

Determination of friction factor over a pool reach, using double-average method

Abstract

Friction factor is the main parameter in hydraulics of open channels and rivers. This study was conducted in Saymareh River in western Iran. Two reaches were selected to investigate friction factor, one with pool bed form and other with plane bed. The objectives of the study are: to use double-average method over the selected pool for calculating friction factor and to compare the results with the calculated friction factor over the selected plane bed. In each reach, four cross sections were investigated and average flow velocity, shear velocity, shear stress and friction factor were determined. The results revealed that the prediction of friction factor change considerably between two selected reaches and double-average method works well for application of the law of the wall over a pool in a gravel-bed river. The form friction contribution to total friction is up to 82 percent over the selected pool.

Key words: Friction Factor; Double-Average Method; gravel-bed River; pool.

1. Introduction

Friction factor is one of the main parameters in river engineering projects. The sediment particles can significantly decrease the bed shear stress. For example, form friction due to bed forms in gravel-bed rivers can result in bed resistance that are 10–75% less than the total resistance to flow. Therefore, one of the main challenges for river engineers is to predict friction factor due to bed forms. The reason to underestimate friction factor in coarse-bed Rivers is not considered to the bed form effects at the flow direction [15]. Bed forms studies always are faced with the questions such as how each hydraulic parameter like Froude number (Fr), average flow velocity (V_m), shear velocity (V_*), shear stress (τ) and friction factor (f), can represent all variations along a reach.

Pools are one of dominant bed forms in Mountain Rivers, especially in gravel-bed Rivers. Many researchers have worked on the interaction of flow and bed forms [2,10,12,21].

The total friction factor can be divided into two components [2,4,5,20,22]:

(i) Skin friction factor which is due to surface of bed materials [17, 18], (ii) form friction which is due to bed forms such as pool. The existing friction factor equations estimate

flow discharge up to 100% error [9]. This error is partly due to ignoring the bed forms effect on friction factor and considering only the grain size effect in calculations.

Double-averaged (in time and space) Navier–Stokes equations were derived from a spatial averaging operation applied to the conventional time-averaged Reynolds equations provides a means of incorporating the effect of irregular bed boundaries. These equations include friction terms and form-induced momentum fluxes due to spatial heterogeneity of the time-averaged flow in the near-bed region. The double-averaging method (DAM) represents an accurate alternative of characterizing of 3D flows over irregular boundaries. An early application of this method was developed in the study of hydraulically rough beds due to dunes over gravel dunes and pools by Nasiri et al and Fazlollahi et al [6,15,24].

Nikora et al (2007) and Franka et al (2008) used DAM to determine friction factor [8,16]. For each variable depending on time, one can write:

$$u = \langle \bar{V} \rangle + \tilde{u} \quad (1)$$

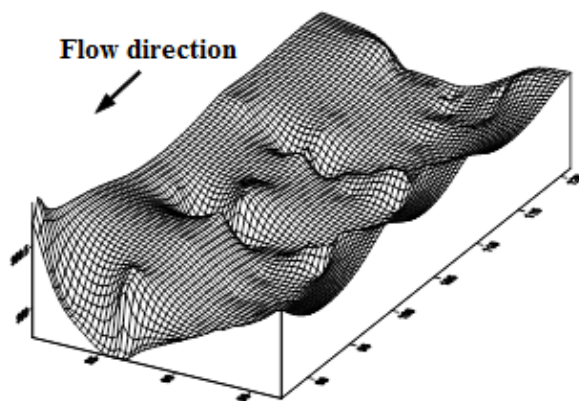
In which $\langle \bar{V} \rangle$, is double average velocity operator in time and space and $\tilde{u}$, is difference between space average value and double average value.

Few studies have been done using DAM on rivers in comparison with numerous laboratory experiments [3].

Since the pool reaches are one of the important features in gravel-bed Rivers, this study applies the double average method to evaluate friction factor along a pool reach. Therefore, objective of this research is to estimate friction factor over a pool using double average method and compare the results with friction factor over a plane-bed reach.

