulty associated with the determination of the sand bed slope is elucidated and a method to overcome this difficulty is suggested. The results of experiments carried out in a 2 metre wide sediment transport flume at the National Water Research Institute at Burlington, Ontario, Canada according to the new criterion of uniform flow conditions were compared with a number of the existing equations of sediment transport rate and friction factor of mobile boundary flows.

PRELIMINARY CONSIDERATIONS

Yalin (1977) has shown that for a two-dimensional, uniform flow over a bed composed of uniformly sized, cohesionless particles of similar shape, the transport rate and friction factor may be expressed in dimensionless form as

$$q_{*} = \phi\,[X, Y, Z] \qquad (1)$$

and

$$C = f\,[X, Y, Z] \qquad (2)$$

where q_{*} is the dimensionless transport rate/unit width, C is the friction factor, X is the grain size Reynolds number, Y is the mobility number, Z is the relative depth, and ϕ and f are dimensionless functions. The expressions of q_{*}, C, X, Y and Z are given as

$$q_* = \frac{\rho^{1/2} q_s}{(\gamma_s D_{50})^{3/2}} \; ; \quad C = \frac{U}{U_*} \; ; \quad X = \frac{U_* D_{50}}{\nu}$$

$$Y = \frac{\rho U_*^2}{(\gamma_s D_{50})} \; ; \quad Z = \frac{h}{D_{50}} \qquad (3)$$

in which q_s is the sediment transport rate in kg/s/m, ρ is the density of the fluid (109.4 kg sec²/m⁴), γ_s is the submerged unit weight of the sediment (1650 kg/m³), D_{50} is the median grain size in m, U_* is the shear velocity in m/s, U is the average flow velocity in m/s, ν is the kinematic viscosity (10^{-6} m²/s) and h is the depth (in m) of the uniform flow. Equations (1) and (2) show that the sediment transport rate and friction factor of mobile boundary flows are completely determinied by three dimensionless parameters.

For a given sediment and the flowing medium, the four variables that must be measured in the flume are q_s, h, slope of uniform flow, S and water discharge Q. These data will then be sufficient to compute all the dimensionless parameters that appear in equations (1) and (2). The experimental equipment and procedures required to obtain reliable measurement of above four variables are described in the following sections.

EXPERIMENTAL EQUIPMENT

The experiments were conducted in the sediment transport flume at the National Water Research Institute, Burlington, Ontario, Canada. It is a tilting flume with rectangular cross section (2 m wide and 3/4 m high with glass sidewalls) and has an overall length of about 22 m. The flume could be tilted to slopes up to ±1%.

Water was fed from a large constant head tank through a 16 in (406 mm) I.D. pipe, which was terminated by a diffuser in the head box of the flume. In addition, baffles were placed in the head box to improve the entrance condition. Sediment was introduced into the flow from a gravity feed hopper located above the entrance section of the flume. The feed rate could be accurately controlled by using a rotating grooved shaft installed at the bottom of the hopper, and was driven by a variable speed motor. The flume channel floor was recessed 20 cm below the lip of the head box floor to permit placement of a sediment bed. The water level in the flume was controlled by a set of vertical louvres at the downstream end of the flume. The flow leaving the flume was split into three streams of equal width, each of which flowed into a separate sediment trap. The two outside traps were used to collect sediment during the setup period. The centre trap was kept closed by means of a pneumatically controlled gate. Once the right flow conditions were achieved, the centre trap was opened to begin collection of sediment for weighing. With this procedure sediment transport from the centre 1/3 of the flume, where the flow was close to being two dimensional, was collected. As a result the effects of side walls could be neglected.

