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Particle Size-Dependent Cohesion of Sands: Insights from a Fluidized Bed Approach

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ABSTRACT

Erosion dynamics in channels are significantly influenced by the interaction between frictional forces among sand particles and hydrodynamic shear stresses exerted by flowing water. Understanding how particle size affects cohesion and resistance to entrainment is crucial for accurate sediment transport modeling and erosion control. This study quantifies the mechanical cohesion characteristics of sand particles across different size classes using a fluidized bed approach. Cohesion was assessed by measuring the pressure drop (ΔP) at the fluidization point (ΔP_f) and the corresponding flow velocity (V_f) through sensor-based precise measurements. Five sand classes—very coarse sand (VCS), coarse sand (CS), medium sand (MS), fine sand (FNS), and very fine sand (VFNS)—were tested under controlled hydraulic conditions. Results indicate that cohesion (Co) decreases with decreasing particle size, confirming the strong correlation between particle size and internal friction. The highest cohesion values were observed in VCS (23268 Pa m^{-1}), while VFNS exhibited the lowest (8881 Pa m^{-1}). Conversely, the fluidization velocity followed an inverse trend, with coarser particles requiring higher velocities for entrainment. These findings align with previous research on sediment stability and suggest that finer sands are more prone to mobilization under lower shear stresses. Additionally, findings highlight implications for channel stability and erosion control strategies, particularly in environments where sediment mobilization influences hydrological and geomorphological processes. The integration of these findings into prevailing models, such as the Revised Universal Soil Loss Equation (RUSLE) and the Water Erosion Prediction Project (WEPP), facilitates a more accurate assessment of soil resistance to detachment and transport. This incorporation could facilitate more precise predictions of sediment transport dynamics, particularly in contexts where particle size and friction forces are pivotal factors. It is acknowledged that laboratory experiments provide precise measurements; nevertheless, it is imperative that they be meticulously evaluated and further validated in natural field conditions.

Keywords: Cohesion, Erosion, Fluidized-bed approach, Sand particles, Sensors

1. Introduction

Cohesion in granular materials arises primarily from frictional forces, but additional mechanisms such as electrostatic forces, moisture-induced capillary effects, and particle shape significantly influence particle interactions. Electrostatic forces can enhance interparticle attraction, particularly in dry conditions, while moisture can induce capillary cohesion, strengthening particle bonding and resisting erosion. Furthermore, angular particles with irregular shapes enhance interlocking and frictional resistance, further influencing sediment transport dynamics (Reddi & Bonala 1997; Nase et al. 2001; Wei et al. 2015; Osipov 2016; Doan et al. 2023). Under flow condition, the initiation of particle movement is primarily determined by the balance between hydrodynamic forces exerted by flowing water and the resistive frictional forces acting between individual particles. These forces play a pivotal role in controlling particle detachment, transport, and eventual deposition, directly influencing channel morphology and sediment dynamics (Gran et al. 2006; Nouwakpo et al. 2014; Deviren Saygin 2021; Van Damme 2021).

Studies on the effect of pore water pressure on soil disintegration have concluded that increasing subsurface water pressure has a significant impact on sediment concentration transported along with surface runoff (Römkens et al. 2002). The stability of granular layers in channel beds is influenced by particle-to-particle interactions, including cohesion, interlocking, and pressure fluctuations. The magnitude of friction depends on several factors, including particle size, shape, packing density, moisture content, and mineralogical composition (Zhu et al. 2008; Grabowski et al. 2011; Bradley & Venditti 2017). Frictional forces in sands mainly arise from intergranular interactions such as direct contact friction, moisture-induced cohesion, and electrostatic attraction, which collectively resist shear stresses imposed by flowing water, thus determining particle entrainment thresholds (Wiącek, et al. 2012; Yang et al. 2023). Additionally, particle shape and angularity significantly influence mechanical interlocking and frictional resistance, impacting overall sediment stability and transport. When shear stress induced by the flow surpasses a critical threshold, particles become entrained and transported downstream (Bradley & Venditti 2017). Larger, angular particles such as coarse sands interlock more effectively, increasing frictional resistance and enhancing stability against erosion. Conversely, fine-grained sands with higher porosity exhibit reduced particle-to-particle contact efficiency, leading to weaker frictional interactions and increased susceptibility to erosion. Previous studies have demonstrated this relationship, indicating that finer sands tend to have higher void ratios and lower packing densities, contributing directly to their lower resistance to entrainment (Mitchell & Soga 2005; Grabowski et al. 2011; Cho et al. 2006). Particle shape also plays a critical role; angular and irregularly shaped particles enhance interlocking and frictional resistance, leading to increased stability and erosion resistance (Grabowski et al. 2011; Zhu et al. 2008; Guo et al. 2019). Understanding the balance between friction forces and water flow dynamics is critical for predicting channel stability and designing erosion control strategies (Cassel et al. 2021; Abualshar et al. 2024).

