Multi-Layer Interface Shear Testing

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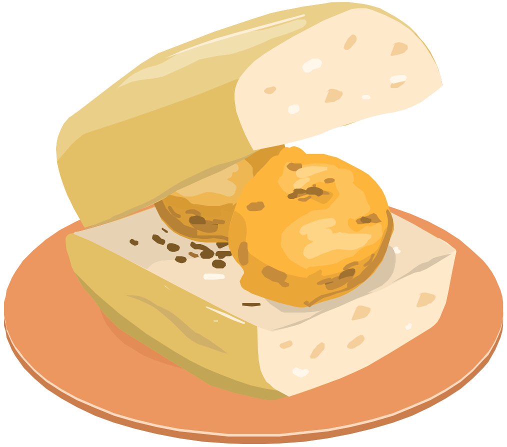
Outline of Presentation

- Introduction to multi-layer interface shear testing
- Importance of simulating field conditions
- Insight and reasoning on using multi-layer testing
- Preparation of test specimens and direct shear box
- Interruption of multi-layer test results
- Discussion of Pros and Cons of multi-layer testing
- Review of Case Studies
- Questions

Introduction: Multi-Layer Interface Testing

What Are We Talking About?



Single Interface

Multiple Interfaces

Importance of Simulating Field Conditions

- Interface direct shear testing is a performance test.
- Used to develop test data used in design of:
  - lined slopes
  - cover systems
  - other geotechnical structures with soil/geosynthetic interaction.
- Test conditions used in performing these tests must closely model anticipated field conditions.

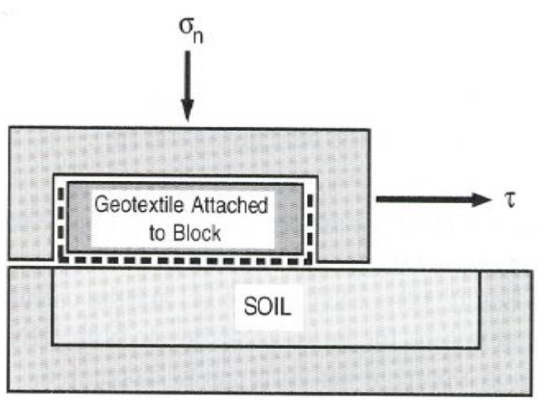
Importance of Simulating Field Conditions

- Typical conditions that are modeled include:
  - Site specific soils materials (compaction γ_d and w_c)
  - Site specific geosynthetic materials
  - Normal stress range
  - Wetted conditions
  - Hydration and/or Consolidation conditions
- With multi-layer interface shear testing one can:
  - Model normal stress transfer through geosynthetics and soils
  - Model shear stress transferred through geosynthetics and soils
  - Model complete lining system of interest

Insight and Reasoning for Multi-Layers

- Single interface tests are restrained (coupled) tests.
  - Typically measure higher peak shear strengths due to tension within geosynthetic components.
  - Allow more combing (strain softening) causing lower large displacement strengths.

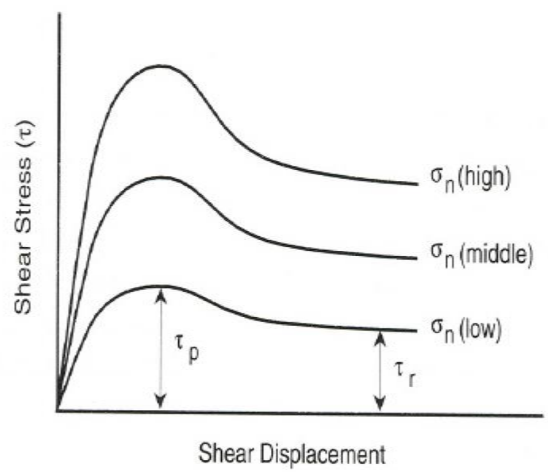
Typical Single Interface Shear Test Configuration

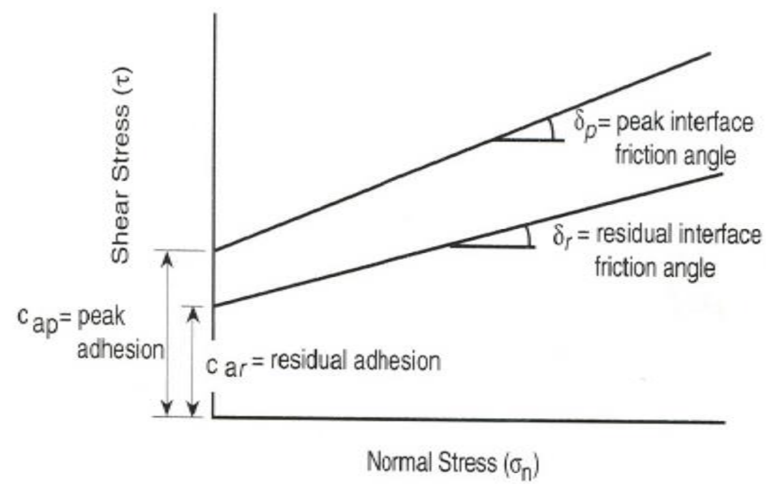


After Koerner (1998)

Insight and Reasoning for Multi-Layers

Typical Test Results Single Interface Shear Test Series





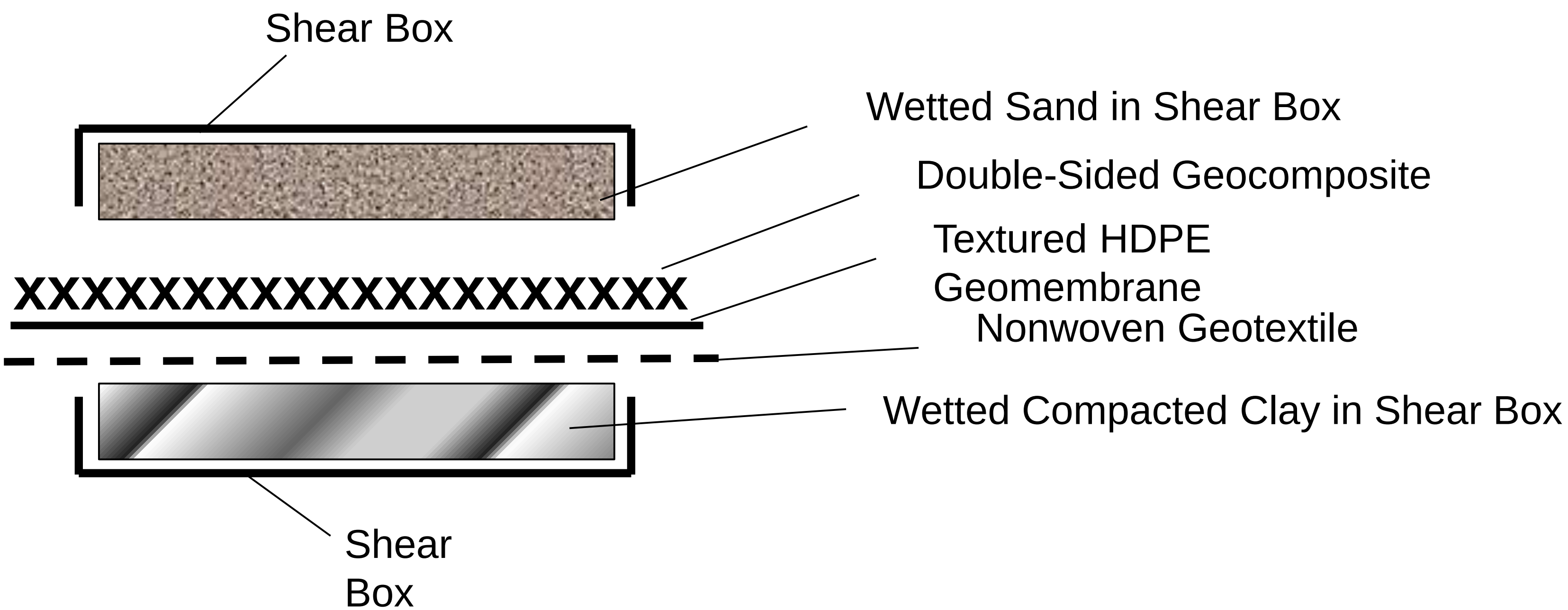
May require numerous single interface tests to determine critical interface for a design.

Insight and Reasoning for Multi-Layers

When conducting a multiple layer interface shear test:

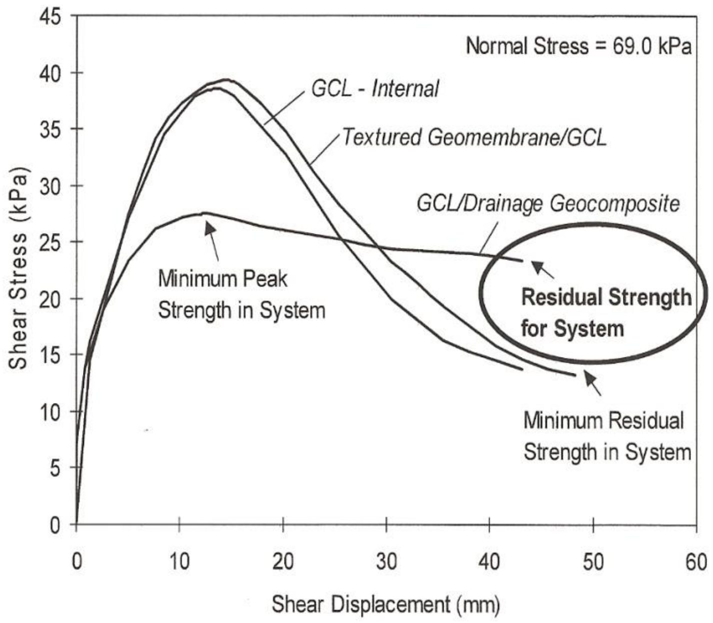
- Once system begins to shear (fail), shear stress gets transferred within system
- Little to no tension developed within layers.

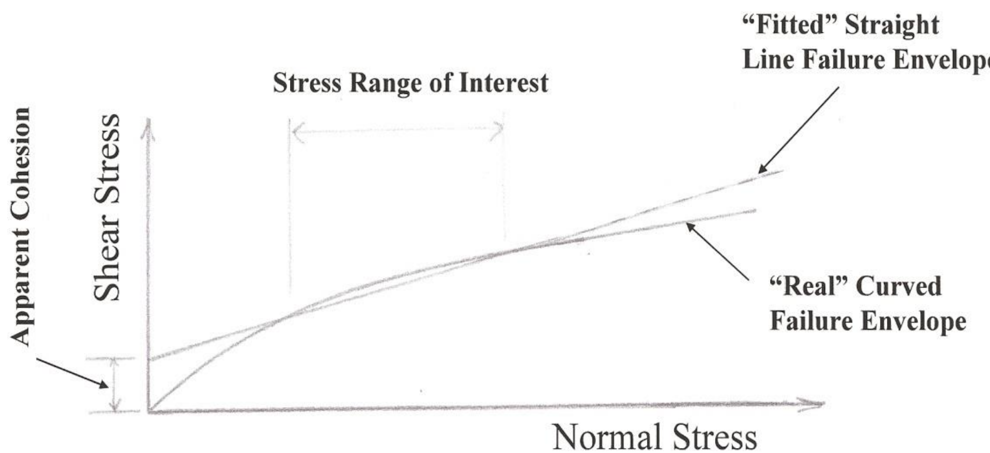
A Typical Multi-Layer Interface Shear Test Configuration



Insight and Reasoning for Multi-Layers

Typical Test Results Multiple Interface Shear Test Series





After Kavazanjian (2007)

Preparation of Specimens and Shear Box

- Soils prepared to requested w_c and (γ_d).
- Compacted to represent construction of lining system.
- If a clayey soil will underly geosynthetics, clayey soil <u>should not be compacted directly on geosynthetic</u>.
- Soil should be compacted away from interface and then placed on interface.
- This will prevent:
  - Build up of compaction stresses and pore water pressures at interface
  - Embedment of soil into geosynthetic

Preparation of Test Specimens and Shear Box

- Geosynthetics will not be attached to either of shear box components
- Each geosynthetic should be trimmed larger than shear box.
- Typically, geosynthetic specimens cut to approx.15 inches in shear direction and 13 inches in width.
- Geosynthetics should be condition as per requested test conditions.

Preparation of Test Specimens and Shear Box

- For multi-layer interface shear tests larger lower shear box should be sectioned down to a 12 in. by 12 in. shear area.
- Place less compressible soil (sand or gravel) in lower shear box
- Place more compressible soil (clayey soil) in upper shear box.
- If this is done, compact soil to represent orientation and placement in field.