The sediment flume is equipped with a self propelled instrument carriage which can travel along the length of the flume on rails fastened to the laboratory floor. This carriage was used to make profile traverses of the mobile bed and water surface, as well as to level the sand bed. To measure the profiles, an adjustable instrument rack was used which was mounted on the upstream face of the carriage. The bed level and water level probes were mounted on this instrument rack. The bed level probe was an electro-optical sensor that follows the sediment bed and is able to pick up changes in bed elevation as small as 1.5 mm. The water level probe measured water surface elevations by maintaining contact with the water surface using the water as a conductor and keeping a constant resistance through a feedback system. Displacement of the carriage along the length of the flume was measured by an aluminum wheel whose circumference was 1/10 of the overall length of the flume. It was attached to the instrument carriage and travelled on the same rails. This wheel ensured precise measurement of profile lengths. Each of the profilers and the measuring wheel provided a signal between 0 and 10 volts. These signals were fed through an A/D converter into an ARISIA minicomputer which is run on a CPM operating system. The profiling information was stored on 8 in (20 cm) double sided, double density discs having a storage capacity of 981 K bytes.

The river wash sand used for the experiments was fairly uniform in size with a median sieve diameter of 1.2 mm. Most of the grains were rounded with specific gravity of about 2.65 and a porosity of 0.45.

EXPERIMENTAL PROCEDURE

Prior to a run, the flume was set at a zero slope and the sand bed was prepared by levelling the sand with a blade attached to the instrument carriage. After preparing the sand bed, the flume was set at the desired slope. Then, water was slowly let in to wet the sand bed completely. Care was taken to make sure that the sand bed was not disturbed. As the flume was slowly filling, a traverse with the instrument carriage was made over the working length of the flume to obtain the profile of the initial plane bed. A linear regression on the trace of the plane bed was then performed to compute the slope of the plane sand bed. The slope, thus computed, in general, agreed very well with the pre-set slope of the flume.

The flow was then gradually increased, allowing the depth to rise to almost the full height of the flume walls. The flow was kept at this depth as the discharge was increased to a desired value by slowly opening the louvre gates. The depth of flow was such that there was no sediment movement during this phase of flowrate establishment. When the desired discharge has been obtained, the gates were opened further to bring the flow depth slightly below the desired value to allow for subsequent increase due to the development of sand waves. With the onset of the sediment transport in the flume, the sediment feeder was turned on.

As the flow transported sediment, dune patterns began to form. The bed levels and water levels along the centre line of the flume were monitored at regular intervals of time by traversing the probes along the length of the working section. After each traverse, the slope of the water surface was computed by performing linear regression on the measured water surface profile. If the computed water surface slope was different from the desired slope for the run, then adjustments to the louvre-gates were made until the two slopes are equal.

The use of the linear regression method for computing the bed slope was not satisfactory when the sand bed was covered with sand waves. This is illustrated in Figure 1 which shows the traces of two consecutive profiles taken at five minute intervals. The slopes computed using linear regression for these two traces are also given in this figure. It can be seen that the solid trace gives a much higher slope than the dotted trace. The difference in slopes between the two traces is as high as 50 percent. Such a difference in bed slope does not reflect the reality as the evolution of bed slope is rather a slow process. The reason for the difference is the position of the crest and trough of the sand waves at the beginning and at the end of the traverse. Indeed, the solid trace begins with a crest at the beginning whereas the dotted trace begins with a trough. As a result, the solid trace yields a higher slope and the dotted trace yields a lower slope. Therefore, the difference in computed slope using the linear regression method reflects the relative positions of the sand waves rather than the change in the average slope of the sand bed. Therefore, it became apparent that a different method had to be devised to determine the uniformity of the flow conditions.

A new method suggested for this study is as follows:
A trace of the bed profile taken in a bed covered with sand waves is superimposed on the trace of the bed profile obtained when the bed was plane. From these two traces, a net change in the volume of sediment within the working section is computed. Since the downstream bed level is controlled and maintained by the downstream lip of the sand placement recess and as the water surface slope is continually adjusted to the desired slope equal to the slope of the plane bed, it can be argued that a positive value for the net change in sediment volume would indicate that the sand bed is aggrading in the upper reaches of the working section and hence the average slope of the sand bed will be larger than the plane bed slope. A negative value would indicate that the bed is eroding and the average slope will be less than the plane bed slope. For the sand bed slope to be equal to the slope of the plane bed, it is required that the net change in sediment value be near zero or fluctuate around zero. This was the criterion adopted in the present study to objectively determine whether the flow is a quasi-uniform or not.

