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IDENTIFICATION OF THE GOVERNING MECHANISM IN THE BEHAVIOR OF SILTY SAND

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ABSTRACT: The behaviour of soil varies due to its diverse mineral compositions and particle sizes. Soil can be classified into two main groups: fine-grained soils, which are influenced by electrostatic forces, and coarse-grained soils, which are governed by gravity. While most studies have focused on sand and clay, there is another soil type called silt that falls between them in terms of particle size. Silt can behave similarly to clay when it possesses plasticity, while non-plastic silt exhibits characteristics similar to sand, such as dilation under shearing and liquefaction under cyclic stress. However, silt behaves differently from both clay and sand due to its unique characteristics. One possible reason for this behavioural shift in silt, where it compresses and then dilates during shearing with a delay, could be the reduction in particle size compared to sand particles. To investigate the variations in silt behaviour, several tests including relative density and standard proctor tests were conducted on sand, silt, and different combinations of sand-silt mixtures. This study aims to explore the governing force behind silt behaviour. The proposed mechanism for determining the governing force in silt is adapted from powder technology. As a result, a new test called the cylindrical flow test is suggested, which allows the determination of the force using the kinetic energy formula. This study outlines the mechanism governing silt behaviour and the technique employed to determine it.

Keywords: Non-plastic silt, Fine-grained soil, Surface energy force, Relative density, Sand-silt mixtures.

1. INTRODUCTION

In natural soil deposits, a variety of minerals and particles with different sizes are typically present. Geotechnically, these soils can be categorized as fine-grained or coarse-grained. When discussing soil behaviour, the focus is often on clay and sand, which are extensively studied in textbooks. However, there is another soil type called silt, which falls between the particle sizes of sand and clay. Silt exhibits characteristics of both clay and sand, such as the plasticity of clay and the mechanical properties of sand, including dilation under shearing and liquefaction under cyclic loading.

Clay behaves differently from sand in various aspects, making it challenging to extrapolate the behaviour of silt [1,2]. When sand contains silt particles, its behaviour also undergoes variation, necessitating the study of silty sand characterization. Silty sand characterization is distinct and more complex compared to clay or sand behaviour due to its tendency to dilate [3-9]. Increasing the amount of non-plastic silt in Nevada sand made specimens more volumetrically contractive in both undrained and drained triaxial tests, even when the density was raised [10-12]. The presence of non-plastic silt may either decrease the undrained shear strength [13] or leave it unaffected, depending on the intergranular void ratio. The stress-strain response and strength of sand-silt mixtures are analyzed using various ratios such as void ratio, intergranular void ratio [14], skeletal void ratio, inter-fine void ratio [13], and equivalent granular void ratio [15]. Experimental data suggests that an increase in fine content reduces the shear strength when considering the global void ratio. However, the shear strength for the intergranular void ratio remains largely unaffected by fine content. Conflicting findings exist regarding the impact of fines on shear strength, and the threshold fine content (F_{cth}) and fabric influence were determined based on the data. Coarse particles dominate the fabric behaviour when the fine content is below the F_{cth}, while fines control the fabric behaviour when the fine content exceeds the F_{cth} [4].

Silt can be further divided into plastic silt and non-plastic silt. Plastic silt exhibits behaviour similar to clay, while non-plastic silt behaves more like sand. Preliminary tests conducted at City University on Bothkennar clay, where organic and clay contents were removed, revealed that the behaviour of pure silt composed of clastic particles, such as fine quartz, cannot be described within the framework of clay behaviour. This is because the interparticle behaviour in silt is primarily governed by grain crushing, similar to sands, rather than electrostatic forces that govern clay behaviour [16]. Preparing silty samples for triaxial testing is challenging [3,17] due to their ease of disturbance. There are significant differences between undisturbed and reconstituted silty sand specimens, emphasizing the importance of a reliable reconstitution technique that accurately replicates density, grain size, and fabric [3].

