

Development and Laboratory Assessment of a Small Torsional Direct Shear Test Apparatus

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Research Article

Keywords: Torsional shear strength, Direct shear test, Cohesion, Angle of internal friction, Vane shear, Sand–clay mixture, Vane diameter

Posted Date: August 7th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10518789/v1>

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Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Transportation Infrastructure Geotechnology on October 17th, 2026. See the published version at <https://doi.org/10.1007/s40515-026-01083-3>.

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ABSTRACT

Shear strength parameters obtained from the conventional Direct Shear Test (DST) are affected by a shearing plane whose area changes progressively as the two halves of the box displace, which limits the strain that can be imposed and complicates interpretation of the results at large displacement. Torsional shearing devices avoid this constraint by rotating a specimen about a fixed axis, so that the nominal shearing area stays constant regardless of displacement. A field-deployable Torsional Direct Shear Test (TDST) apparatus, intended for in-situ assessment, was previously developed and patented (Waghmare and Tripathi 2023). The present work reports a compact laboratory counterpart of that device, retrofitted onto a conventional small-box DST loading frame, aimed at the routine characterization of remoulded soils and sand–clay mixtures passing the 4.75 mm sieve, as a laboratory step toward the eventual field validation of this small TDST against its large-scale counterpart. The apparatus accepts interchangeable 90 mm and 60 mm diameter vanes and converts measured torque and lever-arm travel into equivalent shear stress and shear displacement, assuming uniform mobilization of shear stress across the vane base. Fourteen soil and mixture conditions — six natural soils spanning high- and low-plasticity clays, a silt, and a cohesionless artificial sand; two further cohesionless sands; and six artificial crushed-sand/clay mixtures spanning 0–100% clay by weight — were tested with the small TDST and a companion small-box DST prepared at matched density and moisture content. The 90 mm vane reproduced the DST cohesion and friction angle reasonably well for most of the natural soils, generally on the conservative side, whereas the crushed-sand/clay mixtures showed the reverse trend, with TDST cohesion equalling or exceeding the DST value above 40% clay content. The 60 mm vane substantially under-predicted both parameters and became mechanically unstable above 40% clay content, confirming vane diameter as a governing design and interpretation variable for the device. The apparatus, its data-reduction basis, and its observed limitations are reported in support of its continued development as a laboratory precursor to, and validation step for, the field-scale TDST.

Keywords: Torsional shear strength, Direct shear test, Cohesion, Angle of internal friction, Vane shear, Sand–clay mixture, Vane diameter

INTRODUCTION

The design of geotechnical structures is governed primarily by bearing capacity and settlement, both of which depend on the shear strength parameters of the founding soil — cohesion (c) and the angle of internal friction (ϕ). These parameters are not intrinsic material constants; they vary with stress path, strain rate, drainage conditions, and specimen scale, and are therefore sensitive to the testing method used to obtain them (Das 2006). The Direct Shear Test (DST) remains the most widely used laboratory method because of its simplicity, but it has two well-recognized limitations. First, the area of the shear plane decreases as the two halves of the shear box displace relative to one another, so the nominal stresses computed from measured loads become increasingly approximate as displacement increases. Second, the total displacement achievable in a DST is limited by the box geometry, which restricts the test's usefulness for soils that require large strains to reach a fully mobilized or residual strength condition. These limitations motivated the development of ring and torsional shear devices, in which the specimen is sheared about a fixed axis so that the nominal shearing area remains constant and the displacement is, in principle, unbounded (Bromhead 1979; Stark and Vettel 1992).

Building on this concept, a field-deployable Torsional Direct Shear Test (TDST) apparatus was previously designed, fabricated, and patented for in-situ assessment of soil shear strength (Waghmare and Tripathi 2023). That field device performs well for in-situ investigation but is not readily suited to controlled laboratory work: it does not easily accommodate remoulded specimens prepared at a specified density and moisture content, it is impractical for repeatable testing of finer-grained soils under laboratory conditions, and its scale restricts the throughput needed for a systematic comparison against a standard method. The long-term objective of this research program is a compact, field-portable TDST device for the routine assessment of soils and soil–aggregate mixtures passing the 4.75 mm sieve — the particle-size range for which the conventional small-box DST is applicable — with its performance validated jointly against the existing large-scale field TDST and against the small-box DST. As a necessary first step toward this goal, the present study reports (i) the design and fabrication of a compact, small-box TDST apparatus retrofitted onto a conventional small-box DST loading frame, so that existing laboratory infrastructure (normal-load frame, box, data acquisition) is reused; and (ii) a laboratory-scale validation of this device against a conventional small-box DST, run in parallel at identical density and moisture content on a range of natural soils and artificially prepared sand–clay mixtures, establishing the basis on which its results can subsequently be cross-checked against the large-scale field TDST.

This paper first reviews the relevant literature on shear testing devices, with particular attention to torsional and ring shear apparatuses and to the interpretation of vane-type shear tests, since the small TDST shares its data-reduction basis with the vane shear test. The design of the individual components of the small TDST apparatus is then described, followed by the theoretical basis used to convert the measured torque and displacement into shear stress and

shear strain. The testing procedure, the soils and mixtures used, and the resulting shear strength parameters are then presented and compared against the companion DST results, and the paper concludes with a discussion of the observed trends, the limitations of the current device, and the scope for further work.

LITERATURE REVIEW

Laboratory assessment of soil shear strength has historically relied on the Direct Shear Test and the Triaxial Shear Test, both standardized and well documented (Das 2006). The DST subjects a specimen to a predetermined normal stress while forcing shear along a single horizontal plane by displacing the upper half of the shear box relative to the lower half. Because the two halves of the box slide past one another, the effective area of the shear plane reduces progressively with displacement, and the test cannot readily be carried to the large strains needed to characterize residual strength. This limitation motivated the development of shearing devices in which the specimen is sheared about a fixed vertical axis, keeping the nominal shear area constant regardless of the magnitude of displacement.

The ring shear apparatus is the most established device of this type. Bromhead (1979) introduced a simple, low-cost ring shear apparatus intended to make large-displacement residual strength testing practical outside specialist research laboratories, and it has since become a standard tool for slope stability investigations. Stark and Vettel (1992) subsequently examined sources of error in the Bromhead apparatus, in particular sidewall friction developing between the confined annular specimen and its container, and proposed a modified test procedure that produced residual strengths in better agreement with back-analyzed field case histories. These studies illustrate a recurring theme in torsional/ring shear testing: the constant-area advantage over the DST is real, but the interpretation of measured torque in terms of shear stress is sensitive to the assumed distribution of mobilized stress across the shearing surface and to the boundary conditions imposed by the specimen container.

A closely related body of work concerns the interpretation of the field vane shear test, which — like the TDST — derives shear strength from a measured torque rather than a directly measured shear force. Chandler (1988) reviewed the assumptions underlying the conventional vane shear interpretation and highlighted that the distribution of mobilized shear stress over the ends of the vane is not known with certainty; a uniform distribution and a triangular (linearly increasing with radius) distribution are the two limiting idealizations commonly adopted, and they lead to different back-calculated strength values from the same measured torque. This distinction is directly relevant to the present study and is adopted as the basis for the data-reduction procedure described later. Suits et al. (2011) described a pressurized vane shear apparatus developed to extend vane testing to stress conditions representative of deep or overburden-pressurized deposits, illustrating the continued development of vane-based torsional devices for specialized applications. Klotz et al. (2003) examined the effect of

inherent soil anisotropy and the mode of shearing on the mobilized strength of geomaterials, underscoring that shear strength parameters obtained from any single testing method — direct shear, triaxial, or torsional — should be interpreted with an awareness of the shearing mode imposed by that method, rather than treated as a unique material property.

Taken together, this body of work establishes two points that motivate the present study. First, torsional shearing devices offer a genuine advantage over the DST in maintaining a constant shear area, but this advantage is only realized in practice if the torque-to-stress conversion is stated explicitly and its assumptions are examined, rather than treated as self-evident. Second, while field-scale torsional and ring shear devices are well established, there is comparatively little published work on compact, laboratory-scale torsional direct shear devices that can be retrofitted onto standard DST loading frames for routine testing of remoulded specimens — the gap the present study addresses. The following sections describe the design of such a device, the basis on which its torque and displacement readings are converted to shear stress and shear displacement, and its assessment against a conventional small-box DST across fourteen soil conditions of varying plasticity, gradation, and (for the artificial mixtures) clay content.