Preparation of Test Specimens and Shear Box

- Configuration of Shear Box:
  - Place and compact soil in lower shear box
  - Place oversized individual geosynthetic layers in correct orientation to represent placement in field:
    - Use “Tail Tell” wires attached to rear of each geosynthetic layer to determine movement (shear displacement) of each layer.
  - Place and compact soil in upper shear box.

- Continue with rest of direct shear box setup similar to a single interface test, apply normal stress and initiate shearing phase.

Interruption - Let's Look At An Example

Some Typical Published Single Interface Direct Shear Test Data

Interface	ϕ_{peak} (Eff.)[1]	ϕ_{res}
Sand – nonwoven geotextile (GTX)	26° - 35° (90-100%)	20° – 30°
Sand – HDPE geomembrane (GM)	17° – 30° (55-80%)	17° – 30°
Clay – smooth GM	8° – 12°	6° – 10°
Clay – textured GM	12° – 24°	6° – 20°
Smooth GM – nonwoven GTX	6° – 15°	4° – 12°
Textured GM – nonwoven GTX	24° – 35°	6° – 12°
Textured GM – reinforced hydrated GCL[2]	10° – 30°	6° – 18°
Unreinforced hydrated GCL[3]	17° – 30°	4° – 6°
GM – geonet[4]	10° – 14°	8° – 10°

Notes:
1. Eff. = Interface Efficiency = $[\tan\phi_{interface} / \tan\phi_{soil}]$ or $[(S_u)_{interface} / (S_u)_{soil}]$
2. Failure plane may be internal (within GCL) at higher normal stresses
3. Failure plane is internal (within GCL)
4. Strength may be slightly lower with textured geomembrane than smooth

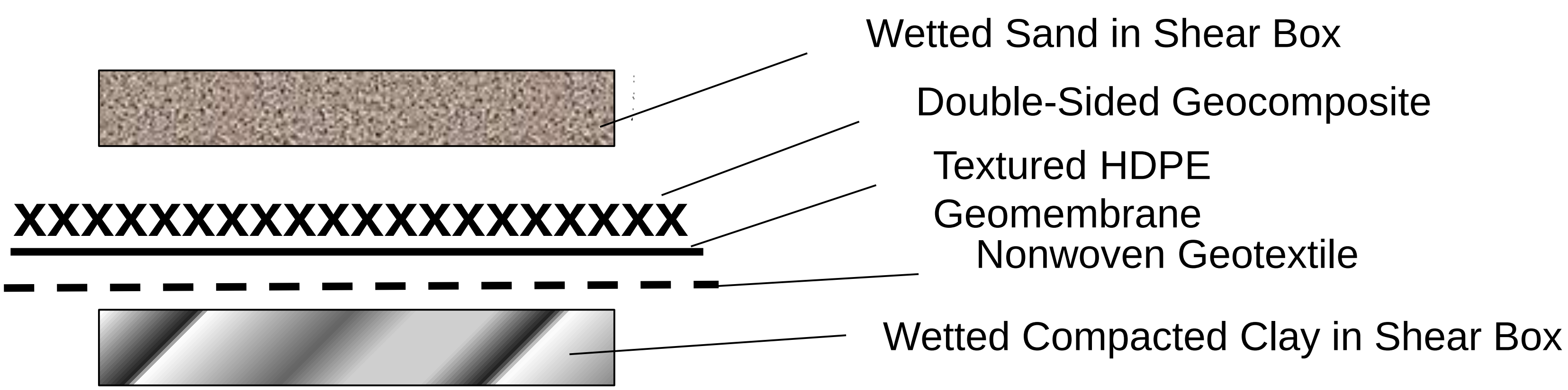
After Kavazanjian (2007)

Interruption - Let’s Look At An Example

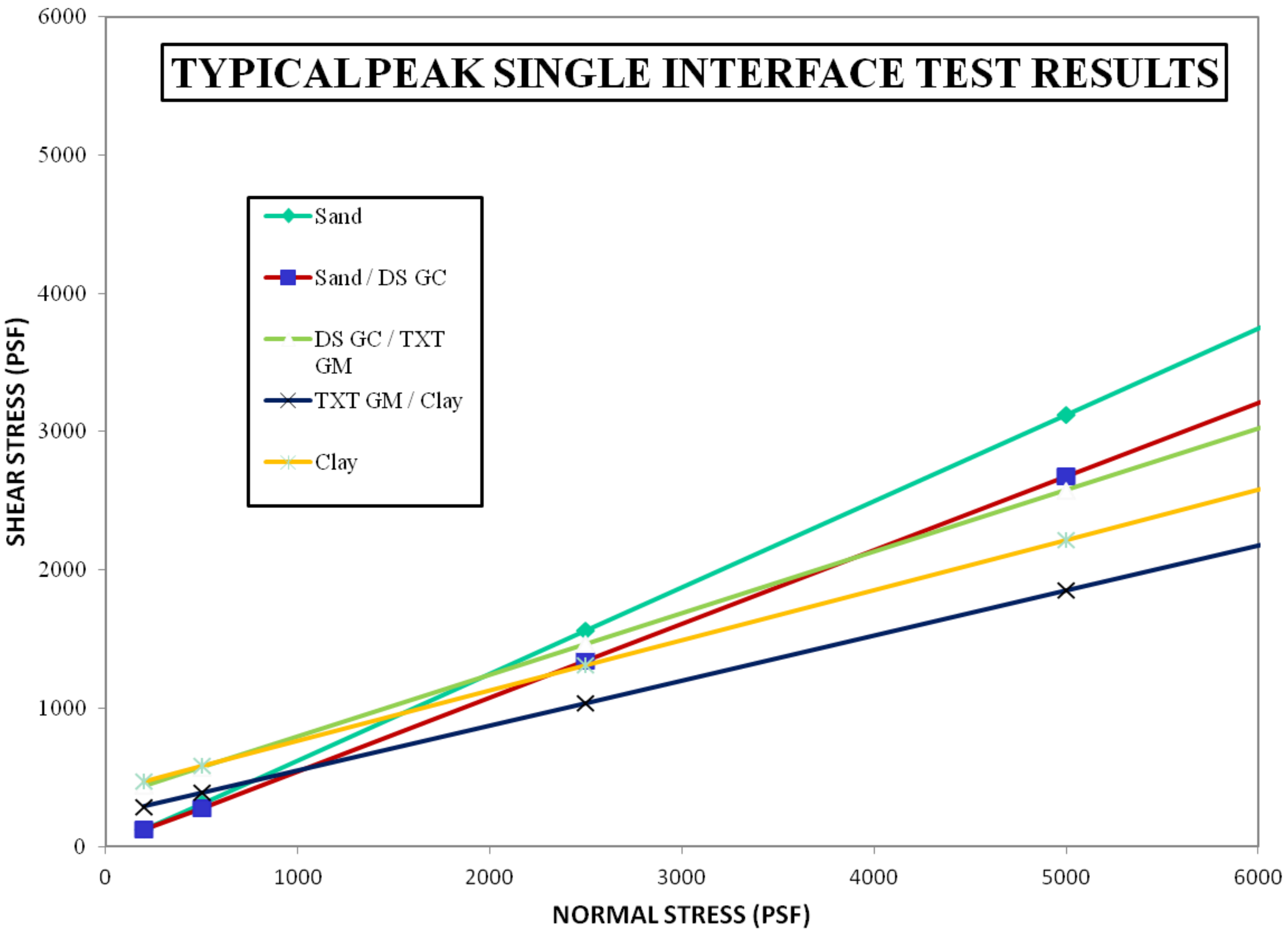
Let’s Consider an Example Simple Lining System

Material / Interfaces Of Concern

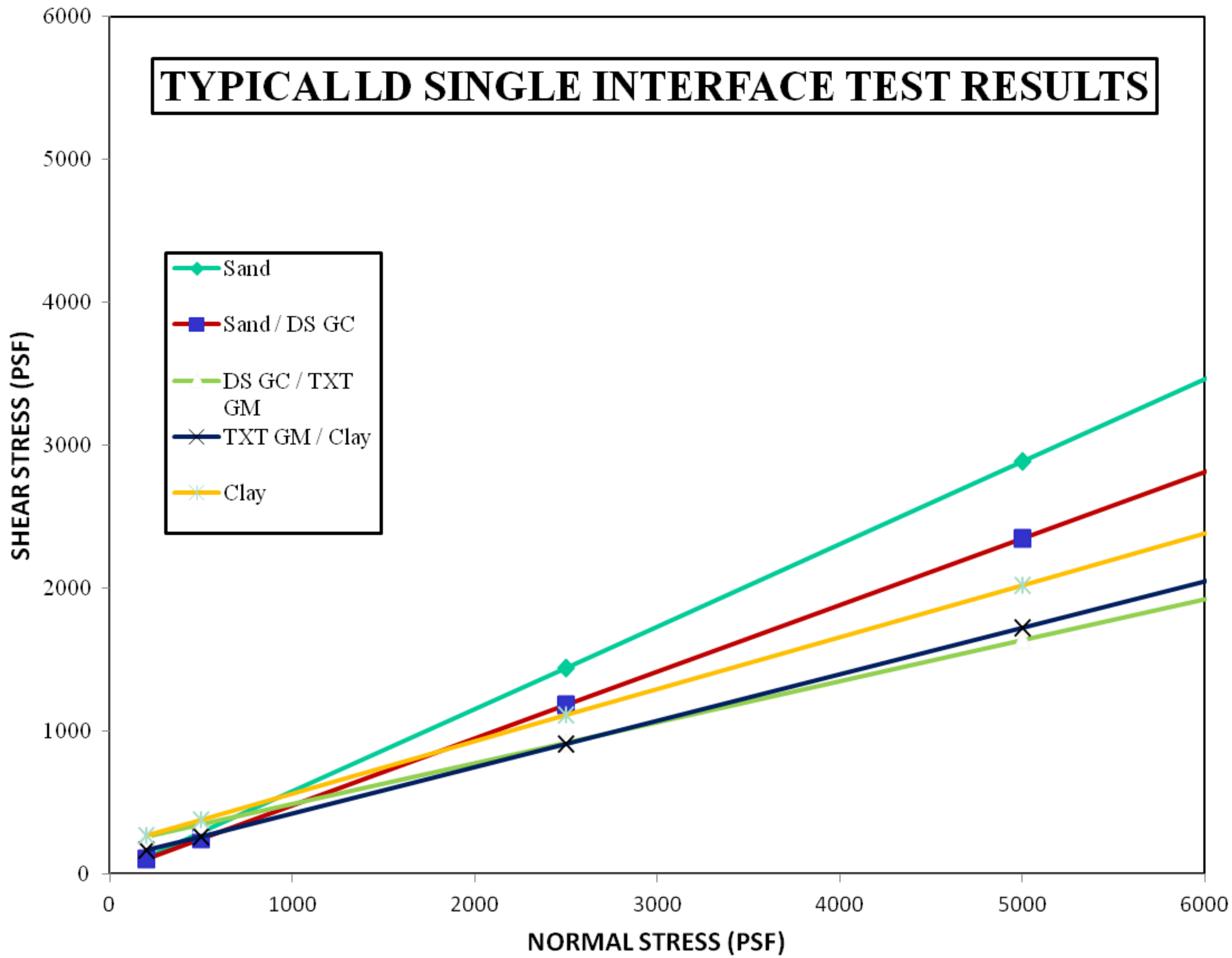
- Internal Strength of Wetted Sand
- Wetted Sand Against DSGC
- Wetted DSGC Against Textured HDPE Geomembrane
- Textured HDPE Geomembrane Against Wetted Clay
- Compacted Clay



Interruption - Let's Look At An Example



Interruption - Let's Look At An Example



Interruption - Let's Look At An Example

TYPICAL SINGLE INTERFACE TEST RESULTS

	Sand	Sand / DS GC	DS GC / TXT GM	TXT GM / Clay	Clay
Normal Stress	Peak Shear Stress	Peak Shear Stress	Peak Shear Stress	Peak Shear Stress	Peak Shear Stress
200	125	121	439	290	473
500	312	281	573	387	582
2500	1562	1344	1463	1037	1310
5000	3124	2674	2576	1850	2220
10000	6249	5332	4802	3474	4040
Shear Strength	c = 0 psf	a = 15 psf	a = 350 psf	a = 225	c = 400 psf
Parameters	Φ = 32 deg	δ = 28 deg	δ = 24 deg	δ = 18 deg	Φ = 20 deg