Previous studies have underscored the combined influence of external flow conditions and internal sediment characteristics on erosion processes. For example, Van Rijn (1993) identified critical thresholds for sediment entrainment based on particle size and bed configuration. Additionally, Best (2005) highlighted the significance of flow turbulence around river dunes in determining sediment transport mechanisms, whereas Garcia (2008) emphasized how particle density and size distribution influence erosion rates in fluvial channels. Deviren Saygin et al. (2018) demonstrated that particle size distribution directly impacts critical shear stress values required for initiating erosion, particularly highlighting finer sediments' greater mobility under lower shear stress conditions. This detailed understanding of cohesion mechanisms underscores their critical influence on sediment behaviour and erosion processes in natural environments. Research on sediment transport has previously demonstrated that factors such as particle size distribution, particle density, and pore-water pressures significantly modulate the resistance of sand/dune beds to erosion (Hjulström 1935; Shields 1936; Lepesqueur et al. 2019; Zheng et al. 2024). Moreover, existing sediment prediction models often do not comprehensively incorporate these detailed particle-level interactions, limiting their accuracy. The present study, by clearly quantifying friction-driven cohesion based on particle size under controlled laboratory conditions, provides data that can enhance existing sediment prediction models. However, further validation and incorporation of these results under natural field conditions, which include complexities such as flocculation processes, remain essential steps toward improving the accuracy and applicability of sediment transport predictions in real-world scenarios.

The fluidized bed approach offers significant advantages over alternative methods, such as flume experiments and empirical shear stress models, particularly in terms of precision and repeatability under controlled laboratory conditions. Flume experiments, though valuable, often introduce complexities such as flow turbulence and boundary-layer effects, potentially confounding the clear measurement of particle-level interactions. Empirical shear stress models, such as Shields and Hjulström diagrams, rely on generalized formulations and assumptions that may overlook microscale particle interactions. In contrast, the fluidized bed method directly quantifies mechanical cohesion through precise real-time monitoring of pressure drop and fluidization velocity, allowing more explicit isolation of cohesion and frictional effects from other complicating variables. This comparative advantage underscores our choice of the fluidized bed approach for assessing particle cohesion and improving sediment transport predictions. The "Fluidized Bed Approach" is a measurement technique that was proposed by Nouwakpo et al. (2010) for the purpose of evaluating the cohesive forces that hold soil particles together under flow conditions (Nouwakpo & Huang 2012). The method involves the gradual increase in water pressure through a soil sample, with the pressure drop being measured as it occurs. This process continues until the cohesive forces between particles are overcome, thereby effectively fluidising the bed. Deviren Saygin et al. (2021) further advanced this approach by developing a sensor-based precision measurement system and investigating its effectiveness for different soil types. They stated that this technique has significant potential for simulating the behaviour of solid materials in water, offering advantages over indirect methods e.g. some geotechnical indices proposed by several researchers (Dunn 1959; Lyle & Smerdon 1965; Flaxman 1963; Al-Durrah & Bradford 1982; Nearing & West 1988).

Considering early studies, the technique provides a direct and observable means of evaluating solid particle behaviour in fluid systems by simulating flow conditions and monitoring pressure dynamics in a solid mass. But challenges remain in standardizing the technique, accounting for variability in the magnitude of friction forces depend on particle sizes, and ensuring that results accurately represent sediment transport processes in a channel. Because of that, in this study, it is planned to study non-cohesive sand particles to simplify the analysis of particle behaviour, to monitor the basic effects of flow dynamics under controlled conditions, and to better understand the basic separation and transport mechanisms without the complicating effect of internal cohesive forces, in order to contribute to a better understanding of more complex cohesive soil systems. The interaction of these forces with hydrodynamic shear stress governs sediment entrainment, transport and deposition. In summary, this information obtained on friction-shear interactions is intended to improve predictions of channel development under changing hydrological conditions by contributing to sediment transport models. As a result, frictional forces between sand particles constitute a fundamental control on the dynamics of water erosion in channels. It is aimed to determine the variations depends on particle sizes affecting this balance with a precise measurement technique developed with a sensor-based approach and to contribute to the sustainable management of soil and water resources by managing channel erosion. This study also aims to quantify the mechanical cohesion of sands of varying particle sizes using a fluidized bed approach and to assess their resistance to fluid-induced entrainment.

2. Material and Methods

2.1. Soil

Sand samples were carefully prepared by sieving through standard sieves conforming to the USDA particle size classification, ensuring consistent size ranges across replicates. Sieving was conducted mechanically by using a dry sieving apparatus (D200-230V, Endecotts, Octagon Digital Sieve Shaker D20, London UK) to guarantee uniform particle size separation. Each sieved sample was then compacted gently by vibration to maintain consistent bulk density across tests (Flanagan & Nearing 1995). To minimize handling variability, samples were compacted uniformly using a vibrating compaction table for a standardized duration (approximately 1 minutes per sample), ensuring reproducible packing densities and minimizing heterogeneities in particle arrangement. Samples were handled carefully to prevent particle size segregation or contamination throughout the process. In this study, commercial quartz sand, characterized by a mean particle density of 2.65 g cm^{-3}, a bulk density ranging from 1.50 to 1.70 g cm^{-3} depending on particle size class, a predominantly hexagonal crystal structure (Mitchell & Soga 2005), and an angular shape, was employed as a non-cohesive granular material. To analyse the effects of particle sizes on flow-driven particle movement, USDA soil texture classification system was used to categorize sand particles into different size classes based on its diameter. In this system, “very coarse sand (VCS)” ranges from 2.0 to 1.0 mm, “coarse sand (CS)” from 1.0 to 0.5 mm, “medium sand (MS)” from 0.5 to 0.25 mm**, “**fine sand (FNS)” from 0.25 to 0.10 mm, and **“**very fine sand (VFNS)” from 0.10 to 0.05 mm (Soil Survey Staff 2017). In this study, we used the same size sieves to get VCS, CS and MS materials. For FNS and VFNS, we used the 0.125 mm sieve opening replace to 0.10 mm and 0.063 mm replace to 0.05 mm as lower boundaries. These fractions are important in soil classification, erosion studies, and hydrological processes, as they influence infiltration, runoff, and sediment transport. For experiments, sand particles sieved according to the above-mentioned these five particle size classes, ensuring controlled and reproducible conditions for analyzing mechanical cohesion properties of different sand sizes to explain the relationship between cohesion arising from interparticle friction forces that hold particles together under flow conditions and sediment detachment, transport, and deposition in water erosion processes. This understanding is crucial for assessing critical shear stress thresholds, rill and gully initiation, and the influence of cohesion on channel development and stability in eroding landscapes.

