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PARTICLES- FLUID INTERACTIONS IN THE SETTLING VELOCITY OF NATURAL SANDS.

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ABSTRACT

Experiments with non-uniform natural sands were developed in a suspended sediment transport channel of 22m long and cross section of 1.2x1 m**.** Using image analysis the settling velocities for different range of particle diameters in the sand mixture were calculated. The Particle Tracking Velocimetry (PTV) method was used**.** The images of particles illuminated by laser light were captured using the software Looksee. Particle identification and displacement was made using the software AIP that uses analysis by integrated processing. The results show that the settling velocities of particles are affected by fluid velocity and the presence of other particles; the largest particles are more prone to be effected in its settling velocity. A model for the settling velocity of particles in cross flow should include the effect of the fluid velocity. A physical explanation of the phenomena of increasing settling velocity as the particles move away from the sediment supplier is related with the changes in turbulent characteristics of the fluid by other sizes particles.

General Terms

Optical methods for settling velocity measurements of natural sands.

Keywords: Sediment transport, natural sands, PTV, turbulence, fluid-solid interactions, settling velocity.

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1. INTRODUCTION

In river engineering suspended sediment transport is important in relation to fluvial morphology, filling of reservoirs, endangered fish habitat and water quality. Wastewater processes and industrial applications like fluidized bed reactors also benefit of a better knowledge of suspended sediment fluid dynamics. Sediment mixtures are characterized by a large variation of particle sizes. In engineering practice in order to calculate suspended sediment parameters it is common to use a representative diameter of the sand mixture usually the average particle size (Chien and Wan 1999). For example settling velocity is calculated with the average particle size using formulas like Rubey (Yang1996), Hallermeier(1981) or She et al. (2005). All those formulas are empirically derived from experiments in settling columns with no crossflow. When a particle is settling into a fluid with a velocity in the direction perpendicular to the vertical, there is a modified resulting settling velocity that depends on the velocity of the fluid. Also the results

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from settling tanks don't take into consideration the settling velocity variation according to the different particle sizes and more important the effect of other particles interacting between them and the fluid in this variation (García*et al*, 2000). In this research using experimental results, the goal is to establish the effect of the fluid velocity on the settling velocity of the particles and the effect other particles interacting with the fluid. The sand mixture was analyzed for different ranges of particle sizes using optical methods. A comparison is made with the experimental results and the different settling velocity formulas in the literature including Salinas and Garcia (2011) formula that takes into account the effect of the fluid velocity.

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2. EXPERIMENTAL SET-UP.

A sedimentary natural sand mixture constituted of cohesionless particles of different sizes was used. The mixture was poured into a channel by means of an elevated sediment distributor. Once the sediment flux uniformized digital images were taken in an area of the cannel illuminated by a laser sheet. The CCD cameras were synchronized with the laser pulses by means of a PC. The images were analyzed by the software AIP (analysis by integrated process) that uses Particle Tracking Velocimetry(PTV).

A 22 m long cannel was used, the cross section of the cannel is 1m x1.2m. At the entrance of the channel a flow uniformizer was installed in order to obtain parallel streamlines. Channel exit is provided with a sliding gate in order to control flow depth. Water is discharged into a sand deposit that clears the water that can be recirculated to the channel.

During the experiments the sand mixtures were poured into the channel by means of a distribution system installed above the channel, it is constituted of an elevated sediment tank, a conical distributor and a mechanical sieve. In this way an uniform distribution along the cross section of the channel is intended. The flow rate was kept constant at 180 l/s. Also the solid flow rate was kept constant at 4 l/min. The opening of the conical distributor was calibrated previously at the experiments in order to obtain the same flow rate for all the sediment sizes ranges (figure 1).