Software in BASIC was developed to calculate the net change in sediment volume. After each traverse, this programme was executed to calculate the net change in sediment volume since the start of the experiment. If the trend in the net change in sediment volume values was positive and showed a gradual increase, then the sediment feed rate was reduced. If a reverse trend was noticed then the sediment feed rate was increased. The process was continued until the net change in sediment volume was reasonably steady around zero value.

When the feed rate was adjusted, it took a considerably longer time for conditions to stabilize and often it took one or two days before the equilibrium conditions could be established. Because of the limited capacity of the sand hopper, sometimes the runs had to be terminated before equilibrium conditions were attained. In such cases, the bed was relevelled and the test was restarted.

When equilibrium conditions were achieved, the centre trap was opened for a known duration of time (usually a few hours) and the sediment was collected. During this period, traverses were made to compute the average flow depth and to check the constancy in water surface slope and the parameter reflecting the net change in sediment volume within the working section. At the end of the sand collection period, the sediment trap was closed and a sample of the sediment feed at the hopper was collected to check the sediment feed rate. When this was done, water and sediment feed were shut off and the test considered completed. The working section was relevelled in preparation for the next run. When doing this, the net volume of deposition or scour was determined by removing or adding material to return the bed to its original plane bed level. The net volume was compared with the computed net volume change. For successful runs, there was always good agreement between these values. The sediment in the centre trap was removed and its submerged weight determined by standard methods. The transport rate was then compared with the feed rate.

Altogether 15 runs were successfully completed. The summary of hydraulic characteristics of these runs are summarized in Table 1, together with the corresponding dimensionless parameters given by equation (3).

RESULTS AND DISCUSSION

For the present considerations, values of Z, reflecting the effect of flow depth, were kept nearly constant. The effect of Z on sediment transport rate has already been demonstrated by Krishnappan and Engel (1986). Values of Reynolds number X were near 70 or greater except for two runs in which values were 45 and 51. Therefore, the flows can be treated as rough turbulent and the effect of the Reynolds number X can be neglected. Values of q_* and C were, therefore, plotted only versus the mobility number Y as shown in Figures 2 and 3, respectively.

Sediment Transport Rate

In Figure 2, a single smooth curve was fitted by eye to the plotted points. The curve shows that initially values of q_* rise very rapidly as Y increases with the rate of increase gradually decreasing. This effect is primarily due to the change in bed roughness. As the size of the dunes increases, the form drag increases thereby reducing the effective shear stress responsible for the sediment transport. To compare the present measurements of transport rate with existing data, results for comparable values of X and Z from Guy et al. (1986) and Williams (1967) were also plotted in Figure 2. The data set of Guy et al. agrees very well with the present data set except it shows a higher experimental scatter. Williams data exhibit less scatter, but they are consistently lower than both the present data and those of Guy et al.

The present values of q_* were also compared with existing transport rate equations and the comparison is shown in Table 2. Four equations were selected. These are: 1. Ackers and White (1973), 2. Engulund and Hanson (1967), 3. Van Rijn (1984), and 4. Yang (1972). The details of these equations can be found in the original references. Table 2 clearly shows that all four equations underpredict the transport rate. Predictions by Yang (1972) are found to be the closest to the measurements whereas the equation of Van Rijn (1984) underestimates by the largest amount. The basic reasons for the differences in these equations need to be further examined.

Friction Factor

In Figure 3, a single smooth curve was fitted by eye through the authors' data, providing a reasonable fit. The curve shows a smooth decline in C with the rate of change decreasing as Y increases. The decrease in C (increased resistance) reflects the progressive bed form development. Values of C for the same data set from Guy et al (1966) and Williams (1967), used in Figure 2, were also plotted in Figure 3. The data from Williams shows good agreement with the authors' curve for values of $Y \leq 0.15$. Thereafter, values of C progressively deviate from the curve as Y increases, resulting in much higher values. The data from Guy et al. agree quite well with the authors' curve for values of $Y < 0.15$ as well as for values of $Y > 0.45$. However, for values of Y in the range from 0.25 to 0.4, values of C from Guy et al. are significantly below the authors' curve. The scatter in the data from Guy et al. (1966) and Williams (1967) when $0.25 < Y < 0.4$ indicates that there is a great deal of variability in the parameters that need to be measured in order to obtain the friction factor. This uncertainty is considerably reduced by the authors' computer-interactive method of monitoring steady state conditions during experiments.