Although non-plastic fines are generally considered non-cohesive, observations of the cohesiveness intercept led researchers to explore relevant literature to understand the mechanism. It is commonly known that fine-grained soils are governed by electrostatic forces, while coarse-grained soils are governed by gravity forces [18]. However, laboratory studies have shown that non-plastic silt also exhibits some cohesiveness and behaves similarly to c-φ soils, which have cohesion. The gravitational force in non-plastic silt is noticeably reduced due to its smaller particle size compared to sand, resulting in decreased frictional resistance. Understanding the activation of cohesion in silt is important. Cohesiveness in soils on Earth arises from electrostatic forces and surface-energy forces, including van der Waals forces (intermolecular potential energy). Surface-energy forces operate over a very small area and are insignificant compared to gravitational forces for soils with particle sizes equal to or greater than 0.06 mm, such as sand or silty sand. However, as the particle size approaches that of clay, the surface-energy forces have a more significant impact on the material's strength [7, 19-23].

2. RESEARCH SIGNIFICANCE

Understanding the behaviour of soil and its governing forces is essential. The behaviour of sand has been well-established, but it undergoes changes in the presence of silt. This study aims to investigate the force that governs the behaviour of silty sand and gain a better understanding of sand behaviour variation in the presence of non-plastic silt.

3. EXPERIMENTAL WORK

3.1 Sample Collection

The sand was collected from the Palar riverbank at Padalam, Tamil Nadu, India. Samples were collected at a depth of 1 m. The silt used for the study was collected as silty sand from Sholinganallur, Tamil Nadu. The silty sand was subjected to wet sieve analysis to know the percentage passing through the 75μ sieve. The particle percentage passing through the 75μ sieve was washed continuously to remove clay particles to collect washed non-plastic silt which was dried and used for the laboratory investigation.

3.2 Index Properties Tests

Specific gravity tests were conducted using a specific gravity bottle as per IS: 2720 (Part 3/Sec - 1) – 1980 [24]. Grain size distribution analyses were performed by mechanical sieve analysis for sand and by hydrometer analysis for silt and sand-silt mixtures as per IS: 2720 (Part 4) – 1985 [25] and the grain size distribution curve for different sand silt mixtures is shown in Fig.1. The results of these tests for sand, silt and different sand – silt mixtures are tabulated in Table 1,2.

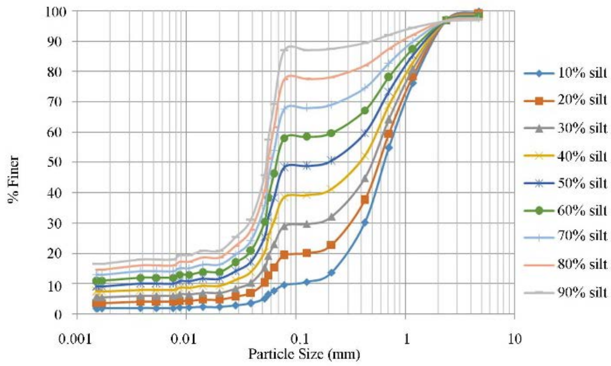


Fig.1 Grain Size Distribution curve for sand-silt mixtures

Table 1 Index properties of Sand and Silt

Physical property		Sand	Silt
Designation		S100	M100
Specific gravity		2.59	2.6
Grain size	Fine	21	92
distribution	Medium	76	6
(%)	Coarse	3	2
D10 (mm)		0.28	0.024
D30 (mm)		0.49	0.042
D60 (mm)		0.84	0.054

Table 2 Index properties of Sand–Silt Mixtures

Physical property	Sand-Silt mixtures				
Designation	S90 M10	S80 M20	S70 M30	S60 M40	S30 M70
D_{10} (mm)	0.08	0.06	0.04	0.02	0.002
D_{30} (mm)	0.4	0.3	0.15	0.06	0.055
D_{60} (mm)	0.8	0.7	0.65	0.55	0.45
C_u	10	11.6	16.25	27.5	225
C_c	2.5	2.14	0.86	0.32	3.36

3.3 Relative Density Test

Relative density tests on sand-silt mixtures were done to determine the impact of the non-plastic silt content in the sand, and proctor compaction tests were done to determine the impact of the sand's presence in the non-plastic silt. The relative density test was carried out for sand, silt and different sand-silt mixtures as per IS: 2720 (Part 14) – 1983, Reaffirmed – 2006 [26].