2. Material and Methods

This study was conducted in two different reaches of Saymareh river in western Iran, located in ($46^{\circ}07' - 49^{\circ}10'E$ and $33^{\circ}01' - 35^{\circ}00'N$). The first selected reach was a pool bed form with a 30-m long and 14 to 17-m wide. At this reach, four sections were selected to measure velocity, flow depth, water slope, particle size, cross section. In each section between 4-6 velocity profiles with 10-12 point velocity were measured. The water slope was determined 0.022. Fig. 1 shows a view of this reach along with bed form topography.



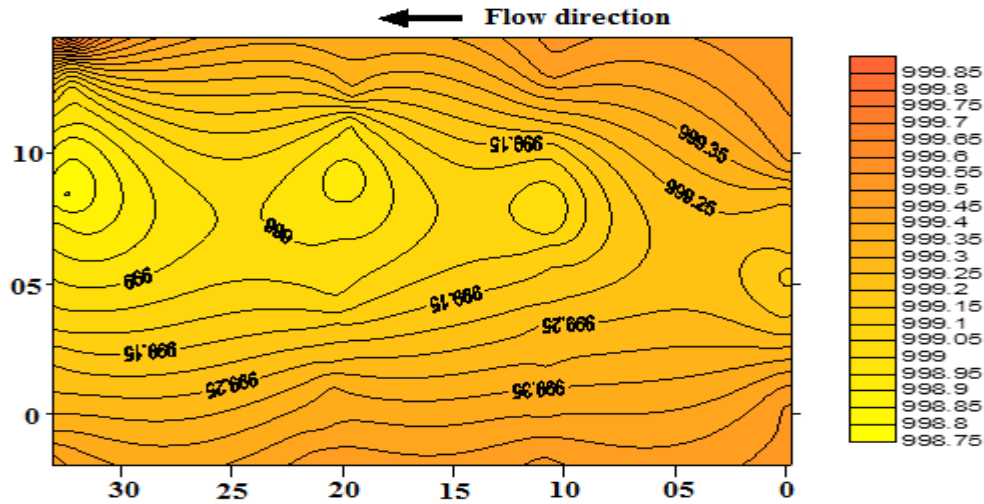


Fig. 1. (a) A view of the bed form reach (b) schematic of bed form (c) topographic contours of bed form

49 The second selected reach had a plane bed with 22-m long and of 6-8-m wide. In this reach, also
 50 four sections were measured where 3 to 5 velocity profiles with 8-10 point velocity were
 51 measured. Fig 2 shows a view of the plane reach and its topographic contours.