TABLE 1. Summary of Experimental Data.

Test No.	Depth h cm	Slope S $x10^{-3}$	Sediment Transport q_s gm/s/cm	Discharge Q ℓ/s	X	Y	Z	q_*	C
6	15.78	1.71	0.368	186.6	61.74	0.136	131.5	0.133	12.25
8	16.34	6.25	3.301	316.3	120.1	0.516	136.2	1.196	9.47
9	16.41	6.17	3.010	310.7	120.0	0.511	136.8	1.091	9.29
10	16.55	6.14	2.878	302.8	120.0	0.513	137.9	1.043	8.98
11	15.72	5.96	2.811	277.6	115.0	0.473	131.0	1.019	9.09
12	15.03	5.56	2.322	267.1	108.7	0.422	125.3	0.841	9.81
13	15.13	4.83	1.925	253.2	101.6	0.369	126.1	0.698	9.71
14	15.55	3.75	1.388	242.6	90.76	0.295	130.0	0.503	10.40
15	15.16	3.80	0.990	227.2	90.21	0.291	126.3	0.359	9.75
16	14.56	3.13	0.791	211.9	80.24	0.230	121.3	0.287	10.91
17	15.15	2.65	0.715	201.1	75.31	0.203	126.3	0.259	10.37
19	14.16	2.74	0.516	189.0	74.03	0.196	118.0	0.187	10.80
20	15.07	1.37	0.177	169.0	54.01	0.104	125.6	0.064	13.05
21	15.11	0.972	0.074	168.8	45.55	0.074	125.9	0.027	14.93
22	15.01	2.03	0.323	172.2	65.61	0.154	125.1	0.117	11.17

TABLE 2. Sediment Transport Rate Comparison.

Test No.	Flume Data	Case 1		Case 2		Case 3		Case 4	
		q_s	Δq_s%	q_s	Δq_s%	q_s	Δq_s%	q_s	Δq_s%
6	0.368	0.306	-16.85	0.174	-52.71	0.066	-82.06	0.243	-33.97
8	3.301	2.445	-25.93	2.461	-25.44	1.014	-69.28	3.420	3.61
9	3.010	2.245	-25.42	2.413	-19.83	1.005	-66.61	3.205	6.48
10	2.878	1.990	-30.85	2.443	-15.11	1.001	-65.22	2.967	3.09
11	2.811	1.795	-36.14	1.966	-30.06	0.844	-69.98	2.541	-9.61
12	2.322	1.795	-22.70	1.476	-36.43	0.633	-72.74	2.357	1.51
13	1.925	1.300	-32.47	1.092	-43.27	0.482	-74.96	1.685	-12.47
14	1.388	1.030	-25.79	0.683	-50.79	0.299	-78.46	1.185	-14.63
15	0.990	0.775	-21.72	0.660	-33.33	0.297	-70.00	0.962	-2.83
16	0.791	0.735	-7.08	0.412	-47.91	0.192	-75.72	0.736	-6.95
17	0.715	0.410	-42.66	0.332	-53.57	0.146	-79.58	0.448	-37.34
19	0.516	0.493	-4.45	0.305	-40.89	0.146	-71.71	0.463	-10.27
20	0.177	0.187	5.65	0.115	-35.03	0.033	-81.34	0.132	-25.42
21	0.074	0.121	63.51	0.071	-4.05	0.014	-81.08	0.070	-5.41
22	0.323	0.280	-13.31	0.207	-35.91	0.085	-73.68	0.257	-20.43
Average Deviations			-15.74		-35.96		-74.16		-16.98