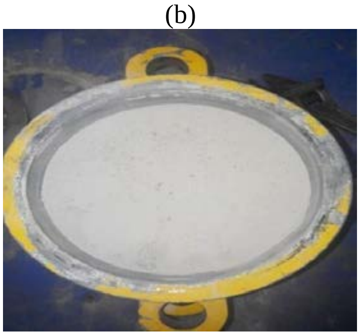
When silt content is increased, it is seen that both e_{max} and e_{min} fall up to a certain percentage before increasing again as more silt is added. The S80M20 combination has a minimal e_{max}. For an S70M30 mixture, the e_{min} is the lowest value. The minimum e_{max} is for lower silt content than the minimum e_{min}, and it is mentioned that the minimum e_{min} and minimum e_{max} are not for the same mix (Table 3).

Table 3 Relative density test for sand, silt and sand-silt mixtures

Physical property	Sand-Silt mixtures						
Designation	S100	S90M10	S80M20	S70M30	S60M40	S30M70	M100
γ_{dmin}, g/cc	1.634	1.711	1.758	1.648	1.658	1.625	1.509
γ_{dmax}, g/cc	1.957	1.968	2.051	2.010	1.759	1.937	1.813
e_{max}	0.5908	0.523	0.485	0.587	0.586	0.622	0.7560
e_{min}	0.4220	0.323	0.273	0.244	0.334	0.360	0.461

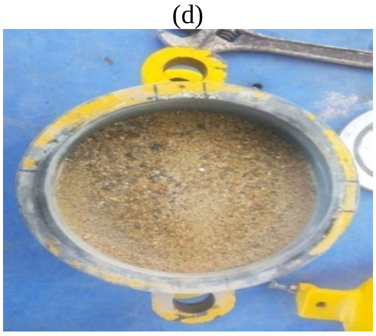
(a)

(b)



(c)

(d)



(e)

Fig.2 Top surface of soil after compaction for (a) M100 (b) S30M70 (c) S40M60 (d) S80M20 (e) S90M10

Some silt flew out of the mould during vibration, and the surcharge base plate has become buried in the silt (Fig. 2(a)-2(e)). The sample, however, appears to be tightly packed beneath the base plate. Figure 2(b) demonstrates that some samples for the S30M70 combination also flew over the base plate, although the sample appears to have been well-compressed underneath. The sample fits together nicely for all other combinations. These findings lead to the conclusion that the current method of determining relative density needs to be modified for higher percentages of silt content.

3.4 Standard Proctor Compaction Test

The standard proctor compaction test was performed per IS: 2720(Part 7) - 1980, Reaffirmed – 2011 [27] for various sand-silt mixture proportions. Sand-silt mixtures and silt both underwent the standard proctor compaction tests.

Fig.3 Expulsion of water from the mould during proctor compaction test

Some of the noteworthy findings from the test include the fact that water begins to evacuate from the mould for the S100, S90M10, S80M20, and S70M30 combinations (Fig. 3). With an increase in the sand, more water is ejected, although the specimen's weight was unaffected by this. As a result, it was not possible to establish the maximum dry density, and good compaction curves could not be obtained for sand over 40% in the sand silt mixture.

3.5 Triaxial Compression Test

Based on IS-2720-Part 11, 1993 and IS-2720-Part 12, 1981, triaxial tests were carried out for sand, silt, and sand-silt mixtures and a density of 1.47-1.57 g/cc was maintained throughout the testing. Dry compaction technique for the preparation of dry sand and sand silt mixtures and moist tamping technique for sand silt mixtures of different drainage conditions were used in the specimen preparation for triaxial testing to achieve the required density. 10% of water was added to the samples during the mixing of sand-silt mixtures. The triaxial apparatus and the specimen prepared on the cell is shown in Fig.4. To achieve the required density, mild tamping was employed for dry tests and moist tamping was employed for tests under different drainage conditions. The shear strength parameters of sand and sand-silt mixtures in dry and different drainage conditions are found (Table 4). The