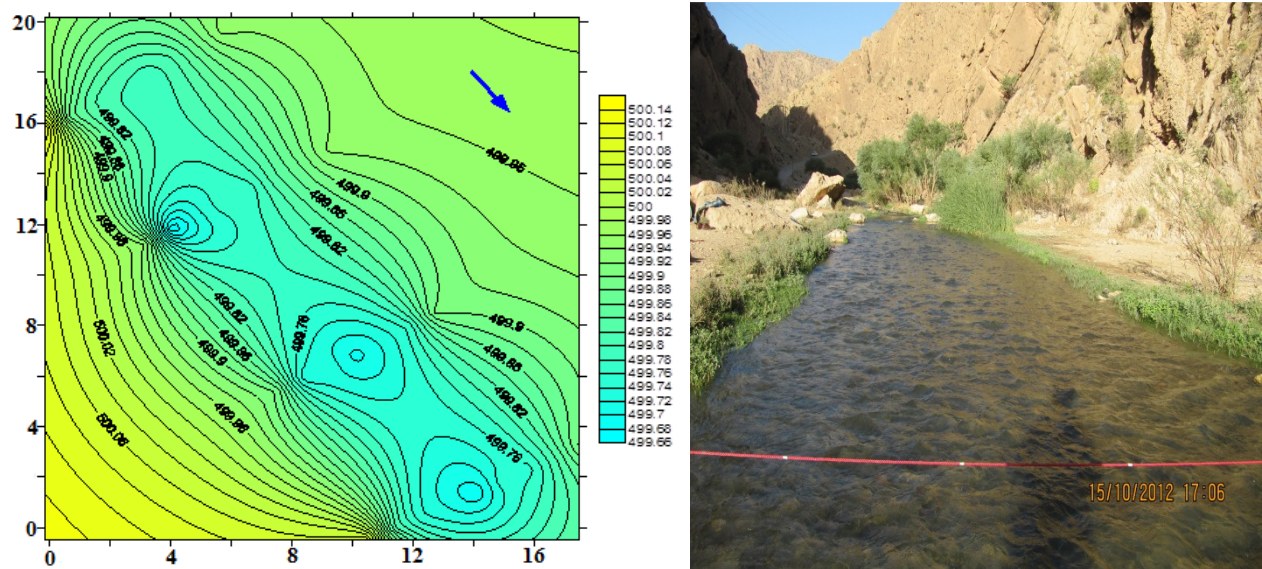


Fig. 2. (a) A view of the plan reach (b) schematic view of bed form (c) topographic contours of plane bed

52 To surveying the selected reaches and measuring the water slope, a total station camera was
 53 used. The bed forms and topographic contours were plotted using Surfer software and the curves
 54 were drawn with Sigma plot software.

55 The point velocity measurements were carried out at various flow depths using a current-meter
 56 made in Vale Port Company of England. The measuring time at each point velocity was 50
 57 seconds with three repeats.

58 Fig. 3 shows the flow velocity and topographic measurements as well as velocity profiles along
 59 the central axis of the selected reaches.

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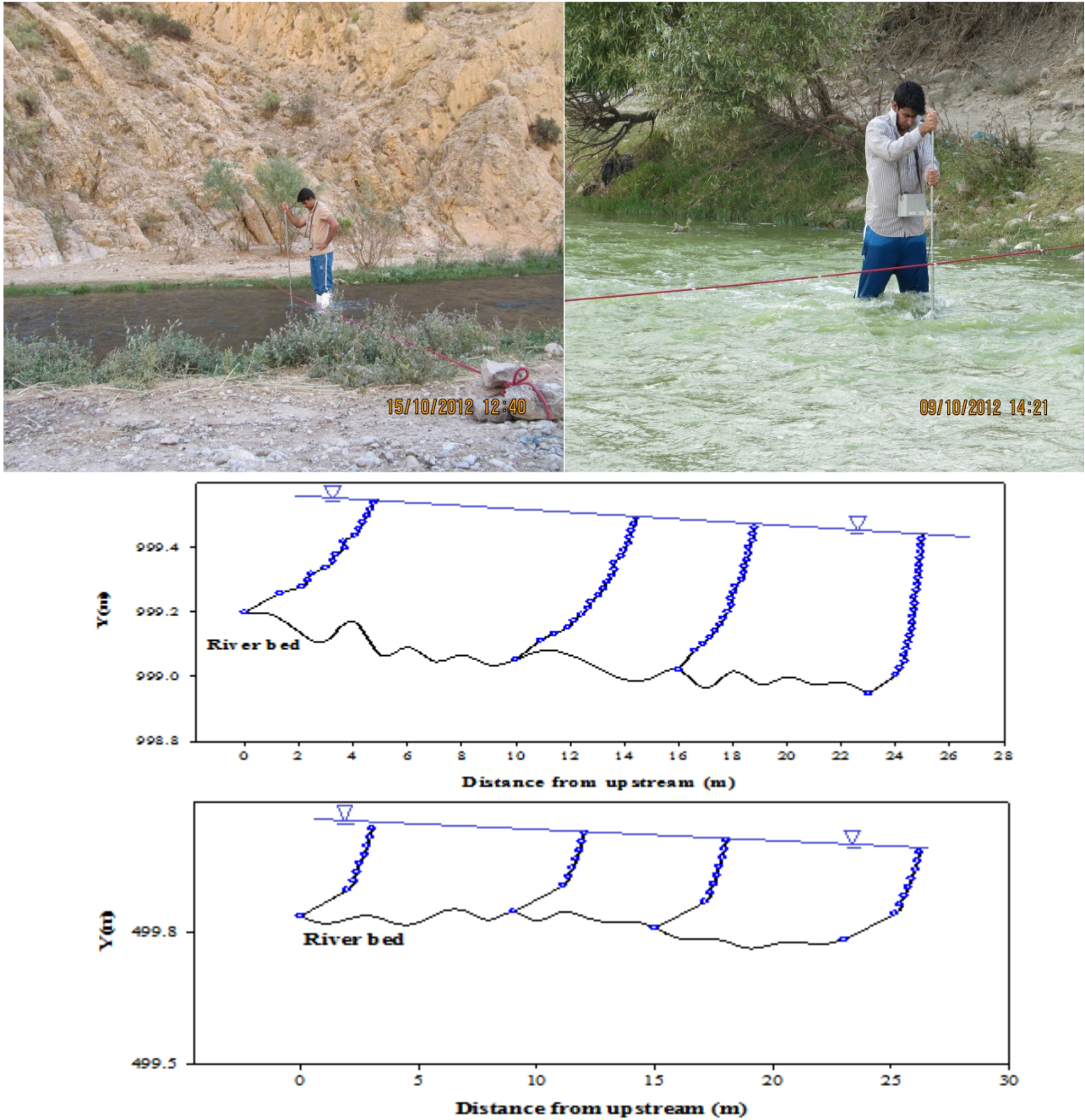