2.2. The concept of the fluidized bed approach and measurements

In this approach, the movement of pressurized fluid into the pore of a solid particle bed forces the bed to behave as a fluid. The formation of a fluidized bed is characterised by a convergence of water pressures, with incoming and outgoing pressures tending towards equilibrium. In cohesive soils, water pressure applied to the soil mass is progressively increased until the cohesive forces between particles are overcome, allowing fluid to permeate the soil mass. Once the cohesive forces are no longer present, the soil moves with the water and reaches the outlet. Conversely, in non-cohesive granular materials, such as the quartz sands utilized in this study, significant internal bonding is absent, and fluidization primarily occurs through the overcoming of interparticle frictional forces rather than true cohesion. The fluidized bed formation is driven purely by the upward fluid flow, and the material will behave more like a fluidized suspension, with the particles more freely dispersed throughout the fluid (Nouwakpo et al. 2010; Nouwakpo & Huang 2012; Deviren Saygin et al. 2021).

In principle, fluidization of a particle bed (L) is achieved when the combined forces of buoyancy and fluid velocity exceed the gravitational force acting on the solid particles. In this case, the fluid exerts pressure on the particle bed, which is proportional to the fluid's flow rate (V). The pressure difference (ΔP) between the bed's bottom and top is determined by the Ergun equation (Yang 2003) (Equation 1):

$$\frac{\Delta P}{L} = (\gamma_t - \gamma_s)g \tag{1}$$

Where; ΔP represents the measured pressure drop (Pa), L is the thickness of the bed (m), γt and γs denote the densities of the fluid and particles (kg m^{-3}), respectively, and g is the acceleration due to gravity (N kg^{-1}).

This technique employs Darcy's law (Darcy 1856) to establish a linear correlation between the water flow velocity (V, m s^{-1}) and the pressure drop (ΔP, Pa) (Equation 1 & 2).

$$\Delta P = \Delta P_m - \Delta P_0 = a.V \tag{2}$$

The reduction in water pressure as it moves through the solid bed is closely linked to the flow rate, the specific gravity of the solid and water, and the particle size of the packed soil. Consequently, the discrepancy between the pressure drop (ΔP_f) measured at the point of fluidization and the particle and fluid densities is utilised to ascertain the soil cohesion value (Co, Pa m-1 or N m-3), which reflects the internal friction forces of sand particles for this study (Nouwakpo et al. 2010; Nouwakpo & Huang 2012; Nouwakpo et al. 2014) (Equation 3).

$$C_0 = \Delta P_f - (\gamma_p - \gamma_f) \tag{3}$$

In the experimental study, the "Mechanical Cohesion Measurement Device" located at the Soil Erosion Research Laboratory of the Faculty of Agriculture at Ankara University was used to physically measure the cohesion (C_o, Pa m^{-1}) that explains the physical soil behaviour against to erosion processes by directing particle movement in the solid bed.

As illustrated in Figure 1, the device's schematic representation is provided for reference. The detailed design and measurement principles of the device have been previously outlined by Deviren Saygin et al. (2021). In summary, the system is computerised and utilises sensors within the fluidized bed cells to detect and record real-time pressure and weight changes. The fluidized bed mechanism uses the Arduino platform, known for its user-friendly, open-source hardware and software, to enable interactive electronic projects. The Arduino IDE and Matlab were used to manage functions like start/stop control, parameter settings, and real-time data logging. Automation minimizes the potential for human error throughout the measurements.

As illustrated in the Figure 1, the mechanical soil cohesion measurement setup consists of four main components clearly numbered for clarity:

(1) Three sets of fluidized bed cells holding the sand samples.

(2) A computer-controlled lifting system ensuring uniform and regulated application of hydraulic pressure to the bottom of each fluidized bed cell.

(3) High-accuracy differential pressure sensors installed at specific levels of the fluidized bed cells for precise real-time monitoring of pressure variations.

(4) High-precision load cells (weight sensors) that accurately measure the volume of water exiting the system during the tests.