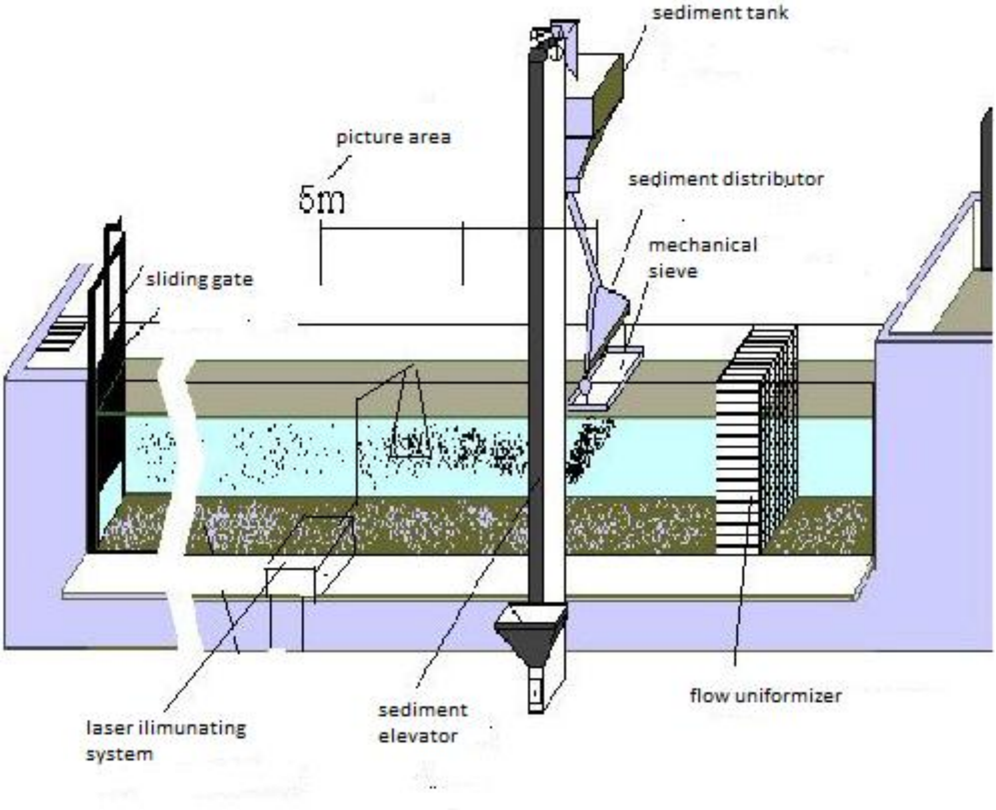

Figure 1. Experimental set-up.

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The laser light sheet, obtained by argon ion laser Spectra-Physics 165 de 5W, illuminated sections of the channel each 0.5 m until 5 m far from the sediment distributor. A chopper was used in order to pulse the laser light. Images were captured by 3 CCD cameras JAI synchronized with the laser pulses by means of a PC. The sediment distributor can be displaced along the cannel so that without moving the laser different sections of the channel can be captured. The images were analyzed with the software AIP that uses Particle Tracking Velocimetry (PTV). That allowed us to obtain settling velocities and size of the particles in the mixture used at distances of 1 to 5m from the sediment distributor. The particle sizes varied between 0.3 mm and 1 mm. Table 1 presents the characteristics of the mixture used and figure 2 is its graphic representation. The density of the sediments is 1710 kg/m^3.

Table 1. Granulometric characteristics of sediments.

Sieve	*opening mm*	*2.1.1.1 weight*	*Container gr*	*Retained Weight-gr*	*% Retained*	*% accumulated passing.*
5	*4*		*6.37*	*116.5*	*1.646*	*98.35*
8	*2.36*		*6.23*	*293.9*	*4.299*	*94.06*
18	*1*		*6.24*	*1144.8*	*17.014*	*77.04*
20	*0.85*		*39.07*	*315.5*	*4.1308*	*72.91*
40	*0.425*		*6.26*	*1335.6*	*19.865*	*53.05*
50	*0.3*		*6.15*	*812.2*	*12.045*	*41.00*
100	*0.15*		*157*	*2191.4*	*30.401*	*10.60*
200	*0.075*		*39.07*	*564.8*	*7.856*	*2.74*
	Sum total		*305.47*	*6997.4*	*100*	

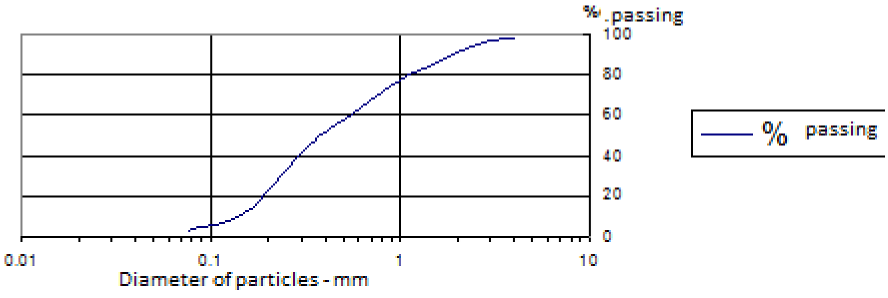

Figure 2 Granulometric curve of sediment used in experiments

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In order to try to maintain the same turbulent characteristics of the fluid the fluid flow rate was maintained constant at 180 L/s. Figure 3 presents the velocity profile, the flow height h was 0.50 m and Reynolds number was 180000.