Fig. 3. (a) A view of topographic measurement (b) A view of velocity measurement (c) velocity profile along the pool (d) velocity profile along the plane bed

62 Darcy-Weisbach friction factor (f) is defined as follow [26]:

$$\frac{V_m}{V_*} = \sqrt{\frac{8}{f}} \quad (2)$$

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64 In which V_m is depth averaged velocity calculated by a velocity profile, V_* is shear velocity.

65 Shear velocity (V_*) was calculated using boundary-layer characteristics method (BLCM) using
66 each velocity profile as follow [1]:

$$u_* = \frac{(\delta_* - \theta)u_{max}}{4.4\delta_*} \quad (4)$$

67 In which δ_* is the displacement thickness; θ is the momentum thickness and u_{max} is maximum
68 velocity observed in a velocity profile; these thicknesses are defined as [23]:

$$\delta_* = \int_0^h \left(1 - \frac{u}{u_{max}}\right) dy \quad (5)$$

$$\theta = \int_0^h \frac{u}{u_{max}} \left(1 - \frac{u}{u_{max}}\right) dy \quad (6)$$

69 The total friction factor is presented as [26,27]:

$$f = f' + f'' \quad (7)$$

70 The total friction factor consists of two parts: the skin friction f' which is due to particle size and
71 the form friction f'' due to bed form effect. To calculate the skin friction factor, the equation 8 is
72 applied [2]:

$$f' = [0.9742 - 1.5225 \log(S_f)]^{-2} \quad (8)$$

73 In which S_f is friction slope, which is determined by Saint-Venant equation as:

$$S_f = S - \frac{dh}{dx}(1 - Fr^2) \quad (9)$$

74 Where Fr is the Froude number defined as $(V_m/\sqrt{gh})$; h = flow depth and g = gravitational
75 acceleration; S is the water slope and dh/dx is the water surface variation.

76 Wolman's method was used to calculate d_{16} , d_{50} , d_{84} and d_{90} from the particle size distribution
77 where for example d_{84} is the diameter that 84% of bed materials are finer and d_{16} is the diameter
78 that 16% of bed particles are finer.

79 To investigate, uniformity and non-uniformity of bed particle distribution, the geometric
80 standard deviation is defined as:

$$\sigma = \sqrt{\frac{d_{84}}{d_{16}}} \quad (10)$$

81 Bed materials are considered uniform if $\sigma < 1.5$ and non-uniform if $\sigma > 1.5$.

To apply the double average method (DAM), two average values are required: (1) time average which is the average of measured velocities during 50 seconds and three repeats, (2) spatial average that is the average of velocities having equal distance from the bed (see Fig.4).

