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Creep Velocity of Non-Spherical Gravel Particles in Mountainous Regions

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Authors' contribution

This work was carried out in collaboration among all authors. Author AK designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors AK and PVS managed the analyses of the study. Author AK managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

The movement of sediment particles is governed by the relative magnitude of acting drag and the resistance offered by the particle. The magnitude of drag force that acts on a sediment particle depends on flow parameters as well as on the surface area of the particle exposed to flow. Similarly, the resistance offered by the particle depends on its weight and the surface area of the particle in contact with the stream bed. In the case of spherical particles, orientation does not play an important role, while in the case of non-spherical particles how particle orients itself play a vital role. Therefore, in the case of non-spherical particles, which is the real situation, the movement velocity of sediment particles will depend on their orientation. Numerous studies have been conducted for spherical particles but literature is lacking information for non-spherical particles. In this study, experiments were conducted on coarse solitary non-spherical gravel particles to observe their creep velocity with their changed orientations under varying flow conditions. The experimental finding unveiled that the creep velocity of these particles not only depended on the shape and size of the particles but also on their orientation relative to the flow direction. It was observed that for a particle of a given size, the orientation of the particle which leads to maximum exposed area i.e O2 orientation resulted in the highest creep velocity. The findings of the study have been illustrated with mathematical relationships and graphical representations for various combinations of input variables.

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1. INTRODUCTION

In mountainous regions stream beds constitute coarse gravel particles and sediment transport in gravel-bottomed streams is generally through surface creep as bedload transport due to the presence of larger-sized particles. In surface creep, gravel particles moved along the ground rather than moving in bounces and in suspension with a velocity which is defined as the creep velocity of particles. The bedload transport process is a very complex phenomenon owing to the involvement of a large number of variables related to channel (bottom slope, width, depth, roughness), fluid (flow velocity, flow type), and sediment (shape, size, density) characteristics and to quantify each factor, theoretically and experimentally remains challenging. Accurate information about the mechanism and the extent of sediment transport is mandatory to design programs to solve the problems of excessive erosion, reservoir sedimentation, channel scoring, river morphological changes, etc. Many studies are done and are underway to extract information about the flow conditions and sediment characteristics that affect the movement of sediment particles [1-7]. Gogus and Defne (2005) [8] have aimed to clarify the effect of shape and size of particles having constant specific weight on the threshold of motion. However, they did not examine the grain velocity of particles. Julien and Bounvilay (2013) [9] analyzed the reach-averaged bedload particle velocity for particles of different sizes and densities on smooth and rough plane surfaces. Cheng and Emadzadeh (2014) [10] included the effect of the bed roughness on the bed-load grain velocity, however, they did not consider different orientations of particles. The other earlier studies include Einstein (1950) [11], Ippen and Verma (1955) [12], Meland and Norrman (1966) [13], Francis (1973) [14], Fernandez Luque and van Beek (1976) [15], and Bridge and Dominic (1984) [16]. There are numerous studies have also focused on advanced methods of field measurements of bedload transport by De Vries (2002) [17], Habersack and Laronne (2002) [18], Kleinhans and van Rjin (2002) [19], Bunte et al. (2004) [20] and Rennie et al. (2002) [21]. To simplify relevant physical phenomena, laboratory observations of sediment motion near the bed could focus only on a solitary bedload grain.

Normally in natural streams, the sediment particles are not spherical. In situations where sediment particles are not spherical and cubical, the orientation or placement of these particles over the bed will play an important role in their movement. The nature of the orientation of the particle will change the entire force dynamics a particle is experiencing for a particular set of conditions. There are many parameters used to characterize irregular particle-like sphericity, Corey shape factor (CSF), and Zingg's classification factor (ZCF). With the change of orientation, the area of the particle exposed to the flow and the area of the particle in contact with the channel bed will change. This will alter the entire force dynamics on the particle though the bed shear stress will remain the same for a given discharge condition. However, very little work is reported in the available literature on non-spherical particles, particularly on the effect of orientation of these particles on their movement. In this study, a new parameter in the form of the ratio of the exposed area (A_e) to the base area (A_b) of particle and represented by the term EATBAR (λ). For a given particle with the change in placement position i.e., change in orientation, the value of EATBAR (λ) will change which will lead to changed movement behavior of a sediment particle though the flow and other conditions remaining unchanged. Considering this fact, in this study, experiments were conducted under controlled conditions of a laboratory on artificially constructed rectangular-shaped gravel particles of different sizes with the following objectives.

