RATIO OF BED LOAD TO TOTAL SEDIMENT LOAD IN COARSE-BED RIVERS

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The main characteristics of the flow in coarse-bed rivers are the development of an armor layer during low to mean flows, and the increase of channel instability and sediment load during flood flows. The main aim of the present study was to investigate the contribution of bed load in the total sediment load. Three river reaches were selected as representatives of coarse-bed rivers in North-West of Iran. Mean flow characteristics were determined from the calibrated HEC-RAS flow model in these river reaches. A sediment transport model (STM-CBR) was developed to calculate the sediment load from different methods. Sediment transport rates of different modes (i.e. bed, suspended and total loads) were evaluated in these three reaches. The effects of bed material characteristics were also examined. The best fitted relationships to the field data were determined for the proper evaluation of different modes of sediment loads. The ratio of bed load to total load was determined from field measurements and compared with the corresponding predictions from different methods. Two approaches were tested: using those predictive methods that are best fitted with field measurements; and using those methods that calculate both suspended and bed loads on similar basis. The ratio of bed load to total load was found to be in the range between 0.4 and 0.8 with an average value of 0.57, with the inclusion of sub-surface bed material characteristics. The ratio decreases with the increase in the flow rate. The results indicate that the ratio is significantly much higher in coarse-bed rivers than that in sand-bed rivers.

Key Words : *coarse-bed rivers, sediment transport, bed load, total load, STM-CBR model*

1. INTRODUCTION

Coarse-bed rivers are characterized by relatively high degrees of bed slope, stream power, sediment transport, particularly in the mode of bed load; and are relatively wide and shallow with potential of deposition of non-cohesive coarse sediment such as gravel and cobbles[1)]. The process of flow and sediment transport is different and more complex in coarse-bed rivers than in sand-bed rivers. The main characteristic of the flow in coarse-bed rivers is the development of an armor layer with coarse gravel, cobbles and boulders[2)]. While this surface layer establishes a stable and smooth boundary at low to mean flows, its mobility introduces a different mode of the flow resistance during high flows resulting in excessive bed load transport of finer sub-surface material, and channel instability[3)].

Reliable prediction of the sediment transport capacity and determination of the different mode of transport (i.e. bed load, suspended load, and total load) in coarse-bed rivers are of major importance in river engineering. Direct measurements of bed load are difficult to achieve in coarse-bed rivers, and less data is available. Therefore, the evaluation of total sediment load, and the contribution of bed load to the total load are uncertain. The conventional approach suggests a small portion of suspended load is to be taken into account for the bed load (usually 5 to 25 percent). Such a fraction is generally applied to

Table 1 Different sediment transport relationships, applicable to coarse-bed rivers.

Methods	Bed Load	Suspended Load	Total Load	Application Remarks
Schoklitsch (1934)	*			Coarse-bed rivers; D= (0.3-5) mm
Schoklitsch (1943)	*			Coarse-bed rivers; D= (0.3-5) mm
Meyer-Peter & Muller (1948)	*			Coarse-bed rivers; D= (0.4-30) mm
Einstein (1950)	*	*	*	Different Rivers
Laursen (1958)			*	Flume Data; D= (0.01-4.1) mm
Rottner (1959)	*			Flumes & Rivers
Engelund (1965)		*		Different Rivers
Bagnold (1966)	*	*	*	Rivers with bed form
Engelund & Hansen (1967)			*	Dune bed form rivers
Yalin (1977)	*			Sand & Gravel bed rivers
Brownlie (1981)			*	Flumes and Rivers
Parker, et al. (1982)	*			Gravel bed rivers, with armoring layer
Yang (1982)			*	Different Rivers
Samaga (1985)		*		Different Rivers
Zanke (1987)	*			Coarse-bed rivers
Ackers & White (1990)			*	Different Rivers, mostly sand-bed
Karim & Kennedy (1990)			*	Different Rivers
Parker (1990)	*			Gravel bed rivers, with armoring layer
Karim (1998)			*	Rivers, without armoring layer
Sun & Donahue (2000)	*			Coarse-bed rivers; D= (2-10) mm
Cheng (2002)	*			Coarse-bed rivers
Wilcock & Crowe (2003)	*			Coarse-bed rivers; D= (0.5-82) mm
Yang & Lim (2003)			*	Rivers; D= (0.8-2.2) mm