	Sand	Sand / DS GC	DS GC / TXT GM	TXT GM / Clay	Clay
Normal Stress	LD Shear Stress	LD Shear Stress	LD Shear Stress	LD Shear Stress	LD Shear Stress
200	115	108	257	165	273
500	289	248	343	262	382
2500	1443	1181	917	912	1110
5000	2887	2347	1634	1725	2020
10000	5774	4678	3067	3349	3840
Shear Strength	c = 0 psf	a = 15 psf	a = 200 psf	a = 100	c = 200 psf
Parameters	Φ = 30 deg	δ = 25 deg	δ = 16 deg	δ = 18 deg	Φ = 20 deg

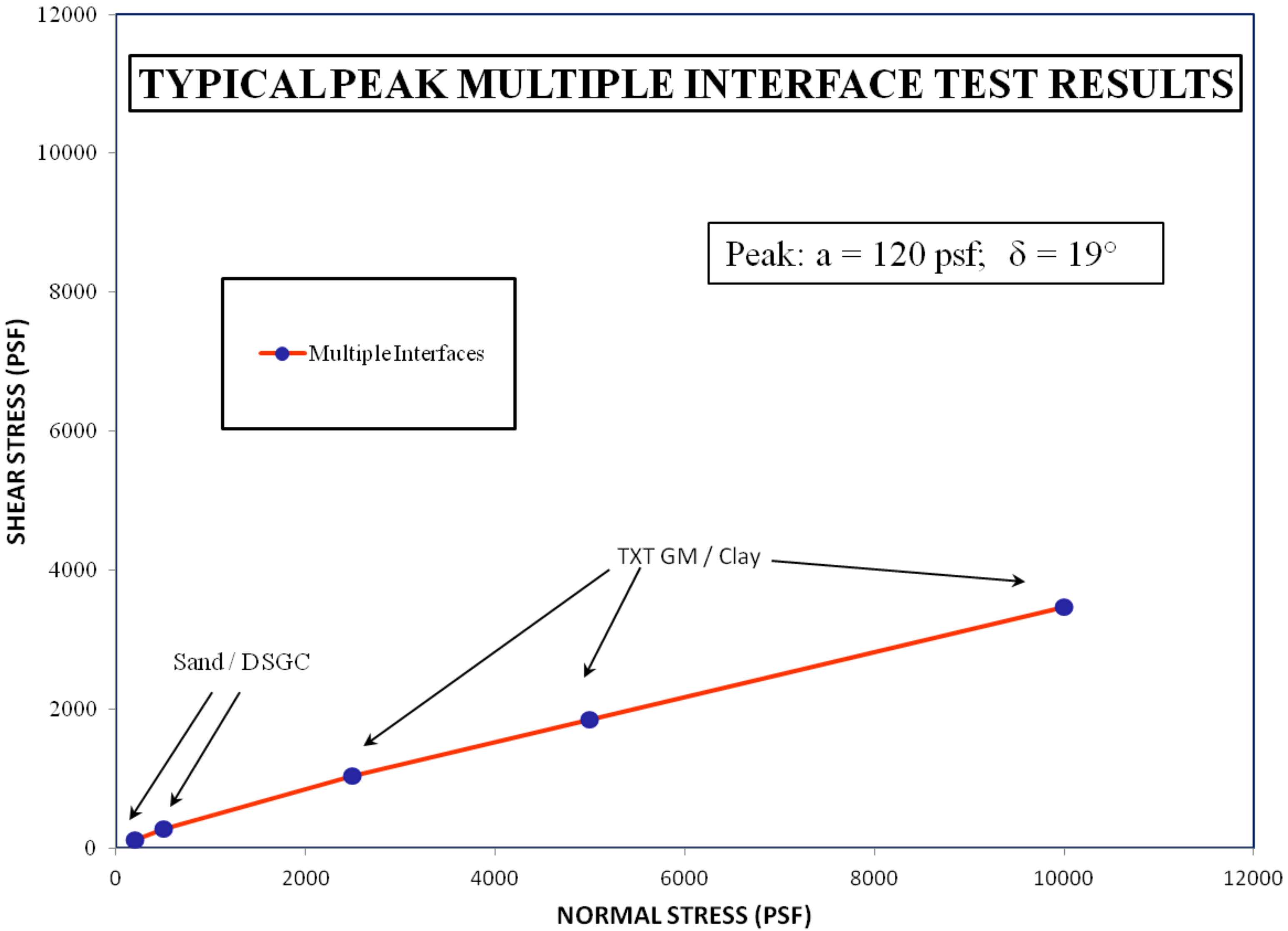
Interruption - Let's Look At An Example

TYPICAL SINGLE AND MULTIPLE INTERFACE TEST RESULTS

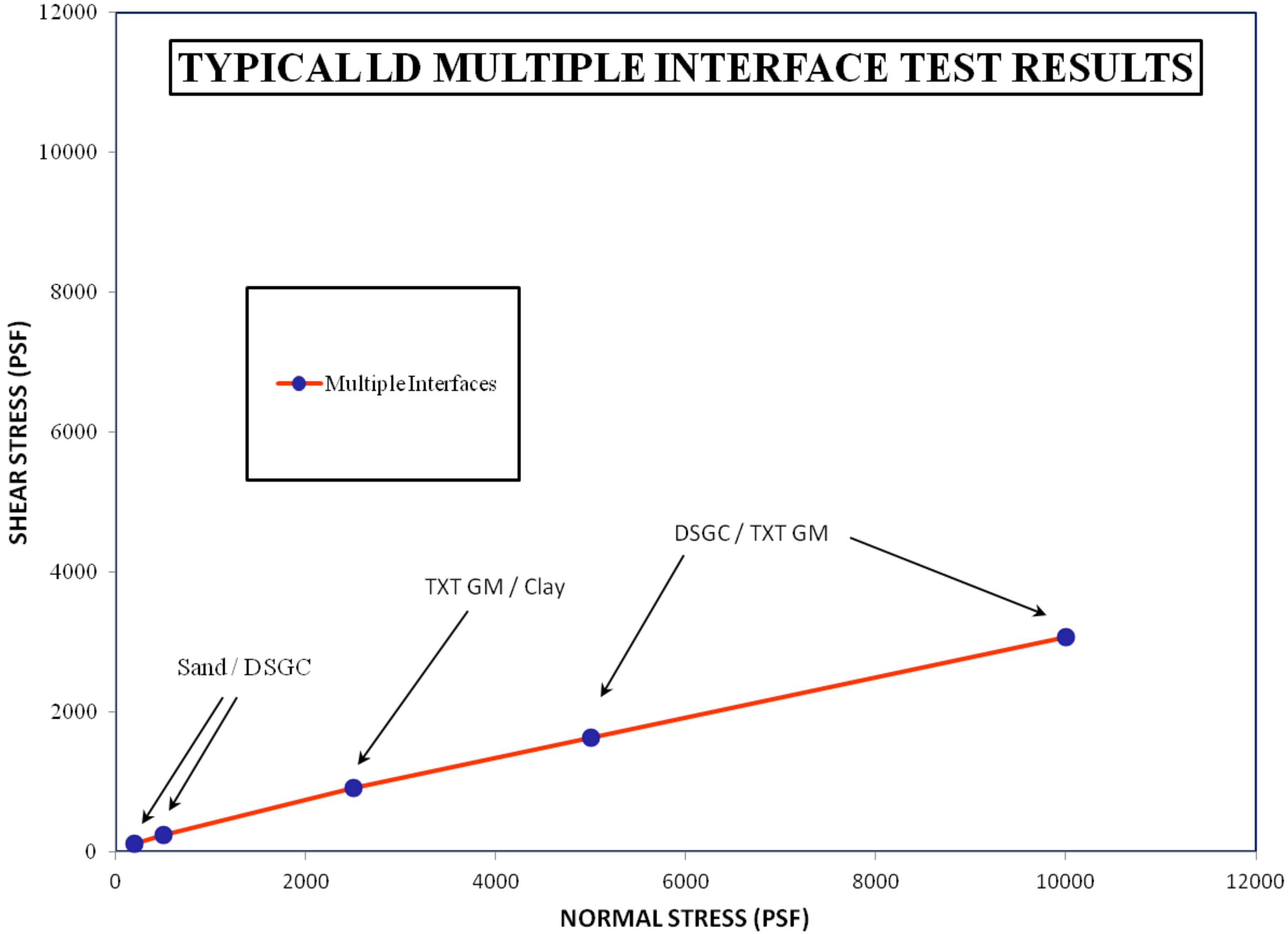
	Sand	Sand / DS GC	DS GC / TXT GM	TXT GM / Clay	Clay	**Multiple Interfaces**
Normal Stress	Peak Shear Stress	Peak Shear Stress	Peak Shear Stress	Peak Shear Stress	Peak Shear Stress	**Minimum Peak Shear Stress**
200	125	121	439	290	473	**121**
500	312	281	573	387	582	**281**
2500	1562	1344	1463	1037	1310	**1037**
5000	3124	2674	2576	1850	2220	**1850**
10000	6249	5332	4802	3474	4040	**3474**
Shear Strength	c = 0 psf	a = 15 psf	a = 350 psf	a = 225	c = 400 psf	**a = 120**
Parameters	Φ = 32 deg	δ = 28 deg	δ = 24 deg	δ = 18 deg	Φ = 20 deg	**δ = 19 deg**

	Sand	Sand / DS GC	DS GC / TXT GM	TXT GM / Clay	Clay	**Multiple Interfaces**
Normal Stress	LD Shear Stress	LD Shear Stress	LD Shear Stress	LD Shear Stress	LD Shear Stress	**Minimum LD Shear Stress**
200	115	108	257	165	273	**108**
500	289	248	343	262	382	**248**
2500	1443	1181	917	912	1110	**912**
5000	2887	2347	1634	1725	2020	**1634**
10000	5774	4678	3067	3349	3840	**3067**
Shear Strength	c = 0 psf	a = 15 psf	a = 200 psf	a = 100	c = 200 psf	**a = 105**
Parameters	Φ = 30 deg	δ = 25 deg	δ = 16 deg	δ = 18 deg	Φ = 20 deg	**δ = 17 deg**

Interruption - Let's Look At An Example



Interruption - Let's Look At An Example



Pros for Using Multi-layer Interface Tests

- Ability to analyze a complete system (i.e., clay liner to protection layer).
- See how failure plane shifts as a function of normal stress.
- Failure will occur at weakest interface / internal
- Good for CQA/CQC testing.
- Finding minimum shear strength.
- Typically produces lower peak and higher large displacement strengths.
- Allows quick evaluation of many materials.
- Better simulates field conditions.

Cons for using Multi-layer Interface Tests

- Sometimes difficult to see which plane is failing first.
- Peak shear strength may occur on one plane and large displacement strength may develop on an other plane.
- To get specific shear strength for an interface may require additional testing
- Can be difficult to conduct with a lot of materials.
- Sometimes difficult to analyze.
- Need a well trained technician to conduct testing with good peer review.