THEORETICAL BASIS AND DATA REDUCTION

Unlike the field vane, in which the vane blades penetrate the soil and mobilize shear resistance along a cylindrical surface generated by the blade edges plus the top and bottom of the cylinder, the small TDST vane described here shears the soil only across its base: the vane is confined within the box on its sides and top by the surrounding soil and quarter plates, and rotation of the vane relative to the confined soil mobilizes shear resistance only across the horizontal circular area at the base of the vane, of radius $R = 45$ mm for the standard (90 mm diameter) vane. This distinction is important because it removes the side-shear contribution present in the classical vane shear formula and simplifies the torque balance to an integral over a single circular area. (Fig. 1)

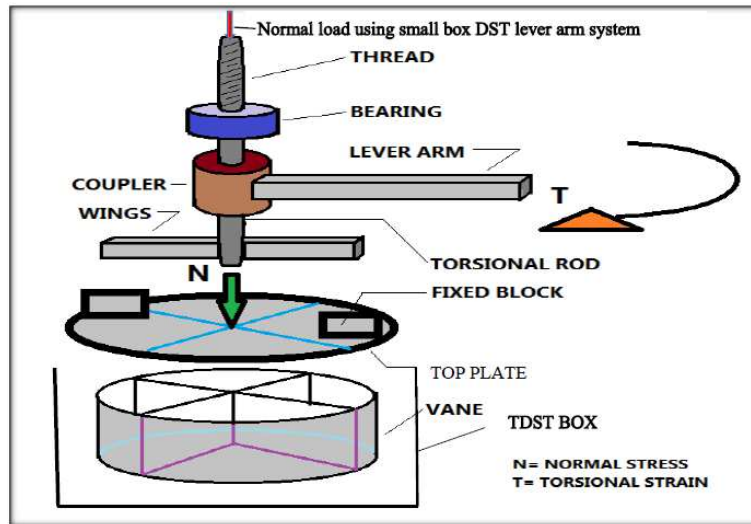


Figure 1. Torsional direct shear test concept: assumed uniform mobilization of shear stress across the vane base

For an assumed shear stress τ mobilized uniformly across the base of the vane, the resisting torque is obtained by integrating the moment of shear stress acting on an annular ring of radius r and width dr over the full radius of the vane:

$$T = \int_0^R \tau \cdot r \cdot (2\pi r) dr = (2/3)\pi\tau R^3$$

which rearranges to give the mobilized shear stress directly from the measured torque:

$$\tau = 3T / (2\pi R^3) = T / (\beta\pi R^3), \text{ with } \beta = 2/3$$

The coefficient $\beta = 2/3$ corresponds to the assumption of a uniform stress distribution across the vane base and is analogous to the uniform-mobilization coefficient discussed by Chandler (1988) for the field vane shear test, as distinct from the alternative triangular (linearly increasing with radius) distribution, for which $\beta = 1/2$. Trial back-calculations against the companion DST results for the present soils showed the uniform-mobilization assumption to give the closer match, consistent with the observation of earlier workers that a uniform distribution is generally the more representative idealization once the vane has been rotated sufficiently to mobilize a fully developed shear zone across its base (Chandler 1988); the uniform-mobilization coefficient is therefore adopted throughout this study, including for the supplementary 60 mm vane ($R = 30$ mm) results discussed later. Since the torque is generated by the load cell force F acting at the end of a lever arm of length L ($T = F \cdot L$), the working equation used to reduce every load-cell reading to a shear stress is:

$$\tau = 3FL / (2\pi R^3)$$

Because the lever arm length L enters the numerator directly, this expression automatically normalizes for any change in the lever arm length used in a given test setup; the load cell force alone is not, and should not be, treated as a direct index of shear stress. Because R appears in the denominator raised to the third power, the same torque-to-stress relation is markedly more sensitive to vane radius for the smaller vane; this sensitivity is discussed further in relation to the 60 mm vane results in the Analysis and Discussion and Limitations sections below.

The horizontal axis of the TDST shear stress plots (Figs. 9 and 10) is not a displacement measured directly at the shear plane, since the vane rotates rather than translates. Instead, it is obtained by first converting the winch/rope travel at the lever arm into an angular rotation of the vane, using the small-angle relationship $\theta \text{ (rad)} = (\text{winch travel})/L$, and then converting this angle to an equivalent linear shear displacement at the periphery of the vane, $\delta = \theta R$. This peripheral displacement δ represents the shear displacement at the radius where the vane mobilizes its largest moment arm and is therefore also the location at which shear strain first localizes; it is reported here on the same axis as, and is directly comparable in physical meaning to, the horizontal shear displacement recorded in the companion DST.

The normal stress applied to the TDST specimen is obtained in the same way as in the conventional DST: the normal load transmitted through the loading frame and bearing block is divided by the plan area of the vane (πR^2), since the same loading frame, hangers, and calibrated weights used for the small-box DST were adapted, via the bearing block described in the following section, to apply normal load to the TDST assembly.

DESIGN OF THE SMALL BOX TDST APPARATUS

The laboratory TDST was configured around an existing small-box DST loading frame, replacing the conventional split shear box with a new, open-topped torsional assembly so that the normal-load lever-arm system of the DST frame could be reused to apply a controlled normal stress to the vane (Fig. 2). The vane assembly is interchangeable: a standard 90 mm diameter ($R = 45 \text{ mm}$), 50 mm deep vane was used for the great majority of tests reported here, and a smaller 60 mm diameter ($R = 30 \text{ mm}$), 35 mm deep vane was additionally used for a subset of the crushed-sand/clay mixtures, to examine the sensitivity of the device to vane size (see Results). The principal components of the assembly are described below and shown in Figs. 3–7.

TDST box: A closed-bottom, open-top box with internal dimensions of $150 \times 150 \times 100 \text{ mm}$ (height) and a wall thickness of 5 mm houses the soil specimen (Fig. 3).

Vane: A quadratic (cruciform, four-blade) vane, 90 mm in diameter and 50 mm in height (or, for the supplementary comparison, 60 mm in diameter and 35 mm in height), with a blade thickness of 2 mm, is inserted into the compacted soil (Fig. 4). The blades intersect at 90° at the vane centerline. The vane is confined on its curved periphery by the surrounding soil, so

that rotation of the vane transfers shear strain to the soil across the vane's circular base at a constant nominal area, as described in the preceding section.

Top plate: A circular grooved plate (Fig. 5) engages the top of the vane; two staggered solid blocks fixed to the plate transfer torsional moment from the drive column to the vane, so that rotation of the top plate produces a corresponding rotation of the vane.

TDST column: A solid square column, 15×10 mm in section and 40 mm in height, terminates in a 2 mm thick top plate. Two 30 mm wings welded to the base of the column transfer torque efficiently from the column to the top plate.

Bottom flange: A composite assembly comprising a $15 \times 10 \times 20$ mm hollow block welded to the periphery of the TDST column, with a 15×10 mm, 20 mm long square tube welded to one face of the block (Fig. 6).

Bearing block: A thrust-type bearing block (Fig. 7a) transfers normal load from the DST loading frame to the TDST column while allowing free rotation for torque transmission. A 300 mm lever arm connects to the TDST column.

Lever arm: The 300 mm lever arm is rigidly attached to the outer face of the column. A 1 mm diameter high-tensile steel strand is attached at the free end of the lever arm, oriented at 90° to the arm. One end of the strand connects to the winch rope; the other end connects, via the moving block described below, to a calibrated load cell, so that the pulling force applied by the winch is measured directly at the point of load transfer to the lever arm (Fig. 7b).

Winch mounted on a fixed column: A hand-operated winch, incorporating a spur-and-main gear train with a mechanical (force) reduction factor of 5 — i.e., the force delivered to the winch rope is five times the force applied by the operator at the winch handle, allowing a smooth, low, controllable pulling rate to be maintained by hand — pulls the lever arm through a rope-and-pulley system to impose a constant rate of rotation. The winch assembly is mounted on a permanently fixed steel column 810 mm in height, itself bolted with three horizontal bolts to an M15-grade concrete block of 200 mm depth.

