II EFFECTS OF SAND STRUCTURE

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1. Introduction

2. Inherent Structure and Anisotropy

3. Induced Anisotropy

4. Miscellaneous

5. Summary and Conclusions (Also applies to Part I)

Sheet A: Inherent Anisotropy of Dense Toyoura
B1,2,3: CID DSC Data on LBS
C: CIU TSHC Data on Ham River Sand
D: Sample Preparation method vs Cyclic Behavior

II EFFECTS OF SAND STRUCTURE

1. INTRODUCTION

1.1 Definitions

Structure = Fabric < preferred particle orientation
particle packing = distribution < uniform
non-uniform

+ Interparticle Forces - preferred direction of interparticle contacts

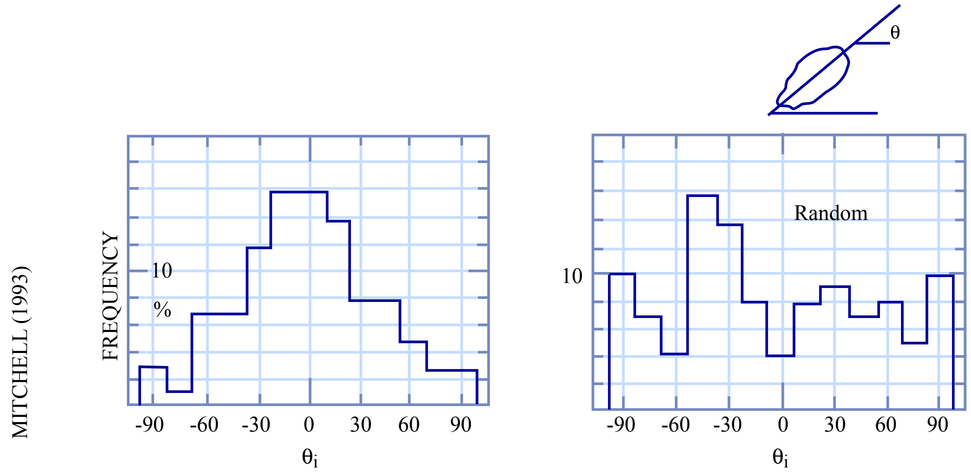
1.2 Coverage

- Inherent anisotropy : how measure & effects on stress-strain behavior
- Induced anisotropy !
- Miscellaneous : sample preparation, etc.

2. INHERENT STRUCTURE AND ANISOTROPY (1-D stress-strain history)

2.1 Inherent Structure

1) Preferred particle orientation



(1) V-section (2) H-section

Frequency histograms of long particle axis orientations in two planes for a uniform fine sand.

Figure by MIT OCW.

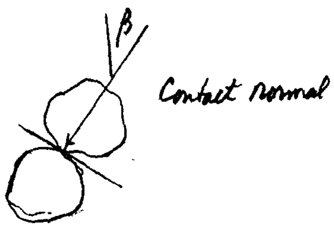
Adapted from: Mitchell (1993)

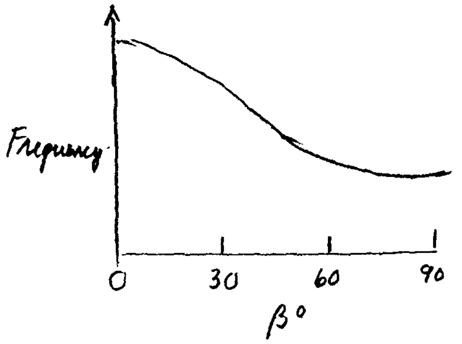
Reprinted from "Initial Fabrics and Their Relations to Mechanical Properties of Granular Material," by M. Oda, *Soils and Foundations*, Vol. 12, No. 1, pp. 17–37, Copyright 1972. With permission of The Japanese Society of SMFE.

- Elongated particles have preferred orientation $\perp$ to deposition (just like platy clay particles).

2.1 Cont.

2) Interparticle contacts (Oda 1972)





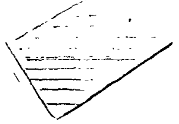
- Also get preferred orientation of interparticle contacts (even for spheres)

3) Summary: 1-D deposition → pronounced inherent structure, both regarding fabric and interparticle forces.

2.2 Effects of Inherent Anisotropy on Strength-Deformation Properties: Measurement Techniques

1) CID tests on inclined specimens

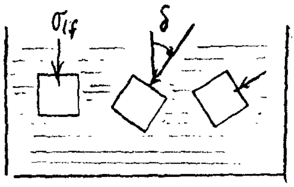
a) Arthur et al. (1972, 1975) Geot. 22(1), 25(4)



Pour inclined specimens

b) Oda et al. (1978) Soils & Fdn. 18(1)

Cut specimens from frozen sample



c) Arthur et al. (1977) 9th ICSMFE

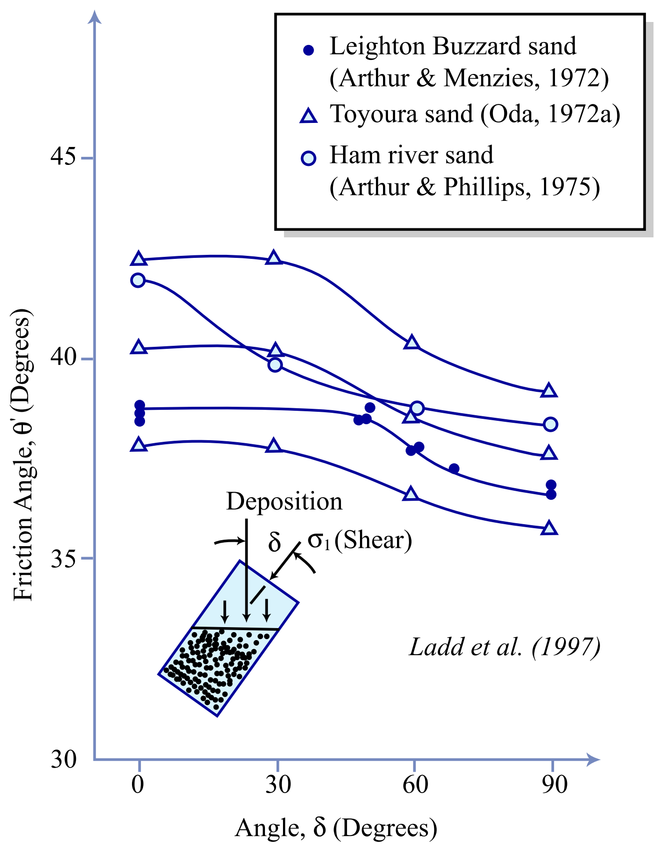
Cut specimens from sample impregnated with soap

2) Special shear devices

a) DSC: see Section 2.4 for CD tests

b) TSHC: " " 2.5 for CU tests

2.3 Effects of Inherent Anisotropy : CID Tests on Inclined Specimens



Effect of direction of loading on the friction angle of three sands.