I. To determine creep velocity for different orientations of particles under varying discharge
II. To analyze and develop mathematical relationships for creep velocity of the particle under varying conditions of discharge.
III. To compare observed and predicted creep velocity of the particle.

2. MATERIALS AND METHODS

2.1 Experimental Setup

Laboratory experiments were conducted using a 7 m long metallic rectangular hydraulic tilting flume with a 1m long settling chamber at its upstream end to ensure a smooth water flow. The testing section of the flume was 6m long, 0.30 m wide, and 0.60 m deep. The sides of the flume were provided with a thick transparent

Perspex sheet to facilitate visual observation of flow patterns along the flume. The water supply is through a centrifugal pump of 5 hp installed downstream of the flume and receives water from a water storage tank. The water supply to the flume is regulated through regulatory valves mounted on the water supply line of the flume. The flow measurement is done through a water flow meter fitted in the supply line near the upstream end of the flume. The flume has two adjustable gates with rack and pinion arrangement and is provided with a pipe railing in total flume length between the gates for movement of pointer gauge trolley over the entire length of the flume. The uniform flow condition was maintained by monitoring the depth with a mobile point gauge attached to the channel. The experimental setup is available in the Soil and Water Conservation Laboratory of the Department and used in this study is shown in Fig. 1.

2.2 Description of Particle Size and Orientations

In this study, three different sizes of artificially cast sediment particles, of rectangular shape were used. These particles were designated as P_1, P_2, and P_3 with respective of size (length x width x height) as (2x2x3) cm, (2x2x4) cm, and (3x3x4) cm. The specific weight of these particles was 3.68 and are taken to maintain the same specific weight of these particles constructed by using a common mixture of sand, cement, and gravel. These rectangular particles were examined in three orientations namely O_1, O_2, and O_3 according to their exposed surface area facing the flow. The orientation, O_1, was with the major dimensions aligned with the flow direction, while in the second orientation, O_2, it was the major dimensions as perpendicular to the flow. In both of the above cases, the minor dimension was always the height of the particle. In the third orientation, O_3, the minor dimension of the particle was perpendicular/aligned with the flow direction to the flow and the major dimension was always the height of the particle. Although, in O_3 orientation particle is not in stable condition and is likely to transform to any other orientation according to flow dynamics. In this way, three combinations were possible for one sized particle (P_1) for three sizes of particles total of nine combinations have experimented for their movement behavior. Accordingly, combinations of orientations with three particle sizes were referred to as P_1O_1, P_1O_2, and P_1O_3 for Particle P_1, while P_2O_1, P_2O_2, and P_2O_3 for particle P_2, and P_3O_1, P_3O_2, and P_3O_3 for particle P_3. Each combination was experimented with six rates of selected discharge thus making the total number of trials fifty-four. The description of orientations is presented pictorially in Fig. 2.