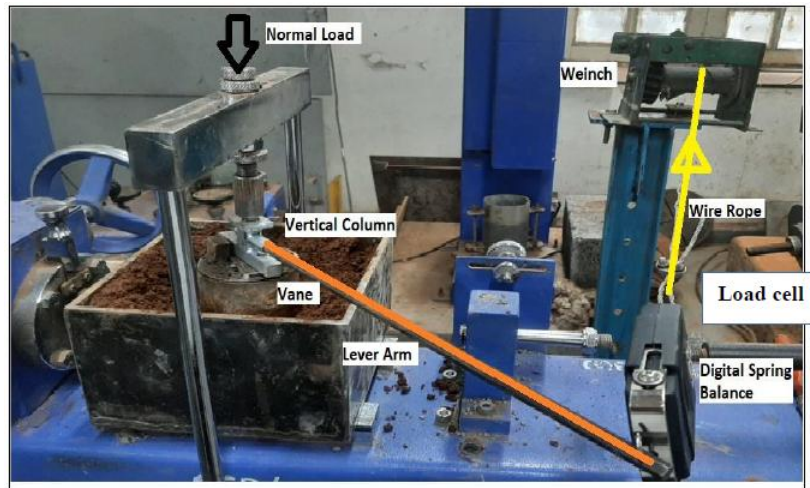


Figure 2. Conceptual setup of the small box TDST apparatus adapted onto the DST loading frame

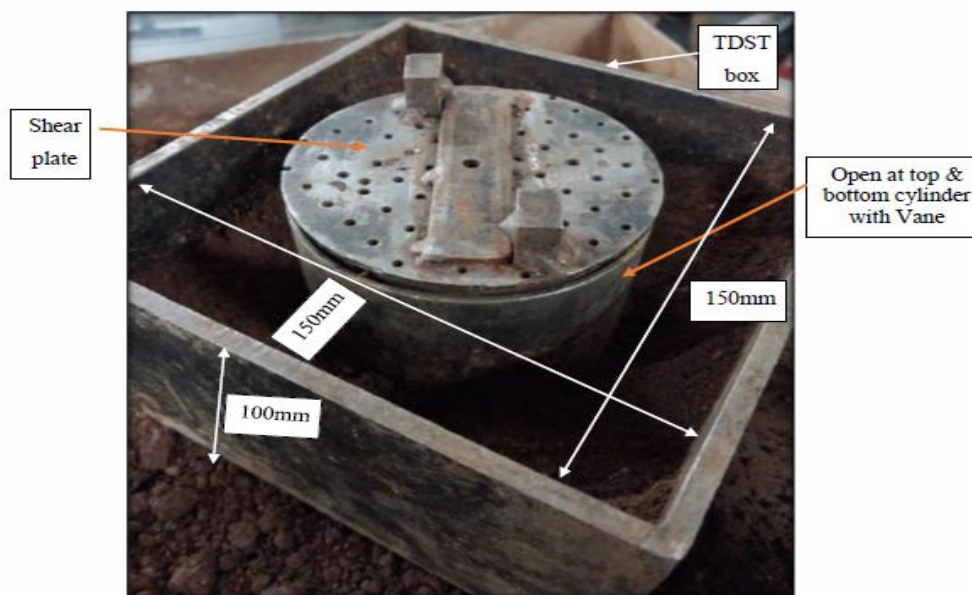


Figure 3. Small TDST box with vane and top shear plate



Figure 4. Details of the vane (90 mm / 60 mm diameter interchangeable vanes)



Figure 5. Bottom view of the grooved top shear plate

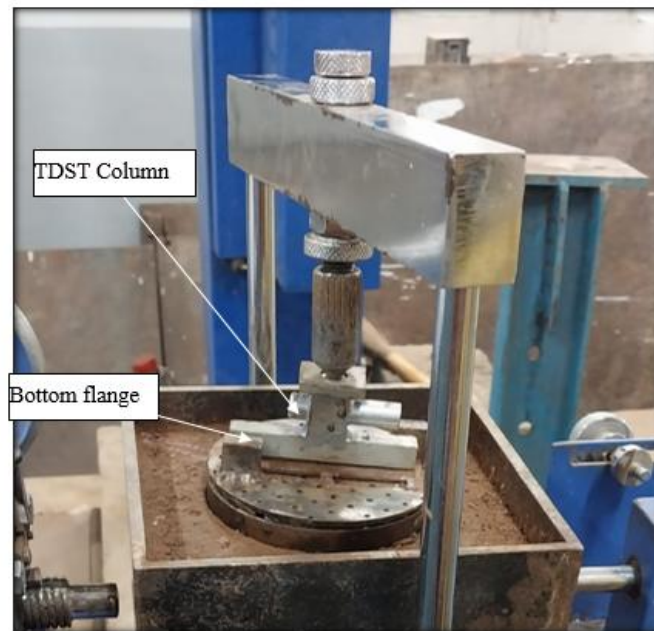


Figure 6. TDST column and drive arrangement above the shear plate

TESTING PROCEDURE

The small TDST is carried out following the sequence below (photographic record in Fig. 8):

1. Soil preparation: The mass of soil (or sand–clay mixture,) required is computed from the target maximum dry density (MDD) and the internal volume of the TDST box, and mixed to the optimum moisture content (OMC) determined from a standard Proctor compaction test.
2. Box preparation: The TDST box is cleaned with a wire brush and lightly greased on the inside. The internal height is divided into three equal compaction layers, marked with chalk, with the top 15 mm left unmarked to accommodate the vane.
3. Layered compaction: Soil is placed and compacted in three approximately equal layers to the target MDD; the surface of each layer is scarified before the next layer is placed, to promote bonding between layers. The final layer is compacted, levelled, and marked for vane placement.
4. Vane insertion: The vane is centered over the marked location and pressed into the compacted soil, at a slow, controlled rate to minimize disturbance to the surrounding soil fabric.
5. Trimming and quarter-plate placement: Soil surrounding the vane is trimmed away to the height of the vane without disturbing it. Quarter plates are then placed in each quadrant to distribute the normal load evenly and to allow the confined soil to dilate freely during shear.
6. Bearing and shear plate assembly: Ball bearings are seated in the quarter plates, and a matching shear plate is placed over them; this arrangement minimizes friction between the

shear plate and the quarter plates and ensures that normal load is transferred to the specimen in the same manner as in a conventional DST.

7. Drive and bearing arrangement: The shear plate blocks engage the moving block that transmits torque to the vane; a ring bearing and ball bearing are placed over the moving block to further reduce parasitic friction.

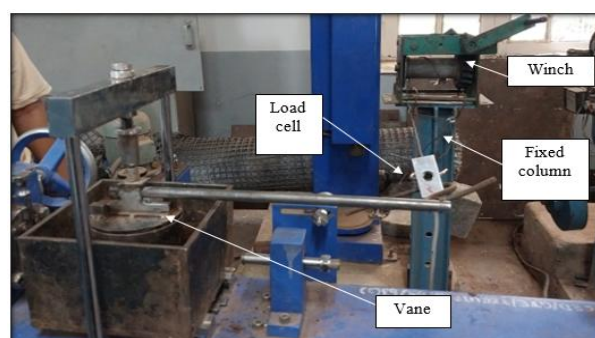
8. Loading frame and instrumentation: The DST loading frame is placed over the assembly to apply normal load. The moving block is linked to the load cell, and the load cell is connected by rope to the hand-operated winch.

9. Shearing: The winch is rotated manually to pull the lever arm at a constant strain rate of 1.2 mm/min — the same rate conventionally adopted for small-box DST testing under IS 2720 (Part 13) practice, retained here so that the two tests are directly comparable and not confounded by rate effects. Load cell readings are logged at fixed time intervals as torque is applied, and the corresponding shear stress and shear displacement are computed as described in the preceding section.

10. Post-test observation: The failure pattern developed in the sheared specimen is recorded photographically at the end of the test.