Figure by MIT OCW.

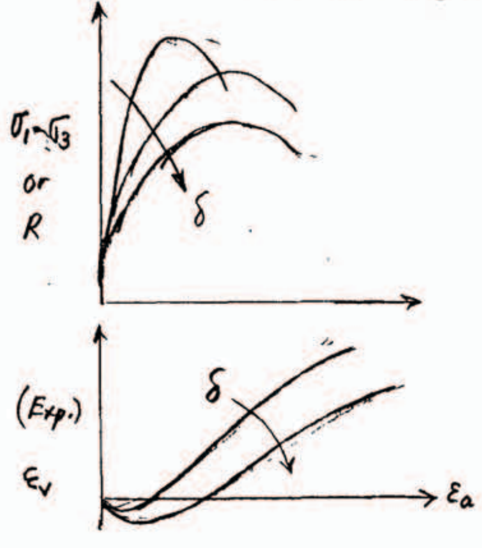
1) Effect on Peak Strength

- Increasing $\delta \rightarrow$ decrease in ϕ'_p
- $\Delta\phi'_p = 2\text{-}5°$
- Similar trend to variation in S_u vs δ for non-varved clays

Toyoura Sand
$D_{50} = 0.18\text{mm}$ $C_u = 1.5$
$e_{max} = 0.99$ $e_{min} = 0.63$
Test $e = 0.67 \pm 0.01 \rightarrow D_r \approx 90\%$

2) Effect on Stress-Strain Behavior

See Sheet A for tests on dense Toyoura Sand PSC & TC ($\sigma'_c = 0.5$ ksc)



Increasing $\delta \rightarrow$
- Decrease in peak strength
- Decrease in dilatancy

} related

- PSC - increase ε_f
  - less strain softening
- TC - no change in shape of curve

NOTE: Peak $\phi'_{PS} > \phi'_{TC}$

		$b=0 \rightarrow b=PS$ $\Delta\phi' =$
51.5 vs 45.5	$\delta = 0°$	+6.0°
46.7 vs 41.2	$\delta = 90°$	+5.5°

2.4 Effects of Inherent Anisotropy : CD DSC Tests

Arthur et al. (1981) ASTM STP 740

1) Introduction

← See Fig 17 for schematic of device → changing σ & τ components → changing σ'_{1f} direction

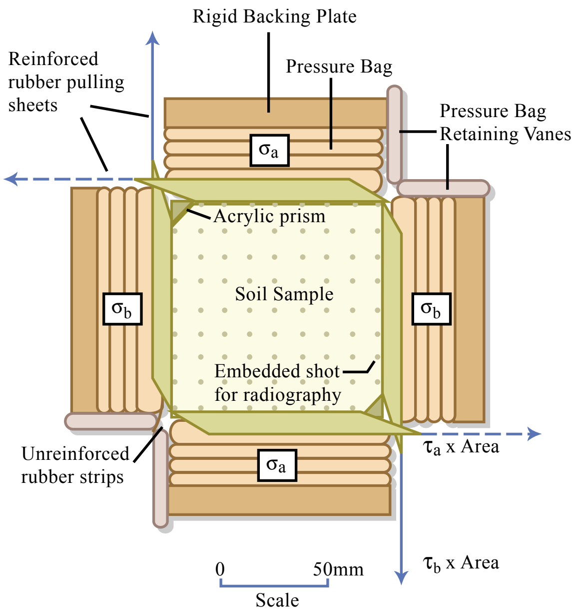
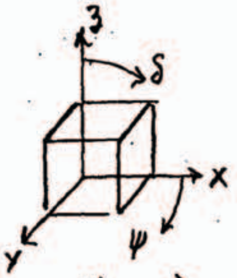


Diagram of Method Used to Apply Normal and Shear Stresses in the Direction and Shear Cell.

Figure by MIT OCW.



- Shear in isotropic x-y plane (ψ) enables proof testing. (See Sheet B1 for data on dense & loose LBS)
- Shear in anisotropic 3-x plane (δ) → measurements of inherent anisotropy

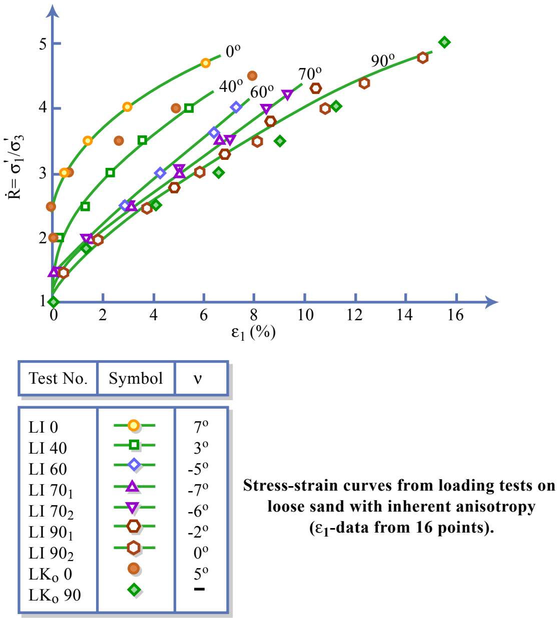
LBS = Leighton Buzzards Sand

D = 0.6-0.85 mm

Dense $e = 0.53 \rightarrow D_r \approx 95\%$

Loose $e \approx 0.74 \rightarrow D_r \approx 25\%$

2) Inherent Anisotropy of Loose LBS



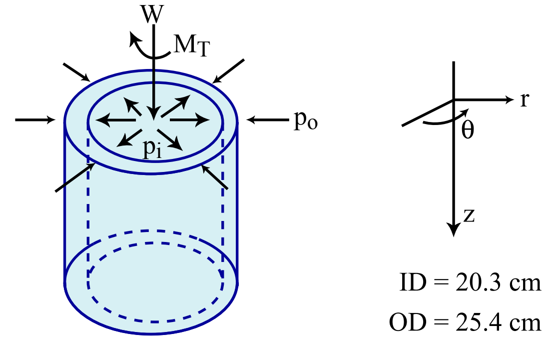
Stress-strain curves from loading tests on loose sand with inherent anisotropy (ε_1-data from 16 points).

Figure by MIT OCW.