sand-bed rivers, but might be greater than 25% in coarse-bed rivers[4)]. Linsely & Franzini (1979) suggested that this ratio is to be generally between 10% to 50%, but greater percent is expected when considering the ratio of bed load to total load, and even much greater in the case of coarse-bed rivers[5)]. However, the order of 40% to 50% error is expected, even in standard sediment measuring system, and particularly in high flows[6)].

Several relationships are available in the literature for predicting sediment transport in coarse-bed rivers, most of which are presented in Table 1[6)]. Some of these relationships evaluate the total load directly (e.g. Karim & Kennedy, 1990), a few methods calculate both the suspended and bed loads on an identical basis (e.g. Einstein, 1950), and others compute either suspended load (e.g. Englund, 1965) or bed load (e.g. Parker, 1990). There is no general guidance to select the best methods applicable to different rivers, or different reaches of a river. The best selection among different relationships is unreliable wherever the field investigations are not involved in the river reach[7)]. The effects of bed sediment characteristics are to be considered in the adoption and reliability of the available relationships[8)]. However, the order of 50% to 70% error is expected, even when fitting the measured data to the best predictors[9)].

The main aims of the present study were to evaluate the different mode of sediment transports from the best fitted methods to the flow conditions in three coarse-bed river reaches, and to investigate the contribution of bed load in the total sediment load. The effects of bed material characteristics were also considered in this study.

2. MATERIALS AND METHODS

Three river reaches were selected as representatives of coarse-bed rivers (Badalan reach in the Aland river, Yazdekan reach in the Ghotor river, and Baron reach in the Baron river), located in the North-West of Iran. Presence of standard gauging station allowed for simultaneous measurements of bed and suspended loads in each of the three reaches. River survey and bed and sediment samplings were carried out. Table 2 presents the characteristics of bed sediments from surface and subsurface layers, and from bed-load samplings in these three reaches. Sediment transport rates and the ratios of bed load to total load were evaluated from the field data, in different flow conditions in these three reaches.

Mean flow characteristics were determined from the calibrated HEC-RAS flow model under different flow conditions in these river reaches, as presented in Table 3. A sediment transport model (STM-CBR) was developed to compute sediment load from different relationships (the bed load from 13 methods, the suspended load from 4 methods and the total load from 10 methods), as presented in Table 1. The flow characteristics in Table 3 were used as input to the STM-CBR model. As reported by van Rijn (1993), total sediment transport rate was evaluated either by using direct methods (such as: Karim & Kennedy, 1990), or indirectly by summing up the suspended and bed loads calculated from the relationships developed on a similar basis (such as: Einstein, 1950).

The effects of sediment characteristics (i.e. surface layer, subsurface layer, and bed-load material) were also examined. The results are described in the following section.

3. RESULTS AND DISCUSSION

Predicted sediment transport rates from the relationships in Table 1 were compared with the corresponding results from the field data, under different flow conditions, at the three river reaches. Examples are presented in Figure 1 and Figure 2 for the evaluation of bed load and total load, respectively, in Badalan river reach, using bed-load material characteristics. These figures indicate the prediction of bed load from 13 relationships, and of total load from 10 relationships; also show both the envelop and the 90% confidence limits of field data.

Table 2 Bed and sediment material characteristics in three river reaches.