Figure 7. Assembly of the TDST apparatus: (a) bearing block and lever-arm connection; (b) load-cell and winch coupling



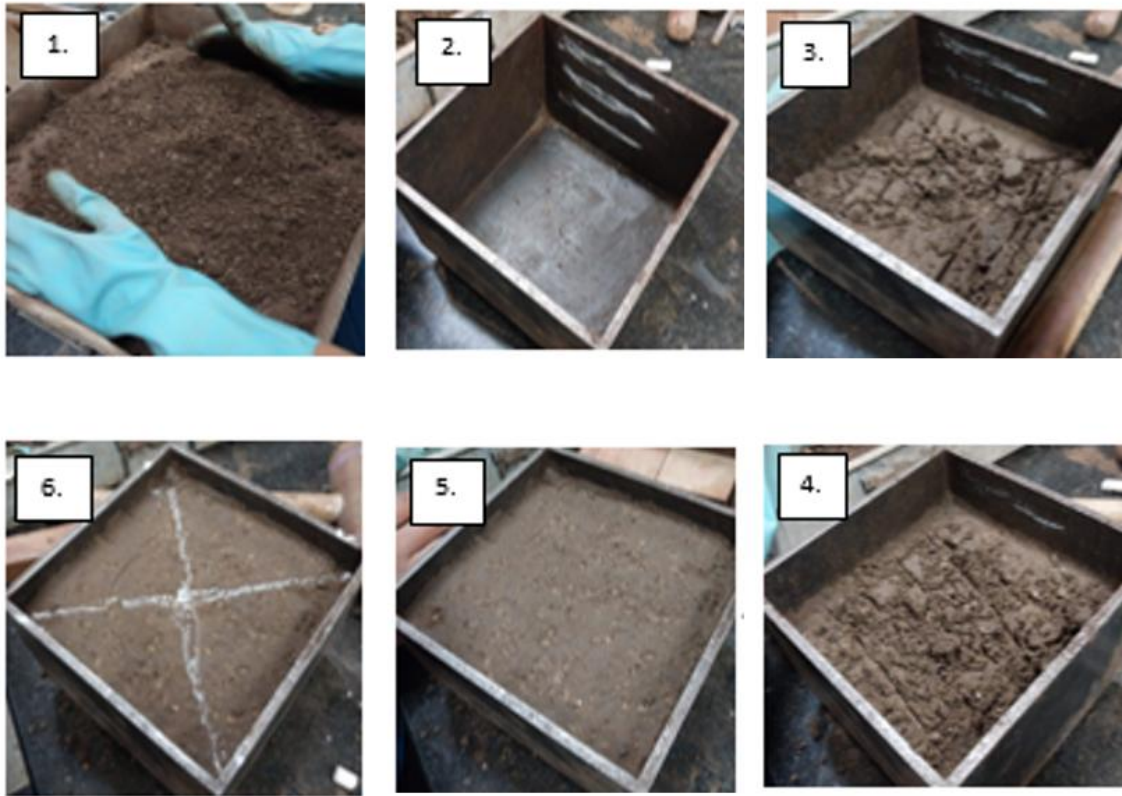


Figure 8a. Photographic record of the TDST test procedure: (a)–(f) specimen mixing, box preparation and vane placement (stages 1–6)

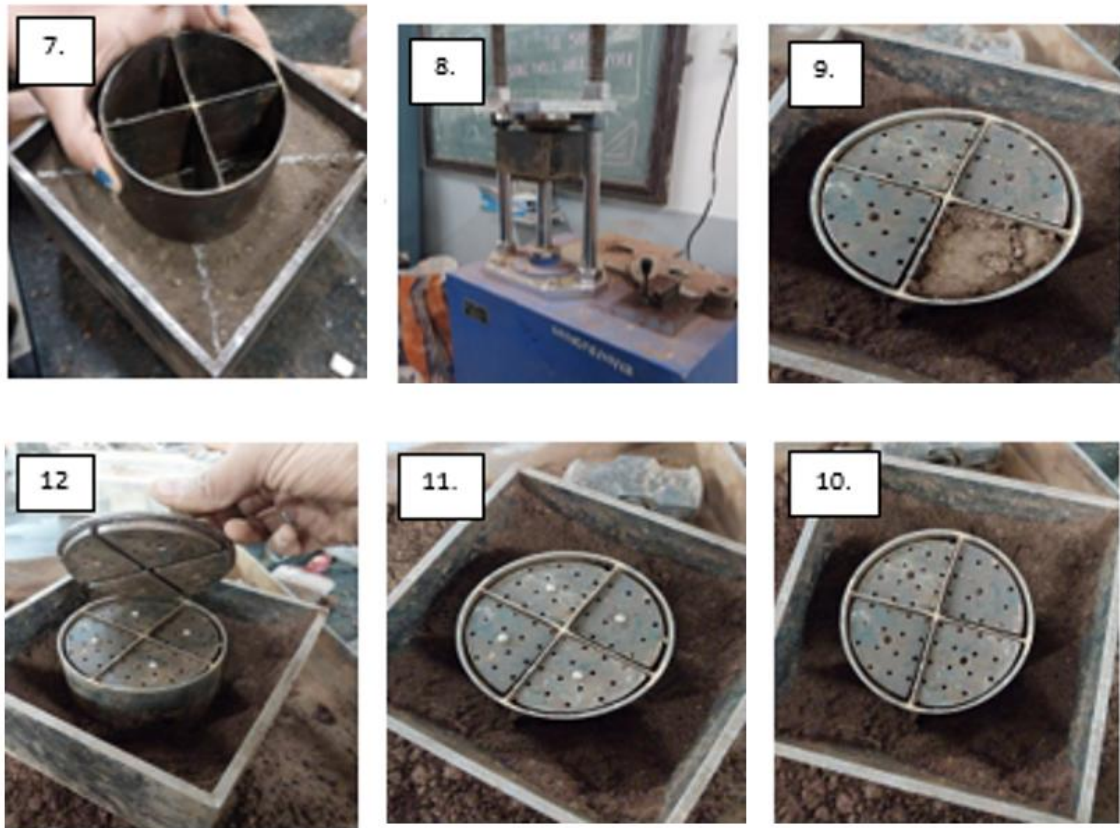


Figure 8b. Photographic record of the TDST test procedure (continued): (g)–(l) top-plate seating, loading-frame assembly and start of shearing (stages 7–12)

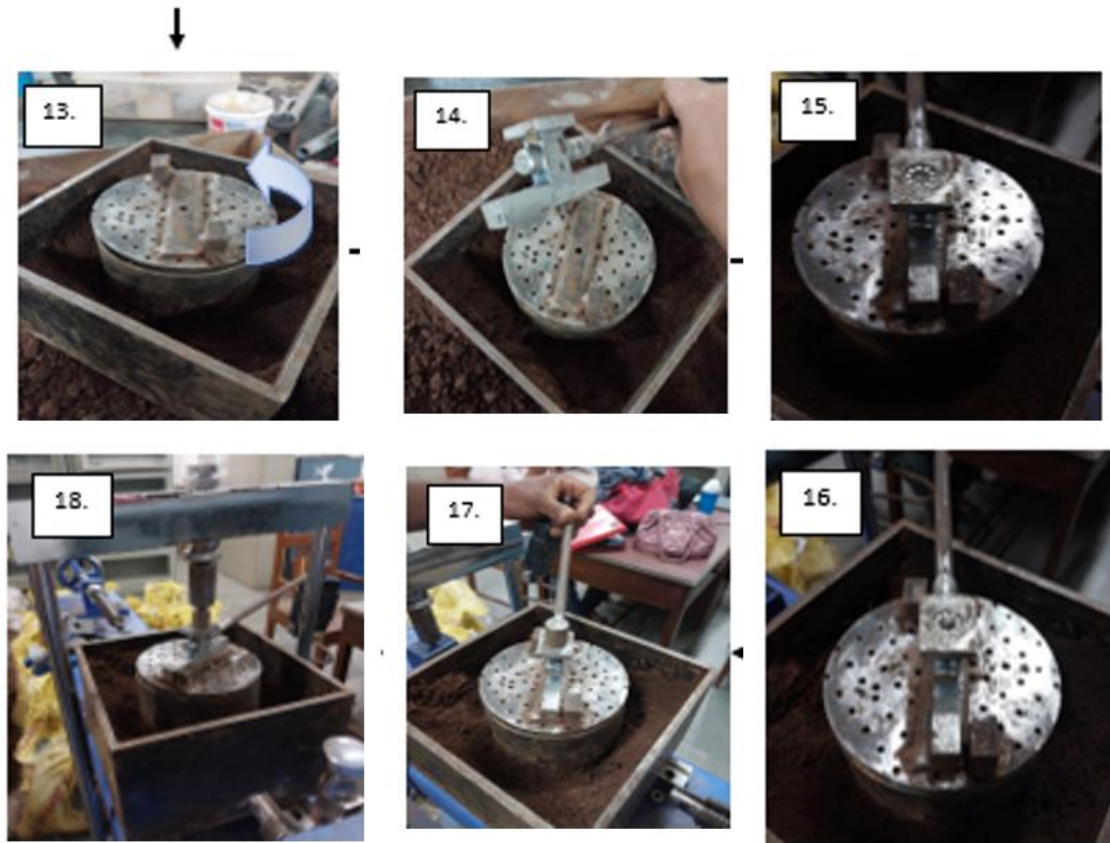


Figure 8c. Photographic record of the TDST test procedure (continued): (m)–(r)
shearing under the loading frame (stages 13–18)