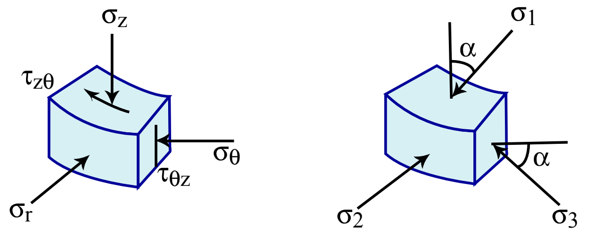
Increasing δ →
- Large decr. in q_f
- Significant change in shape of curve
- Decrease in rate of dilation (smaller ν)

$\nu = -\arcsin \dfrac{(\delta\varepsilon_1 + \delta\varepsilon_3)}{(\delta\varepsilon_1 - \delta\varepsilon_3)}$; min. ν = min. rate of dilation

2.5 Effects of Inherent Anisotropy: CIU TSHC Tests

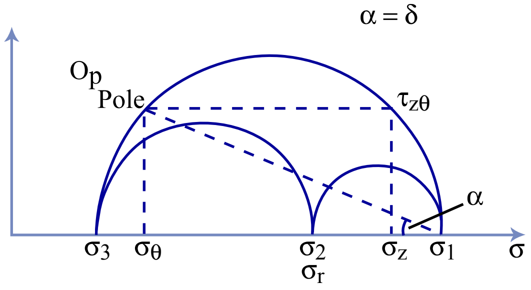


(a) Hollow cylinder sample under axial load W, torque M_T, internal pressure p_i, external pressure p_o.



(b) Stresses on an element in the wall of a hollow cylinder sample

(c) Principal stresses on an element in the wall



(d) Mohr circle representation of stress in the wall

Idealized stress conditions in a hollow cylindrical element subject to axial load, torque and internal and external pressure

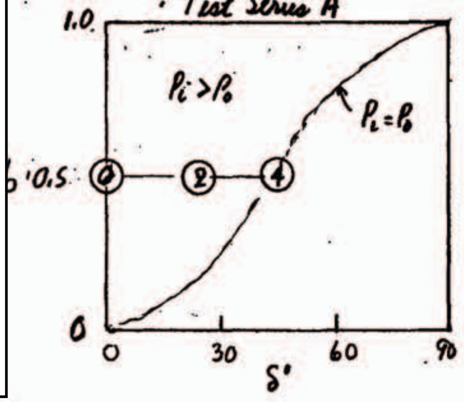
Figure by MIT OCW.
Adapted from: Symes et al. (1984)

1) Stresses in TSHC (Imperial College)

- See Fig. 1 ; Stress controlled;
  $P_o/P_i = 0.9-1.2$

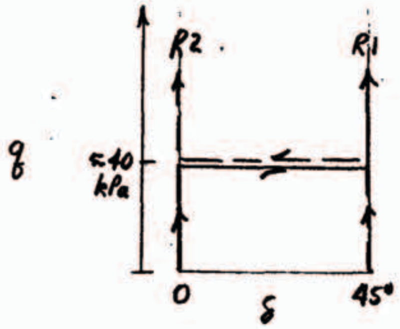
2) Test Program on Ham River Sand

- $D = 0.2-0.5$ mm $e_{max} = 0.92$
  $e_{min} = 0.61$
- Deposited 1-D through water giving "medium loose" state
- $\sigma'_c = 200$ kPa ; $b = 0.50$
- Test Series A



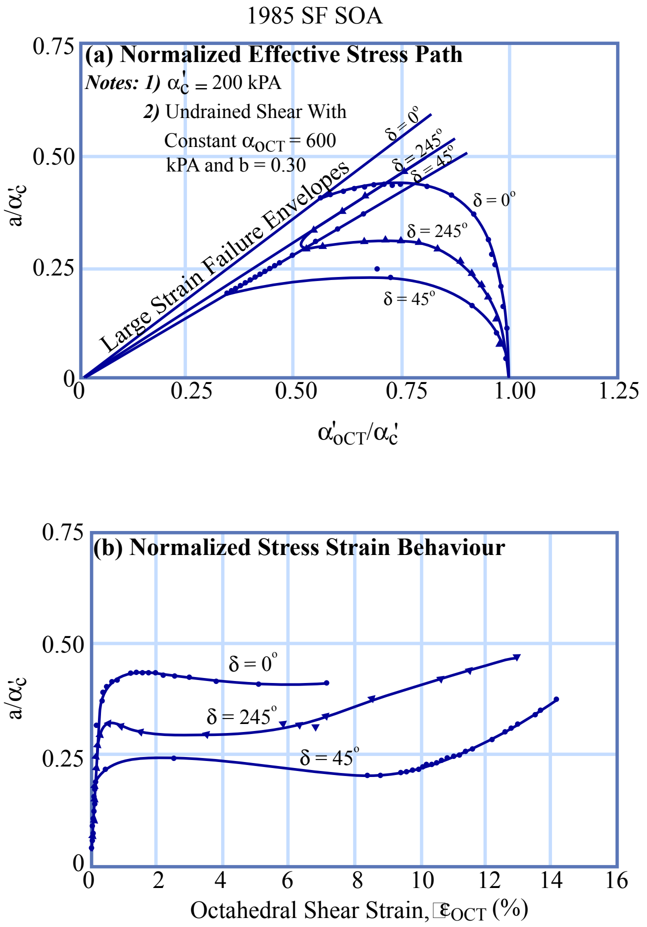
A0: max q at δ = 0°
A2: " " " δ = 24.5°
A4: " " " δ = 45°

- Test Series R



No	q→40	q≈40	max q
R1	δ = 0	δ = 0→45°	δ = 45°
R2	δ = 45°	δ = 45→0°	δ = 0°

2.5 Cont.



Results of CIU Torsional Shear Hollow Cylinder Tests on Medium-Loose Ham River Sand; (a) Normalized Effective Stress Paths and (b) Normalized Stress-Strain Behaviour. [From Symes et al. (1984)].

Figure by MIT OCW.

3) Results from Test Series A (Fig. 20)

No	$\delta°$	q_Y/σ'_c	ε_Y(%)	G/σ'_c	$\phi'°$	
					q_Y	MO
A0	0	0.44	≈1	330	38	47
A2	24.5	0.315	≈0.5	280	25	$38\frac{1}{2}$
A4	45	0.25	≈0.2	250	20	$34\frac{1}{2}$

∴ Increasing δ →

- Lower initial modulus (−25%)
- Lower q_Y (1st peak) occurring at lower ϕ'_Y

$\Delta q_Y \approx -45\%$!

$\Delta\phi'_Y = -18°$

- Lower ESE at max obliquity

$\Delta\phi'_{mo} = -12\frac{1}{2}°$

$$\varepsilon_{oct} = \gamma_{oct} = \frac{2}{3}\sqrt{(\varepsilon_1-\varepsilon_2)^2+(\varepsilon_2-\varepsilon_3)^2+(\varepsilon_1-\varepsilon_3)^2}$$

- Plus increasing δ → very significant lowering of State Boundary Surface (SBS) Note: Later called Bounding Surface for $\delta > 0°$

4) Results from Test Series R. (See data in Sheet C)

Sheet C
Fig 9, 11, 12

- R1 Shear to $q = 40$ kPa at $\delta = 0$; increasing δ at const. q → $\underbrace{\text{signif. incr. } \gamma \text{ \& decr. } \sigma'_{oct}}_{\text{Plastic straining since "loading"}}$; subsequent incr. q at $\delta = 45°$ → same behavior as test A4

Sheet C
Fig 10, 11, 12

- R2 Shear to $q = 40$ kPa at $\delta = 45°$; decreasing δ at const q → $\underbrace{\text{signif. decr. } \gamma \text{ \& } \Delta\sigma'_{oct} = 0}_{\text{Mainly elastic straining since "unloading"}}$; Subsequent incr. q at $\delta = 0°$ → ESP that rapidly climbs up to test A0 ESP & q vs γ similar to test A0

∴ Initial (inherent) anisotropy developed during 1-D deposition controls behavior.