Reach (River)	Bed Material	D_{10} mm	D_{16} mm	D_{50} mm	D_{65} mm	D_{84} mm	D_{90} mm	D_{100} mm	C_u	σ_g	S_g
Badalan	Surface	22.8	25.4	41	49.2	77.2	91	200	2.2	1.7	2.65
	Subsurface	0.42	.67	3.9	7.2	16.7	20.6	37.3	13.4	5.0	2.65
(Aland)	Bed load	0.5	0.73	2.5	3.6	7.8	8.6	31	6	3.3	2.65
Yazdekan	Surface	17	18.7	32.1	41.7	63.1	75	180	2.1	1.8	2.65
	Subsurface	0.6	0.9	3.7	6.8	14.5	22	39	9.2	4.0	2.65
(Ghotor)	Bed load	0.7	0.95	3.7	6.4	13.7	20	30	8.5	4.8	2.65
Baron	Surface	16	22	35	41	48.5	53	90	2.4	1.5	2.65
	Subsurface	0.4	0.57	3.6	8.8	24.5	29	38.5	16.1	6.5	2.65
(Baron)	Bed load	0.47	0.6	1.9	2.8	4.8	7	12.2	5.3	2.8	2.65

D_s = Characteristic size; C_u = Uniformity Coeff.; σ_g = Geometric standard deviation; S_g = Specific gravity.

Table 3 Flow characteristics in three river reaches.

Reach (River)	Water flow rate Q (m^3/s)	Mean velocity V (m/s)	Water surface width B (m)	Hydraulic radius R (m)	Energy slope S (%)	Froude No. Fr	Shear stress τ (N/m^2)
Badalan (Aland)	14.2	1.76	15.6	0.51	0.95	0.78	47.5
	36.6	2.43	17.8	0.83	0.93	0.84	76.2
	62	2.81	20.9	1.03	0.93	0.86	94.5
	100	3.29	23.7	1.26	0.98	0.93	122.3
Yazdekan (Ghotor)	11.7	1.57	18.8	0.40	1.12	0.71	44.4
	48.7	2.46	22.9	0.85	0.95	0.75	79.3
	80.0	2.75	24.8	1.18	0.80	0.72	90.7
	120	3.01	25.8	1.53	0.70	0.68	103.3
Baron (Baron)	50	1.44	84.1	0.42	0.81	0.64	33.73
	100	1.82	91.9	0.61	0.68	0.67	40.16
	166	2.19	101.	0.76	0.78	0.73	58.01
	330	2.87	103.	1.12	0.74	0.78	81.66

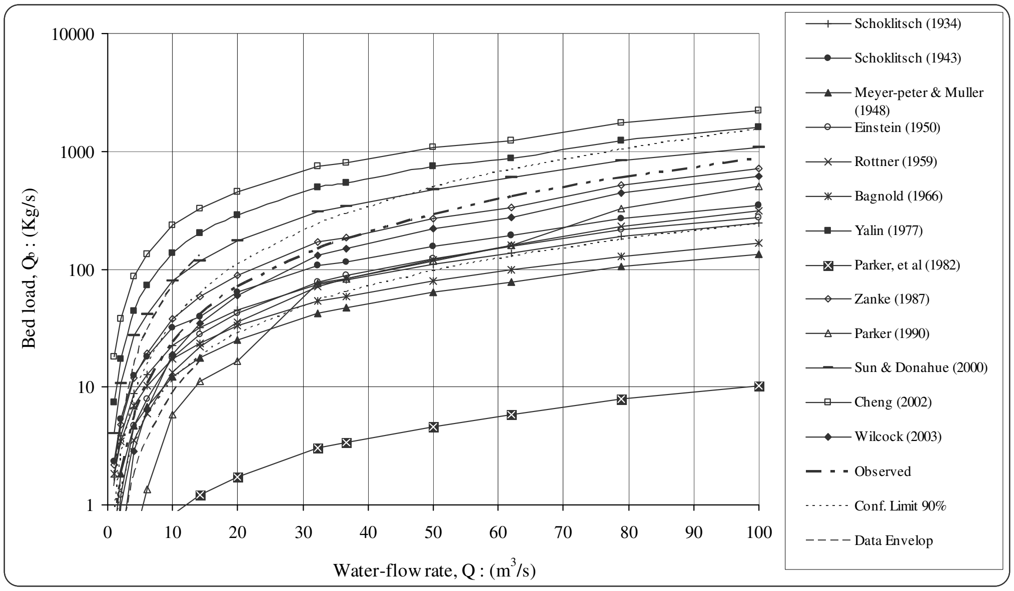

Fig. 1 Evaluation of bed sediment load (Q_b), Badalan River Reach.