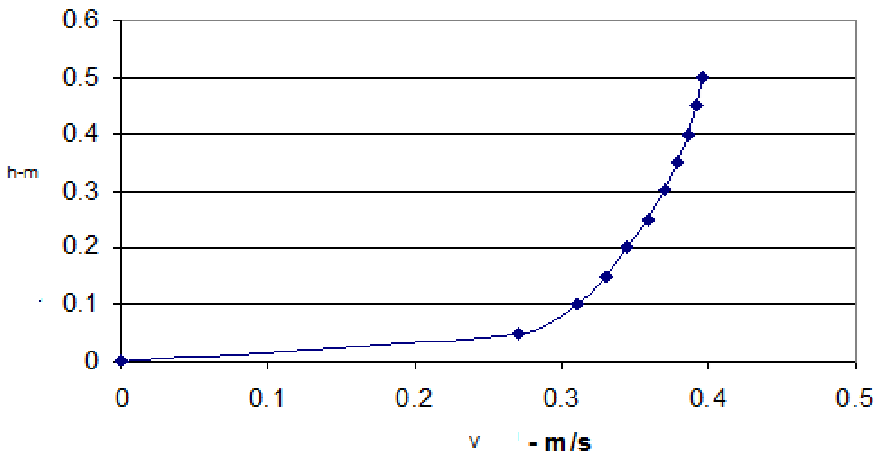

Figure 3. Flow velocity profile

3. IMAGE ANALYSIS

AIP is a computer program that resulted from a large research directed to the automatic extraction of data from digital images that started at the end of the eighties (Bryanston-Cross & Epstein, 1990). The original C program for binary images (Judge, 1991), was later improved and applied to real large velocity transitory flows (Funes-Gallanzi *et al*., 1994a,b). It proved to be useful for slow moving flows (Hayden et al. & Udrea *et al*., 1996). The capacity to analyze images using the autocorrelation technique, cross correlation, displaced images data analysis, and filtration was improved. The final AIP combining tracking and frequency to obtain super-resolution was obtained in 1997 (Funes-Gallanzi & Mendoza Santoyo, 1997).

Some work has being done in high precision positioning (Padilla Sosa *etal*., 2001) in order to identify different populations and posistioning non –spherical particles as those encountered in river flows (García Aragón *et al*., 2001).

There is an inherent error in the aip software that considers spherical particles so the diameters measured are approximations. For this reason we separated the particle sizes of the mixture in four ranges these are the following; particles between 0.30-0.425 mm, particles between 0.425 - 0.6375 mm, between 0.6375-0.85 mm and between 0.85 -1 mm.

4. THEORETICAL FORMULAS FOR SETTLING VELOCITY

The selling velocity w_s for cohesionless materials usually is calculated with the Stokes formula which is only valid for a particle settling isolated in a tank under n particle Reynolds numbers below 1. Fort he general case of particles settling with high Reynolds numbers it is compulsory to use empirical equations like that of Rubey (Yang, 1996).

$$w_S = F\left[dg\left(\frac{\gamma_s - \gamma}{\gamma}\right)\right]^{1/2} \tag{1}$$

Where $F = 0.79$ for particles with diameter d>1 mm., γ,γ_s are specific weights of water and solids respectively, d is particle diameter and g is the gravity. In order to use Rubey formula for particles of d< 1mm, F should be expressed in the following way

3 $$F = \left[\frac{2}{3} + \frac{36.\nu^2}{gd^3\left(\frac{\gamma_s - \gamma}{\gamma}\right)}\right]^{1/2} - \left[\frac{36.\nu^2}{gd^3\left(\frac{\gamma_s - \gamma}{\gamma}\right)}\right]^{1/2} \tag{2}$$

Where ν is the kinematic viscosity of water.