3 INDUCED ANISOTROPY

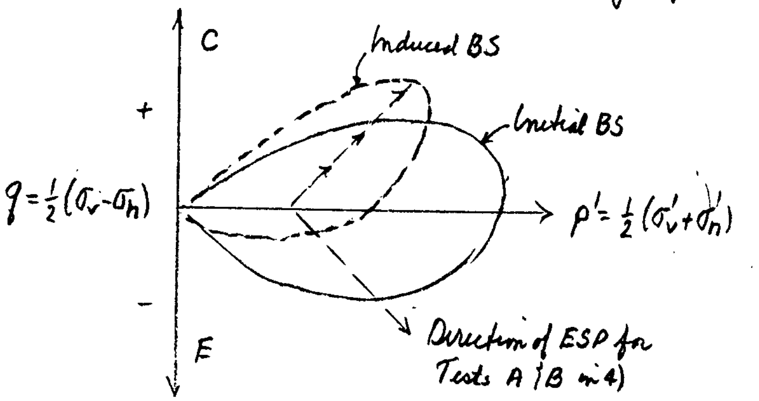
3.1 Definitions

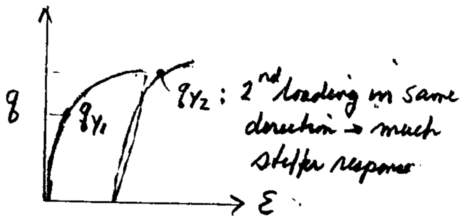
1) Application of q & p' causes plastic strains that alter the structure of the sand and hence the size & shape of its yield surface / bounding surface

CCL understanding. Check w AJW for details

Note: Bounding surface plasticity describes irrecoverable (plastic), anisotropic and path dependent behavior of overconsolidated soils (vs. yield surface of MCC → isotropic, elastic behavior for OC clay within the YS). A bounding surface is equivalent to a yield surface for NC soil

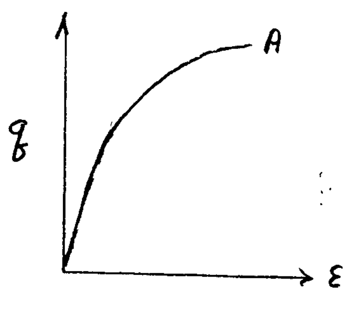
2) Example of induced anisotropy from CIDC(L) test on initially isotropic sand BS = Bounding Surface





3) Similarly, plastic straining of a soil with a prior 1-D history (hence inherent anisotropy) will alter the initial bounding surface corresponding to K_0 consolidation. This was referred to as <u>evolving</u> anisotropy in Part II C on Strength-Deformation of clays

4) Question. A = CIDE(L) on isotropic sand. Predict B = same test, but now run on sand that had been subjected to a CIDC(L) test.

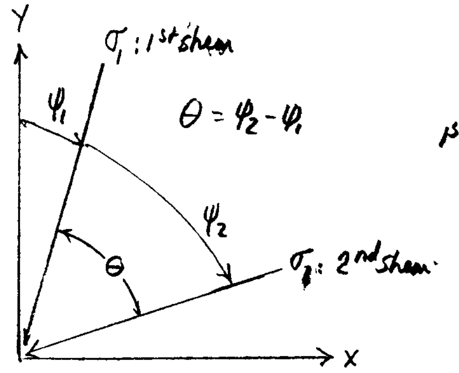


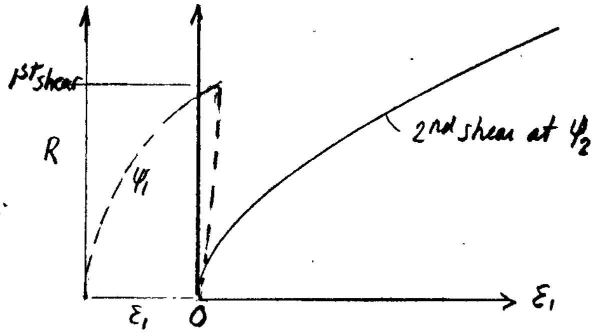
3.2 Example of Induced Anisotropy

1) Data from DSC tests on dense & loose Leighton Buzzard Sand (Arthur et al 1981 : 1st use of DSC at MIT)

2) CID PS testing procedure (all shearing in initially isotropic X-Y plane)

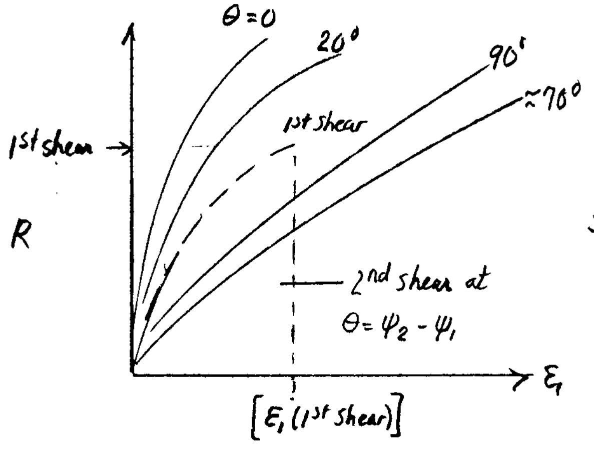
Note: See Sheet B1 for 1st shear data = "proof tests"

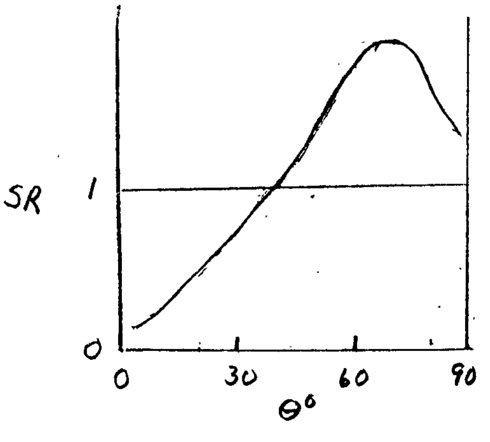




3) Resulting trends abstracted from Sheets B2 & B3 for dense & loose sand.