Table 4 Shear strength parameters of sand-silt mixtures

S.No	Sample Designation	SAND-SILT MIXTURES					
		Dry		CU		CD	
		C kN/m^2	$\phi°$	C kN/m^2	$\phi°$, $\phi'°$	C kN/m^2	$\phi°$
1	S100	–	33.0	–	26, 29	–	33.7
2	S90M10	–	32.2	–	25, 27	–	32.2
3	S80M20	–	29.0	–	24, 26	–	–
4	S70M30	–	27.2	–	23, 25	–	32.1
5	S60M40	–	24.8	–	22, 24	–	29.5
6	S50M50	–	23.6	–	21, 22	–	28.2
7	S40M60	–	22.1	8	20, 21	–	–
8	S30M70	–	21.1	20	18, 19	–	–
9	S20M80	–	21.0	25	16, 17	–	–
10	S10M90	–	20.0	30	14, 15	–	–
11	M100	–	19.5	40	12, 16	55	14

findings demonstrate that for all triaxial test conditions, an increase in non-plastic silt reduces the angle of internal friction(ϕ). The decrease in the angle of internal friction is somewhat larger under dry conditions, with a range of 30% to 50% of silt content. The amount of decrement is less for silt content greater than 50%, which is consistent with Thevanayagam's [13] floating fabric concept.

Up to a silt percentage of 50%, the behaviour of sand is dominant in the sand silt mixture and silt acts more like a voids whereas, beyond 50% silt content, the sand in the sand silt mixture becomes a floating fabric and reduces the internal angle of friction, silt being dominantly contributing to the shear strength behaviour. The ϕ of the dry condition is higher than that of the consolidated undrained (CU) condition while the ϕ of the sand-silt mixture in dry and consolidated drained (CD) is almost the same for S100 and S90M10. At transition fine content 30% and 50% silt content, the ϕ in CD is higher than dry while for 100% silt in CD, ϕ is less but there is mobilisation of cohesion.

The drained shear strength determined based on CU tests is comparatively lower than that of CD tests. For more than 50% silt, there is a mobilization of cohesion in addition to friction. This cohesion value increases with an increase in the percentage of silt content. With the usage of non-plastic silt, the maximum cohesion range of 8 kN/m^2 – 55 kN/m^2 is mobilized. All the tests were conducted at low relative density. Unlike normal consolidated clay, there is mobilization of cohesion in both the CD and CU triaxial tests.