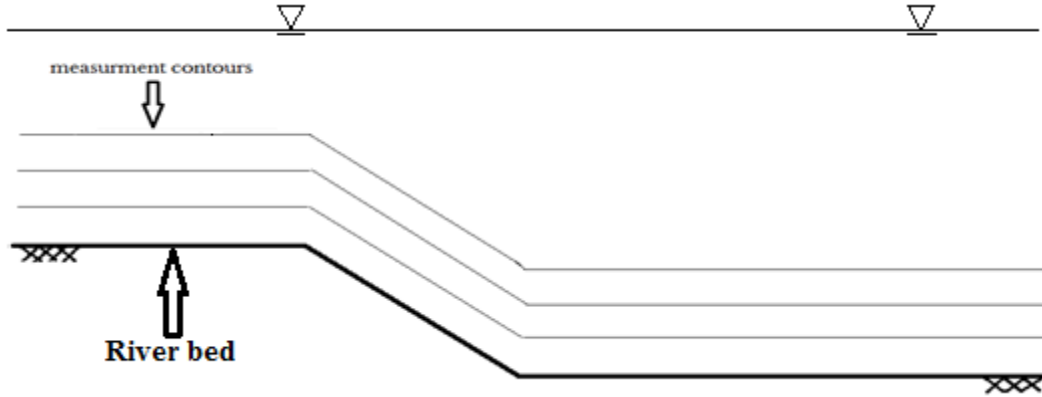


Fig. 4. Schematic of river bed and average contours

Time average is determined using equation 11 as:

$$\langle \bar{V}_t \rangle = \frac{\sum_{i=1}^n u_{ti}}{n} \quad (11)$$

In which $\langle \bar{V}_t \rangle$ is time average in each depth, n is number of repeat to calculate mean velocity and u_t is the measured point velocity by the current-meter.

Spatially average velocity is determined by equation 12 as:

$$\langle \bar{V}_s \rangle = \frac{\sum_{j=1}^m \langle \bar{V}_t \rangle_j}{m} \quad (12)$$

In which m is number of velocity profiles along the reach.

3. Results and discussion

The values of geometric standard deviation (σ) in table 1 show that the particle size distribution is non-uniform at the crest of pool; however, toward the pool center it becomes uniform gradually. This non-uniformity of particle size influences the velocity distribution and estimation of the friction factor. Results of particle size distribution showed that the particles over the pool especially at the crest are larger than the other parts of bed form, showing the reason of higher friction factor at the crest of pool. Different particle size diameters and the geometric standard deviation of particles are presented in table 1.

Table 1. Particle size diameters and geometric standard deviation in the selected reaches

Section number	d_{90} (mm)	d_{84} (mm)	d_{50} (mm)	d_{16} (mm)	σ
pool					
1	102	90	57	34	1.626
2	83	76	61	40	1.378
3	81	75	58	39	1.386
4	88	74	57	38	1.395
Plane bed					
1	68	55	34	25	1.483
2	60	51	37	26	1.400
3	61	58	40	28	1.439
4	62	52	35	24	1.471

Fig 5-a shows the velocity distributions along the central axis of the selected pool. This figure reveals that the flow velocity increases from section 4 toward the crest of pool (sections 1 and 2) due to increasing the flow depth. Therefore, the maximum velocity is observed at the top of the pool and the minimum velocity at the deepest part of the bed. This variation for velocity, the flow depth and shear velocity reveals that the measured or the calculated values at one section cannot be considered as the representative of the total reach. Therefore, it is required to apply the double average method for the hydraulic parameters, including velocity and shear velocity to obtain a unit value for each hydraulic parameter along a reach. Fig. 5.-b displays the particle size distribution at the locations where the flow velocity was measured. This figure illustrates the uniformity in the sizes of particles along the selected pool reach.

Fig 6-a shows the velocity distributions along the central axis of the plane-bed reach. This figure clearly reveals that all velocity profiles are similar and the flow depth, velocity and bed elevation have no considerable variations along the plane-bed reach. According to Fig. 6-b and the results of table 1 for the plane bed, particle size distribution is uniform ($\sigma < 1.5$).