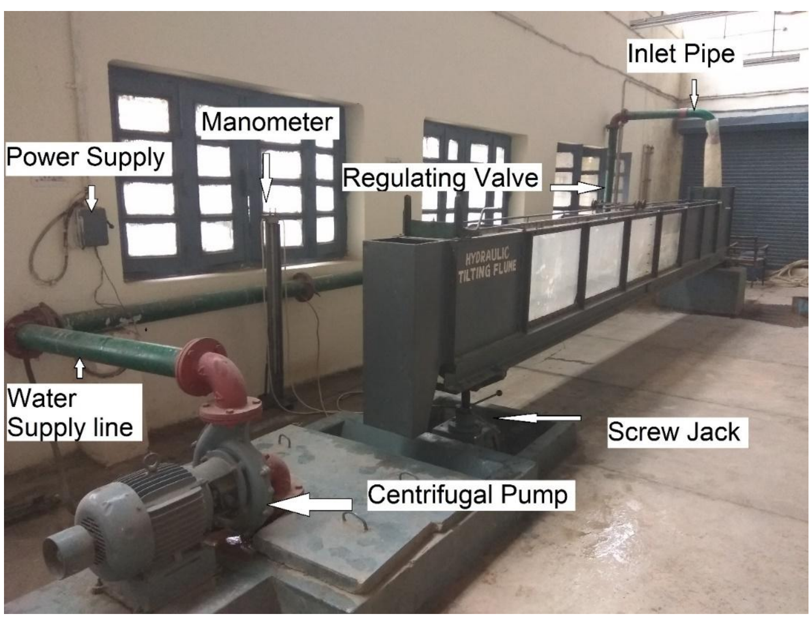

Fig. 1. A view of an experimental set-up

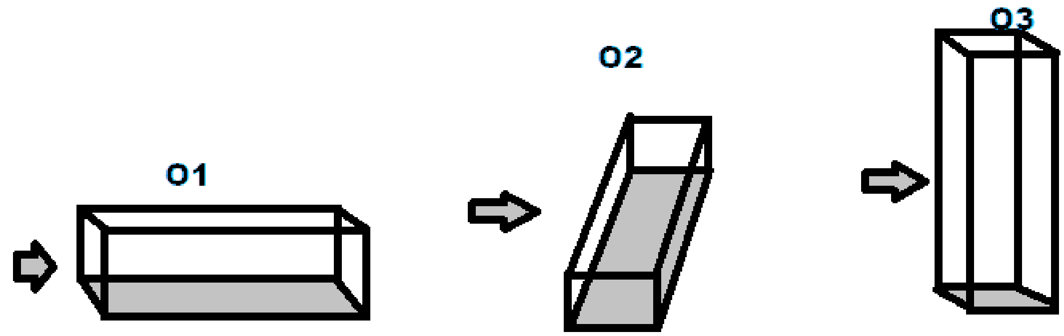

Fig. 2. Orientations of particle and their plan view with the flow direction

2.3 Experimental Procedure and Observations

In this experiment, a sediment particle of a given size was placed in the desired orientation on the bed at a 3.5 m distance from the upstream end of the flume to get a fully developed flow. The bed slope of the flume was set at 0.025. The specified discharge was allowed to the setup with the help of a regulating valve. Care was taken to avoid turbulence and to create smooth flow along the entire length of the flume. After the establishment of smooth flow, the observations of flow depth were made by using a point gauge. The remaining downstream span of 2.7 m length in the flume was available for the movement of the particle. The time taken by the particle to complete the travel distance was noted with the help of a precise stopwatch. The total distance of the span divided by the total time taken by the particle to travel provided the velocity of the particle. The individual particle velocity measurements were repeated at least 3 times to eliminate error, if any, to ensure accuracy in average velocity. During the experiment, varying discharge conditions were created to conduct an experiment and to obtain definite findings. The sediment particle showed consistent sliding motion for all different hydraulic conditions. Thus, recording of flow depth and particle velocity were done for each combination of three orientations of particle (P_1) i.e.; P_1O_1, P_1O_2, and P_1O_3 for six different discharges such as 12.8 l/s/m,17.6 l/s/m, 23.2 l/s/m, 25.9 l/s/m,29.6 l/s/m and 33.6 l/s/m, at fixed slope. In this way, the experiment was conducted for a total of 54 (3x3x6) runs for the particle creep velocity determination.

The value of the newly incorporated term EATBAR (λ) which is the ratio of the exposed area (A_e) to the base area (A_b) of particle which changed with the change in orientation is mainly responsible for the change in the movement behavior of a particle of a non-spherical particle is expressed as:

$$\lambda = \frac{Ae}{Ab}$$

Values of EATBAR (λ) were determined for different orientations of the particles considered in this study and are presented in Table 1.

The average creep velocity of the particle was observed for three artificially constructed particles of 2x2x3 cm, 2x2x4 cm, and 2x3x4 cm called P_1, P_2, and P_3 respectively with orientations as O_1, O_2, and O_3 used in this study. A fixed span of 2.7 m length in the flume was considered for particle travel under a particular orientation and flow condition. The total time taken by the particle to complete the travel distance was noted. The total distance of the span divided by the total time taken by the particle to travel provided the average creep velocity of the particle for a particular set of conditions. This way observations were recorded for various combinations of input variables including particle size, particle orientation, and flow rate. The recorded observations were put to statistical analysis to develop mathematical models for creep velocity for selected orientation in terms of flow rate and EATBAR **(λ)** by following multiple regression analysis.