Figure 8d. Photographic record of the TDST test procedure (continued): (s)–(u) test completion, disassembly, and the observed failure pattern in the sheared specimen (stages 19–21)

Materials and Soil Characterization

Fourteen soil conditions were used to assess the small TDST against a conventional small-box DST, conducted within this research program. Six natural soils formed the baseline assessment: two high-plasticity clays (Vashala Dam and Ratnagiri), one low-plasticity fine-grained soil (Sindhudurg), one low-plasticity silt (Boat Club), a black cotton soil, and an artificial (crushed) sand. Two further natural cohesionless sands — a beach sand and a crushed sand — were additionally tested to extend the assessment across a wider range of gradations. Separately, prepared six artificial crushed-sand/clay mixtures, spanning 0%, 20%, 40%, 60%, 80%, and 100% clay content by weight (crushed sand blended with the fines fraction of a locally sourced garden soil), to examine the device's performance across a controlled gradation/plasticity spectrum in addition to the naturally occurring soils.

Each sample was characterized for gradation or plasticity (as appropriate), Atterberg limits (where applicable), specific gravity, and standard Proctor compaction parameters, following the relevant IS methods, prior to preparing specimens for testing. The Unified Soil Classification (USCS) group symbol for each soil was assigned from the Atterberg limits using the Casagrande plasticity chart for the fine-grained soils, and from the coefficient of uniformity/curvature for the cohesionless sands; the properties of all fourteen soils/mixtures are summarized in Table 1.

Table 1. Properties of the soils and sand–clay mixtures used for laboratory small-box

TDST and DST assessment

Sr. No.	Soil / Mixture	USCS Group	Gradation / Fines Description (Cu & Cc, or Silt & Clay %)	LL (%)	PL (%)	PI (%)	Gs	MDD / OMC
1	Vashala Dam Soil	CH	Cu = 11.73, Cc = 0.64	69.7	29.0	40.7	2.65	16.0 kN/m ³ / 23.5%
2	Ratnagiri Soil	CH	Cu = 10.0, Cc = 1.03	64.5	20.8	43.7	2.63	17.0 kN/m ³ / 18.0%
3	Sindhudurg Soil	CL ¹	— (fine-grained)	29.7	22.0	7.7	2.8 ²	22.2 kN/m ³ / 14.0%
4	Boat Club Soil	ML	Silt 66.2%, Clay 33.8%	34.1	25.43	8.67	2.20	17.0 kN/m ³ / 18.0%

Sr. No.	Soil / Mixture	USCS Group	Gradation / Fines Description (Cu & Cc, or Silt & Clay %)	LL (%)	PL (%)	PI (%)	Gs	MDD / OMC
5	Black Cotton Soil	MH ³	Silt 55.4%, Clay 27.9%	69.9	52.97 ³	16.93 ³	2.13	13.5 kN/m ³ / 29.0%
6	Artificial Sand	SP	Cu = 4.24, Cc = 1.8	—	—	NP	2.56	16.9 kN/m ³ / 19.9% ⁴
7	Beach Sand	SP ⁸	Cu = 2.21, Cc = 0.85	—	—	NP	2.03	1.65 g/cc / 22.91% ⁷ (at 60% Dr)
8	Crush Sand	SW ⁸	Cu = 14.60, Cc = 1.8	—	—	NP	2.75	2.04 g/cc / 12.6% ⁷ (at 60% Dr)
9	Crush Sand (0% clay)	SP ⁸	Cu & Cc not separately reported; crushed sand only	—	—	NP	2.07 ⁵	2.26 g/cm ³ / 9.15%
10	Crush Sand + 20% Clay	—	Sand–clay mixture, 20% clay by weight	—	—	—	1.84 ⁵	2.08 g/cm ³ / 13.0%
11	Crush Sand + 40% Clay	—	Sand–clay mixture, 40% clay by weight	—	—	—	1.631 ⁵	1.90 g/cm ³ / 16.45%
12	Crush Sand + 60% Clay	—	Sand–clay mixture, 60% clay by weight	—	—	—	1.359 ⁵	1.68 g/cm ³ / 23.64%
13	Crush Sand + 80% Clay	—	Sand–clay mixture, 80% clay by weight	—	—	—	1.24 ⁵	1.57 g/cm ³ / 26.6%
14	100% Clay (Garden Soil)	MH ⁶	100% clay (fines) fraction	73.50	62.33	11.17	1.064 ⁵	1.41 g/cm ³ / 32.5%

Note: Sindhudurg soil is reported as CL (marginally above the A-line). Specific gravity, Atterberg limits, and classification values for soils 3, 5, and 9–14 — including the plasticity index for Black Cotton soil, the sub-unity Gs values for several crushed-sand/clay mixtures, and the classification of the 100% clay sample — are reported as recorded in the source dissertations (Naik 2023; Pawar 2022) and are flagged for verification against the original laboratory records before

design use. The crushed sand tested by Pawar (2022, soil 9) and Naik (2023, soil 8), though from the same locality, were characterized independently and are reported as distinct materials.

EXPERIMENTAL PROGRAM

The experimental program was designed to assess the small TDST directly against a conventional small-box DST under matched conditions. For each of the fourteen soils/mixtures listed in Table 1, a specimen was prepared at the same target density and moisture content for both tests. The small-box DST was performed in accordance with IS 2720 (Part 13): 2012, at a strain rate of 1.2 mm/min matching the TDST rate described above, and over the same set of normal stresses. For each soil, shear stress was plotted against shear displacement at each normal stress level, and against normal stress at peak/ultimate shear stress, for both the TDST and DST; cohesion and angle of internal friction were then obtained from the linear Mohr–Coulomb fit to the normal-stress–shear-stress data for each method. The resulting parameters for the standard 90 mm vane are compared soil-by-soil in Table 2.

In addition, performed a supplementary comparison using the smaller, 60 mm diameter vane for three of the crushed-sand/clay mixtures (0%, 20%, and 40% clay content), to assess the sensitivity of the device to vane diameter. Testing with the 60 mm vane could not be extended beyond 40% clay content because the vane became mechanically unstable (tilted) in the softer, higher-clay-content mixtures; these results are discussed qualitatively below, alongside the standard 90 mm vane results, rather than tabulated in detail, in view of the wide scatter in the back-calculated strength parameters at this vane size.