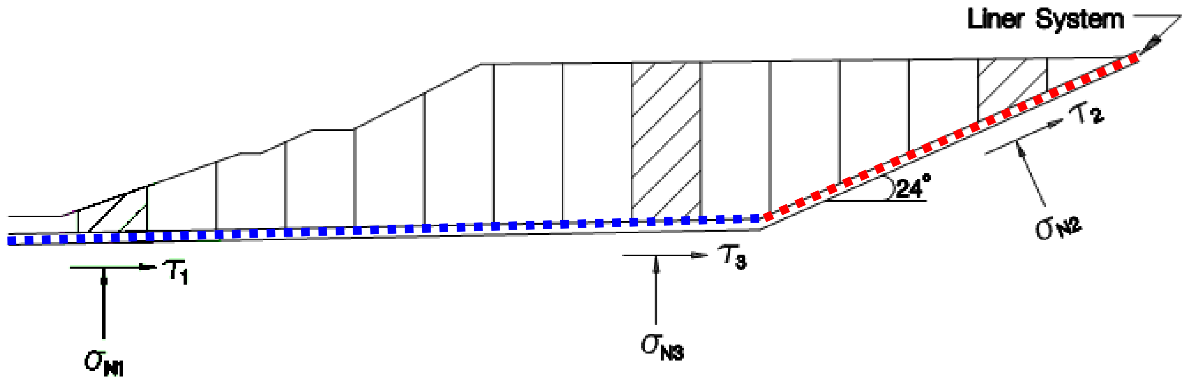
Multi-Interface Test Database

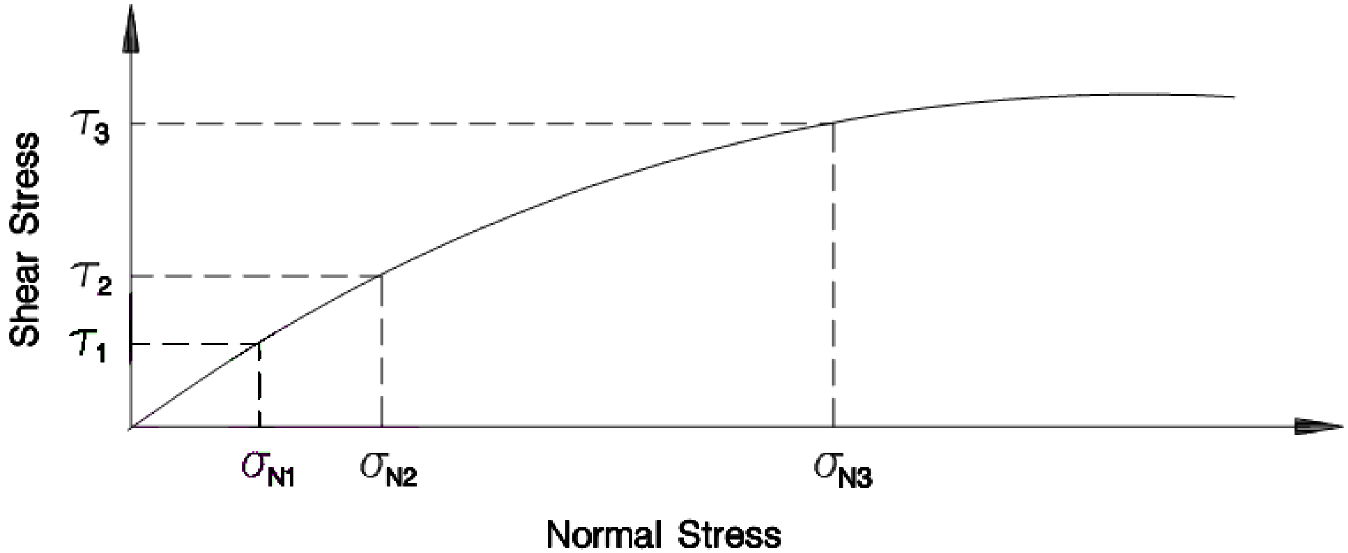
- Shenthan, Khilnani, and Stark (2019)
- Data Reviewed for 9 Sites (14 Projects)
- 82 Tests w/3 to 5 Normal Stresses
- 305 Data Points
- Divided into 4 Categories:
  - DST GM/GCL/DST GM (**Encapsulated GCL**)
    - For encapsulated GCL, Water Boards require average of soaked and unsoaked GCL strength
  - DST GM/GCL/Subgrade (**Unencapsulated GCL**)
  - DST GM/CSL (**no GCL**) – Subtitle D liner
  - **SST GM** on GCL and Overlain by **GT** or GC (for Side Slope Liner)

Bottom Liner Design Strengths

- Stark and Poeppel (1994)
- Design #1
  Peak interface strength on base/nonsloped & Residual on sideslopes & Design with FS ≥ 1.5
- Design #2
  Residual interface strength on sideslopes & base & FS ≥ 1.0
  (1.1 if Direct Shear => Stark and Choi, 2004, Geosyn. Intl., December, pp. 491-498)
- Design #3
  If permanent deformations on base/nonsloped (seismic), Residual Everywhere

Bottom Liner Design Strengths



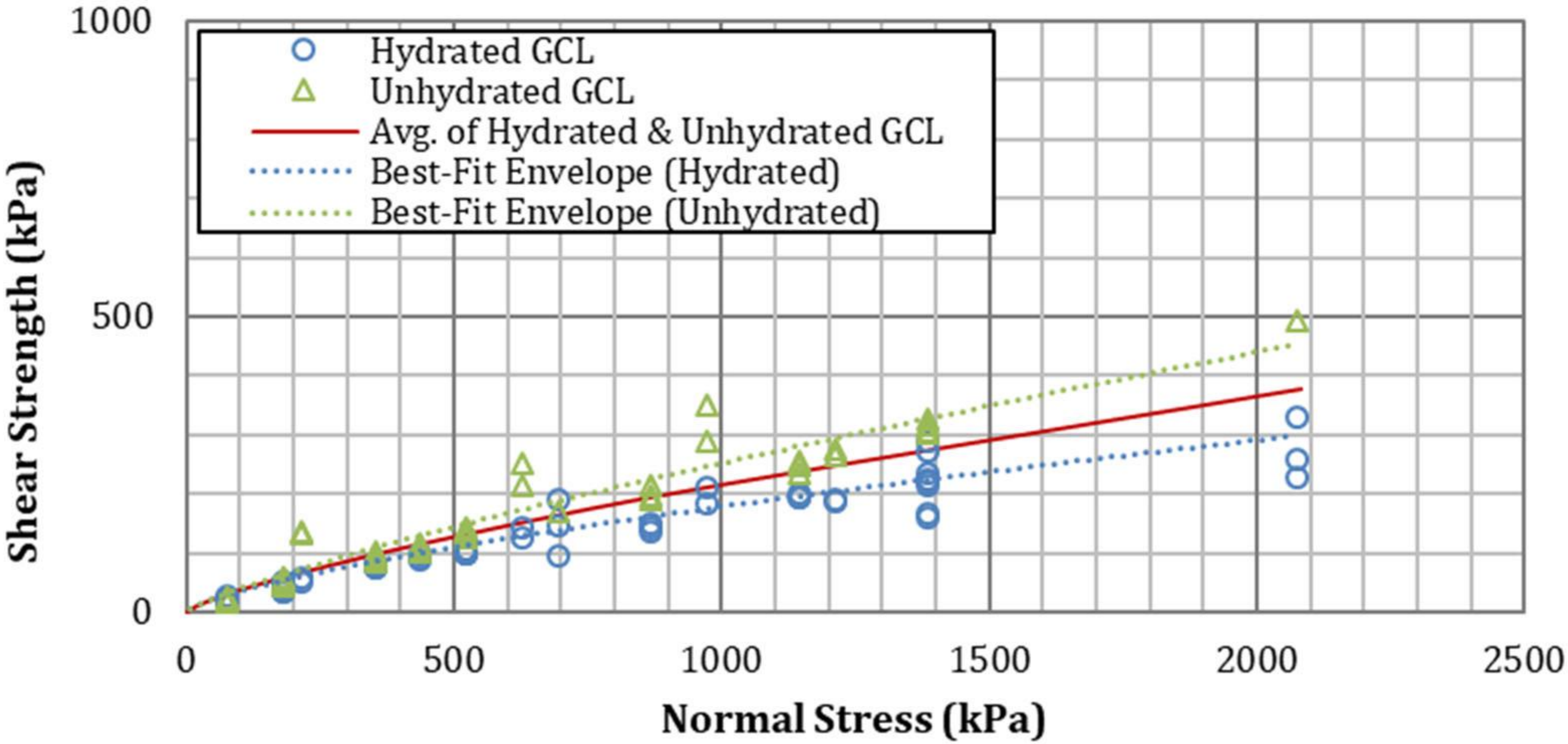


Multi-Interface LD Database

- **From Shenthan et al. (2019)**
- **5 Projects**
- **LD Shear Strength: Stress Dependent**

Bottom Liner System: DST GM/Encapsulated GCL

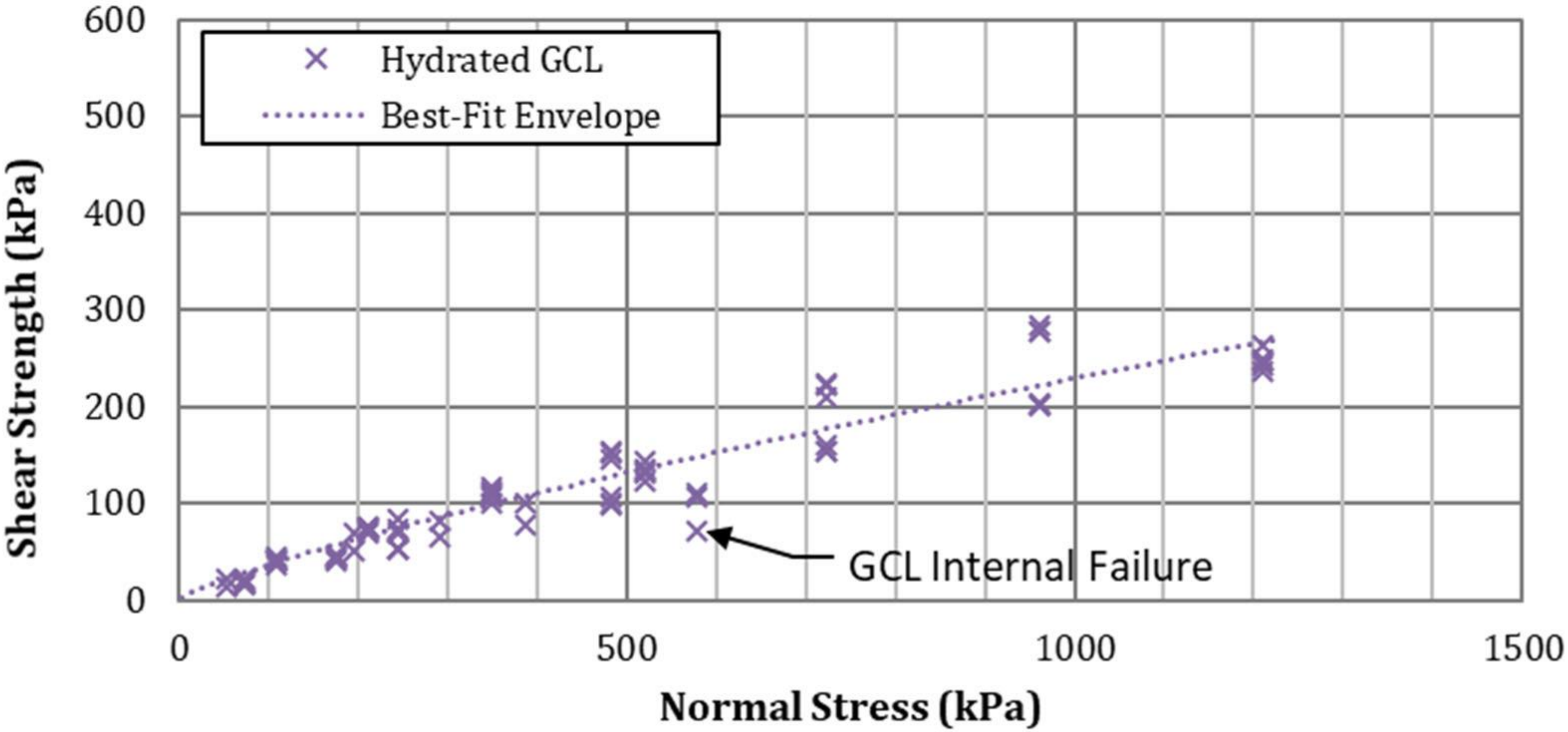
Hydrated: 9.0 to 12.4^0 v. Unhydrated: 13.1 to 16.2^0



Multi-Interface LD Database

- **From Shenthan et al. (2019)**
- **5 Projects**
- **LD Shear Strength: Stress Dependent**

Bottom Liner System: DST GM/Unencapsulated GCL on Subgrade (hydrated)
Hydrated: 11.9 to 14.8^0