Table 1. Maximum values of EATBAR (λ) for different orientations of rectangular gravel particles

Particle Dimensions	Orientation	Exposed area (cm^2)	Base area (cm^2)	Maximum value of EATBAR(λ)
P_1(2x2x3 cm)	P_1O_1	2x2=4	2x3=6	0.67
	P_1O_2	2x3=6	2x3=6	1.00
	P_1O_3	2x3=6	2x2=4	1.50
P_2(2x2x4 cm)	P_2O_1	2x2=4	2x4=8	0.50
	P_2O_2	2x4=8	2x4=8	1.00
	P_2O_3	2x4=8	2x2=4	2.00
P_3(3x3x4 cm)	P_3O_1	3x3=9	3x4=12	0.75
	P_3O_2	3x4=12	3x4=12	1.00
	P_3O_3	3x4=12	3x3=9	1.33

3. RESULTS AND DISCUSSION

The observations recorded in Table 2. and presented graphically in Fig. 3. clearly indicated that the value of EATBAR (λ) was lowest in orientation O_1 and was the highest in orientation O_3 in all cases. The average creep velocity of a particle was found to be the highest in O_2 orientation and was lowest in orientation O_1 for all sizes of particle. It may be emphasized that in O_2 orientation for all sizes of the particle, the value of EATBAR (λ) is unity i.e., the surface area of particle exposed to flow is equal to the surface area in contact with channel bed. It was observed that with the increased discharge from 12.8 l/s/m to 33.6 l/s/m, the average creep velocity in O_1, O_2, and O_3orientationsfor every particle increased. For discharge of 12.8 l/s/m the average creep velocity of particle for orientations O_1, O_2, and O_3 was 0.443m/s, 0.474m/s, and 0.466m/s respectively for particle size (2x2x3) cm, 0.000m/s, 0.458m/s, and 0.435m/s respectively for particle size (2x2x4) cm and while 0.000m/s, 0.156m/s, and 0.000m/s respectively for particle size (3x3x4) cm. It was found that in O_1 orientation the only particle P_1 having a size (2x2x3) cm moved at 12.8 l/s/m discharge and other particles did not move. Mathematical relationships for average creep velocity (V_p, cm/s) of sediment particles in all three orientations developed in terms of EATBAR (λ) and discharge (Q, l/s/m) using multiple linear regressions are presented in Table 3.

Table 2. Observed flow parameters and average creep velocity of a particle in different orientations

Discharge (Q), l/s/m	Depth of flow (Y), m	Hydraulic radius (R=A/P), m	Orientation	Average Velocity (V_P), m/s		
				P1	**P2**	**P3**
12.8	0.020	0.0176	O1	0.443	0.000	0.000
			O2	0.474	0.458	0.156
			O3	0.466	0.435	0.000
			O1	0.466	0.458	0.000
17.6	0.025	0.0214	O2	0.587	0.643	0.370
			O3	0.563	0.540	0.000
			O1	0.643	0.519	0.466
23.2	0.029	0.0243	O2	0.730	0.643	0.614
			O3	0.675	0.574	0.574
			O1	0.614	0.500	0.491
25.9	0.032	0.0264	O2	0.750	0.675	0.551
			O3	0.692	0.659	0.509
29.6	0.035	0.0284	O1	0.614	0.500	0.491
			O2	0.750	0.675	0.551
			O3	0.692	0.659	0.509
			O1	0.730	0.730	0.711
33.6	0.038	0.0303	O2	0.844	0.844	0.794
			O3	0.818	0.771	0.730