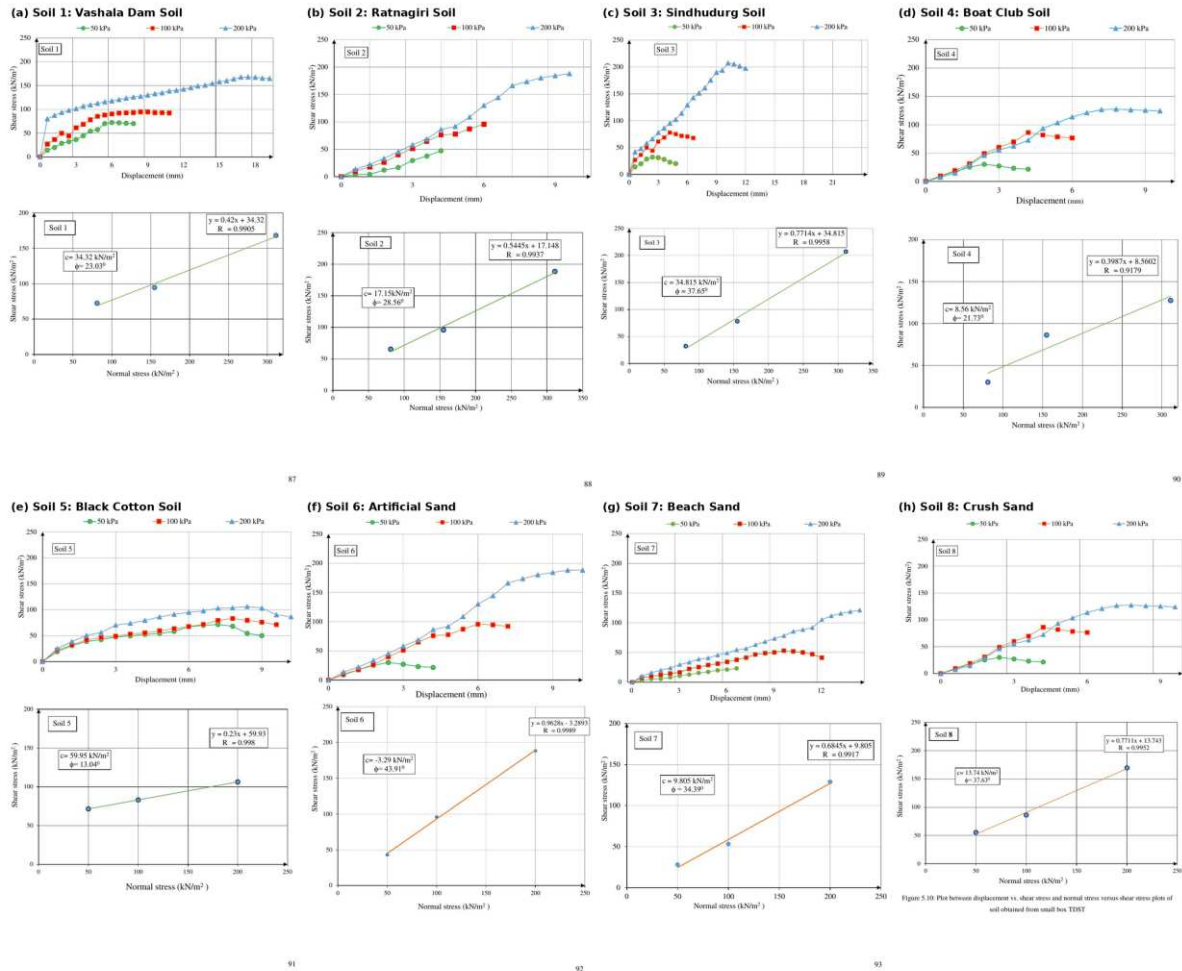
Results for each soil represent the average of at least two repeat tests conducted on independently prepared specimens at the same target density and moisture content, to provide a basic check on repeatability; the repeat trials for a given soil and normal stress level were found to agree closely, and the averaged value is reported as the representative result for that condition.

RESULTS

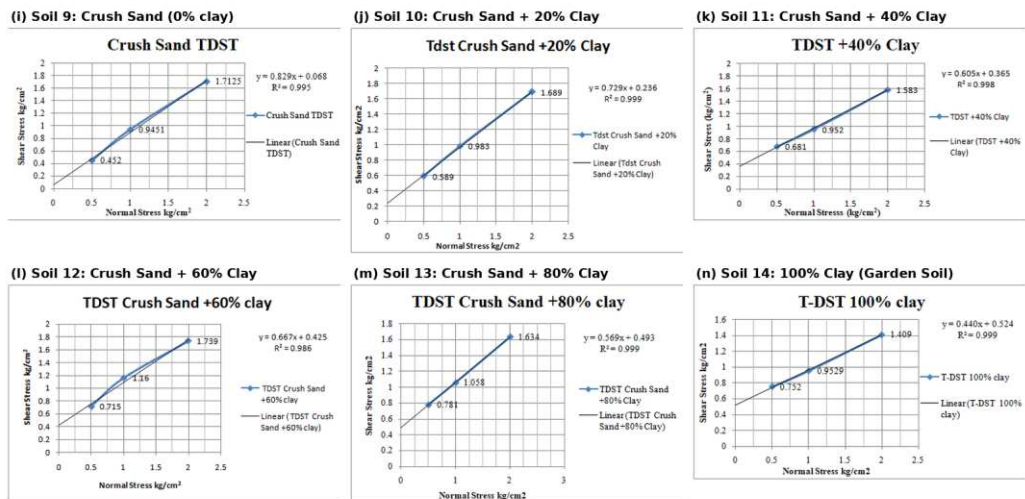
Table 1 summarizes the classification and index properties of all fourteen soils and sand–clay mixtures used in this study. Table 2 compares the cohesion and angle of internal friction obtained from the standard, 90 mm diameter vane TDST against the companion DST for all fourteen soils/mixtures.

Table 2. Cohesion and angle of internal friction from the standard (90 mm, “large box”) small-box TDST and DST, and their ratios, for all fourteen soils/mixtures (c and ϕ units: kN/m² and degrees respectively)

Sr. No.	Soil / Mixture	c TDST (kN/m ²)	c DST (kN/m ²)	c TDST/ c DST	ϕ TDST (°)	ϕ DST (°)	ϕ TDST/ ϕ DST
1	Vashala Dam Soil	34.32	39.15	0.88	23.03	29.95	0.77
2	Ratnagiri Soil	17.15	25.67	0.67	28.56	23.37	1.22
3	Sindhudurg Soil	34.82	36.87	0.94	37.65	39.81	0.95
4	Boat Club Soil	8.56	14.55	0.59	21.73	28.94	0.75
5	Black Cotton Soil	59.95	67.20	0.89	13.04	14.99	0.87
6	Artificial Sand	0.00	2.38	—	43.91	43.79	1.00
7	Beach Sand	9.81	10.82	0.91	34.39	46.48	0.74
8	Crush Sand A	13.74	14.70	0.93	37.63	44.57	0.84
9	Crush Sand B	6.67	9.51	0.70	39.67	43.55	0.91
10	Crush Sand + 20% Clay	23.15	30.21	0.77	36.11	38.11	0.95
11	Crush Sand + 40% Clay	35.80	31.58	1.13	31.19	33.04	0.94
12	Crush Sand + 60% Clay	41.69	36.78	1.13	33.72	35.04	0.96
13	Crush Sand + 80% Clay	48.36	47.58	1.02	29.65	27.53	1.08
14	100% Clay (Garden Soil)	51.40	46.10	1.11	23.76	19.60	1.21



(a)–(h) Small box TDST results, Soils 1–8.



(i)–(n) Small box TDST results (shear stress vs. normal stress), Soils 9–14 (crushed-sand/clay mixtures, 90 mm vane).

Figure 9. Shear stress vs. shear displacement, and shear stress vs. normal stress, for all soils — small box TDST (90 mm vane) (a)–(h) Soils 1–8 (baseline soils, Waghmare dataset); (i)–(n) Soils 9–14 (crushed-sand/clay mixtures,— normal-stress plots only; displacement records were not available in the source dissertation).