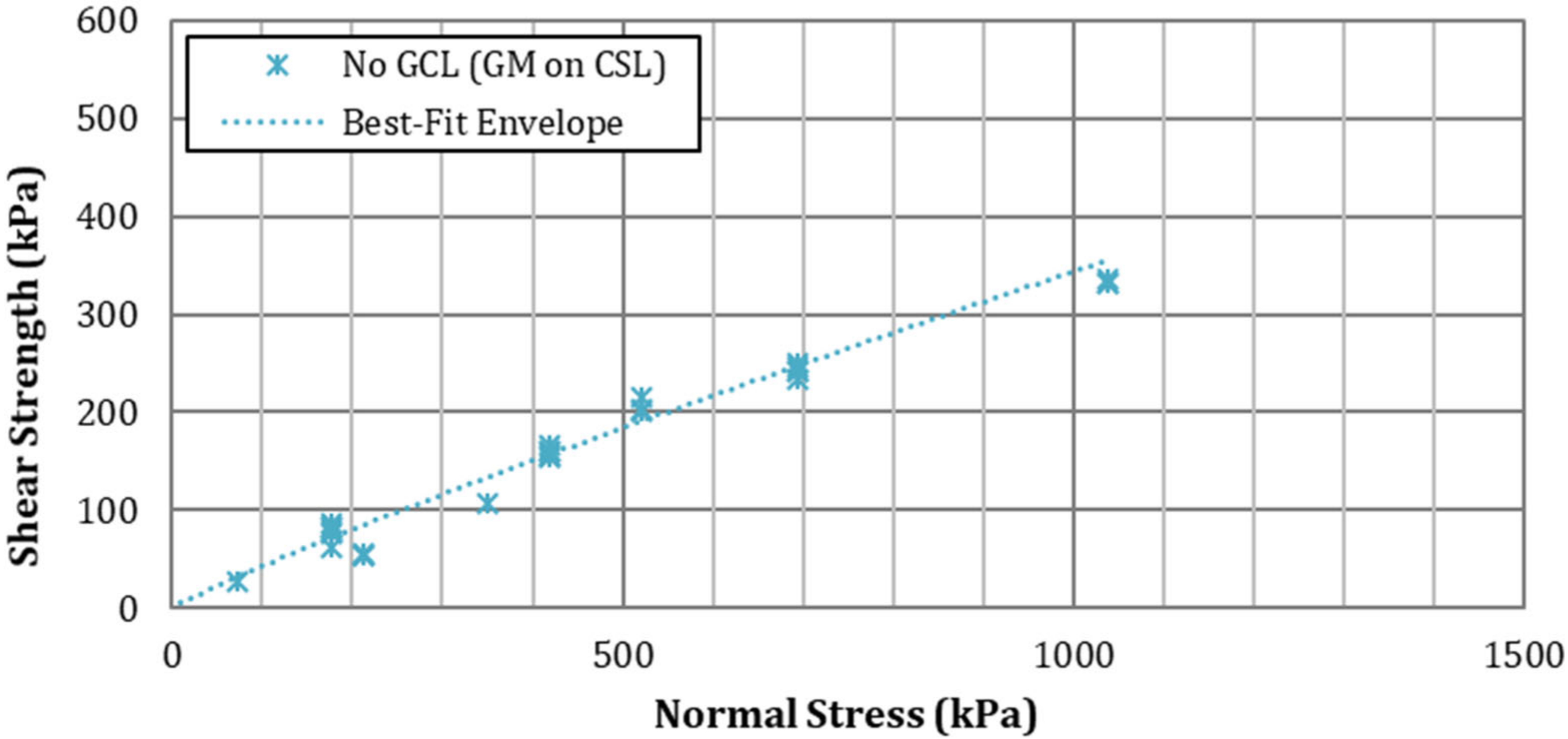


Multi-Interface LD Database

- **From Shenthan et al. (2019)**
- **5 Projects**
- **LD Shear Strength: Stress Dependent**

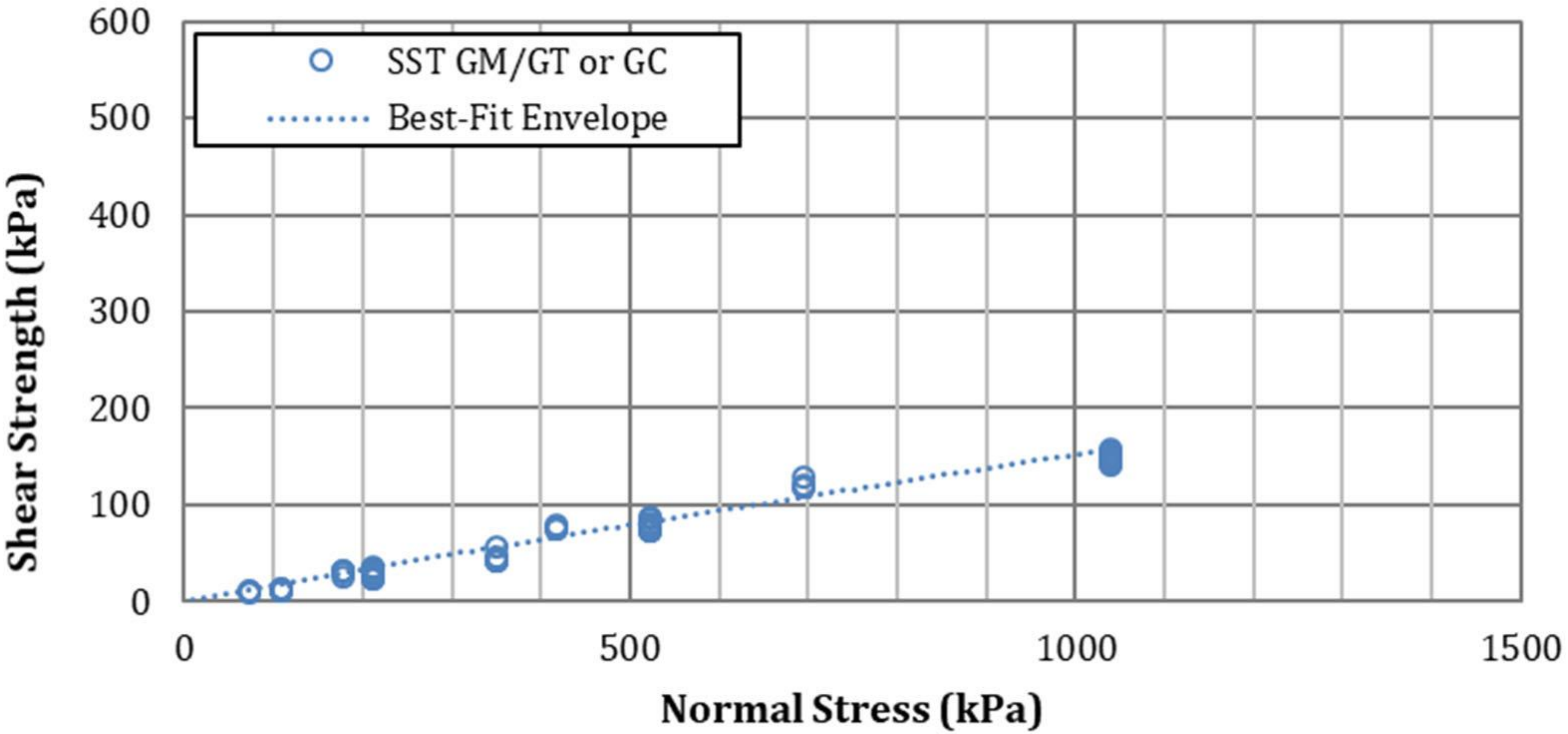
  Bottom Liner System: DST GM/CSL

  As Compacted: 18.3 to 20.2^0



Multi-Interface LD Database

- **From Shenthan et al. (2019)**
- **5 Projects**
- **LD Shear Strength: Stress Dependent**
  Sideslope Liner System: GT/GM-SM/GM-TX/hydrated GCL
  As Compacted: 8.5 to 9.0^0



Summary of Multi-Interface LD Database

- **From Shenthan et al. (2019)**

Table 1. LD Shear Strengths and Secant Friction Angles based on Best-Fit Strength Envelopes

	Category (a) - Encapsulated GCL						Category (b) - Unencapsulated GCL		Category (c) - No GCL (GM on CSL)		Category (d) - SST GM/GT (Side Slope)	
	Hydrated		Unhydrated		Avg. Hyd./Unhy.		Hydrated		-		-	
	τ_{LD}	Φ_{sec}	τ_{LD}	Φ_{sec}	τ_{LD}	Φ_{sec}	τ_{LD}	Φ_{sec}	τ_{LD}	Φ_{sec}	τ_{LD}	Φ_{sec}
a	*1.4038*	-	*0.9966*	-	-	-	*0.9321*	-	*0.6898*	-	*0.2262*	-
b	*0.7017*	-	*0.8012*	-	-	-	*0.7971*	-	*0.8991*	-	*0.9428*	-
σ												
100	36	19.6	40	21.7	38	20.7	37	20.1	43	23.4	17	9.9
500	110	12.4	145	16.2	127	14.3	132	14.8	184	20.2	79	9.0
1000	179	10.1	252	14.2	216	12.2	229	12.9	344	19.0	152	8.7
1500	238	9.0	349	13.1	293	11.1	317	11.9	495	18.3	223	8.5

Note: σ and τ_{LD} are in kPa and Φ_{sec} in degrees

Shenthan, T., Khilnani, K., and Stark, T.D. "Case Histories of Multi-Layer Interface Tests for Composite Liners and Comparison to Single Interface Tests," *Proceedings of Specialty Conf. GEO-CONGRESS 2019*, ASCE, Philadelphia, PA, March, 2019, Geotechnical Special Publication, pp. 42-51.

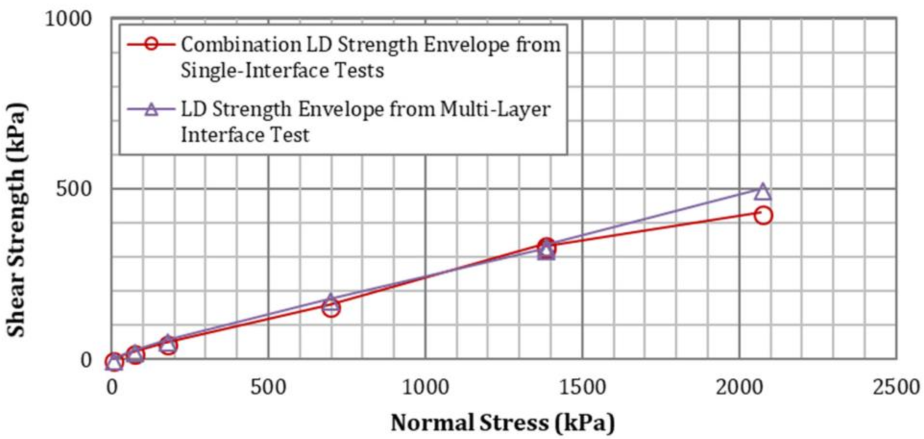
Comparison of Single vs. Multi-Interface Test Results

- **From Shenthan et al. (2019)**
- **Bottom Liner System #1:**
- **Bottom Liner System #2:**
- Excellent agreement with comparison of Peak Strength Envelopes
- Focus on LD Strength Envelopes

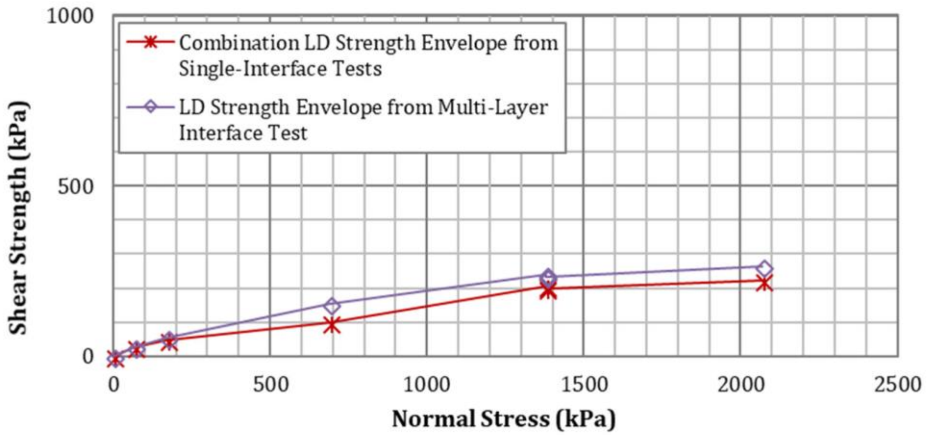
Comparison of Single vs. Multi-Interface Test Results

- **From Shenthan et al. (2019)**
- **Bottom Liner System #1:** Granular Drainage Media/GT/DST GM/GCL/DST GM/Subgrade

- **LD Good Agreement**
- **Encapsulated GCL - Unhydrated**
  (Failure on GCL/DST GM or DST GM/GT)



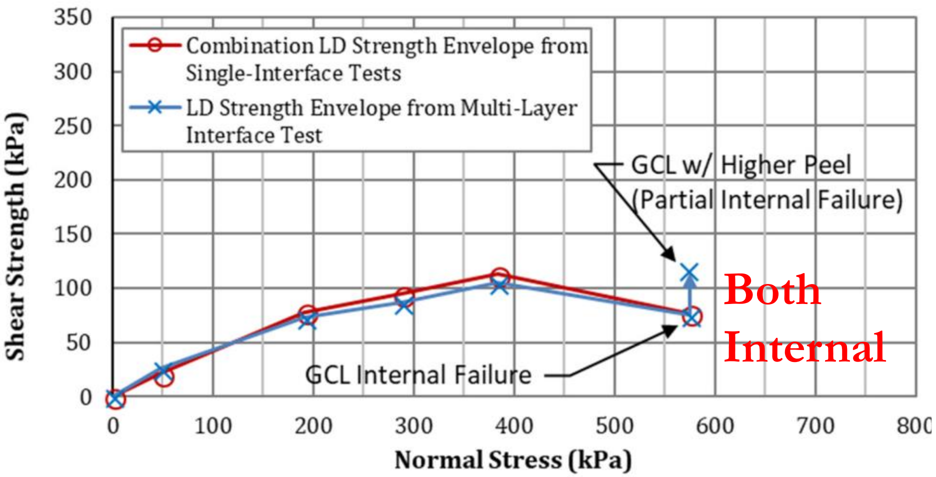
- **Multi LD a little higher**
- **Encapsulated GCL - Hydrated**
  (Failure on GCL/DST GM)