$$SR = \text{Strain Ratio} = \frac{\varepsilon_1 (\text{2nd Shear})}{\varepsilon_1 (\text{1st Shear})} \text{ at same } R$$





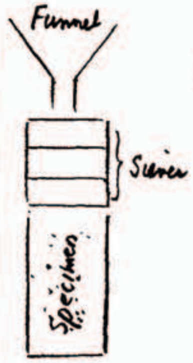
- Stiffest response at $\theta = 0$ (as would expect from load, unload, reload cycle)
- Increasing θ → softer response
- Weakest response at $\theta \approx 70°$ (no extension direction)

∴ Different behavioral pattern compared to inherent anisotropy (varying δ)

4. MISCELLANEOUS

4.1 Method of Sample Preparation

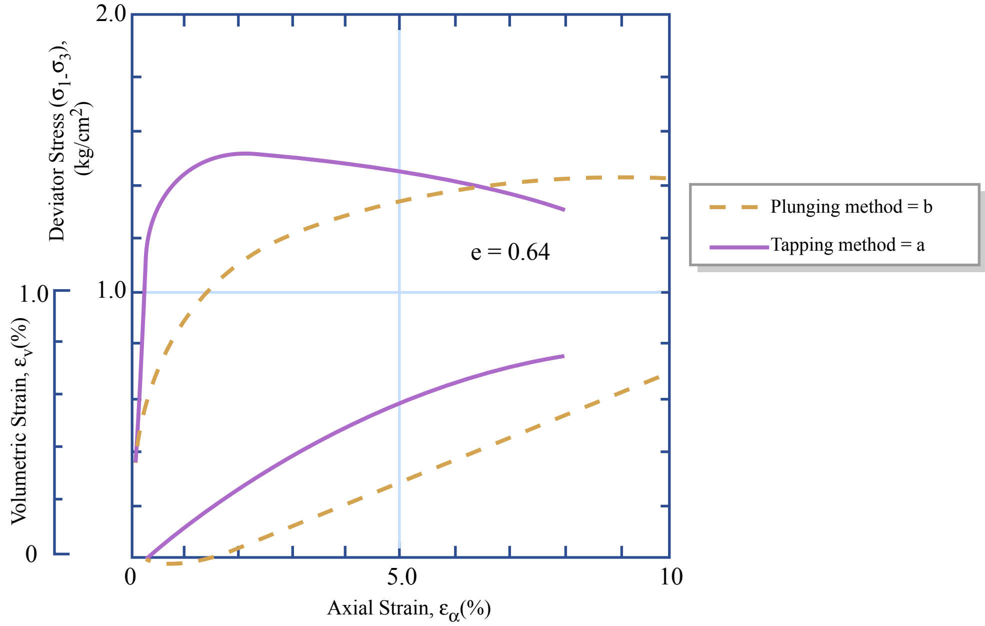
1) Very important factor since
   - Eng. tests usually run on reconstituted specimens (at in situ Dr) to predict in situ behavior; especially for cyclic behavior
   - Most research on sand behavior also uses reconstituted specimens



2) Methods of sample preparation (most typical)
   - a) Moist tamping (compaction in layers) } may have non-uniform densities
   - b) Dry tapping (vibration in layers) }
   - c) Pouring through a funnel < dry / wet

Recommended d) Multi-sieve pluviation: Miura & Toki (1982) Soils & Fdn. 22(1) "MSP"

3) Examples of importance:



Effect of method of sample preparation on CD triaxial compression tests on Soma sand (Oda, 1972b).

Figure by MIT OCW.

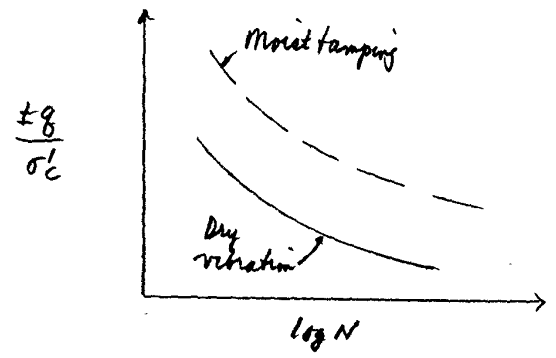
a) CIDC(L) See Fig. 4

Vibration (vs compaction) →
- Much stiffer
- Sl. stronger with lower ε_f
- More dilatancy

NOTE: Compaction in a mold does not give sand structure similar to 1-D stress-strain history

4.1 3) Continued

b) Cyclic strength - (See Sheet D) : No. cycles → $\Delta\varepsilon = 10\%$



- Dry vibration has much lower cyclic strength, presumably due to greater anisotropy

{ Prior to 1974, Seed et al. recommended lab testing to predict potential liquefaction during earthquakes }

4.2 Other

- Effect of heterogeneity on CIDC behavior : Arthur & Phillips (1975) Geot 25(4)
- Effect of preshearing to failure on CIDC behavior : Arthur et al. (1977) 9th ICSMFE
- Aging of sands : Schmertmann (1991) JGE 117(9)

5. SUMMARY AND CONCLUSIONS (Also applies to Part I)

5.1 Sand vs. Clay : Basic Behavioral Trends

1) Anisotropy

2) b

3) Interrelationships CU vs CD shearing

4) "Normalization" technique to predict stress-strain behavior
   a) Clays
   b) Sands