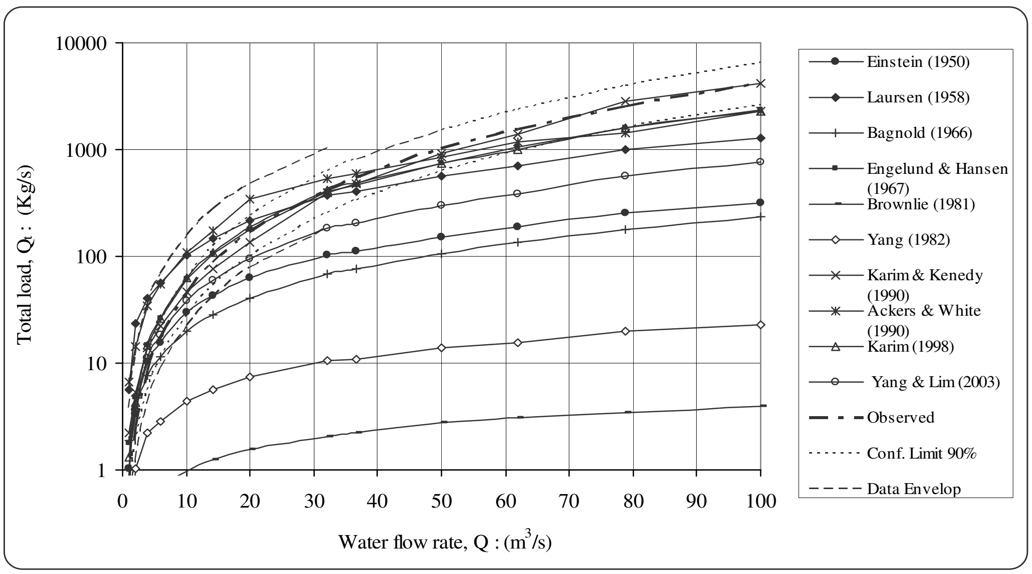

Fig. 2 Evaluation of total sediment load (Q_t), Badalan River Reach.

The overall results indicated that the relationship of Engelund (1965) gives better predictions for the calculation of suspended load with an average error of -77%. For the prediction of bed load, the methods of Schoklitsch (1934, 1943), Rottner (1959), Parker (1990), Zanke (1987), Wilcock & Crowe (2003) and Sun & Donahue (2000) are more reliable, with an average error of +37%. For the evaluation of total sediment load, the relationships of Ackers & White (1990), Engelund & Hansen (1967), Yang & Lim (2003), and Karim & Kenedy (1990) resulted in better predictions with an average error of -74%. The evident discrepancies in the prediction of the sediment loads are considered to be largely as the results of uncertainties in: (1) the present state of the relationships; (2) the contribution of wash load; (3) the lack of field sediment data for the range of the flood flows, and (4) the unavoidable order of errors in the state of the art of the field measuring and techniques.

Results indicated that for most of the relationships, the sediment transport capacity is well described when the characteristics of the bed-load material are included. The inclusion of the sub-surface bed layer into the predictive relationships is considered as the second priority. With the lack of information on bed-material loads in most practical cases, the characteristics of sub-surface bed layer is to be considered as input to the sediment relationships. This study shows that the inclusion of surface layer is not appropriate, which is coincident with the studies of Almedeij and Diplas (2003) and Habersack and Larone (2002).

The ratios of bed load to total load were evaluated in two different approaches: 1) using best fitted predictive methods for the determination of mean values of each of the three modes of sediment loads; and 2) using those methods that calculate both suspended load and bed load, and therefore the total load, on a similar basis (such as methods of: Einstein, 1950 and Bagnold, 1966). The typical results are presented in Figure 3 and Table 4, for the Badalan river reach, using both sub-surface bed layer and bed-load material characteristics.