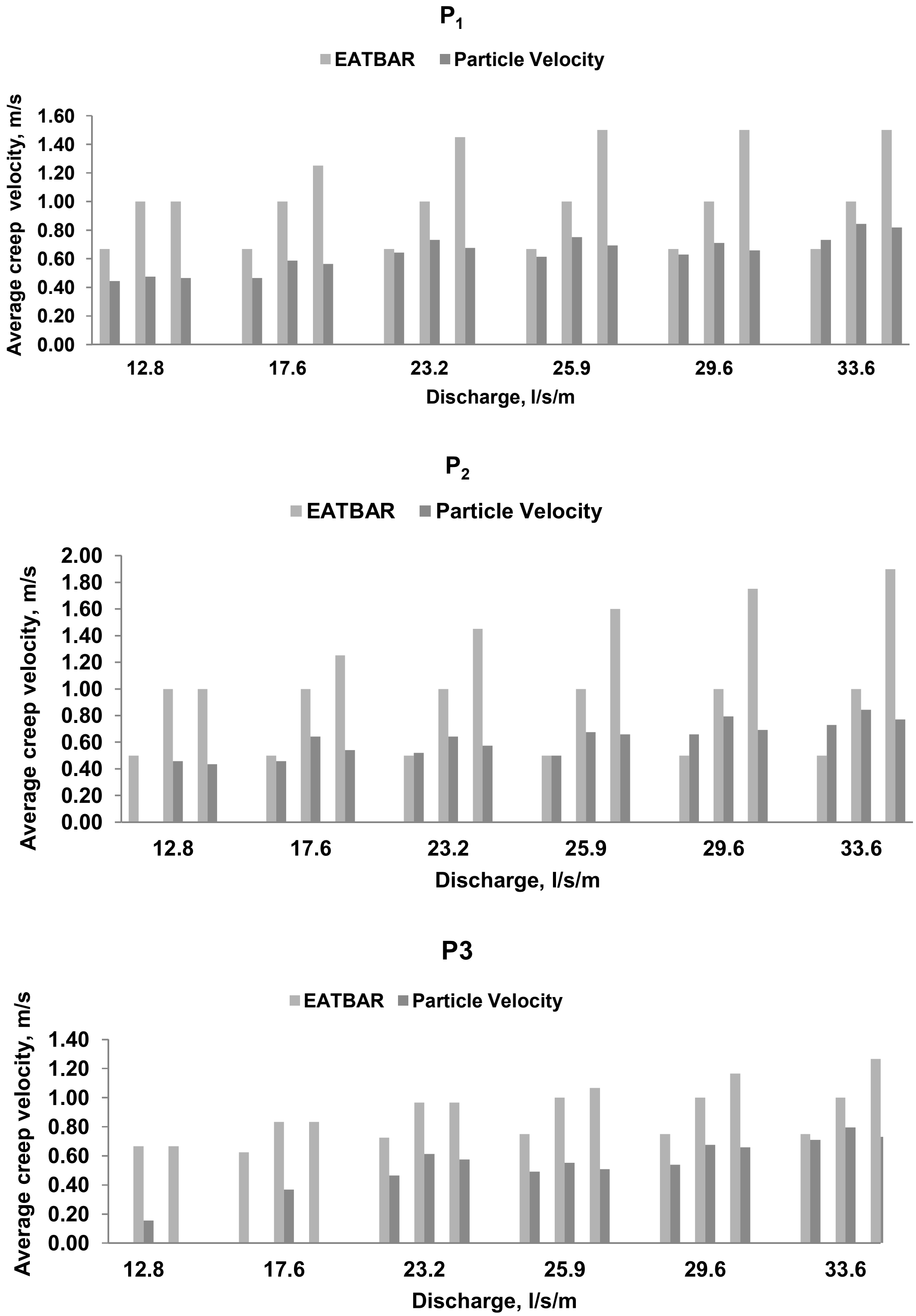

Fig. 3. Average creep velocity of particle for different orientations with varying discharge

