Developing confidence in critical state soil mechanics

2. Calibration of Fraser River Sand

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Elasticity

- Slight detour required – as we do not have time to calibrate elasticity in this workshop……..
- BUT – elasticity is important.
- ELASTICITY
  - This is the small strain value – "G_{max}"
  - Forget strain-dependent elasticity as this doesn't exist.
  - "Measured" by bender elements in the lab
  - "Measured" by the seismic CPT in the field

Fraser River Sand Benders

- Bender elements were used with 7 triaxial tests
  - 5 bender tests overlap with data in NorSandM_txl_FRS.xls
  - 2 bender tests were on “crushed” FRS
  - Measurements taken during both consolidation and shearing stages
- Fitted equation of the form

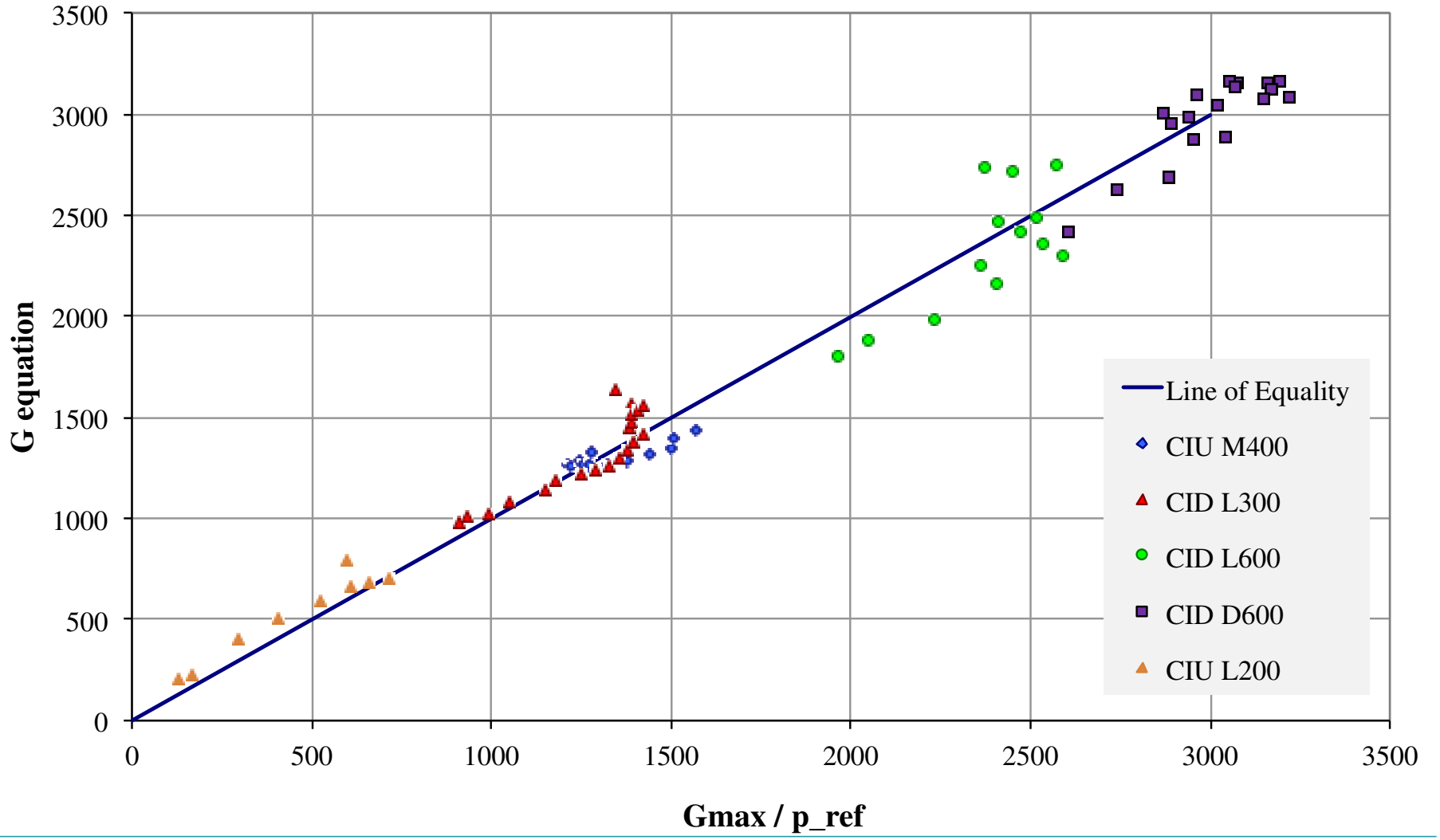
$$\frac{G}{p_{ref}} = \frac{A}{(e - e_{\min})}\left(\frac{p'}{p_{ref}}\right)^{b}$$

….to the shearing portion of the uncrushed triaxials.