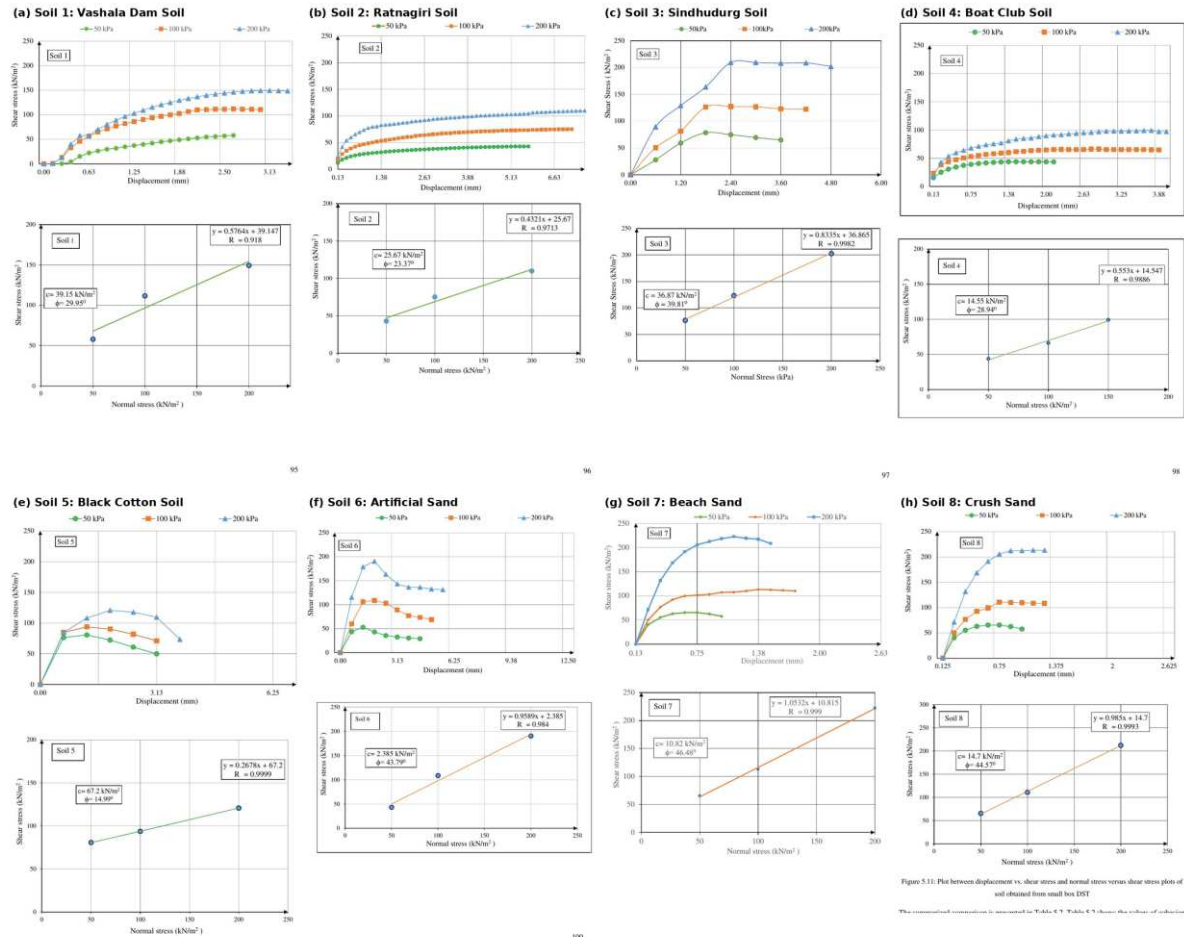
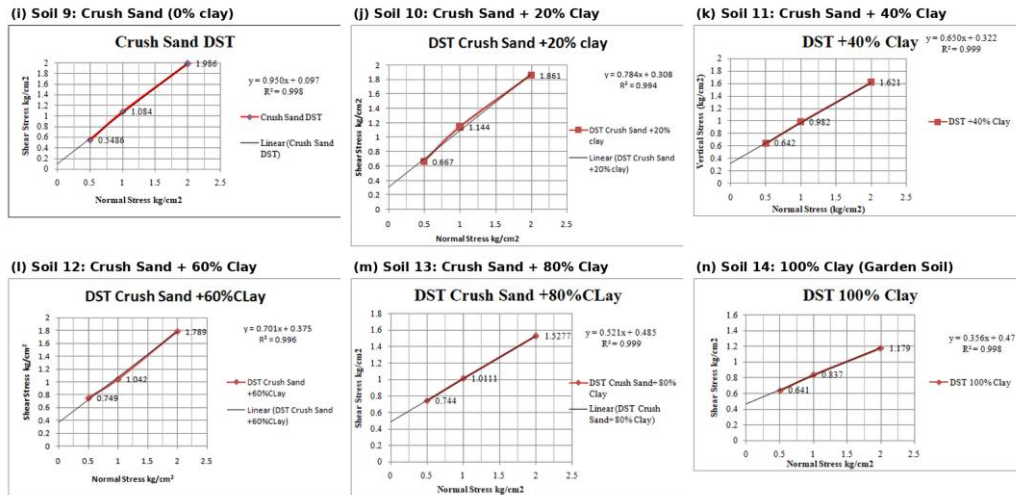


Figure 5.11: Plots between displacement vs. shear stress and normal stress versus shear stress plots of soil obtained from small box DST

(a)–(h) Small box DST results, Soils 1–8.



(i)–(n) Small box DST results (shear stress vs. normal stress), Soils 9–14 (crushed-sand/clay mixtures, 90 mm vane).

Figure 10. Shear stress vs. displacement, and shear stress vs. normal stress, for all soils — small box DST (a)–(h) Soils 1–8 (baseline soils); (i)–(n) Soils 9–14 (crushed-sand/clay mixtures,— normal-stress plots only).

ANALYSIS AND DISCUSSION

1. Across the six baseline natural soils, the small TDST reproduces the DST cohesion and friction angle to within a generally consistent margin, but the two parameters do not behave identically. For cohesion, the TDST value is lower than the corresponding DST value for every baseline soil with measurable cohesion, ranging from 0.59 to 0.94 times the DST value, with a mean ratio of approximately 0.79 across the five cohesive baseline soils (Table 2). This consistent under-prediction of cohesion is attributed principally to two factors inherent to the TDST geometry: first, the uniform-mobilization assumption ($\beta = 2/3$) used to reduce torque to shear stress is itself an idealization, and any progressive (rather than simultaneous) mobilization of shear resistance across the vane base — which would be expected given that the shear strain imposed by a rotating vane increases linearly with radius — would tend to make the true peak shear stress lower than that computed from a uniform-stress back-calculation at a given torque; second, the vane insertion process necessarily involves some remoulding and stress relief immediately around the vane periphery, which would be expected to reduce the mobilized cohesive component more than the frictional component, since cohesion in compacted clays is more sensitive to fabric disturbance than friction angle is.

2. For the angle of internal friction among the baseline soils, the picture is more mixed: four of the six soils show TDST values 5–25% lower than DST, but Ratnagiri soil shows a markedly higher TDST friction angle ($\phi^{\text{TDST}}/\phi^{\text{DST}} = 1.22$) and the artificial sand shows near-identical values (ratio = 1.00) (Table 2). The mean ratio across the six baseline soils is approximately 0.93. The near-unity ratio obtained for the cohesionless artificial sand is notable: because a cohesionless material develops no measurable cohesive intercept, the TDST/DST comparison for this soil isolates the frictional response alone, and the close agreement ($\phi^{\text{TDST}} = 43.91^\circ$ vs. $\phi^{\text{DST}} = 43.79^\circ$) suggests that the torque-to-stress data reduction described earlier is reasonably sound for the frictional component of strength for this soil.

3. The two additional cohesionless sands tested, do not uniformly confirm this frictional agreement, however. Crush Sand gives a friction-angle ratio of 0.84 ($\phi^{\text{TDST}} = 37.63^\circ$ vs. $\phi^{\text{DST}} = 44.57^\circ$), and Beach Sand gives a markedly lower ratio of 0.74 ($\phi^{\text{TDST}} = 34.39^\circ$ vs. $\phi^{\text{DST}} = 46.48^\circ$) — both showing a larger discrepancy than the near-unity result for the artificial sand, and in the opposite sense to the Ratnagiri anomaly. Together with the Ratnagiri result, this indicates that the close TDST–DST frictional agreement observed for the artificial sand should not be generalized to all cohesionless soils; particle shape, gradation, and packing at the vane periphery may all influence how faithfully the uniform-mobilization data reduction captures the true frictional response, and this warrants further, more targeted investigation.

4. The six crushed-sand/clay mixtures tested, with the 90 mm vane (Table 2, rows 9–14) show a systematic trend with clay content that is not apparent in the baseline soils: at low clay content (0% and 20%), TDST cohesion is lower than DST (ratios 0.70 and 0.77, consistent with the baseline trend), but from 40% clay content upward the ratio exceeds unity (1.13, 1.13, 1.02, and 1.11 at 40%, 60%, 80%, and 100% clay, respectively), i.e., the TDST cohesion equals or exceeds the DST cohesion. A parallel, though less pronounced, reversal is seen for the friction angle, which rises from ratios below unity at low clay content to values at or above unity (up to 1.21) at high clay content. This reversal, opposite to the consistently conservative trend found for the baseline natural soils, suggests that the balance between the mechanisms discussed above — progressive mobilization across the vane radius versus insertion disturbance — may shift with the plasticity and consistency of the mixture: as clay content and moulding water content increase, the mixture becomes softer and more workable, which may reduce insertion disturbance relative to the (still-developing) cohesive bonds, allowing the TDST to mobilize a comparatively larger fraction of the true strength, or possibly to over-predict it if lateral confinement effects around the softer vane periphery become more significant. This trend is based on a single set of mixtures prepared and tested by one operator and should be confirmed with independent replicate mixtures before it is generalized.