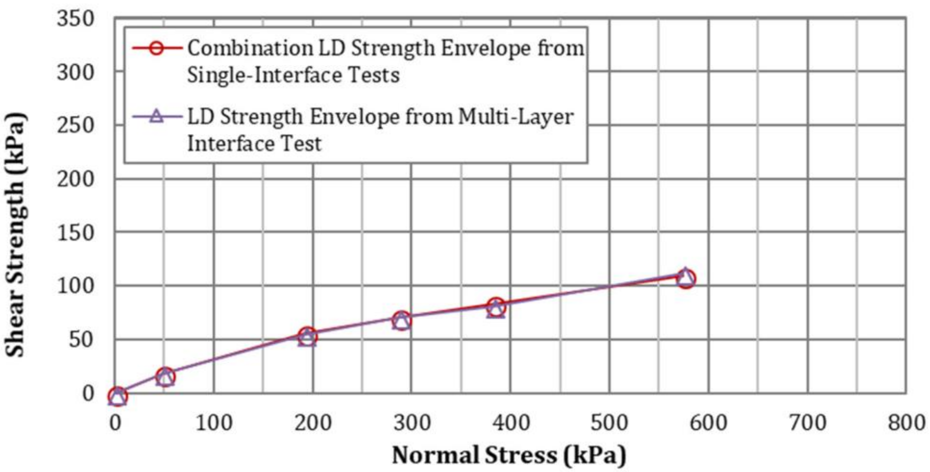
Comparison of Single vs. Multi-Interface Test Results

- **From Shenthan et al. (2019)**
- **Bottom Liner System #2:** Granular Drainage Material/DST GM/GCL/Subgrade

- **Excellent Agreement**
- **Unencapsulated GCL-Hydrated** (Failure on GCL/DST GM)



- **Excellent Agreement**
- **Unencapsulated GCL-Hydrated** (Failure on DST GM/GC)

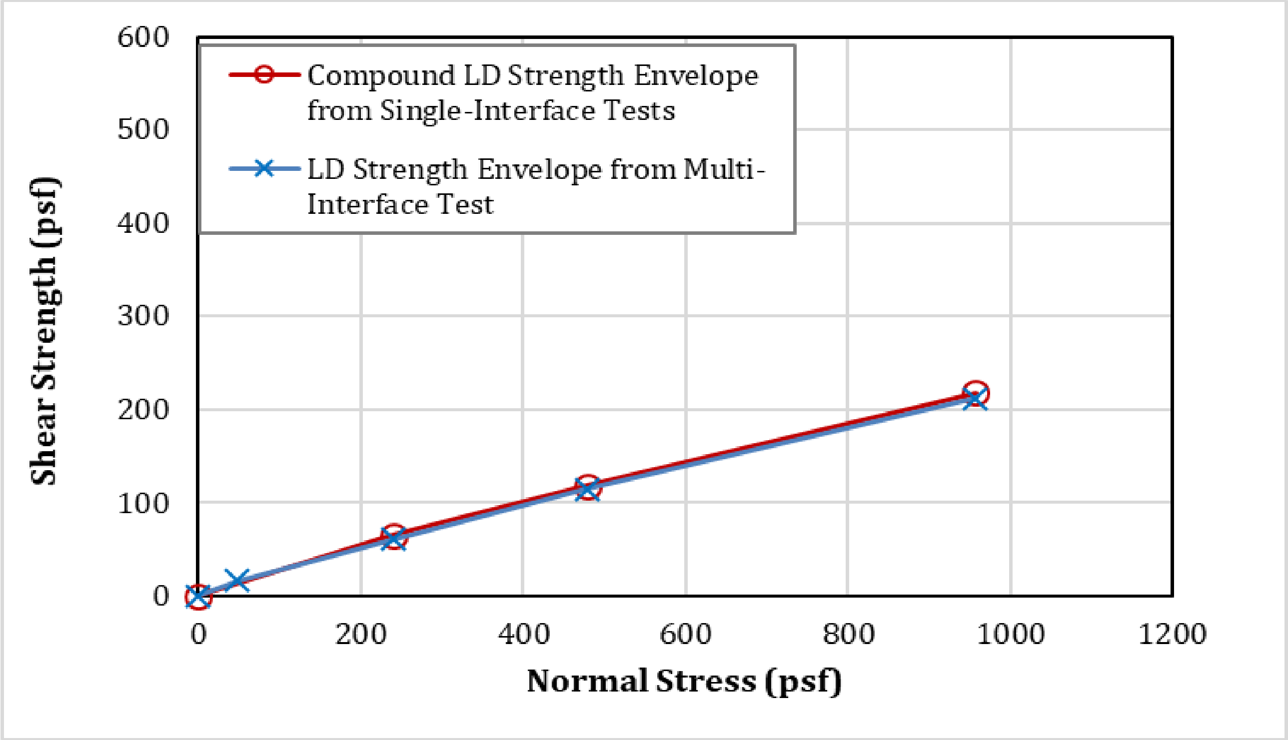


Comparison of Single vs. Multi-Interface Test Results

- **From Shenthan et al. (2019)**
- **Sideslope Liner System #2:** Cover Soil/GC/DST GM/Subgrade
- **No GCL**

3 of 3
(New Data)

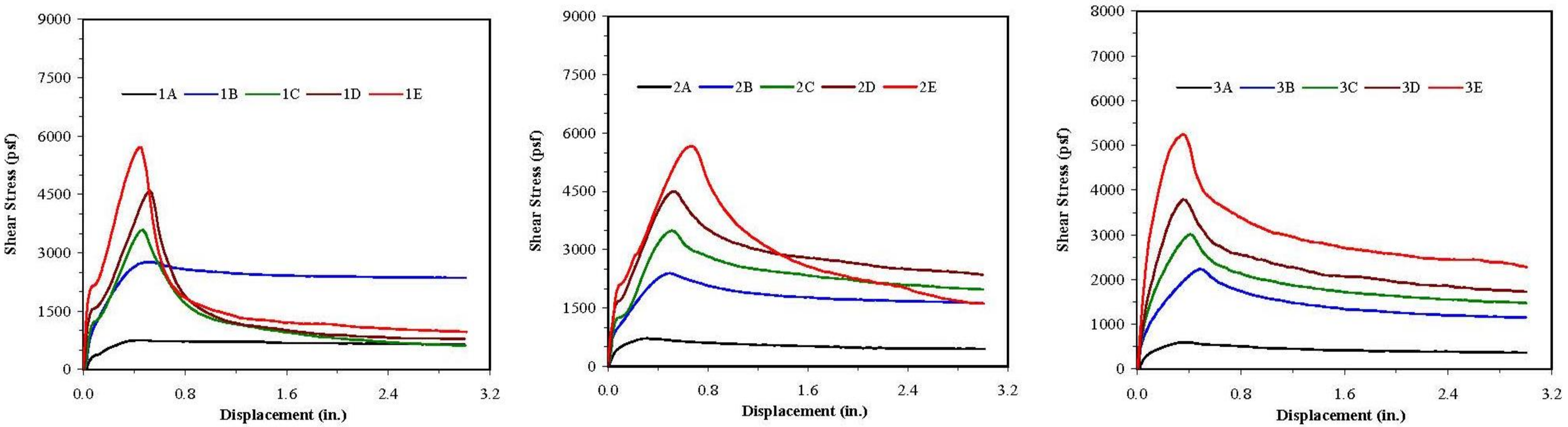
- **Excellent Agreement**
- **GT/DST GM**
  (Failure on GT/DST GM)



Comparison of Single and Multi-layer Tests

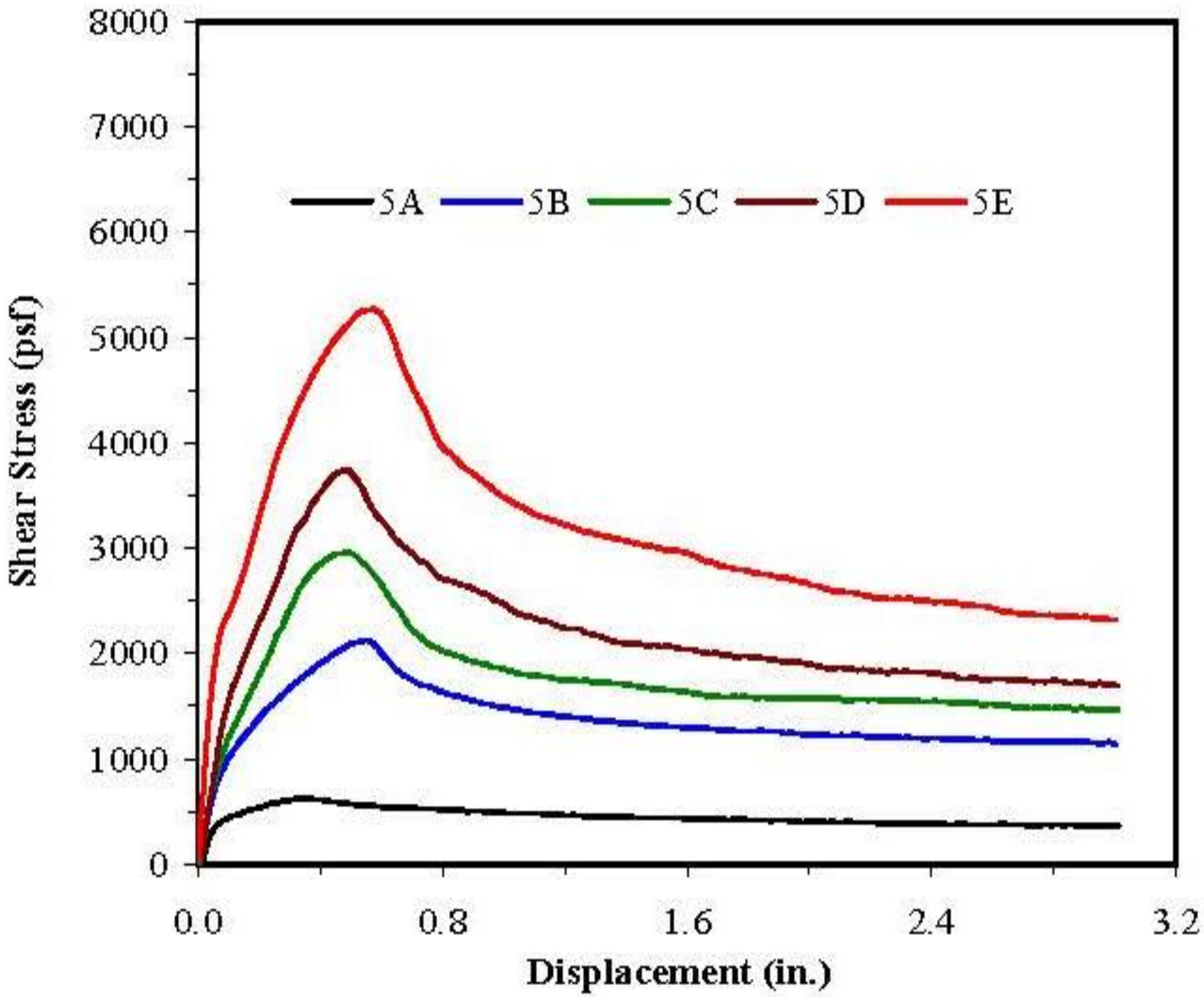
- **Multi-Layer Tests require greater shear displacement?**

- **Subgrade Soil/GCL => Subgrade & Sand**
- **GCL/GM-TX => Sand & Sand**
- **DS GDC/GM-TX => Sand & Sand**