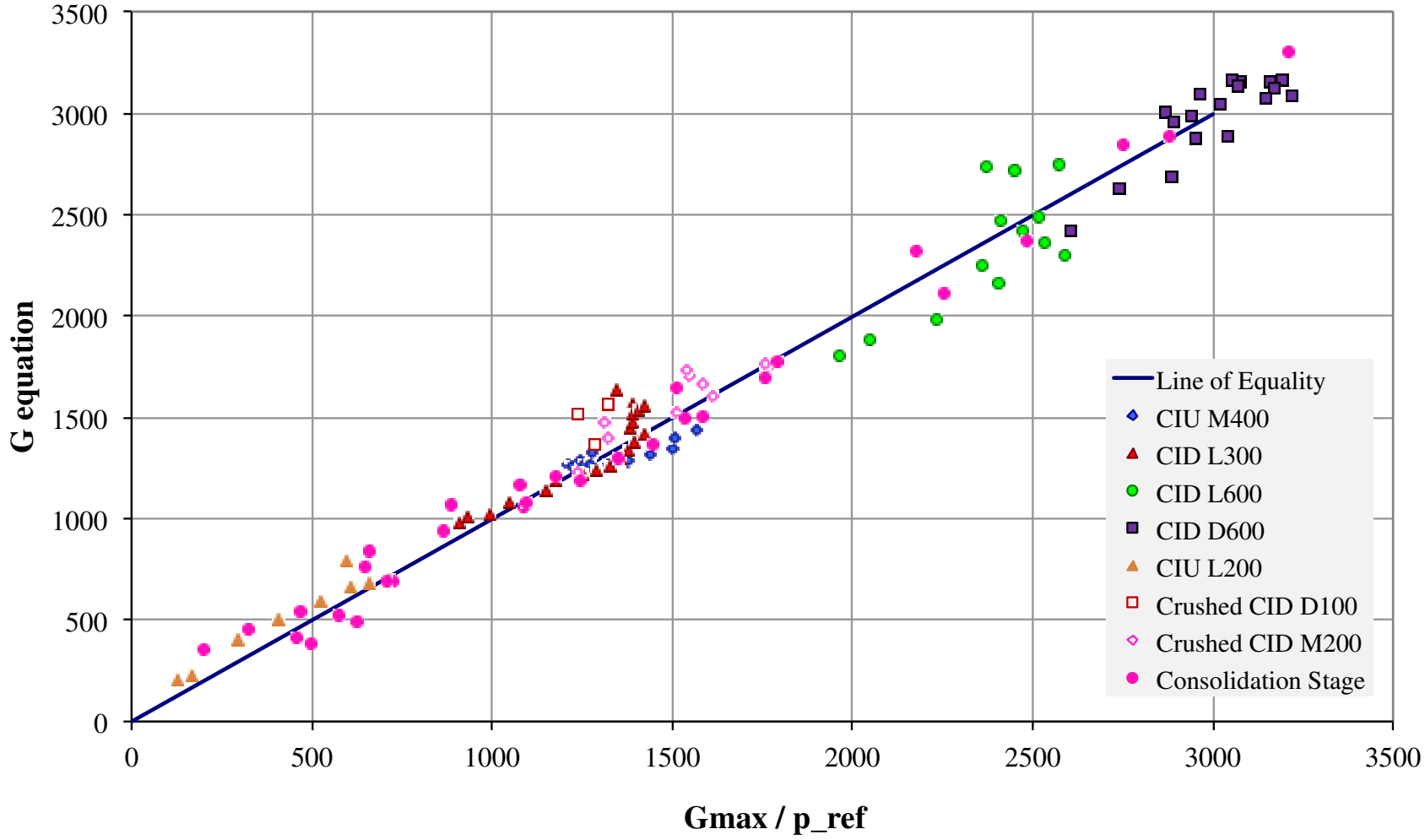
where A, e_{min} and b are fitted soil properties

p_{ref} is 100 kPa (or equivalent in same units as p′)