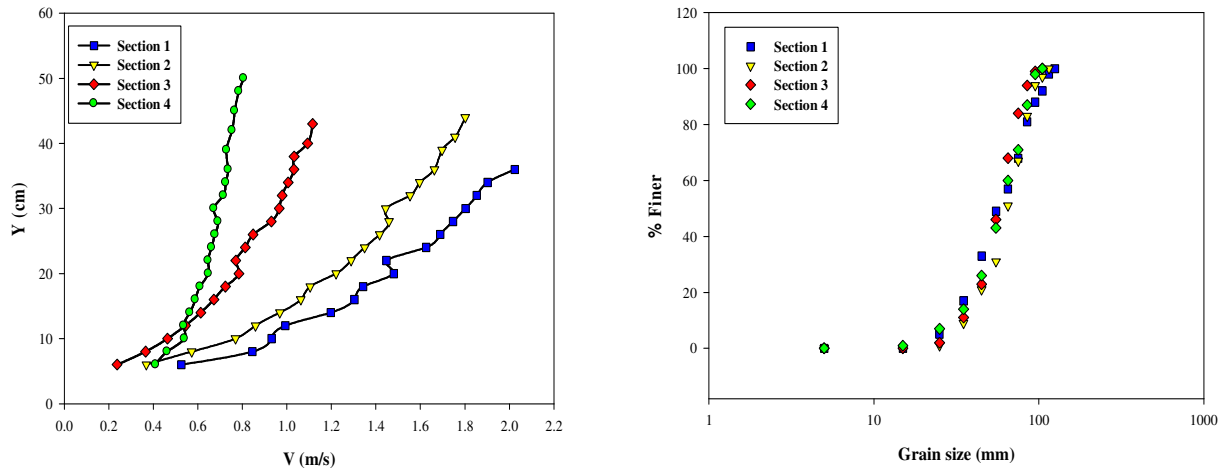


Fig. 5. (a) Velocity profiles along the pool reach (b) Particle size distribution along the pool reach

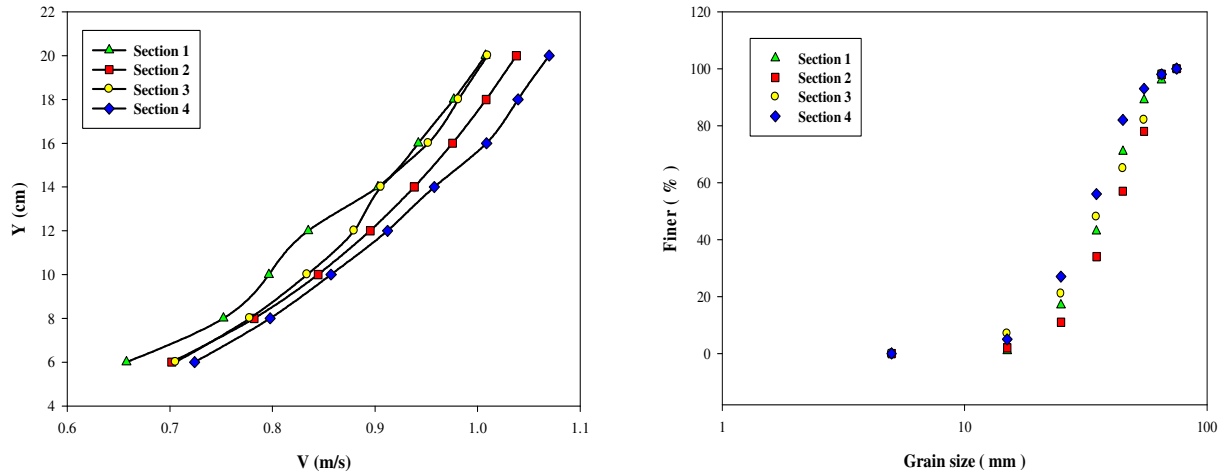


Fig. 6. (a) Velocity profiles along the plane-bed reach (b) Particle size distribution along the plane-bed reach

A summary of the measured and calculated hydraulic parameters are presented in table 2 for the both selected reaches, showing a considerable variation for each parameter along the pool reach. Froude number (Fr) and the relative submergence (h/d_{50}) are among the controlling parameters for friction factor [14]. However, the hydraulic parameters over the plane bed display negligible variation, showing that in the plane-bed reach, the double average method is not required and one section can be considered as the representative of all the sections along a reach.