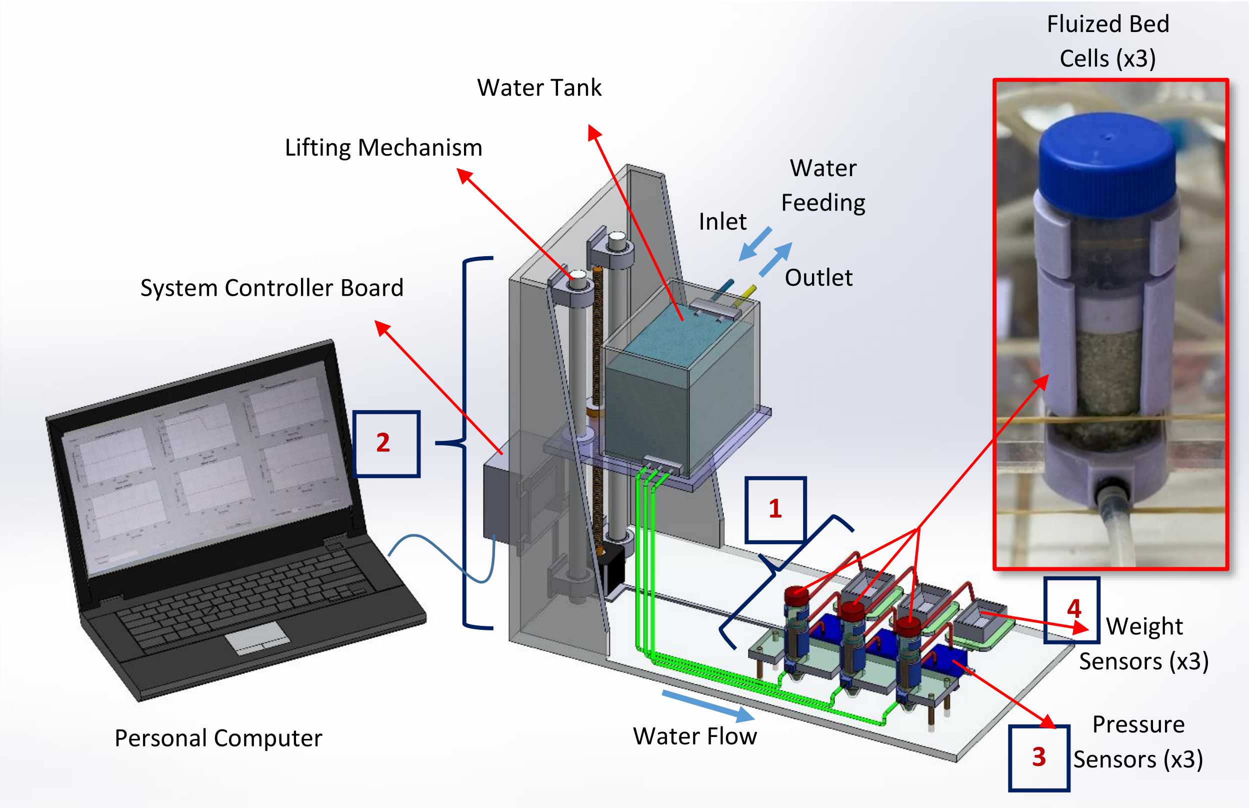

Figure 1- A schematic representation of the mechanical soil cohesion measurement setup

Figure 2 provides a visual representation of the system's operational flow through a flow chart. In experiments, pressured water enters the fluidized bed cells, passing through a 50 mm gravel layer and synthetic filter (Figure 1) to ensure equal pressure at the bottom and reach a 25 mm depth sand layer. To minimize unavoidable heterogeneities of the packed soil beds due to variations in the particle-associated pore distributions resulted in variations in the fluid pressure, sand particles are compacted by vibration and placed above the filter, forming the fluidized bed. As hydraulic pressure increases over time, flow rates are determined by measuring the water exiting the system. Pressure drop (ΔP_f) at fluidization is recorded using differential pressure sensors (Honeywell 26PCBFA6D with HX711 units) placed above and below the soil mass.