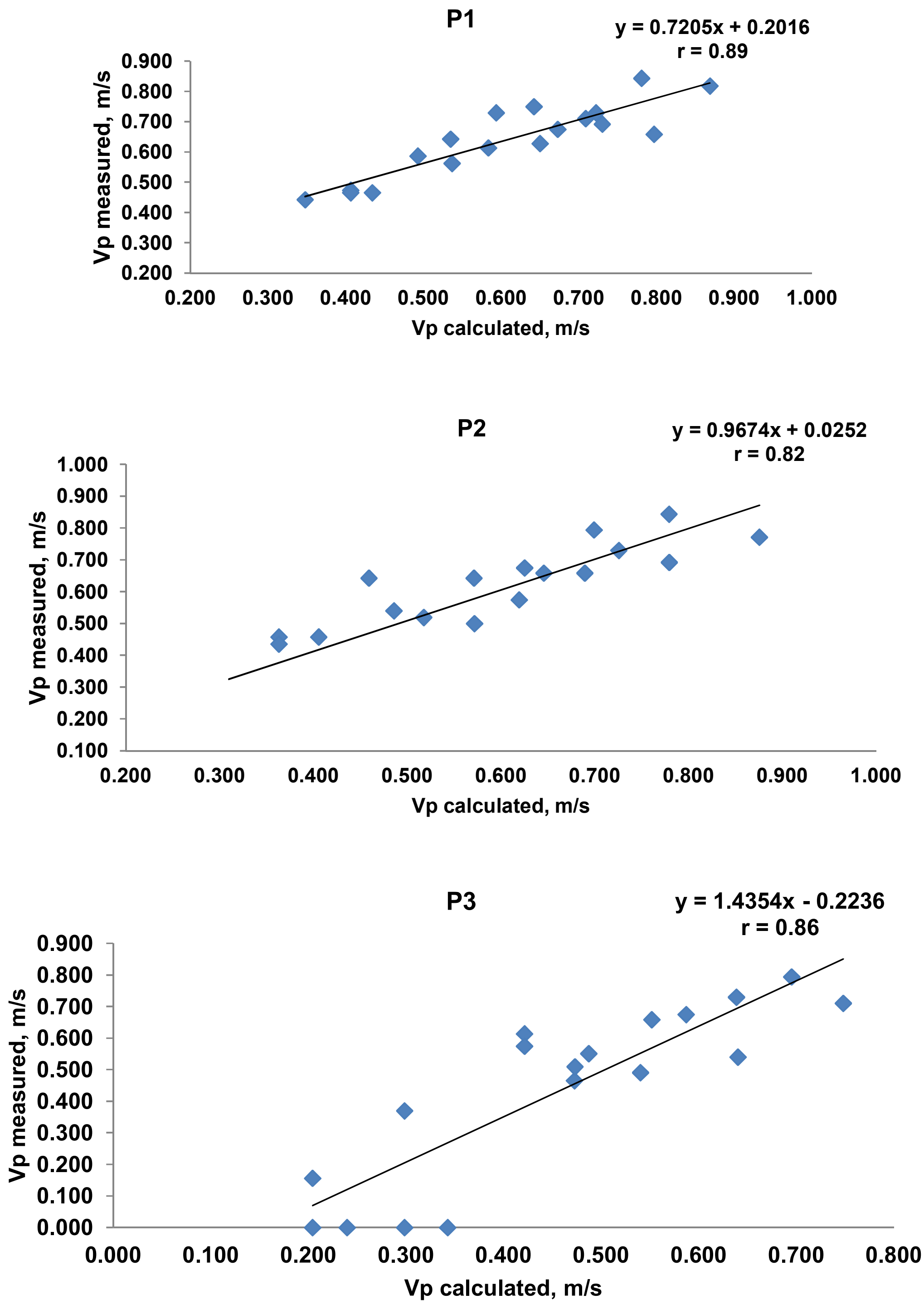

Fig. 4. Model calculated and observed creep velocity for particle P_1, P_2, and P_3

These mathematical models indicated a strong dependence of particle velocity on EATBAR (λ) and discharge with more than 0.90 coefficient of multiple determination. The value of the coefficient of multiple determination has decreased from 0.9882 to 0.9093 as the particle size increased. To assess the performance of developed relationships, the creep velocity calculated by using the developed relationship was compared with the corresponding experimentally observed creep velocity of the particle. In general, a good correlation was found to exist between model calculated and measured values of creep velocity for all three sizes of particles. Graphical plots for visual comparison are shown in Fig. 4 for particlesP_1, P_2, and P_3.

Table 3. Mathematical relationships for average creep velocity (V_p, cm/s)

Particle	(V_p, cm/s)	R^2
P_1	0.176λ+0.018Q	0.9882
P_2	0.107λ+0.020Q	0.9713
P_3	-0.212λ+0.027Q	0.9093