5) Constitutive modeling

5.2 Sand vs Clay : Practical Differences

1) Drainage

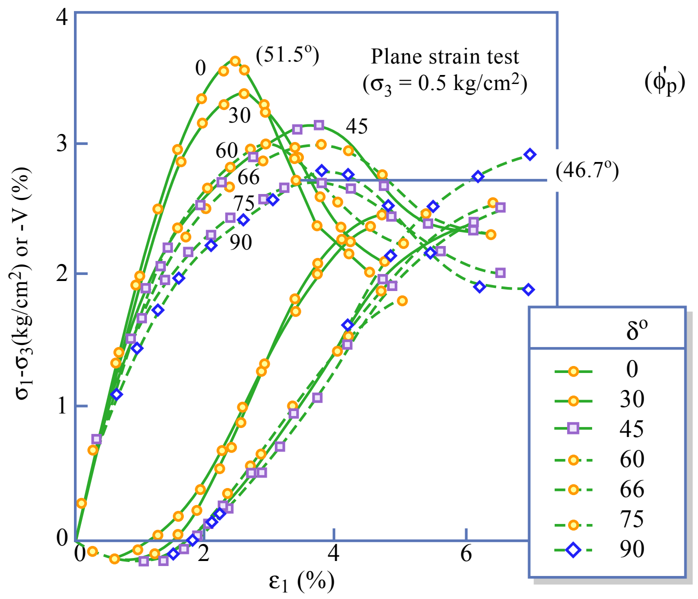
2) Estimation of in situ properties

3) Predictions of:
- Settlement
- Stability
- Lateral earth pressure

5.3 Sand vs. Clay : Sample Preparation

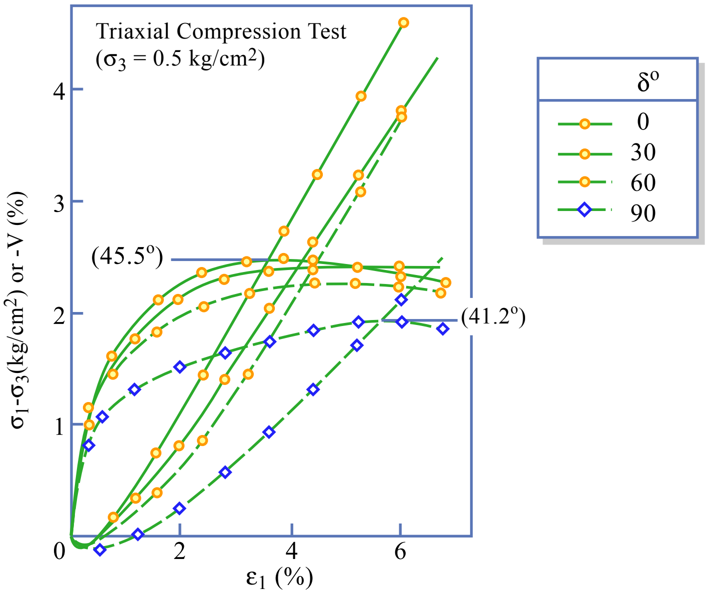
1) Sands
- MSP recommended for reconstituted : Compaction NOT GOOD.
- Freezing technique
  Japan
  WES
  U. Alberta.

2) Clays



Stress-strain relations in the plane strain tests of σ_3 = 0.5 kg/cm²

Figure by MIT OCW.



Stress-strain relations in the triaxial compression tests of σ_3 = 0.5 kg/cm²

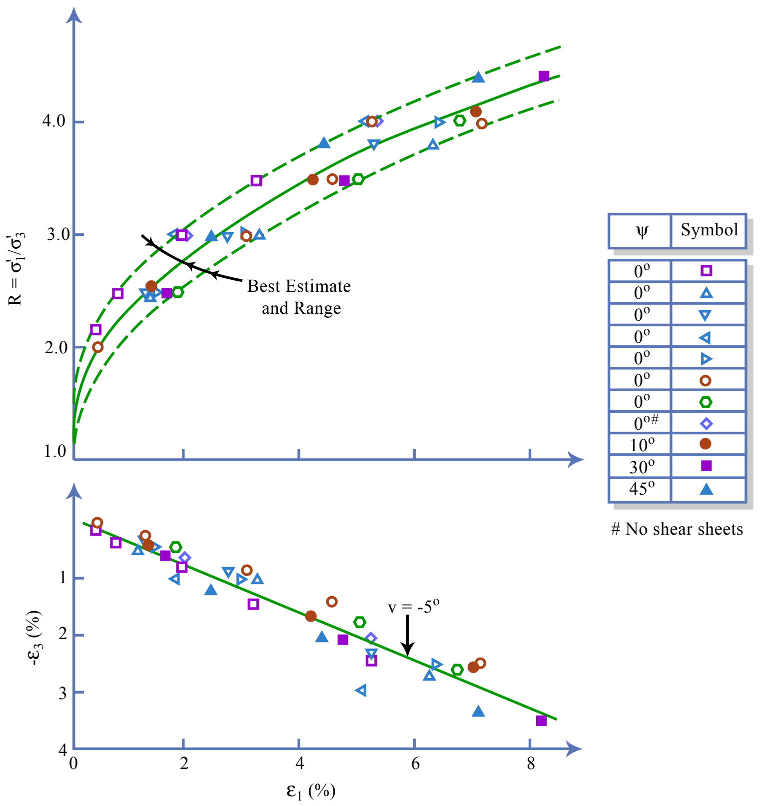
Figure by MIT OCW.

CID PSC & TC Loading Tests on Dense Toyoura Sand: Inherent Anisotropy

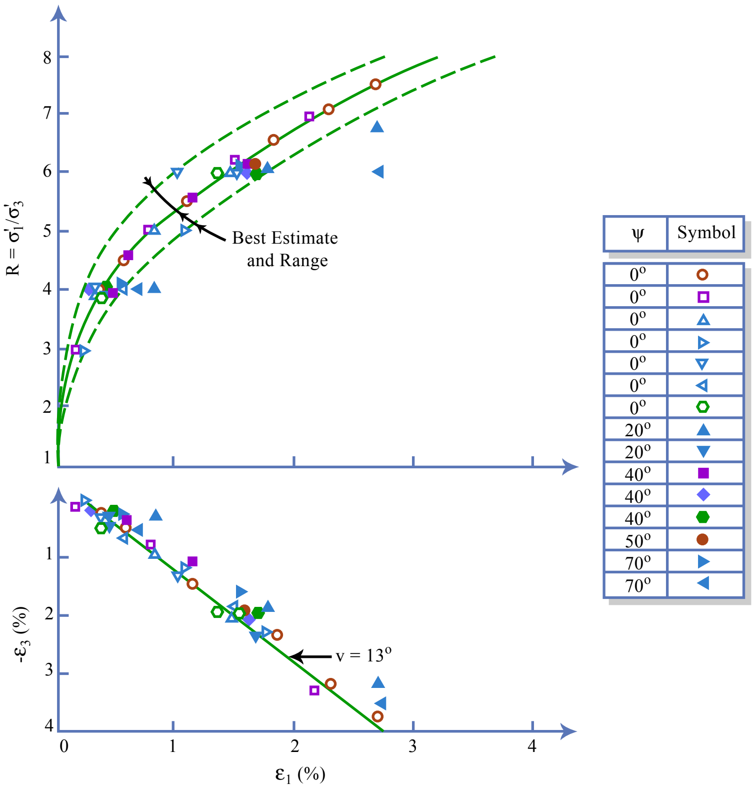
Ⓐ

Adapted from: Oda et al. (1978)

CCL 5/4/96 1.322 Sands II



Stress-strain data from monotonic loading tests on loose sand (ε -data from 16)



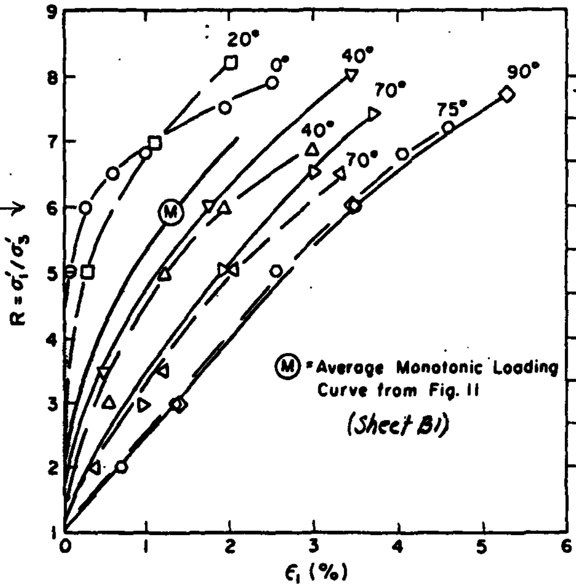
Stress-strain data from monotonic loading tests on dense sand.