Table2.Measured and Calculated Hydraulic Parameters

Section number	$d_{50}(\text{mm})$	$h(\text{m})$	h/d_{50}	$u_m(\text{m/s})$	$u_*(\text{m/s})$	Fr
pool						
1	57	0.36	6.31	1.234	0.267	0.452
2	61	0.44	7.21	1.140	0.238	0.370
3	58	0.46	7.93	0.720	0.146	0.215
4	57	0.56	9.82	0.633	0.080	0.175
Plane bed						
1	34	21	6.17	0.741	0.112	0.363
2	37	20	5.40	0.732	0.123	0.391
3	40	22	5.50	0.706	0.115	0.375
4	35	19	5.42	0.756	0.120	0.404

Table 3 presents the results of friction factor determination using contributions of skin (f') and bed form friction (f''). Third column for the pool reach shows that total friction factor decreases along the reach, due to increasing in the flow depth and relative submergence. The main part of friction factor along the plane bed is due to skin friction. The results of the fifth column indicate that form friction factor consists of 80% of total friction factor along the pool reach.

Table3.Calculated Friction Factor, skin and form Friction Factor

Section number	S_f	f	f' (Kulegan with shields)	f'' (Kulegan with shields)
pool				
1	0.026	0.376	0.087	0.289
2	0.010	0.349	0.063	0.286
3	0.011	0.331	0.065	0.266
4	0.006	0.129	0.054	0.075

In the tables of 4 to 7, the hydraulic parameters and their average values are compared for two selected reaches. Difference of the velocity at each section with the double average method along the pool reach is 18% to 32%, the differences for shear velocity is 19% to 56%, for shear stress is 30% to 82% and for total friction factor is 10% to 56%. On the other hand, these differences are less than 10% for the plane-bed reach. The considerable changes in the hydraulic parameters confirm the application of the double average method to estimate friction factor over the bed form reaches.

Friction factor (f) over the plane-bed reach was calculated using Eq. 2, while for the pool reach it was calculated by Eq. 7. Table 7 present the calculated friction factor for both reaches.

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Table4. Comparison of local velocity with arithmetic average of velocity

Section number	$V_m(m/s)$	V_m . average	Difference between V_m and V_m . average (%)
pool			
1	1.234	0.931	24.55
2	1.140		18.33
3	0.720		22.66
4	0.633		32.00
Plane bed			
1	0.741	0.733	1.07
2	0.732		0.13
3	0.706		3.68
4	0.756		3.04

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Table5. Comparison of local shear velocity with arithmetic average of shear velocity

Section number	$u_*(m/s)$	u_* . average	Difference between u_* and u_* . average (%)
pool			
1	0.267	0.182	31.83
2	0.238		23.52
3	0.146		19.78
4	0.080		56.04
Plane bed			
1	0.112	0.117	4.27
2	0.123		4.87
3	0.115		1.70
4	0.120		2.50

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Table6. Comparison of local shear stress with arithmetic average of shear stress

Section number	$\tau \left(N/m^2 \right)$	τ . average	Difference between τ and τ . average (%)
pool			
1	71.74	39.17	45.40
2	56.75		30.97
3	21.52		45.05
4	6.67		82.97
Plane bed			
1	12.60	13.91	9.41
2	15.23		8.66
3	13.25		4.74
4	14.57		4.52

Table7.Comparison of local friction factor with arithmetic average of friction factor

Section number	f	f.average	Difference between f and f. average (%)
pool			
1	0.376	0.296	21.27
2	0.349		15.18
3	0.331		10.57
4	0.129		56.41
Plane bed			
1	0.183	0.206	11.16
2	0.228		9.64
3	0.212		2.83
4	0.203		1.45

151 In the table 8 hydraulic parameters of DAM profile are presented.

Table 8.Calculated Hydraulic Parameters by the Double Average Method (DAM)

f			
0.859	0.178	31.75	0.344

152 Fig.7-a shows DAM profile along with the measured velocity profiles at the central axis the
 153 pool.This figureshows that DAM profile can be used instead of four profiles to calculate the
 154 hydraulic parameters along a reach, confirming the results of Franca et al [8] for application
 155 DAM.Fig. 7-bshows that the law of the wall fits well on DAM profile. According the shear

velocity can be calculated by the DAM profile and consequently, the friction factor can be evaluated better over bed forms in gravel-bed Rivers.