Hallermeir (1981) proposes the following equations for different range of values og Dgr.

$$\begin{aligned} w_s &= \sqrt[3]{g\nu(s-1)}\frac{D_{gr}^2}{18} && (D_{gr} \le 3.42) \\ w_s &= \sqrt[3]{g\nu(s-1)}\frac{D_{gr}^{1.1}}{6} && (3.42 \le D_{gr} \le 21.54) \\ w_s &= \sqrt[3]{g\nu(s-1)}D_{gr}^{0.5} && (D_{gr} \ge 21.54) \end{aligned} \tag{3}$$

Where D_{gr} is the Yalin no dimensional particle size

$$D_{gr} = D\sqrt[3]{\frac{g(s-1)}{\nu^2}} \tag{4}$$

Later She et al.(2005) proposes the following expressions for Dgr<2 and for Dgr>2 respectively

$$w_s = 1.05\left[\sqrt[3]{g(s-1)\nu}\right]\left[1 - e^{-0.08D_{gr}^{1.2}}\right]D_{gr}^{0.5} \tag{5}$$

$$w_s = 1.05\left[\sqrt[3]{g(s-1)\nu}\right]\left[1 - e^{-0.315D_{gr}^{0.767}}\right]^{2.2} D_{gr}^{0.5} \tag{6}$$

Recently Shahi and Kuru (2014) in order to improve the results taking into account particle shape uses optical shadowgraphs methods to calculate settling velocity. He uses a modified value of particle diameter D*, calculated using the sieve diameter Dc in the following way

$$D* = Sg\frac{Dc^3}{\nu^2} \tag{7}$$

and defining Rs=WsDc/ν with

$$Rs = o.363D*^{0.6008} \tag{8}$$

The value of W_S can be estimated

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Salinas and Garcia (2011) presented a formula to calculate settling velocity taking into account the effect of the fluid velocity in crossflow. This effect is considered taking into account the fluid Reynolds number R_f= Vh/ν, where V is the mean fluid velocity, h is the height of flow.

$$w_s = \sqrt[3]{g(s-1)\nu}\left(e^{\left(\frac{1}{R_f}\right)^b} - 1 \right) D_{gr}^{(a-1)} \tag{9}$$

The parameters a and b depends on Dgr and R_f according to the following table

Table 2. Values of a and b in Salinas and Garcia formula

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	$1.86 \le D_{gr} \le 10.5$		$D_{gr} > 10.5$
	$R_f \le 4200$	$R_f \ge 10000$	$R_f \ge 10000$
a	2.4	2.4	1.65
b	0.295	0.26	0.102

In the experiments R_f was constant equal to 180000 and mean velocity of 0.36 m/s.

5. 5. RESULTS

Figures 4, 5,6 and 7 presents the variation, with the distance from sediment pouring point, of the settling velocity of particles with sizes comprised within the four defined ranges; 0.30-0.425 mm, 0.425 - 0.6375 mm, 0.6375-0.85 mm and 0.85 -1 mm. A number of 36 experiments were done keeping the flow and solid rates constant (180 L/s and 4 L/min). The sediment concentration was kept low in order to have optical Access, large concentrations obscure the flow. The focus was the effect of particles interacting between them and the fluid in the settling velocity.

A statistical analysis of the variation of the settling velocity with the distance from the pouring was done. The best fit was obtained with the statistical package Minitab. The resultant equation and the P(lack of fit factor-LFT) are shown in figures 4 to 7. This factor is better than the cross correlation factor, because it not only indicates a trend, but determines that data comply with a proof of hypothesis.