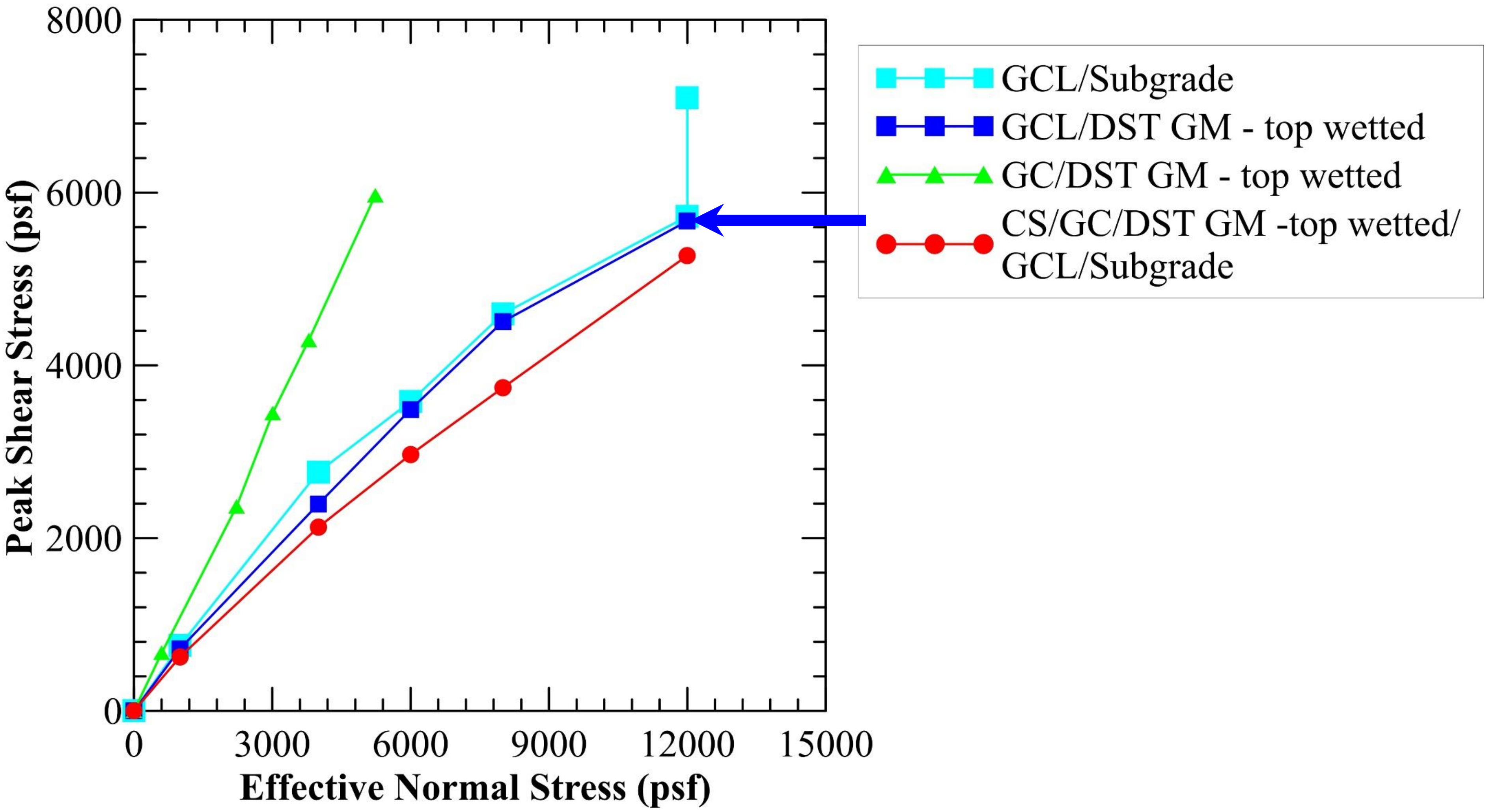


Comparison of Single and Multi-layer Tests

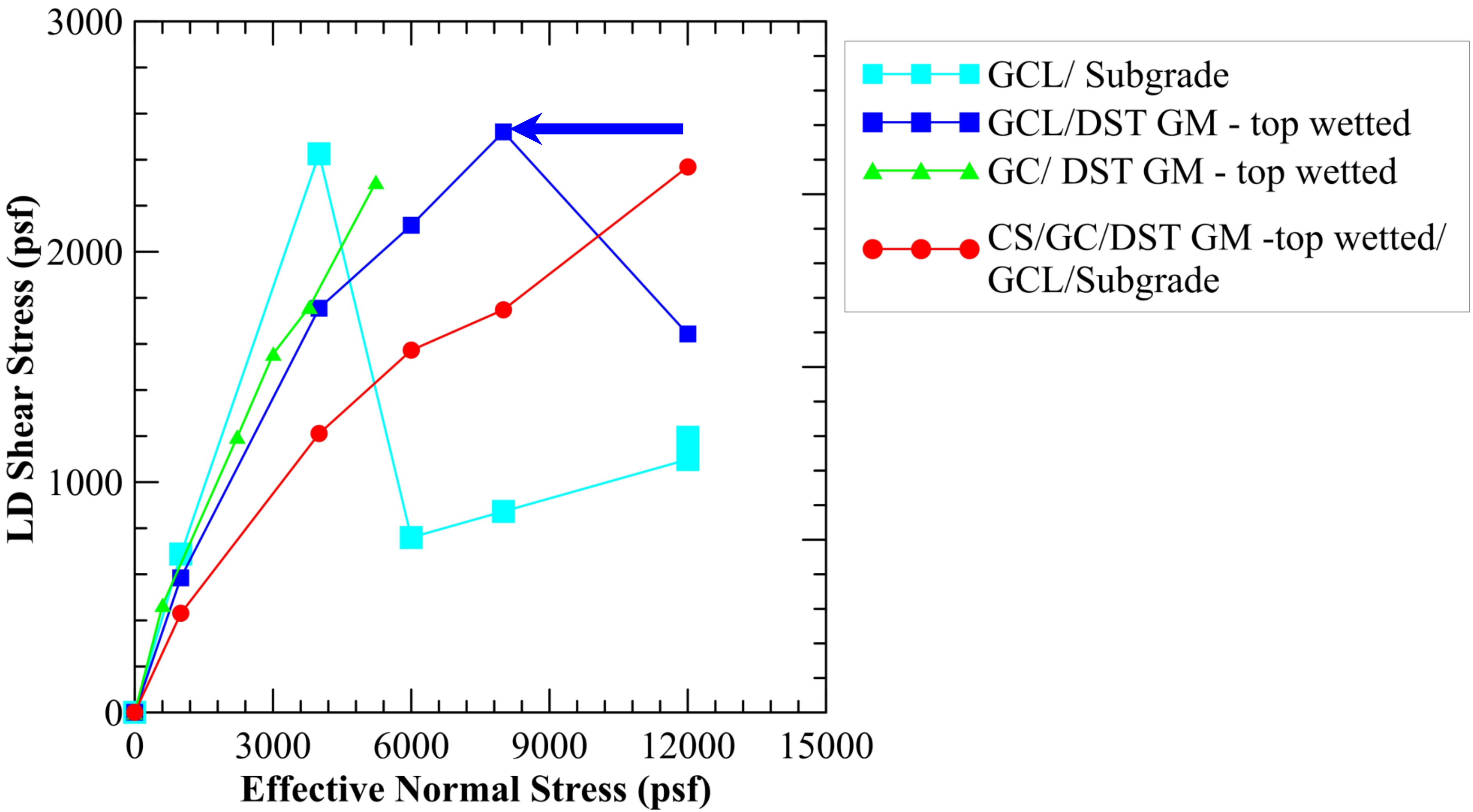
- Subgrade Soil/GCL/GM-TX/LCRS Gravel => Subgrade & Gravel



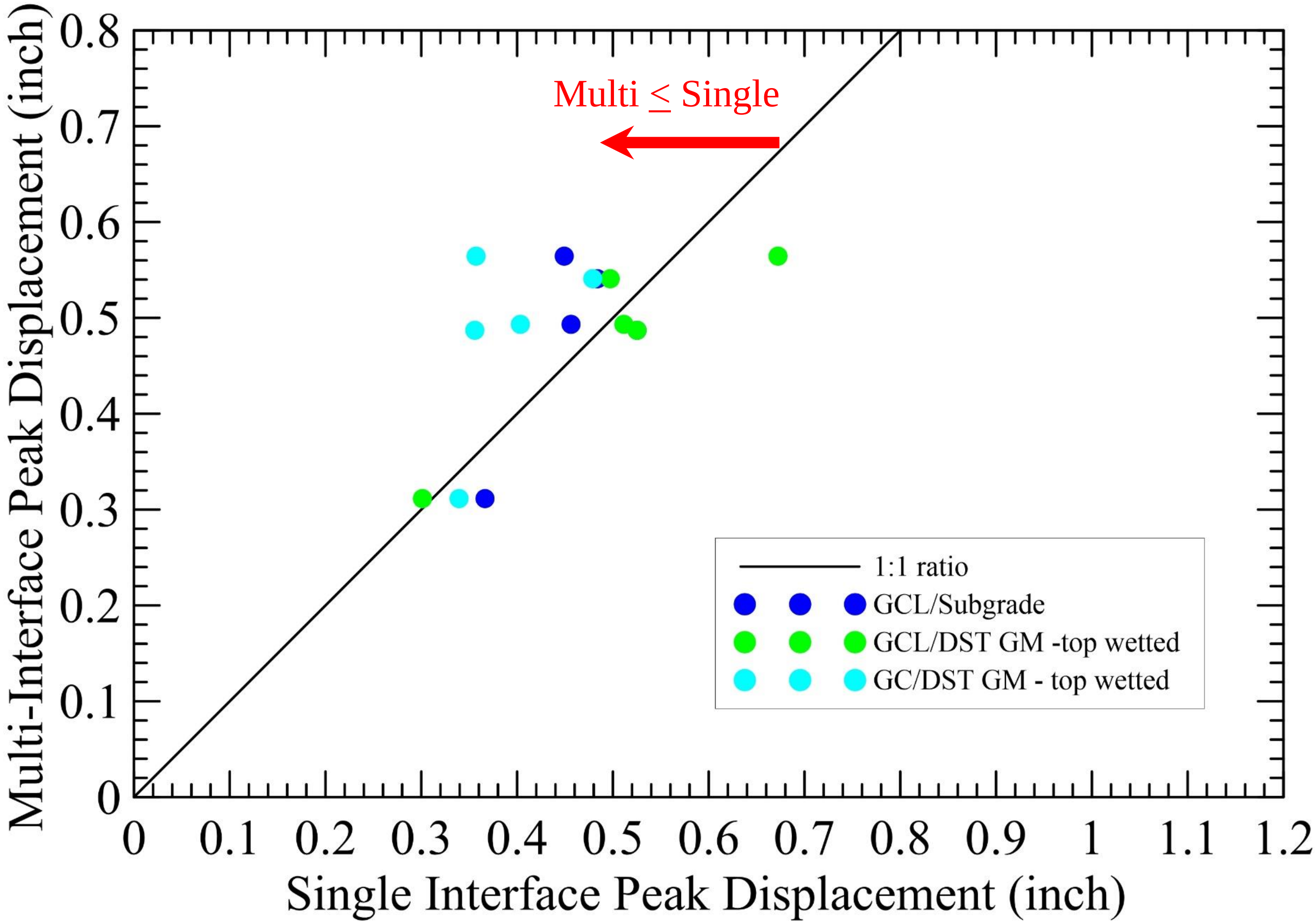
Comparison of Single and Multi-layer Tests