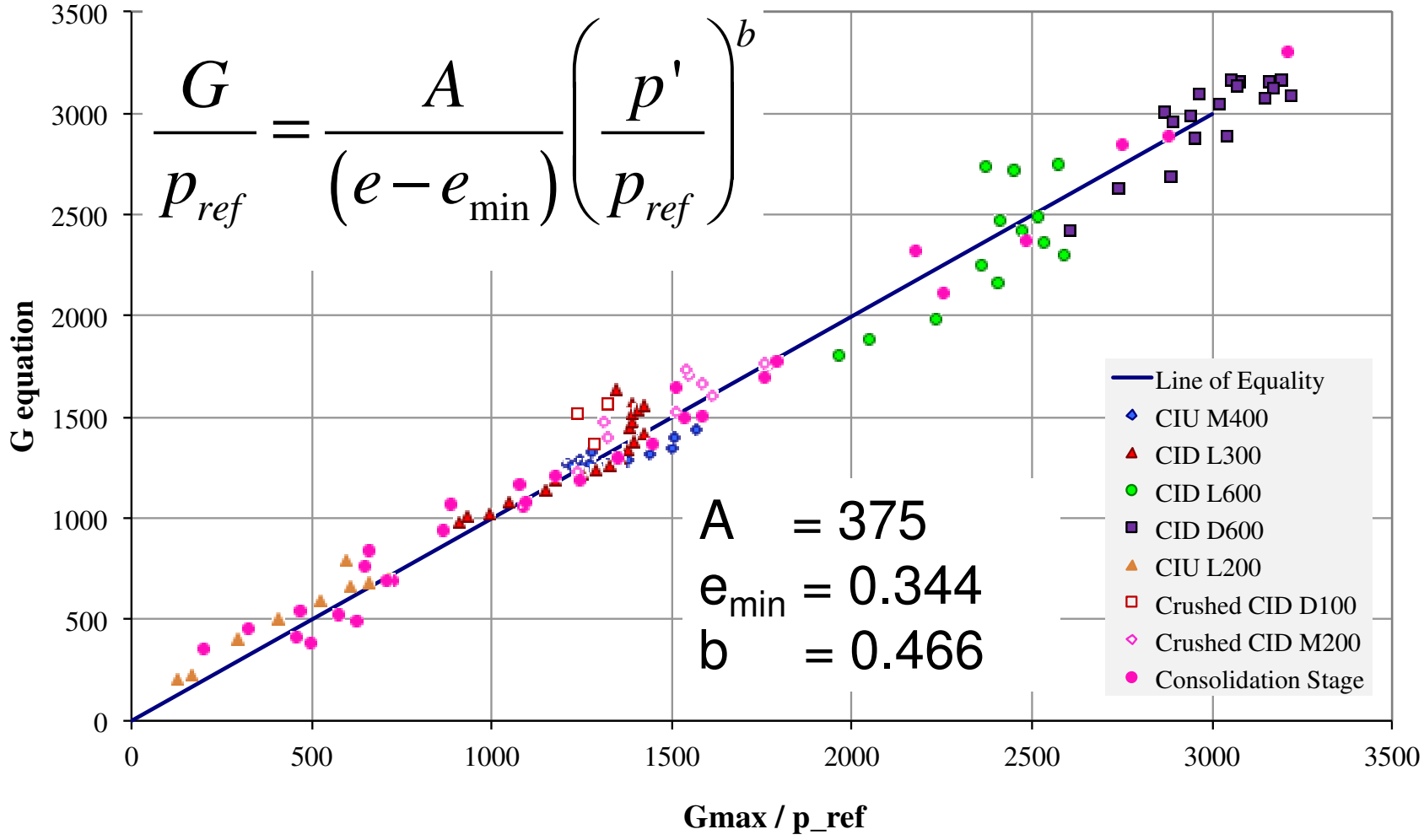
Goodness of fit – fitting data shown



Goodness of fit – incl. consol. & crushed FRS



Elasticity - fit



Elasticity – simpler equation for workshop