Case 1: Model of Ackers & White (1973)
Case 2: Model of Engulund & Hansen (1967)
Case 3: Model of Van Rijn (1984)
Case 4: Model of Yang (1972)

The present measurements were compared with four existing friction factor equations and this comparison is shown in Table 3. These equations are: 1. White (1979), 2. Engulund (1966), 3. Kishi and Kuroki (1974), and 4. Van Rijn (1984). The detail of these equations can again be found in the original references. The table clearly shows that the equations of White (1979) and Van Rijn (1984) provide quite similar results, tending to underestimate the friction factor by about 11%. In contrast, Engulund (1966) and Kishi and Kuroki (1974) also give very similar results but tend to overestimate by about 29%. The basic reason for the differences in these equations should also be examined in view of the present data.

TABLE 3. Friction Factor Comparisons.

Test No.	Flume Data	Case 1		Case 2		Case 3		Case 4	
		C	ΔC%	C	ΔC%	C	ΔC%	C	ΔC%
6	12.249	10.890	-11.09	14.417	17.70	10.517	-14.14	10.813	-11.72
8	9.465	7.930	-16.22	13.236	39.84	15.248	61.40	8.392	-11.33
9	9.291	7.948	-14.45	13.247	42.58	15.312	64.80	8.354	-10.09
10	8.978	7.951	-11.43	13.268	47.78	15.332	70.77	8.392	-6.53
11	9.087	8.022	-11.72	13.150	44.71	13.522	48.81	8.417	-7.34
12	9.810	8.162	-16.80	13.066	33.19	13.421	36.81	8.495	-13.40
13	9.707	8.404	-13.42	13.140	35.37	13.436	38.42	8.703	-10.34
14	10.395	8.874	-14.63	13.360	22.14	19.048	83.24	9.127	-12.20
15	9.753	8.868	-9.07	13.308	36.45	19.080	95.63	9.052	-7.19
16	10.909	9.331	-14.47	13.444	23.24	10.036	-8.00	9.419	-13.66
17	10.365	9.702	-6.40	13.701	32.19	9.150	-11.72	9.814	-5.32
19	10.800	9.697	-10.22	13.578	25.72	9.150	-15.28	9.740	-9.81
20	13.049	11.732	-10.09	14.799	13.41	11.411	-12.55	11.739	-10.04
21	14.934	13.112	-12.20	15.509	3.85	12.788	-14.37	12.723	-14.81
22	11.168	10.444	-6.48	14.086	26.13	10.016	-10.33	10.428	-6.63
Average Deviations			-11.91		-29.62		29.51		-10.03

Case 1: White (1979)
Case 2: Engulund (1966)
Case 3: Kishi & Kuroki (1974)
Case 4: Van Rijn (1984)

CONCLUSIONS

The proposed new method to establish the quasi-uniform flow conditions in the sediment transport flume experiments is an improvement over the subjective visual methods that have been often used in the past to determine the correct amount of sediment feed rate to obtain uniform and equilibrium flow conditions. The data obtained in the present study show better consistency over the existing data sets. The comparison of data from present measurements with the predictions of existing equations of sediment transport rate and friction factor suggests that the existing theories deviate considerably from reality even for laboratory conditions. The comparison of sediment transport rate with equations shows a discrepancy ranging between -11% and +74% depending on the equations used. The friction factor comparison shows a deviation range of -10% and +30% among the equations tested.