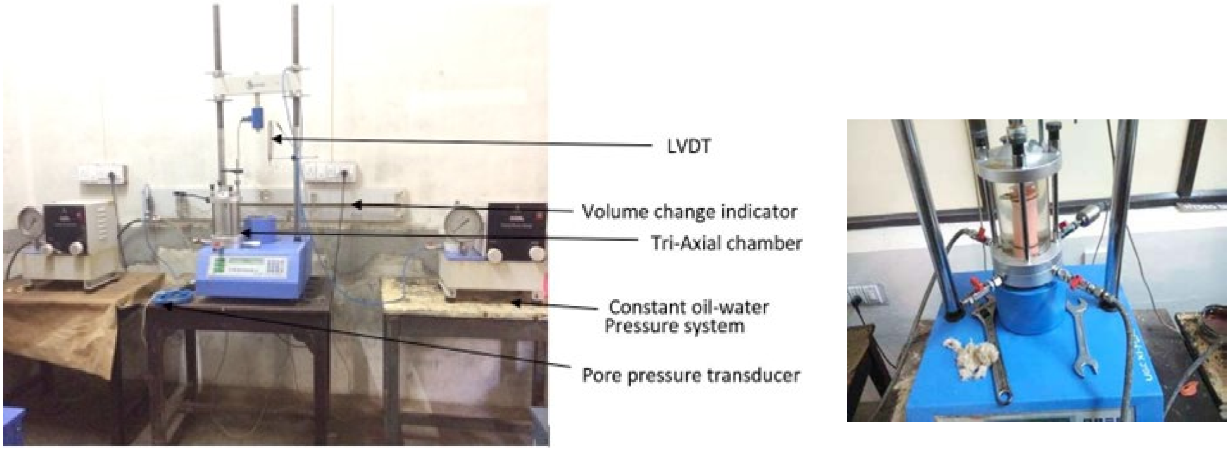


Fig.4 Triaxial cell apparatus and specimen prepared on the cell

3.6 Free-Flow Test

Additionally, sand-silt combinations and clay were subjected to a free-flow test [28], which is employed in powder technology. Layers of soil sample are compacted into a standard test tube with a 1 cm diameter, filled to a height of one-third, and then the test tube and sample are turned upside down. The observations of the force regulating the soil sample are then made on the test tube's upper surface. The photographic view of the flow of different grain sizes is shown in Fig. 5a to 5c.

It is clear that a soil sample with a grain size of more than 600μ does not stand because gravity controls its behaviour. However, the samples from 600μ to clay size remain stationary when turned upside down because inter-particle force controls them (Electrostatic force for clay and surface energy force for silt and fine sand). Fine sand forms the perfect arch, silt forms a partial arch, and clay does not produce an arch, according to observations. The existence of friction and the gravitational force causes the ideal arch to form; partial friction causes partial arches to form; and electrostatic force between the grain pairs in clay prevents arches from forming at all.

(a) (b) (c)

Fig.5 Test tube showing (a) Perfect arch in fine sand (b) Partial arch in silt (c) No arch in clay

4. THEORETICAL METHOD OF CALCULATION OF SURFACE ENERGY FORCE

The soil's shear strength increases as a result of the surface energy force's ability to draw soil particles together. Electrostatic force and Van der Wall forces account for the majority of the adhesive force between two soil grains. There is no electrostatic interaction between the fine sand and silt particles, according to the flow test results. Fine sand and silt, however, are subject to surface energy force. Theoretically, these surface energy forces can be estimated from the energy fields of Van der Walls. Equation (1) gives the surface energy force between two identical spheres [29],

$$F = \frac{AR}{12D^2} \quad (1)$$

where A is the Hamaker's Constant; R is the radius of the particle; and D is the separation distance between two particles.

An Energy Dispersive X-Ray Analyzer (EDX) is used to provide elemental identification and quantitative compositional information. According to the EDX report (Table 5,6), quartz is a prominent mineral found in the sand and silt, and the Hamaker's Constant for sand and silt is 1.5×10^{-20}J and 1.7×10^{-20}J, respectively.

Table 5 EDX results for sand used in the study

Si. No	Elements	Count	Weight	Atom (%)
1	O	490	50	64.29
2	F	9	2	2.23
3	Al	102	4	3.12
4	Si	965	40	29.34
5	K	4	0	0.17
6	K	0	-	-
7	Ca	18	1	0.79
8	Ca	0	-	-
9	Ba	2	0	0.06
10	Ba	0	-	-
		Total		100

It is inferred that the magnitude of surface energy force decreases with a decrease in particle size and also the magnitude of surface energy decreases with an increase in separation distance (Table 7). Hence, the force governing the silt is the surface energy force.

Table 6 EDX results for silt used in the study

Si. No	Elements	Count	Weight	Atom (%)
1	C	0	0	0
2	N	0	0	0
3	O	1111	4	63.51
4	Si	2941	4	36.29
5	V	25	0	0.06
6	V	848	0	0
7	Zn	15	0	0.13
8	Zn	75	0	0
		Total		100

Table 7 Surface energy force in Sand and Silt for different particle sizes – given for a single particle

Soil Type	Condition	Surface energy force F (N)
Fine Sand	Maximum range: D = 0.425 mm	1.47×10^{-17}
	Minimum range: D = 0.075 mm	0.833×10^{-17}
Silt	Maximum range: D = 0.0475 mm	1.489×10^{-17}
	Minimum range: D = 0.002 mm	35.45×10^{-17}