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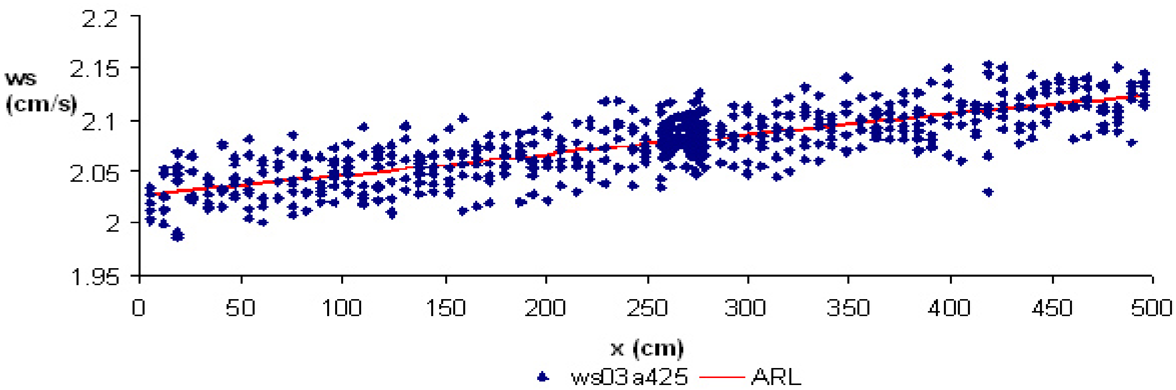
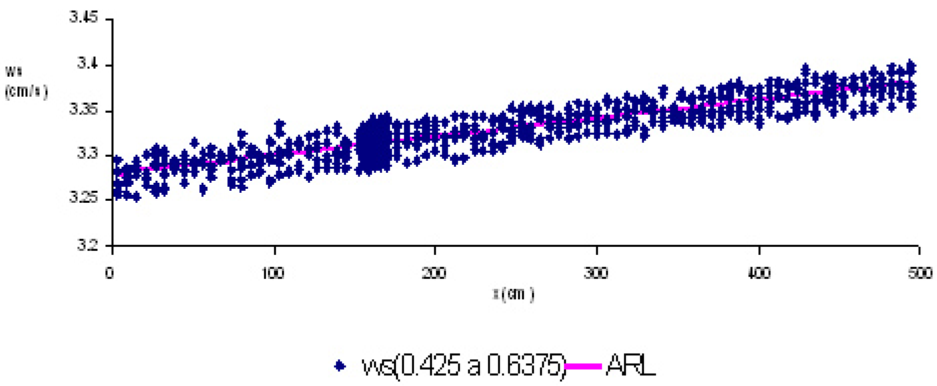


$$y = 2.02676 + 0.000196\,x$$
$$P = 0.999$$

Figure 4 Settling velocity of particles with diameter between 0.3 and 0.425 mm



$$ws = 3.27942 + 0.00020552\,x$$

$$P = 0.993$$

Figure 5 . Settling velocity of particles with diameter between 0.425 and 0.6375 mm

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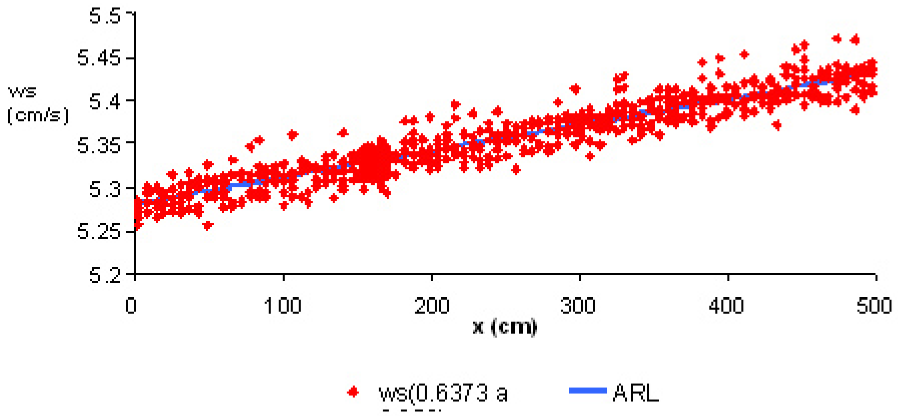
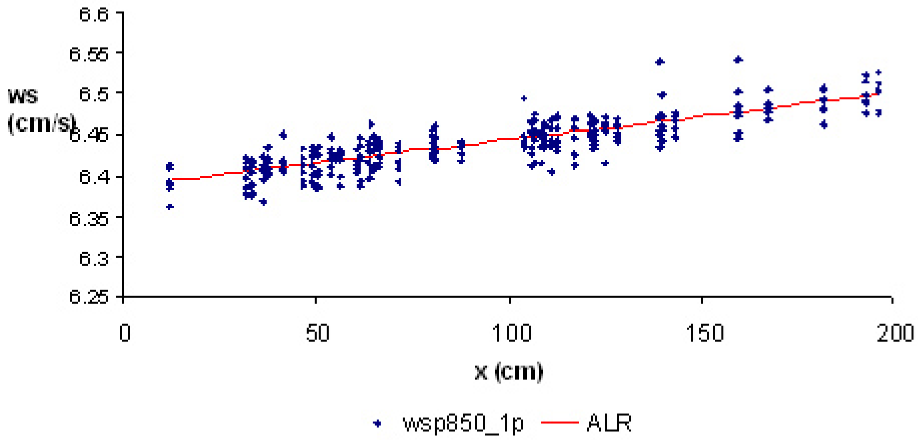