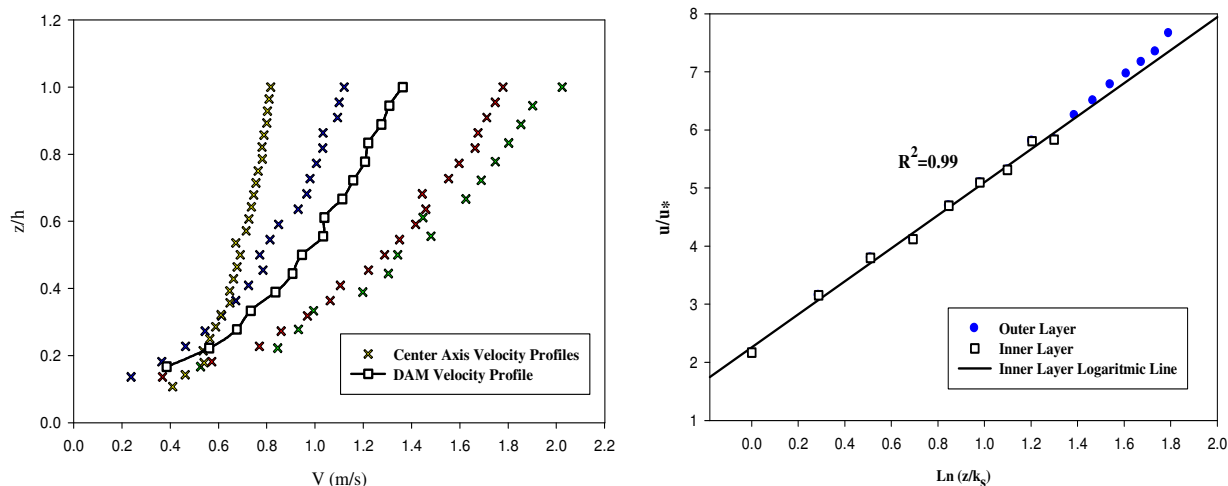


Fig. 7. (a) DAM and local velocity profiles along the central axis of the pool (b) Fitness of the law of the wall using DAM velocity profile

A comparison of total friction factor at each cross section and DAM friction factor is presented in table 9. The fourth column shows that DAM friction factor has little difference with total friction factor toward the crest of pool (sections 2 and 3), however, the difference is considerable (up to 62.5 percent) at the pool center (section 4) due to difficult flow conditions in this section. The results confirm that double average method can be useful to estimation of friction factor in pools.

Table 9. Comparison of local friction factor with the calculated friction factor using DAM along the pool reach

Section number	f	f by DAM	Difference between f and f. DAM (%)
1	0.376	0.344	8.51
2	0.349		1.43
3	0.331		3.77
4	0.129		62.50

4. Conclusion

Results show that a major portion of the total friction factor over the selected pool is due to the form friction. Accordingly, the contribution of form friction over pool reach varies from 58 to 82 percents. Double average method can reasonably apply in a gravel-bed river to estimate shear velocity either by the law of the wall method (Fig. 7) or by the boundary layer characteristics

method (Eq. 4) which is a key parameter in friction factor prediction. Comparison of the calculated friction factor by arithmetic average (table 7) with the calculated one by double average method (DAM) over the pool reach reveals that in general, DAM presents a closer estimation to local values of friction factor. The difference between local estimation of friction factor and the double average method one is up to 62.5 percent. DAM can present results that are more accurate if the number of velocity profiles increase along the reach. The calculations of hydraulic parameters over the plane-reach show that there are no considerable difference between local and average estimation, confirming unnecessary of DAM over a plan-bed reach. Finally, double average method could reduce unnecessary costs in river engineering projects.

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