B1

Figures by MIT OCW. Adapted from: Arthur et al. (1981)

DSC "Proof" Tests on Dense & Loose Leighton Buzzard Sand. ($\sigma'_3 = 14 kPa$)

1st Shear →



Test No.	Symbol	R_f	ν
D0, 0	—○—	8.1	16°
D20, 0	—□—	8.9	18°
D0, 40	—△—	7.1	11°
D40, 0	—▽—	8.5	14°
D0, 70	—◁—	6.8	11°
D70, 0₁	—▷—	8.0	14°
D0, 75	—○—	7.4	13°
D0, 90₁	—◇—	8.1	14°

FIG. 13—*Stress-strain curves from loading tests on dense sand with induced anisotropy.*

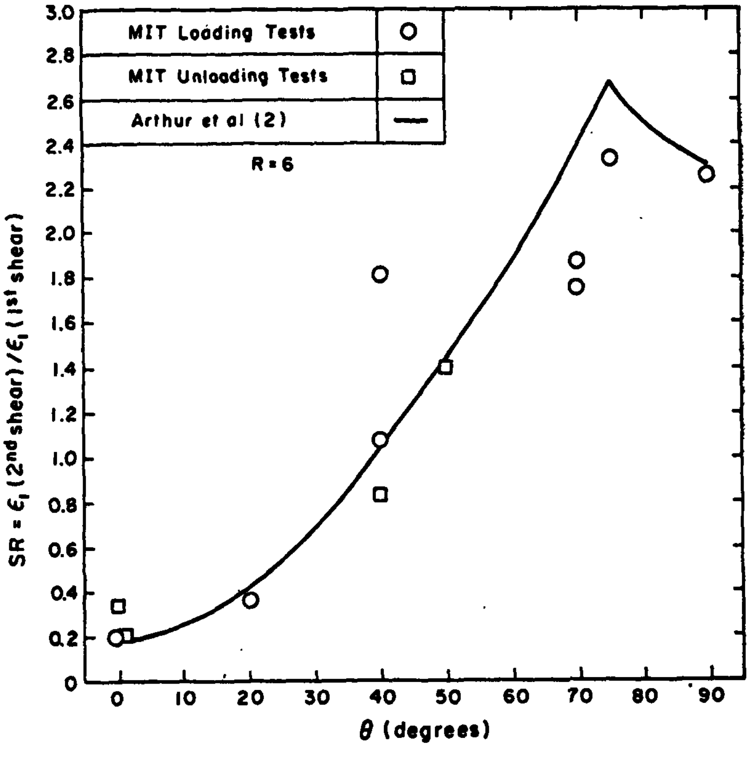
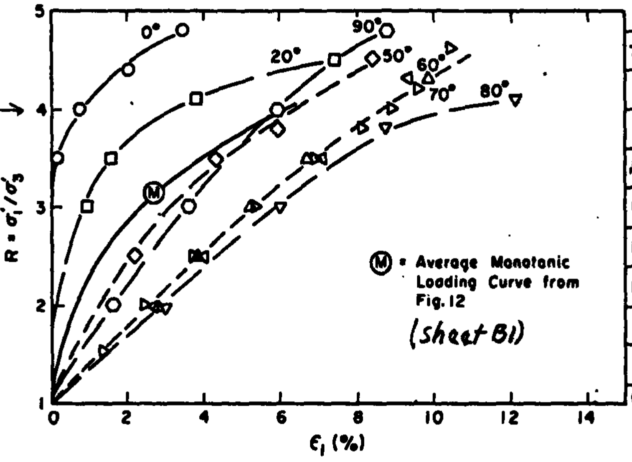


FIG. 14—*Strain ratio versus rotation angle for dense sand with induced anisotropy.*

Induced Anisotropy from DSC Tests on Dense LBS

Arthur et al. (1981)



1st Shear →

(sheet B1)

Test No.	Symbol	R_f	ν
LO,0	—○—	5.0	0°
LO,20	—□—	4.5	1°
LO,50	--◇--	4.9	-1°
LO,60	--△--	–	3°
LO,70_1	--◁--	–	0°
LO,70_2	--▷--	4.8	-1°
LO,80	—▽—	–	2°
LO,90*	—○—	5.5	3°

* No shear sheets

FIG. 15—*Stress-strain curves from loading tests on loose sand with induced anisotropy (ϵ_1-data from 16 points).*

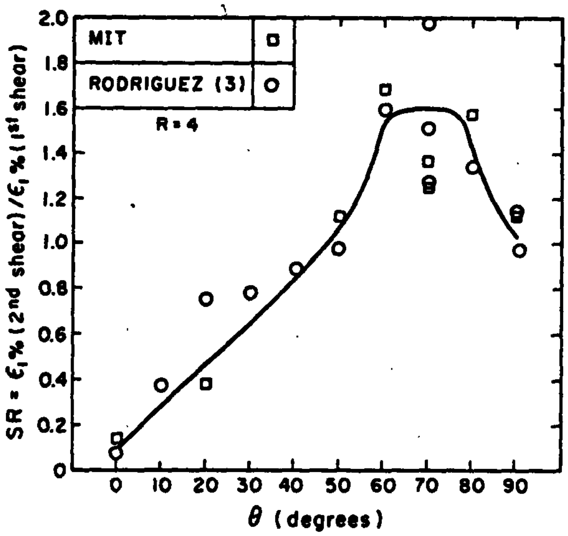


FIG. 16—*Strain ratio versus rotation angle for loose sand with induced anisotropy.*

Induced Anisotropy from DSC Tests on Loose LBS

Arthur et al. (1981)