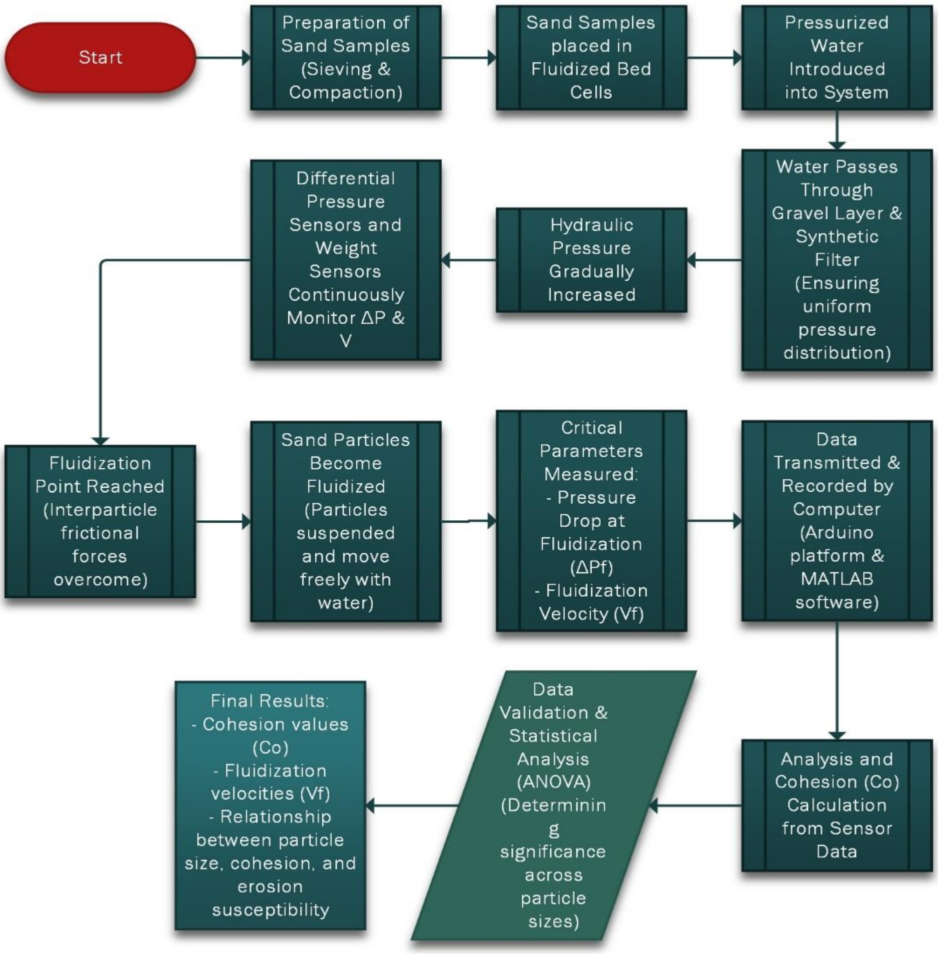

Figure 2- Flow chart illustrating the operational process of the measurement system

Concurrently, the volume of water that is passing through the soil is measured using load cells (0-1 kg with HX711 units), which are sensitive to weight. These sensors are located beneath the collection cups. The data is transmitted to the computer in real-time and used to calculate the pressure difference and critical flow velocities. These velocities are necessary to overcome cohesive forces and fluidise the solid material. Any changes or stress drops, which indicate cohesive failure, are clearly visible on the graph. A series of experiments were conducted, with a minimum of three replicates performed in each instance. Potential sources of measurement uncertainty include sensor sensitivity and environmental variations. To mitigate these uncertainties, high-accuracy differential pressure sensors and high-precision load cells were carefully calibrated before each test to ensure reliable measurements. Environmental variations, such as temperature fluctuations or minor mechanical vibrations, were minimized by performing experiments in a controlled laboratory setting. Nevertheless, slight variations inherent in sensor readings or environmental factors may still contribute to minor measurement discrepancies, highlighting the need for careful interpretation of laboratory findings and subsequent field validation. The duration of these experiments ranged from 30 minutes to 2 hours, contingent upon the specific conditions of the test soils. Utilising the system, a data file was generated, which contained an average of 5,000 readings pertaining to pressure, drop, and flow velocity. Before conducting ANOVA, we carefully checked statistical assumptions, including normality of data distribution using the Shapiro-Wilk test and homogeneity of variances using Levene's test. Results confirmed that the data satisfied the necessary assumptions of normality and homogeneity, thus validating the use of ANOVA for comparing particle size classes. This data was recorded for each individual test. The statistical analyses were performed using SPSS version 22.0 (IBM Corp., Armonk, NY, USA). A one-way analysis of variance (ANOVA) was conducted to evaluate differences in cohesion properties among the five sand classes, with a significance level of 0.05 (corresponding to a 95% confidence interval). Following a significant ANOVA result, Fisher's Least Significant Difference (LSD) test was applied for pairwise comparisons to identify specific group differences.

3. Results and Discussion

In the literature, the critical difference between cohesive and non-cohesive materials lies in the nature and magnitude of interparticle forces. Cohesive materials, such as the clay minerals exhibit significant internal binding forces due to chemical bonds, electrostatic attraction, and moisture-related capillary action. These cohesive forces provide additional resistance against erosion and fluidization (Grabowski et al. 2011; Zhu et al. 2008; Guo et al. 2019). Conversely, non-cohesive materials, such as the quartz sands used in our study, primarily rely on frictional interactions and mechanical interlocking between particles rather than chemical or electrostatic bonding. Thus, their resistance to entrainment and transport is mainly governed by particle size, shape, packing density, and resulting frictional interactions (Van Rijn 1993; Bradley & Venditti 2017).

The fluidized bed enables the quantification of cohesion values (C_o) by measuring the pressure drop (ΔP) at the fluidization point (ΔP_f), as well as the flow velocity at fluidization (V_f). As previously stated in the methodological section of the paper, this approach involves suspending particles, specifically sand grains, in a fluid by passing the fluid upward through the solid column at a sufficient velocity to counteract the gravitational forces acting on the particles and the interparticle cohesion forces (Nouwakpo et al. 2010).

3.1. Cohesion and flow velocity at fluidization point differences among sand size classes

The results of mechanical cohesion of sand particles across different particle size classes are summarized in Table 1 and further analysed through ANOVA in Table 2. The analysis revealed statistically significant differences in C_o and V_f among the studied sand size classes. The measured cohesion values showed a significant increase due to the decrease in particle diameters within the evaluated size classes. But, fluidization velocity follows an inverse trend to cohesion**,** with finer sands fluidizing at much lower flow rates.