4. CONCLUSION

In the case of non-spherical particles, the exposed area and the base area of a particle change with its placement position (orientation) which leads to a complete change of force dynamics responsible for sediment transport. This experimental study mainly focused to ascertain the effect of particle orientations on creep velocity of non-spherical gravel particles under varying discharge conditions. The flow parameters were recorded and the creep velocity of particles was observed for different orientations in terms of the exposed area to base area ratio (EATBAR). Based on experimental observations, the average creep velocity of a particle was found to be the highest in O_2 orientation and was lowest in orientation O_1 for all sizes of particle. It may be emphasized that in O_2 orientation for all sized particles, the maximum value of EATBAR (λ) was unity i.e., the surface area of particle exposed to flow is equal to the surface area in contact with channel bed. In general, it was however observed that for a particle of a given size, the orientation of the particle which leads to the maximum exposed area resulted in the highest creep velocity. It was also observed that for every orientation, the creep velocity increased with increasing discharge. Mathematical relationships developed for average creep velocity of the particle in terms of EATBAR, and discharge provided satisfactory results with a coefficient of multiple determinations more than 0.9. The developed mathematical relationship for average creep velocity is compared with observed average creep velocity which shows good agreement having a correlation coefficient greater than 0.82.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Bridge JS, Bennett SJ. A model for the entrainment and transport of sediment grains of mixed sizes, shapes, and densities. Water Resources Research. 1992;28(2):337-363.
2. Best J, Bennett S, Bridge J, Leeder M. Turbulence modulation and particle velocities over flat sand beds at low transport rates. Journal of Hydraulic Engineering.1997;123(12):1118-1129.
3. Dancey CL, Diplas P, Papanicolaou A, Bala M. Probability of individual grain movement and threshold condition. Journal of Hydraulic Engineering. 2002;128(12):1069-1075.
4. Cheng NS. Exponential formula for bedload transport. Journal of Hydraulic Engineering.2002;128(10):942-946.
5. Guo QC, Jin YC. Modeling nonuniform suspended sediment transport in alluvial rivers. Journal of Hydraulic Engineering. 2002;128(9):839-847.
6. Chang SY, Yen CL. Simulation of bed-load dispersion process. Journal of Hydraulic Engineering. 2002;128(3):331-342.
7. Almedeij JH, Diplas P. Bedload transport in gravel-bed streams with unimodal sediment. Journal of Hydraulic Engineering. 2003;129(11):896-904.
8. Gogus M, Defne Z. Effect of shape on incipient motion of large solitary particles. J. Hydroul. Engg.2005;131(1):38-45.
9. Julien PY, Bounvilay B. Velocity of rolling bed load particles. Journal of Hydraulic Engineering. 2012;139(2):177-186.

10. Cheng NS, Emadzadeh A. Average velocity of solitary coarse grain in flows over smooth and rough beds. Journal of Hydraulic Engineering. 2014;140(6): 04014015.
11. Einstein HA. The bed-load function for sediment transportation in open channel flows (No. 1026). US Government Printing Office. 1950.
12. Ippen AT, Verma RP. Motion of particles on bed of a turbulent stream. Transactions of the American Society of Civil Engineers. 1955;120(1):921-938.
13. Meland N, Norrman JO. Transport velocities of single particles in bed-load motion, GeografiskaAnnaler: Series A, Physical Geography.1966;48(4):165-182.
14. Francis JRD. Experiments on the motion of solitary grains along the bed of a water-stream Proceedings of the Royal Society of London. A Mathematical and Physical Sciences.1973;332:443-471.
15. Fernandez LR, Van Beek R. Erosion and transport of bed-load sediment. Journal of hydraulic research.1976;14(2):127-144.
16. Bridge JS, Dominic DF. Bed load grain velocities and sediment transport rates. Water Resources Research. 1984; 20(4):476-490.
17. DeVries P. Bedload layer thickness and disturbance depth in gravel bed streams. Journal of Hydraulic Engineering.2002;128(11):983-991.
18. Habersack HM, Laronne JB. Evaluation and improvement of bed load discharge formulas based on Helley–Smith sampling in an alpine gravel bed river. Journal of Hydraulic Engineering.2002;128(5):484-499.
19. Kleinhans, MG, van Rijn LC. Stochastic prediction of sediment transport in sand-gravel bed rivers. Journal of Hydraulic Engineering. 2002;128(4):412-425.
20. Bunte K, Abt SR, Potyondy JP, Ryan SE. Measurement of coarse gravel and cobble transport using portable bedload traps. Journal of Hydraulic Engineering. 2004;130(9):879-893.
21. Rennie CD, Millar RG, Church MA. Measurement of bed load velocity using an acoustic Doppler current profiler. Journal of Hydraulic Engineering.2002;128(5):473-483.

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