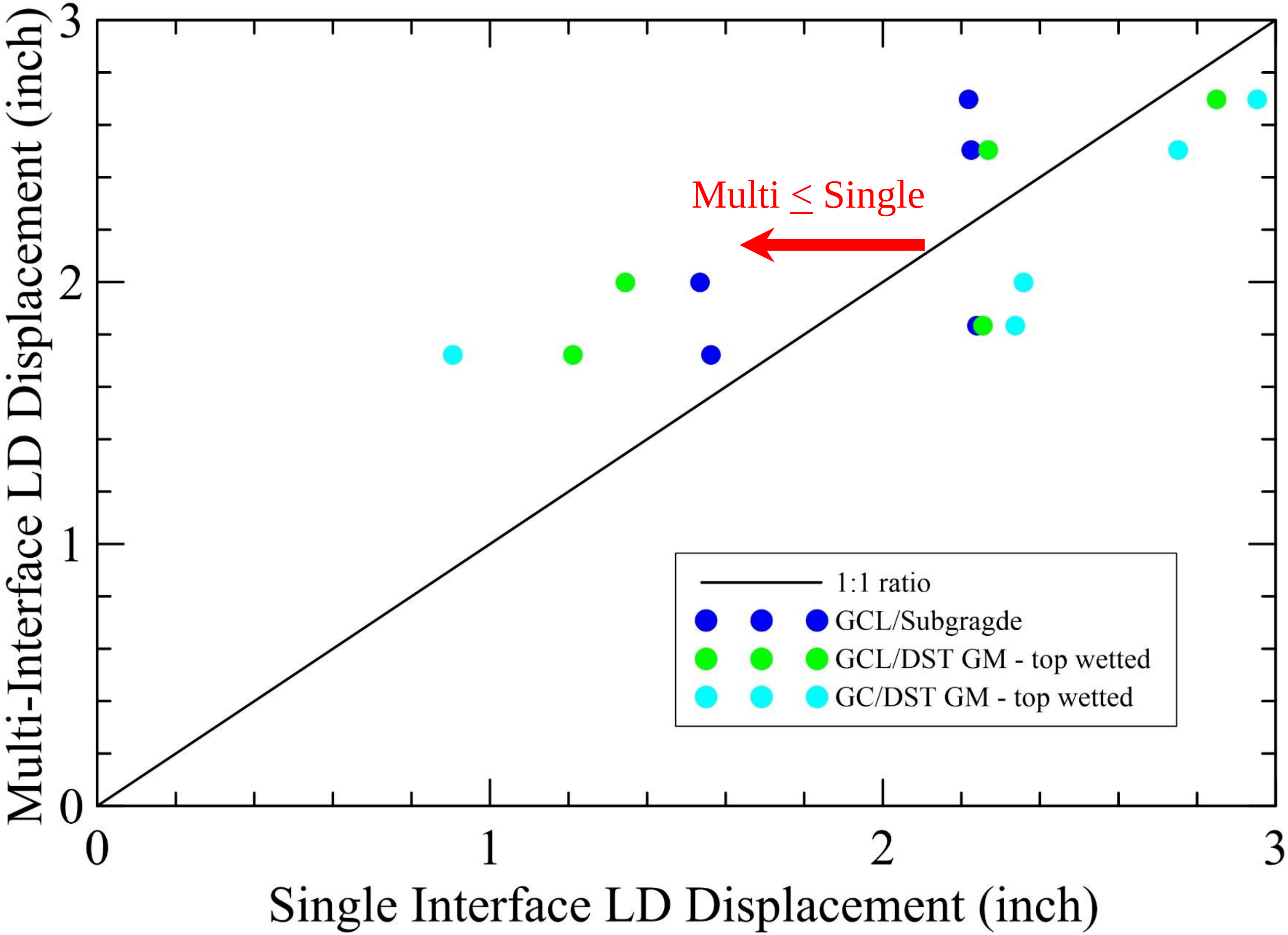
Comparison of Single and Multi-layer Tests



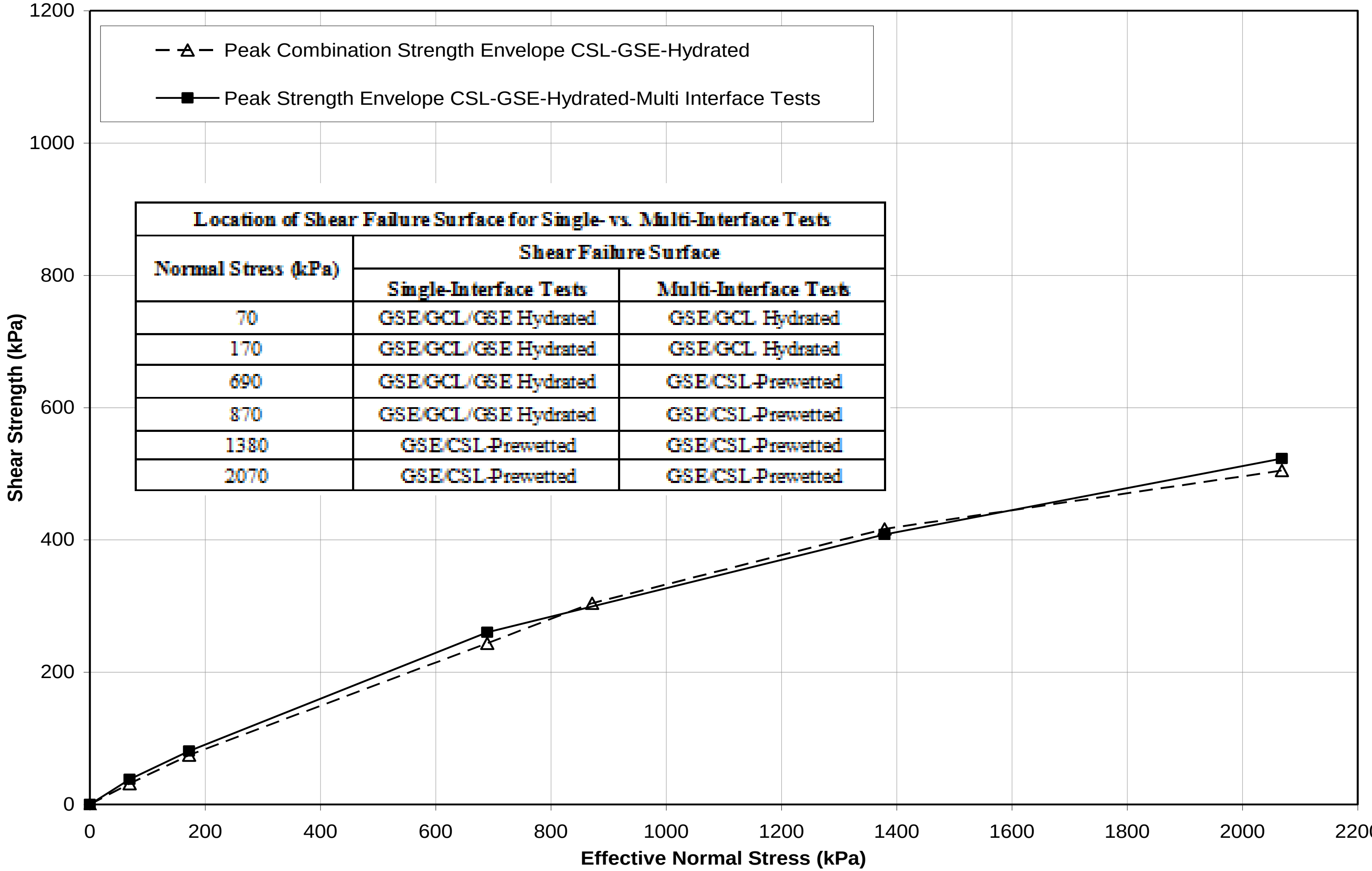
Comparison of Single and Multi-layer Tests



Comparison of Single and Multi-layer Tests



Peak Comparison of Single and Multi-layer



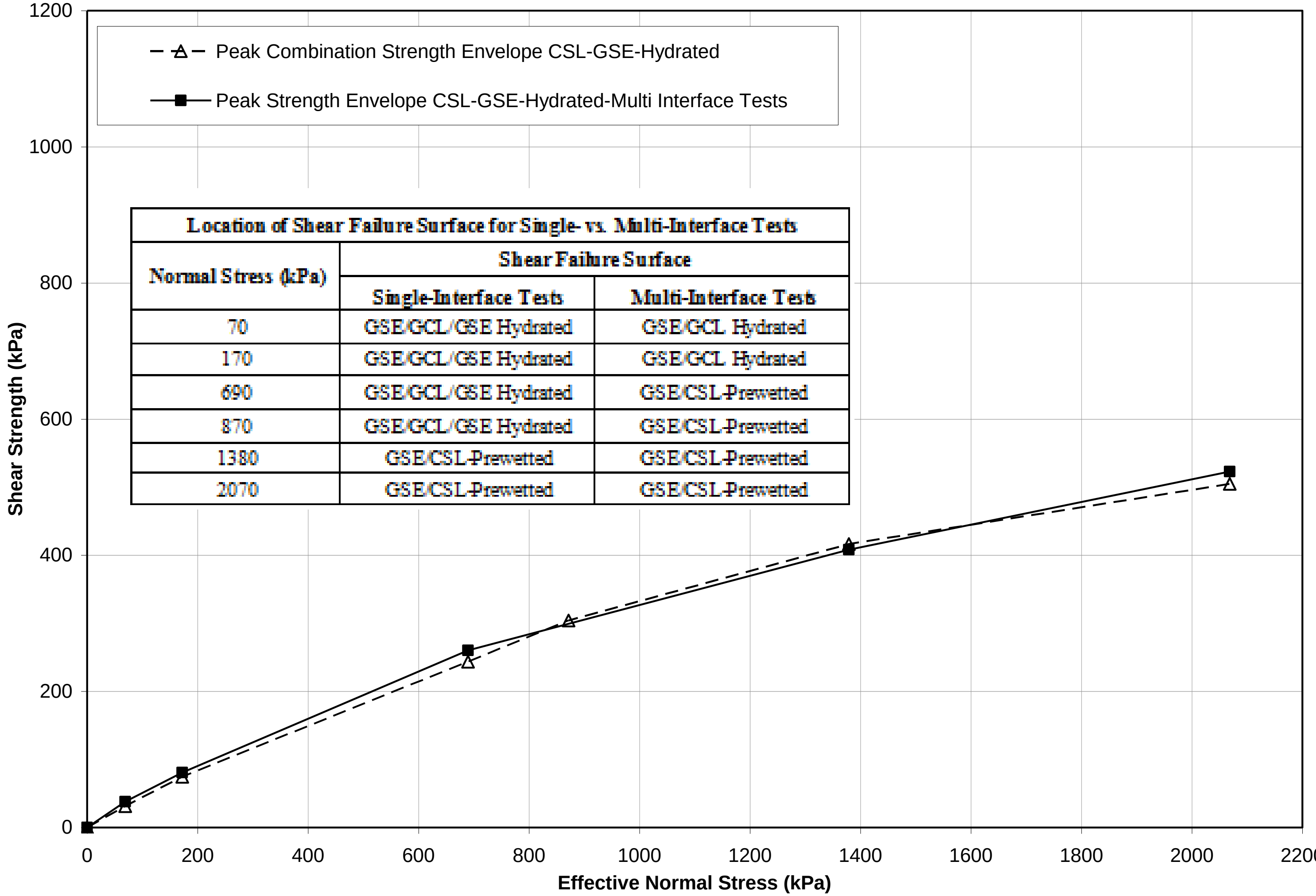
Location of Shear Failure Surface for Single- vs. Multi-Interface Tests

Normal Stress (kPa)	Shear Failure Surface	
	Single-Interface Tests	Multi-Interface Tests
70	GSE/GCL/GSE Hydrated	GSE/GCL Hydrated
170	GSE/GCL/GSE Hydrated	GSE/GCL Hydrated
690	GSE/GCL/GSE Hydrated	GSE/CSL Prewetted
870	GSE/GCL/GSE Hydrated	GSE/CSL Prewetted
1380	GSE/CSL Prewetted	GSE/CSL Prewetted
2070	GSE/CSL Prewetted	GSE/CSL Prewetted

Peak = good agreement

Stark et al. (2015)

LD Comparison of Single and Multi-layer



Location of Shear Failure Surface for Single- vs. Multi-Interface Tests		
Normal Stress (kPa)	Shear Failure Surface	
	Single-Interface Tests	Multi-Interface Tests
70	GSE/GCL/GSE Hydrated	GSE/GCL Hydrated
170	GSE/GCL/GSE Hydrated	GSE/GCL Hydrated
690	GSE/GCL/GSE Hydrated	GSE/CSL-Prewetted
870	GSE/GCL/GSE Hydrated	GSE/CSL-Prewetted
1380	GSE/CSL-Prewetted	GSE/CSL-Prewetted
2070	GSE/CSL-Prewetted	GSE/CSL-Prewetted

LD – Single is lower

Stark et al. (2015)

Summary

- From Shenthan et al., (2019)
- Multi-interface data from 305 tests and comparison w/ 3 single interface tests
- Excellent agreement between Single & Multi-interface tests
  - Same Peak Strength Envelopes
  - Weakest interface at same normal stress
  - LD strengths in good to excellent agreement
- Multi-interface results reliable and repeatable
- Eliminate issues w/clamping in single tests
- Represents actual field conditions
- Only 1 test per liner system configuration vs. 3 or 4 single interfaces
- Should develop an ASTM standard for multi-interface tests

Recommendations

- Use different Design Strength Envelopes for Sideslope and Base Liner Systems - different configurations, normal stresses, & strengths
- If Single Interface Tests specified, use Multi-Layer Tests to verify Combination Strength Envelope
- If anomaly with Multi-Layer Test, conduct relevant single interface tests
- If Single Interface Tests specified, require strength envelope NOT a specified strength but should be defined as interface with lowest peak strength
- Specified strength should be a strength envelope not individual values for each interface

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Multi-Layer Interface Shear Testing

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