Table 1- Measured C_o (Pa m^{-1}) and V_f (m s^{-1}) values with mean, standard deviation, and 95% confidence intervals for different particle size classes

C_o (Pa m^{-1}) / Particle_size	*Mean± standard deviation*	*95% Confidence Interval*		*V_f (m s^{-1}) / Particle_size*	*Mean± standard deviation*	*95% Confidence Interval*	
		Lower Bound	*Upper Bound*			*Lower Bound*	*Upper Bound*
VCS	23268 ± 671A*	20751	25784	VCS	0.013 ± 0.003 E	.003	.023
CS	19958 ± 2304A	17441	22475	CS	0.250 ± 0.005 A	.241	.261
MS	16097 ± 650 B	13580	18614	MS	0.141 ± 0.004 B	.131	.151
FNS	12332 ± 356 C	9816	14849	FNS	0.106 ± 0.005 C	.096	.116
VFNS	8881 ± 256 C	6365	11398	VFNS	0.036 ± 0.006 D	.027	.047

*Mean ± standard deviation of cohesion and flow velocity at fluidization point for each particle classes, and 95% confidence intervals (CIs). Means in same row followed by the same capital case letter are not significantly different using Fisher's least significant difference test (LSD for C_o: 3558.2 LSD for V_f: 0.0144) at $\alpha = 0.05$

Table 2- Analysis of variance for C_o (Pa m^{-1}) and V_f (m s^{-1}) values

Dependent Variable: C_o					
Source	*Type III Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
Corrected Model	397680841.843[a]	4	99420210.461	25.979	.000
Intercept	3891894686.971	1	3891894686.971	1016.988	.000
Particle_size	397680841.843	4	99420210.461	25.979	.000
Error	38268822.298	10	3826882.230		
Total	4327844351.112	15			
Corrected Total	435949664.141	14			
LSD	3558.2				
a. R Squared = .912 (Adjusted R Squared = .877)					
Dependent Variable: V_f					
Source	*Type III Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
Corrected Model	0.107[a]	4	.027	425.898	.000
Intercept	0.180	1	.180	2879.823	.000
Particle_size	0.107	4	.027	425.898	.000
Error	0.001	10	6.253E-05		
Total	0.287	15			
Corrected Total	0.107	14			
LSD	0.0144				
a. R Squared = .994 (Adjusted R Squared = .912)					

Findings generally revealed that the measurement sensitivity of the method and the apparatus developed based on this methodology is highly consistent with previous scientific principles. The largest particles, very coarse sand (VCS), exhibited the highest cohesion (Co=23268 Pa m^{-1}), while very fine sand (VFNS) had the lowest cohesion (Co=8881 Pa m^{-1}) (Table 1 and 2). C_o values of VCS and CS were not significantly different, but both were significantly higher than MS, FNS, and VFNS.

The reduction in cohesion with decreasing particle size aligns with previous studies, which indicate that larger, angular grains exhibit stronger intergranular friction, increasing resistance to flow-induced entrainment (Bradley & Venditti 2017; Cassel et al. 2021). In contrast, finer grains tend to be more easily fluidized due to their lower particle-to-particle contact area, leading to reduced cohesion (Nouwakpo & Huang 2012). Briefly, cohesion decreases with decreasing particle size, supporting the hypothesis that larger grains exhibit stronger frictional interactions.

Similarly, the flow velocity at fluidization (V_f) varied significantly across sand classes, with coarse sands requiring higher velocities to reach the fluidization point. The highest V_f was observed in coarse sand (CS) (0.25 m s^{-1}), followed by medium sand (MS) and fine sand (FNS), while very fine sand (VFNS) exhibited the lowest V_f (0.036 m s^{-1}). These results suggest that finer sands become fluidized at much lower velocities due to their weaker interparticle friction and lower density-dependent resistance, which is consistent with previous sediment transport findings. These results reinforce the role of particle size in fluidization thresholds, with coarse particles requiring stronger flow conditions for entrainment (Best 2005; Garcia 2008).

3.2. Effects of particle sizes & cohesion on sediment transport and erosion control mechanisms

The pressure drops (ΔP) per unit length are plotted against the measured flow velocities (V) of the soils (Figures 3–7). These figures illustrate the gradual increase in pressure resistance as fluid velocity rises until reaching the fluidization threshold (ΔP_f). In there, the increase in dynamic pressure (ΔP) per unit length (V) is examined as a function of the fluidization point (ΔP_f), which is defined as the highest ΔP values of the sands (Equation 2). The data is presented in the form of a plot on the y-axis, with the fluidization point ΔP_f (Pa m^{-1}), indicated by the maximum values of ΔP. The observed trends are in agreement with Ergun's equation (Yang 2003), which describes pressure drop in packed beds as a function of particle size and flow rate.

Particle shape, angularity, and moisture content significantly influence particle cohesion. Angular particles with irregular shapes increase frictional resistance due to enhanced interlocking capabilities. In contrast, spherical or rounded particles typically exhibit lower frictional resistance. Additionally, moisture content introduces capillary forces, forming cohesive bonds between particles through meniscus formation, substantially enhancing resistance to fluidization and erosion (Bradley & Venditti 2017; Cassel et al. 2021). The findings reveal that smaller sand particles exhibited lower ΔP_f values compared to larger ones. The increase in internal cohesion (C_o) of very coarse sand (VCS) led to lower outlet water velocities at the fluidization point than those observed for finer particles. Consequently, the ΔP value, measured using high-precision differential pressure sensors positioned at the top and bottom of the solid layer, showed a rising trend, as evident in VCS, coarse sand (CS), medium sand (MS), fine sand (FNS), and very fine sand (VFNS), respectively.

As anticipated, an inverse relationship has been observed between ΔP and flow velocity (V). Additionally, variations in V, depending on particle size, are noteworthy. The recorded flow velocity values decrease as water movement slows through finer sands, in contrast to the higher velocities observed in coarser sands, consistent with the findings of Nouwakpo et al. (2010). Overall, the variations in ΔP and V across different particle sizes are strongly influenced by cohesive forces, including gravity, buoyancy, and fluid-particle interactions, as functions of particle size, weight, and shape (Guo et al. 2019).