With the inclusion of bed-load material characteristics, the ratios of bed load to total load were found to be in a range between 0.2 and 0.4 with an average value of 0.3 (using the first approach); and in a range between 0.7 and 0.8 with an average value of 0.77 (using the second approach). The second approach was found to be inappropriate, because neither Einstein's relationship nor Bagnold's relationship was well fitted to the field data. With the inclusion of sub-surface bed layer characteristics, the corresponding ratios were found to be in the range between 0.4 and 0.8 with an average value of 0.57, using the first approach. These ratios decrease with the increase in the flow rate.

Table 4 Ratio of bed load to total load (Q_b/Q_t), Badalan River Reach.

Method	Sediment load	Sub-surface layer					Bed-load material				
		Water flow rate: Q (m^3/s)					Water flow rate: Q (m^3/s)				
		14	32	50	79	100	14	32	50	79	100
Einstein (1950)	Q_b : (kg/s)	28	79	123	219	273	34	80	118	192	237
	Q_t : (kg/s)	35	97	153	276	351	42	102	152	255	318
	Q_b/Q_t	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7
Bagnold (1966)	Q_b : (kg/s)	17	54	80	129	165	22	50	74	120	154
	Q_t : (kg/s)	20	69	104	177	231	28	68	105	179	236
	Q_b/Q_t	0.9	0.8	0.8	0.7	0.7	0.8	0.7	0.7	0.7	0.7
Mean of best fitted methods	Q_b : (kg/s)	45	134	213	406	549	38	112	183	349	474
	Q_t : (kg/s)	61	186	320	682	1286	112	382	690	1505	2193
	Q_b/Q_t	0.7	0.7	0.7	0.6	0.4	0.3	0.3	0.3	0.2	0.2

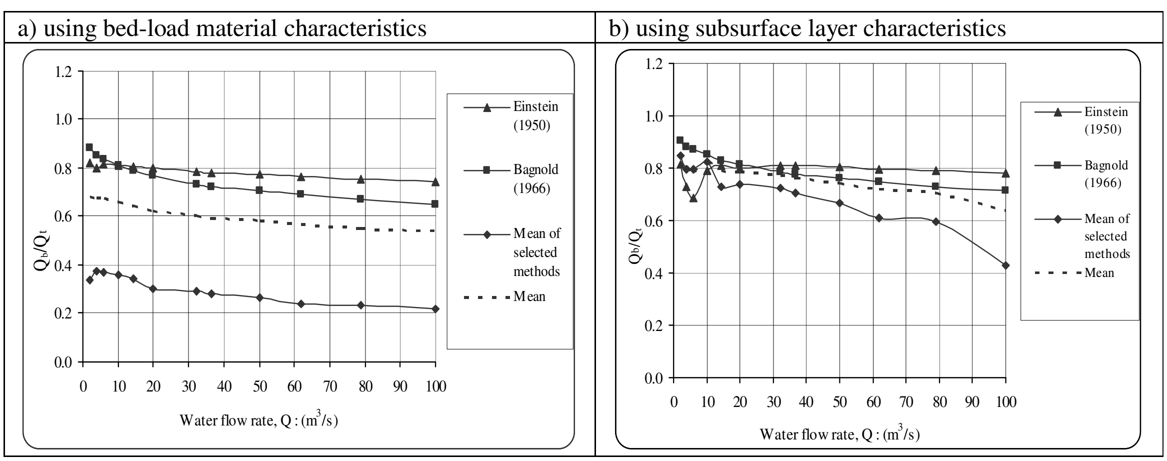

Fig. 3 Ratio of bed load to total load (Q_b/Q_t), Badalan River Reach.

The results indicate that the ratios of bed load to total load in coarse-bed rivers (in order of 40% to 80%) are significantly much higher than that in sand-bed rivers. It is noted that the conventional ratio of 5% to 25% results in significant underestimation in total sediment transport rate where dealing with rivers with coarse bed material. This is important particularly wherever the usefull life period of storage reservoirs are to be determined. However, the contribution of wash load and the need for reliable field sediment data, for the range of flood flows, should be addressed as major challenges in coarse-bed river engineering.

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