5. PROPOSED TEST FOR DETERMINATION OF SURFACE ENERGY FORCE - CYLINDRICAL FLOW TEST

A cylindrical flow test is suggested to understand the flow characteristics of sand, silt, and sand-silt mixtures since they have varied flow properties. Through this test, the presence of the surface energy force is confirmed and may be roughly confirmed. When contrasted with silt and sand-silt mixes, sand often flows more quickly. Due to the difference in kinetic energies, it is possible to measure the surface energy forces. A cylindrical mould that has a shutter fastened at the bottom (resembling a cylinder used for pouring sand [30]) is taken. The shutter is then opened, allowing the sand to flow when the cylinder has been filled with sand to a predetermined height. The amount of sand flown (V), the duration of the flow (t), and the mass of the sample flown (m) are recorded using a box with a known volume. Eq. (2) uses this information to determine the discharge. By measuring the diameter of the hole at the bottom of the mould, the area through which the sample is flown is calculated. The velocity of flow (v) is calculated using Eq. (3). From the mass and velocity of the sample flown, the kinetic energy of flow (KE) is calculated using Eq. (4) and then the force corresponding to the kinetic energy is calculated from the Eq. (5).

$$Q = \frac{V}{t} \quad (2)$$

$$v = \frac{\mathbf{Q}}{\mathbf{A}} \quad (3)$$

$$K.E = \frac{1}{2} mv^2 \quad (4)$$

$$f = \frac{2a(K.E)}{v^2};\ \text{where } a = \frac{v}{t} \quad (5)$$

The same process is used for calculating the kinetic energy and forces for various sand-silt combination amounts. Sand lacks surface energy, hence the presence of surface energy is shown by the difference between the kinetic energies of sand and sand-silt mixes. This difference can be determined using Eq. (6),

Surface energy = K.E of sand – K.E of sand-silt mixtures (6)

Table 8 Kinetic energy and surface energy force for sand-silt mix proportions

Sample	Velocity, v (cm/sec)	Kinetic energy, K.E (kg cm^2/sec^2)	Force, f (N)	Amount of K.E restricted	Surface energy force, f (N)
S100	20.06	84.10	8.56 x 10^{-3}	0	0
S90M10	19.08	78.63	8.034x 10^{-3}	5.47 x 10^{-4}	0.526 x 10^{-3}
S80M20	18.45	76.25	7.795 x 10^{-3}	7.85 x 10^{-4}	0.765 x 10^{-3}
S70M30	18.03	75.42	7.70 x 10^{-3}	8.68 x 10^{-4}	0.858 x 10^{-3}
S60M40	11.82	33.67	3.44 x 10^{-3}	50.43 x 10^{-4}	5.12 x 10^{-3}
S50M50	10.27	24.78	2.78 x 10^{-3}	59.32 x 10^{-4}	5.78 x 10^{-3}
S40M60	6.54	9.19	0.941 x 10^{-3}	74.91 x 10^{-4}	7.62 x 10^{-3}
M100	0	0	0	≥ 84.10 x 10^{-4}	≥ 8.56 x 10^{-3}

The surface energy force generally corresponding to the proportion of silt content demonstrates that the surface energy force increases as the silt content increases (Table 8). In the presence of water, this surface energy force produces cohesion.

6. CONCLUSIONS

It is clear from the results of various tests like relative density test, standard proctor test and test tube flow that, silt is subject to a different force. The test tube flow results in silty sand show that, there is no electrostatic force between them, yet some gravity force governs due to partial arch formation, indicating that the silty sand is governed by another force. Thus, silt and fine sand are theoretically anticipated to be sensitive to the surface energy forces. As the size of the soil grains diminishes from sand to silt, the surface energy force grows stronger. Consequently, surface energy is the dominant force controlling the silt. This research proposes a novel test to determine the surface energy force. The surface energy force is computed for different sand-silt mixture ratios, and in the presence of water, this surface energy force causes cohesion.

7. ACKNOWLEDGMENTS

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