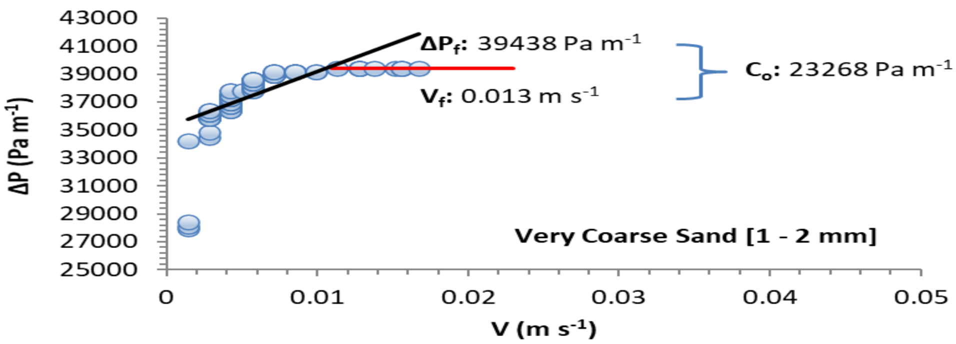

Figure 3- ΔP (Pa m 1) & V (m s^{-1}) distributions of the very coarse sand (VCS)

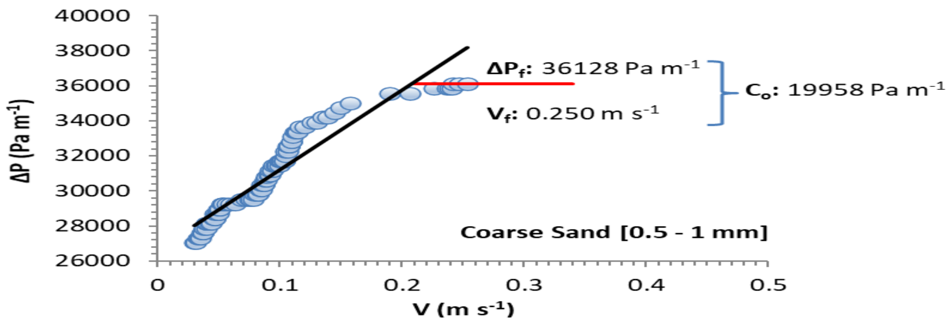

Figure 4- ΔP (Pa m 1) & V (m s^{-1}) distributions of the coarse sand (CS)

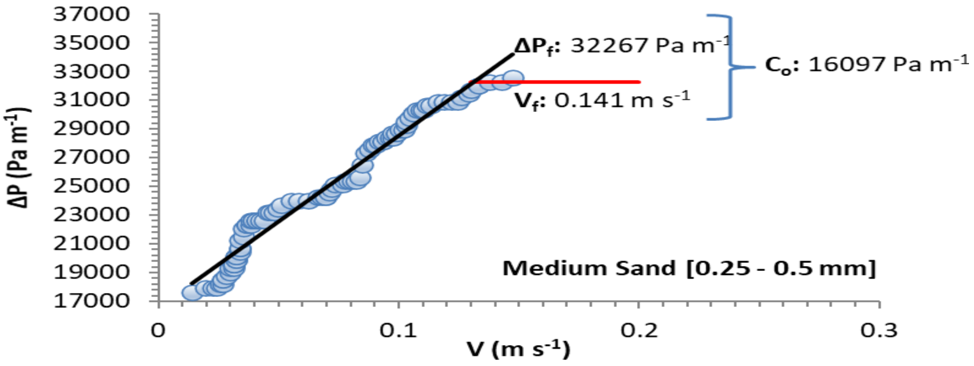

Figure 5- ΔP (Pa m 1) & V (m s^{-1}) distributions of the medium sand (MS)

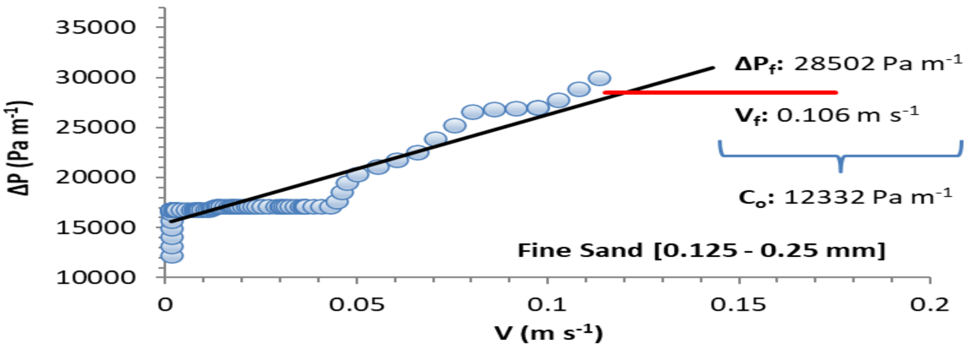

Figure 6- ΔP (Pa m 1) & V (m s^{-1}) distributions of the fine sand (FNS)