$$ws = 5.28105 + 0.00030502\,x$$
$$P=0.880$$

Figure 6 . Settling velocity of particles with diameter between 0.6375 and 0.85 mm



$$ws = 6.38594 + 0.00058363\,x$$
$$P=0.998$$

Figure 7 . Settling velocity of particles between 0.85 and 1 mm.

Table 3. Ws values estimated by different formulas .- (cm/s)

D - (mm)	Rubey	Hallermeier	Salinas and Garcia	She et al.	Shahi and Kuru	Observed
0.363	4.82	4.32	2.16	4.89	4.99	2.08
0.531	6.52	6.57	3.68	7.41	7.44	3.33
0.743	8.18	9.51	5.41	9.98	10.26	5.36
0.925	9.36	12.10	6.23	11.71	12.54	6.45

Table 3 shows the average value of settling velocity for each size range between 0.85-1 mm.

It is observed that all the formulas in the literature except that of Salinas and Garcia(2011) over predict the observed settling velocity of the particles. Salinas and Garcia(2011) formula is the only one that takes into account the effect of the fluid velocity in diminishing the settling velocity of the solids. Using this expression the overestimation for the range 0.30-0.425 mm is 3.8 %, for the range 0.425 - 0.6375 mm is 1.1% , the overestimation is 0.9 % for the range 0.6375-0.85 mm and for the range 0.85 -1 mm there is an underestimation of 3.4%. . In contrast there is overestimation in the other formulas larger than 100 % in the lower ranges. For the larger ranges the best approximation (Rubey) gives an overestimation of 53% in the range 0.6375-0.85 mm.and 45% in the range 0.85-1 mm.

A trend observed in figures 4 to 7 is that settling velocity is slightly increasing as sediments are moving farther away from the sediment supplier. This increase is larger in case of the upper size particle ranges and only small in the lower particle sizes ranges. The slope of the best fit line is larger for the upper size ranges (see table 4). The effect cannot be attributed to the sediment concentration because this diminishes, because of settling of larger diameters, as the particles are further away from the sediment supplier. This research attributes this behavior to the interactions between particles of different diameters, this interaction is larger near the sediment supplier causing an increase in turbulence characteristics that causes a larger drag force.

Near the sediment supplier there are more particles of large diameters. These large particles as has been observed experimentally (Hetsroni, 1989) when they have large particle Reynolds numbers(larger than 10) increases turbulence by the vortex shedding phenomena. In the experimental results presented the average size presents particle Reynolds numbers $\mathrm{Re}_p = \frac{W_s d}{\nu}$; 8, 18, 40 y 60 for the particle size ranges considered.

Table 4. Slope of the best fit line in Ws vs. Distance for each particle size range.

Particle size range (mm)	Slope Ws Vs. X
0.3-0.425	0.000196
0.425-0.6375	0.000205
0.6375-0.85	0.000305
0.85-1	0.000583

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This increase in slope shown in (table 4) reveals that larger particles with larger gravitational forces, as the turbulence decreases due to the deposition of larger diameters in the flux direction, increases its settling velocity faster than the lower size particle ranges.

6. CONCLUSIONS

The analysis of natural sand sediment mixtures has revealed that the settling velocity of particles is affected by the interactions of the particles with fluid and by the interactions of the particles between them.

A comparison of the settling velocity for the average size of four particle size ranges in a sediment mixture, with settling velocity formulas in the scientific literature showed that empirical formulas, coming from experiments in settling tanks with no fluid motion, over predict the observed settling velocity. A formula that considers the fluid velocity in crossflow was able to reproduce the experimentally observed results.

The interactions between particles and the fluid change the turbulence characteristics of the flow and affect the settling velocity of particles.

The optical method of Particle Tracking Velocimetry (PTV) allowed the determination of particle settling velocity without disturbing the flow field. Also it was able to cover a larger area which is more difficult to do with Accoustic Doppler Velocimetry (ADV).

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