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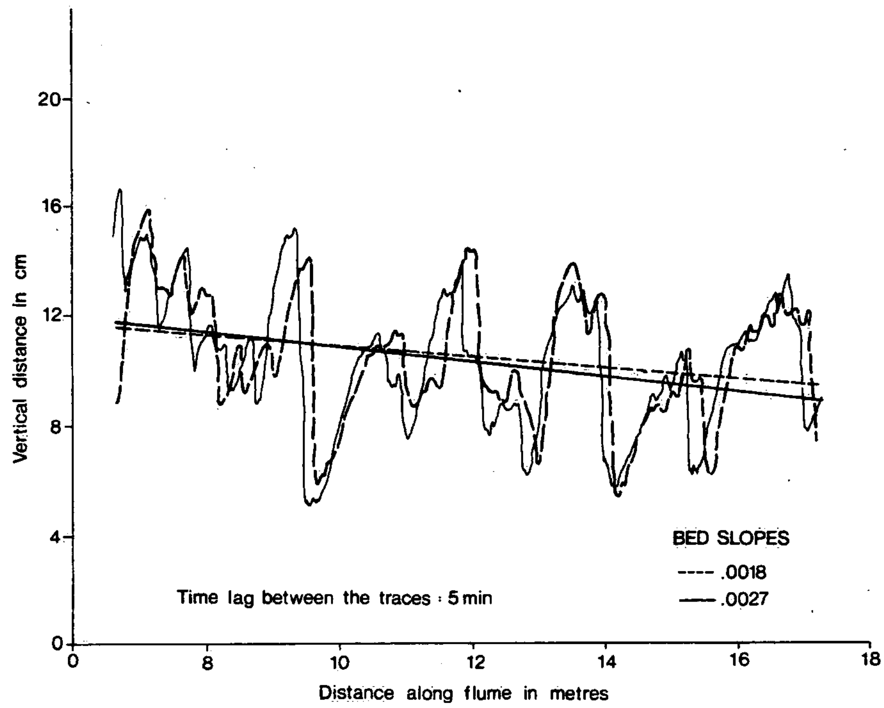

Fig. 1 VARIATION OF THE COMPUTED BED SLOPE DEPENDING ON THE DUNE PROFILE WITHIN THE WORKING SECTION.

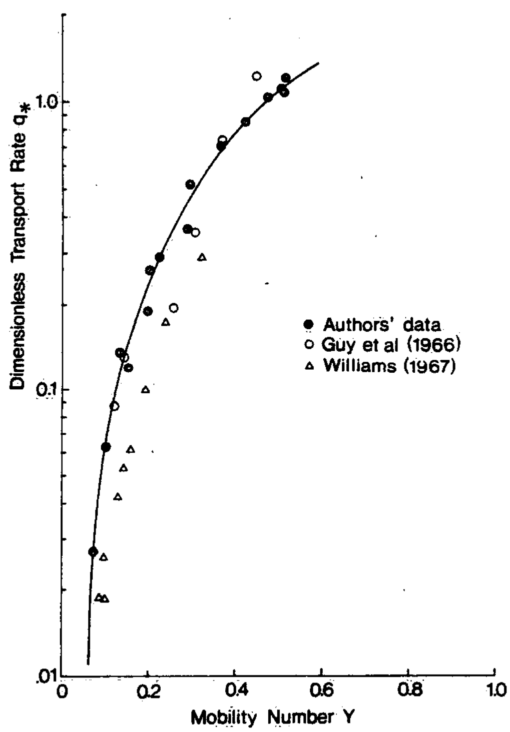

Figure 2. Comparison of Transport Rate Data.

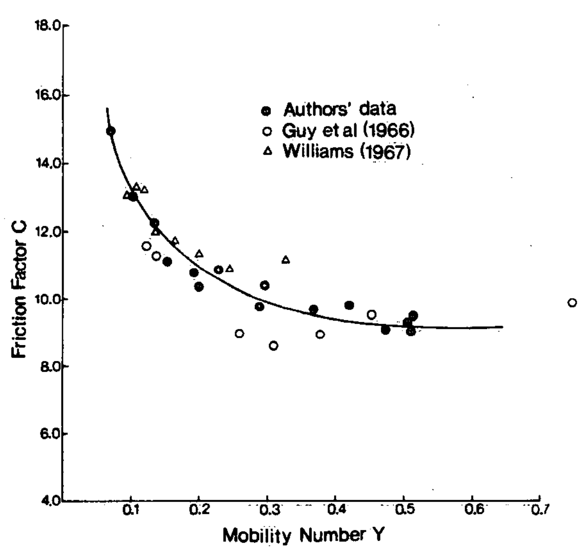

Figure 3. Comparison of Friction Factor Data.