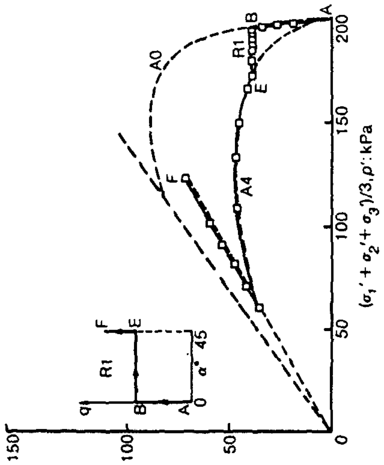


Fig. 9. Effective stress path for test R1

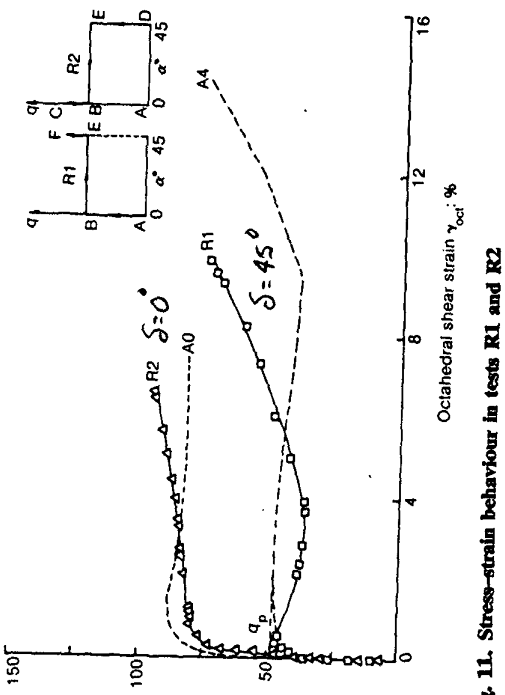


Fig. 11. Stress-strain behaviour in tests R1 and R2

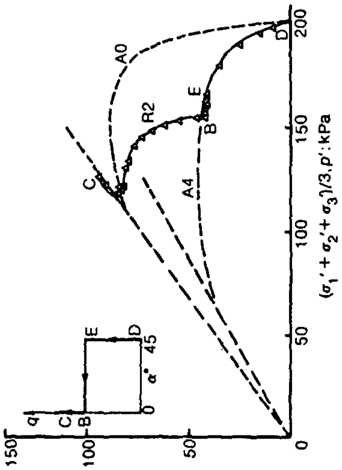


Fig. 10. Effective stress path for test R2

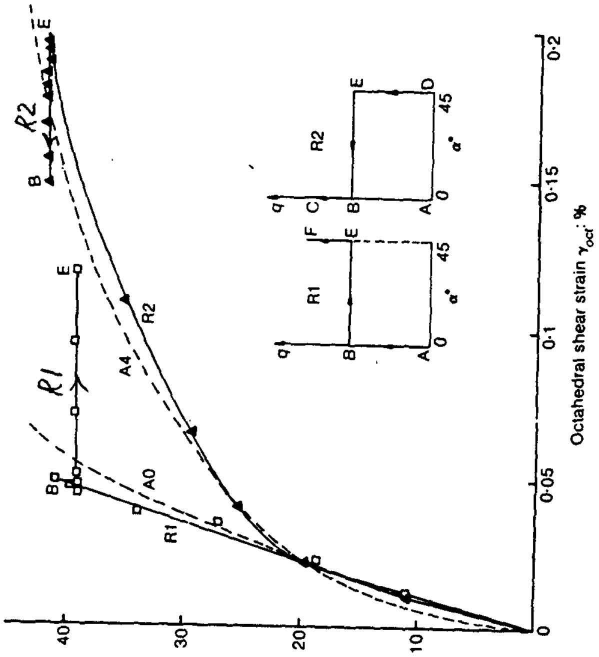


Fig. 12. Octahedral shear strains during principal stress rotation in tests R1 and R2

Test Series R: Effect of Changing δ <u>During</u> Undrained Shear

Medium-Loose Ham River Sand

Symes et al. (1984)

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CCL 5/5/96   1.322   Sands II

TABLE 1.—Index Data

Sand number (1)	Unified soil classification system symbol (2)	Particle Size Data			Dry Unit Weight Data, in pounds per cubic foot	
		D_{50}, in millimeters (3)	C_c (4)	C_u (5)	Maximum (6)	Minimum (7)
1	SP-SM	0.16	1.5	1.9	111.8	87.0
2	SP-SM	0.23	1.7	3.1	114.2	84.0
3	SP-SM	0.52	0.9	4.1	124.0	97.0

[a] C_c = coefficient of curvature = $(D_{30})^2/(D_{60} \times D_{10})$.
[b] C_u = coefficient of uniformity = D_{60}/D_{10}.
Note: 1 pcf = 16 kg/m³.

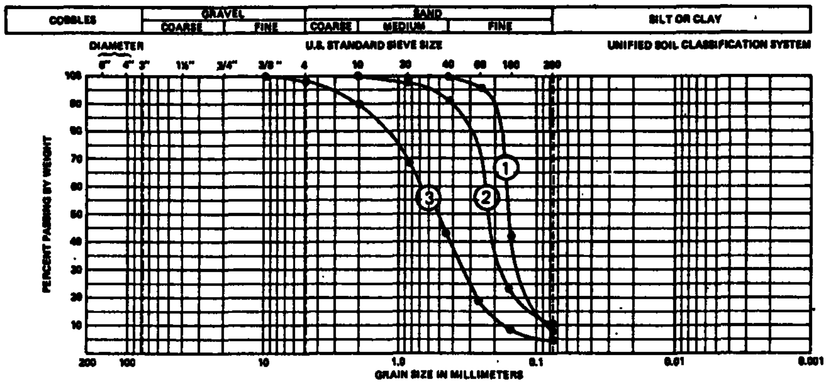

FIG. 1.—Particle Size Distribution

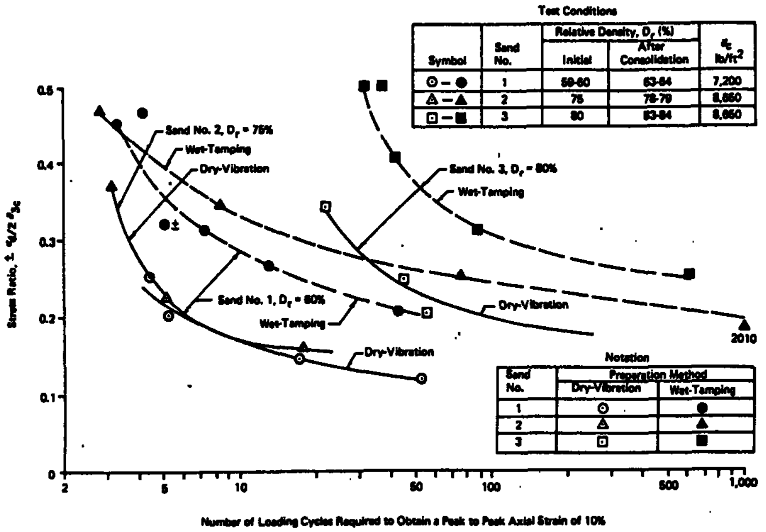

FIG. 2.—Applied Stress Ratio Versus Number of Loading Cycles Required to Obtain Peak-to-Peak Axial Strain of 10% (1 psf = 47.9 N/m²)

Cyclic
CIU C/E

Effect of Sample Preparation on Cyclic Behavior
of Three Medium-Dense Sands

R.S. Ladd (1974) JGED 100(10)

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