5. The supplementary 60 mm vane trials showed a markedly different picture from either trend above: both cohesion and friction angle from the 60 mm TDST were substantially lower than the companion DST for all three mixtures tested, and the scatter in back-calculated strength

across these trials was considerably wider than for the 90 mm vane. Because the torque-to-stress relation is cubic in the vane radius, a given torque measurement resolution and a given level of boundary/insertion disturbance are amplified far more severely for the smaller vane, and the proportionally larger disturbed zone around its periphery would be expected to suppress the mobilized strength more than for the 90 mm vane. Testing with the 60 mm vane could not be extended beyond 40% clay content because the vane became mechanically unstable (tilted) in the softer mixtures. Taken together, these results indicate that the 90 mm vane, not the 60 mm vane, should be regarded as the validated configuration of the device for routine use, and that vane diameter is an important, and previously unquantified, design and interpretation variable for the small TDST; the underlying 60 mm data are not tabulated here in detail in view of their wide scatter, and are recommended for independent re-measurement before quantitative use.

6. Overall, the small TDST with the 90 mm vane is found to give shear strength parameters that are generally somewhat conservative relative to the DST for the natural soils tested, most consistently for cohesion, and this conservatism is judged acceptable, and even desirable from a design perspective, for a device intended as a practical, higher-throughput complement to the DST rather than a replacement for it. The reversal of this trend for the crushed-sand/clay mixtures at higher clay content, and the pronounced under-prediction observed with the smaller 60 mm vane, show that the device's performance relative to the DST is not a single fixed offset but depends on both the material tested and the vane geometry used; the results should not be read as demonstrating general equivalence between the two methods, but rather as establishing the operating range within which the small TDST, in its 90 mm vane configuration, can be expected to perform relative to the DST for soils and mixtures of the type tested here.

LIMITATIONS AND SCOPE FOR FURTHER WORK

The present assessment is subject to several limitations that should be considered when interpreting the results and that define directions for further development of the apparatus.

Boundary effects: No instrumentation (e.g., strain gauges on the periphery of the mold) was used in this study to directly quantify boundary confinement or wall-friction effects on the measured torque. Given the parallels between the small TDST and ring/vane shear devices, in which boundary and sidewall friction are well-documented sources of error (Stark and Vettel 1992), instrumenting the mold periphery to quantify this effect directly is identified as a priority for future work.

Repeatability: The results reported here are averages of duplicate trials per soil and normal stress level for the baseline soils; while the duplicate trials agreed closely, a more extensive repeatability study (a larger number of replicate specimens per soil, with reported standard deviations) is needed before the precision of the device can be stated quantitatively, and is

recommended as a next step, together with additional replicates specifically for Ratnagiri soil in view of the anomalous friction-angle trend noted above. The crushed-sand/clay mixtures and the 60 mm vane results were obtained from a single set of specimens per condition and have not yet been independently replicated.

Basis of comparison: The comparison in this study is against a conventional laboratory small-box DST rather than a field-scale test, since the environmental and boundary conditions of a field test differ substantially from those achievable in a controlled laboratory comparison, and field-scale DST testing is itself comparatively difficult to perform routinely. This is considered an appropriate first-stage assessment; extending the comparison to field vane or field DST data, where available, would further strengthen the case for the device.

Specimen scale and representativeness: The vane footprint (45 mm radius for the standard vane; 30 mm radius for the supplementary small vane) engages a soil volume that is small relative to the overall specimen; as with any small-scale index test, this raises a question of how representative the sheared zone is of bulk soil behavior, particularly for soils with coarse particles, fissures, or macro-fabric. The present assessment is therefore most directly applicable to remoulded, relatively homogeneous fine-grained and fine-to-medium granular soils and mixtures; its applicability to natural, structured, or coarse-grained soils at higher relative densities has not been separately verified and should be treated as an open question pending further testing across a wider range of soil types and states.

Vane diameter: The supplementary 60 mm vane results indicate that the device's performance relative to the DST is sensitive to vane diameter, with the smaller vane substantially underpredicting both cohesion and friction angle and becoming mechanically unstable in soft, high-clay-content mixtures. This sensitivity has only been examined for three sand–clay mixtures at one normal stress range, and a more systematic study of vane-diameter effects, ideally including intermediate vane sizes and instrumented boundary measurements, is recommended before the 60 mm configuration is used for routine testing.

Strain rate: A strain rate of 1.2 mm/min was adopted to match standard laboratory DST practice under IS 2720 (Part 13), and is appropriate for the comparison purpose of this study; it should not be assumed representative of undrained or partially drained field loading rates, and rate-dependence of the TDST results has not been separately examined.

Data provenance: The properties and shear parameters for soils 7–14 (Table 1, Table 2) and the supplementary 60 mm vane trials are drawn; several index properties in these datasets (see Table 1 footnotes) appear inconsistent with typical ranges for the materials described and are flagged for verification against the original laboratory records before the values are relied upon for design.

CONCLUSIONS

A compact, laboratory-scale Torsional Direct Shear Test (TDST) apparatus, retrofitted onto a conventional small-box DST loading frame and configured with interchangeable 90 mm and 60 mm diameter vanes, has been designed, fabricated, and assessed against a companion small-box DST across fourteen soil conditions: six natural soils spanning high- and low-plasticity clays, a silt, a black cotton soil, and an artificial sand; two further natural cohesionless sands; and six artificial crushed-sand/clay mixtures spanning 0–100% clay by weight. The following conclusions are drawn:

1. The small TDST was successfully operated on remoulded specimens across the full range of soils and mixtures tested, confirming that the torsional shearing principle of the field TDST device can be adapted to a compact laboratory format compatible with existing DST loading frames.
2. A torque-to-shear-stress relation, $\tau = 3T/(2\pi R^3)$, derived from the assumption of uniform shear stress mobilization across the base of the vane, together with an angular-to-peripheral displacement conversion ($\delta = \theta R$), provides a consistent basis for reducing load-cell and winch-travel readings to shear stress and shear displacement, and for reporting results on axes directly comparable to those of the DST, for either vane diameter used.
3. For the six baseline natural soils, cohesion values from the 90 mm TDST were consistently lower than the corresponding DST values, by a factor averaging approximately 0.79 (range 0.59–0.94), and the angle of internal friction was, on average, approximately 0.93 times the DST value, agreeing closely with the DST for the cohesionless artificial sand (ratio = 1.00); one soil (Ratnagiri) showed a higher TDST friction angle than DST.
4. The two additional cohesionless sands (Beach Sand and Crush Sand) did not reproduce the near-unity friction-angle agreement seen for the artificial sand, with ratios of 0.74 and 0.84 respectively, indicating that the frictional agreement observed for one cohesionless soil should not be generalized without further testing across a wider range of granular soils.
5. The six crushed-sand/clay mixtures tested with the 90 mm vane showed a trend reversal with increasing clay content: TDST cohesion and, to a lesser extent, friction angle were lower than DST at 0–20% clay content (consistent with the baseline soils) but equalled or exceeded the DST values from 40% clay content upward (cohesion ratios 1.02–1.13), an outcome not observed in the natural soils and warranting further investigation and independent replication.
6. The supplementary 60 mm vane comparison, performed for three of the crushed-sand/clay mixtures, showed substantially lower and considerably more scattered cohesion and friction-angle values than the DST, and could not be extended beyond 40% clay content because of vane instability (tilting) in the softer mixtures; the 90 mm vane, not the 60 mm vane, is therefore recommended as the validated configuration of the device for routine use, and vane diameter

is identified as an important design and interpretation variable requiring further systematic study before the smaller vane is relied upon.

7. On the whole, the small TDST with the 90 mm vane yields shear strength parameters that are, for most natural soils, mildly conservative relative to the conventional DST, a favorable characteristic for a device intended for routine, higher-throughput screening of soils, complementary to rather than a replacement for the DST; this conservatism does not, however, extend uniformly to sand–clay mixtures at higher clay content or to the smaller vane configuration.

8. The principal limitations identified — the absence of direct boundary-friction instrumentation, the limited number of repeat trials for several of the newly added soils and mixtures, the restriction of testing to remoulded fine-grained and fine-to-medium granular soils, and the sensitivity of results to vane diameter — define clear priorities for further development of the apparatus and are discussed in the preceding section.

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LIST OF SYMBOLS

TDST Torsional Direct Shear Test

DST Direct Shear Test

c Cohesion

ϕ Angle of internal friction

G_s Specific gravity of soil solids

C_u Coefficient of uniformity

C_c Coefficient of curvature

MDD Maximum dry density

OMC Optimum moisture content

LL, PL, PI Liquid limit, plastic limit, plasticity index

T Torque

F Load-cell force

L Lever-arm length

R Vane radius

τ Shear stress

θ Angular rotation of the vane

δ Shear displacement at the vane periphery

β Shear-stress mobilization coefficient ($\beta = 2/3$ for uniform mobilization)