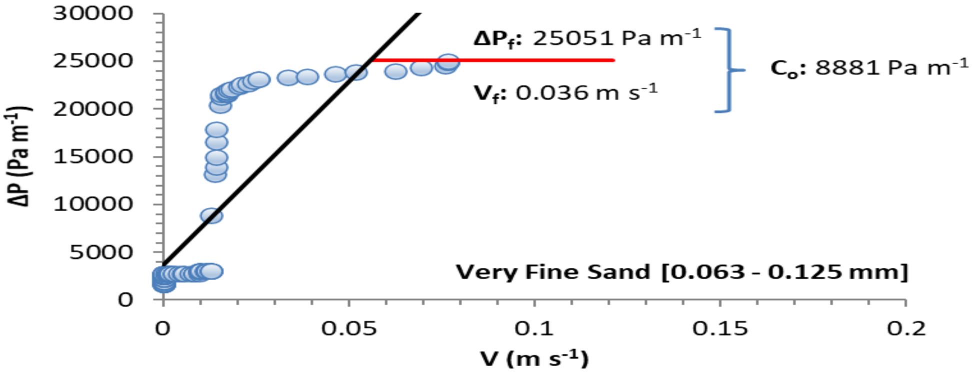

Figure 7- ΔP (Pa m 1) & V (m s^{-1}) distributions of the very fine sand (VFNS)

The findings from this study can be integrated into sediment transport models, such as the WEPP and the RUSLE, through the establishment of empirical relationships or the use of correction factors (Flanagan & Nearing 1995; Renard et al. 1997). Specifically, particle-size-dependent cohesion values obtained from the fluidized bed approach could serve as empirical inputs or correction factors, enhancing the precision of critical shear stress thresholds within these models. Such integration would improve predictions of sediment entrainment and erosion dynamics under varying hydraulic conditions. These results contribute to a better understanding of friction-shear interactions in non-cohesive sediment transport, with implications for erosion modeling and channel stability assessments under varying hydraulic conditions. From an erosion perspective, these findings align with previous research highlighting the role of particle size in sediment stability (Hjulström 1935; Shields 1936). Larger sand particles, due to their higher interparticle cohesion with friction forces, resist entrainment longer and contribute to stable channel formations, while finer sands are more prone to mobilization and transport under lower shear stresses (Van Rijn 1993; Deviren Saygin et al. 2021).

Although our study focuses on non-cohesive quartz sands to precisely isolate friction-driven cohesion mechanisms, it is important to recognize that in natural conditions, fine-grained sediments frequently exhibit cohesive behavior due to flocculation processes involving electrochemical and biological interactions (Grabowski et al. 2011; Nicosia et al. 2024). Therefore, future studies should incorporate cohesive sediments and the effects of flocculation to more accurately reflect real-world sediment transport processes. This would provide comprehensive insights for erosion prediction models under natural field conditions.

Although controlled laboratory conditions enable precise measurement of friction-driven cohesion, it is important to recognize that field conditions introduce complexities, such as variable sediment composition, natural heterogeneity, biological factors, and dynamic hydraulic conditions, which are challenging to replicate accurately in a laboratory setting.

4. Conclusions

The fluidized bed approach entails suspending particles in a fluid by directing the fluid upward through a soil column at a velocity sufficient to counterbalance the gravitational forces acting on the particles. In this research, sand grains function as the solid phase, while water acts as the fluid under cohesionless conditions. This technique is especially useful for analysing the movement of sand particles in suspension, the onset of fluidization, and the associated soil mechanics under dynamic conditions.

This approach helps address the inherent challenges of the technique. Accordingly, this study specifically examines cohesionless conditions to streamline the analysis of particle motion, distinguish the effects of flow dynamics, and develop a more precise understanding of the key processes governing detachment and transport without the complicating factor of cohesion. The results suggest that the fluidized bed technique offers a dependable method for evaluating cohesion; however, further validation through in-situ field measurements is required to confirm its practical relevance.

The results also highlight those fine sands are highly prone to erosion, and the strong correlation between particle size and cohesion could be incorporated into sediment transport models to improve erosion predictions. Given the limitations of existing models such as WEPP (Water Erosion Prediction Project) and RUSLE (Revised Universal Soil Loss Equation), integrating mechanically derived cohesion values from the fluidized bed method could enhance their accuracy by providing a more representative assessment of soil resistance to detachment and transport. This integration would allow for a more precise estimation of sediment dynamics, particularly in environments where cohesion plays a critical role in erosion processes. Further research is needed to refine these parameterizations and validate their effectiveness across diverse soil conditions. Besides that, in agricultural drainage systems**,** excessive fine-sand mobilization could lead to clogging, reducing water infiltration efficiency. Therefore, sediment management strategies should consider particle size-dependent cohesion properties. The findings from this study can be integrated into sediment transport models, such as the Water Erosion Prediction Project (WEPP) and the Revised Universal Soil Loss Equation (RUSLE), through empirical relationships or correction factors. Specifically, particle-size-dependent cohesion values obtained from the fluidized bed approach can refine critical shear stress thresholds, improving predictions of sediment entrainment and erosion dynamics under varying hydraulic conditions. However, considering the controlled laboratory conditions, field testing and validation are essential to ensure these findings accurately reflect real-world scenarios. While laboratory-based results provide fundamental insights into sediment cohesion and transport mechanics, further in-situ field validations are essential to confirm these findings and assess their practical applicability across diverse environmental and hydraulic conditions. Future research should specifically address the integration of cohesion data into model frameworks and test the robustness of these relationships under diverse environmental conditions, including varying sediment types, moisture contents, and hydraulic regimes.

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