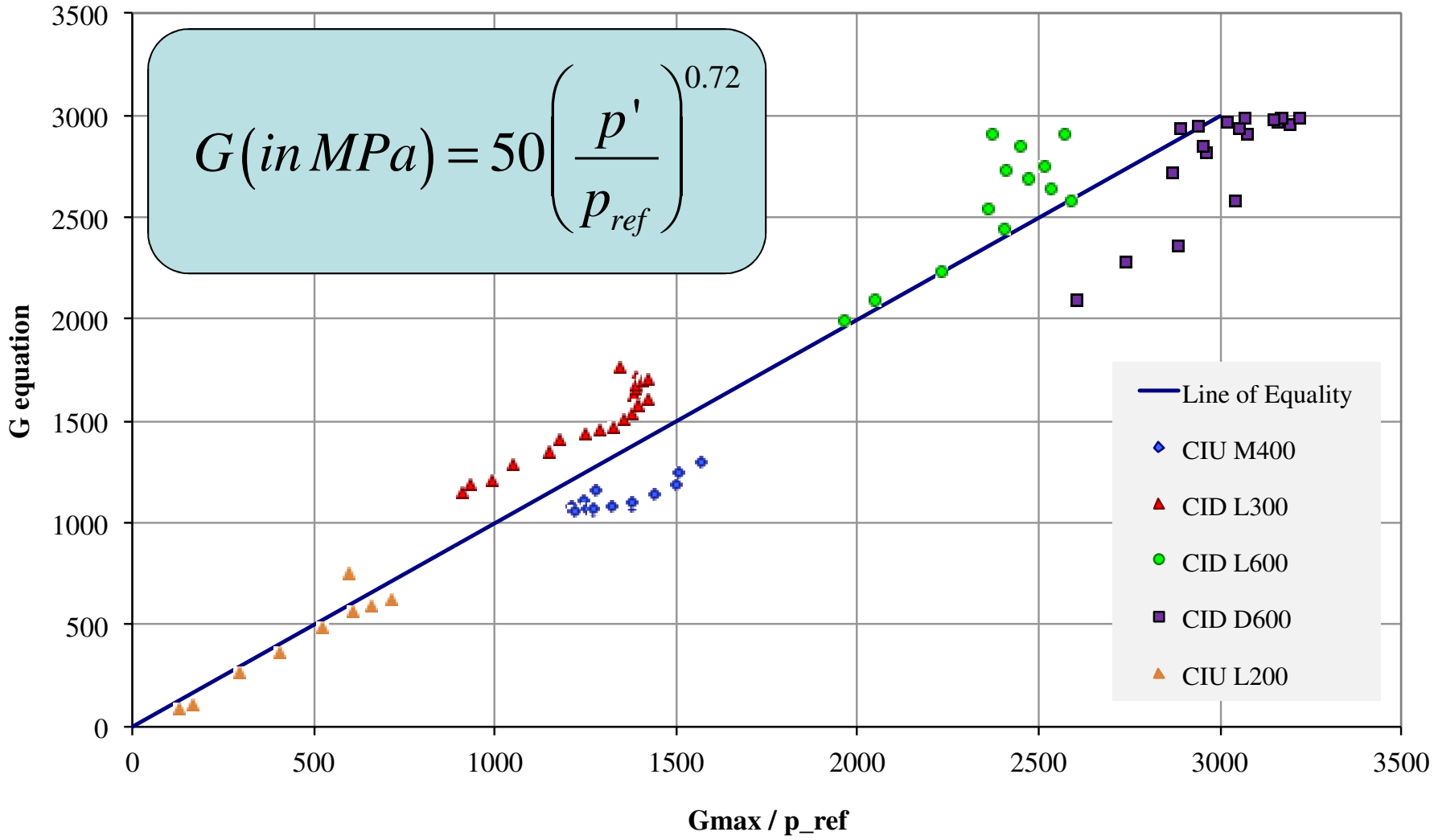
- For simplicity the workshop spreadsheet adopts the simpler (but less accurate) equation:

$$G = a\left(\frac{p'}{p_{ref}}\right)^{b}$$

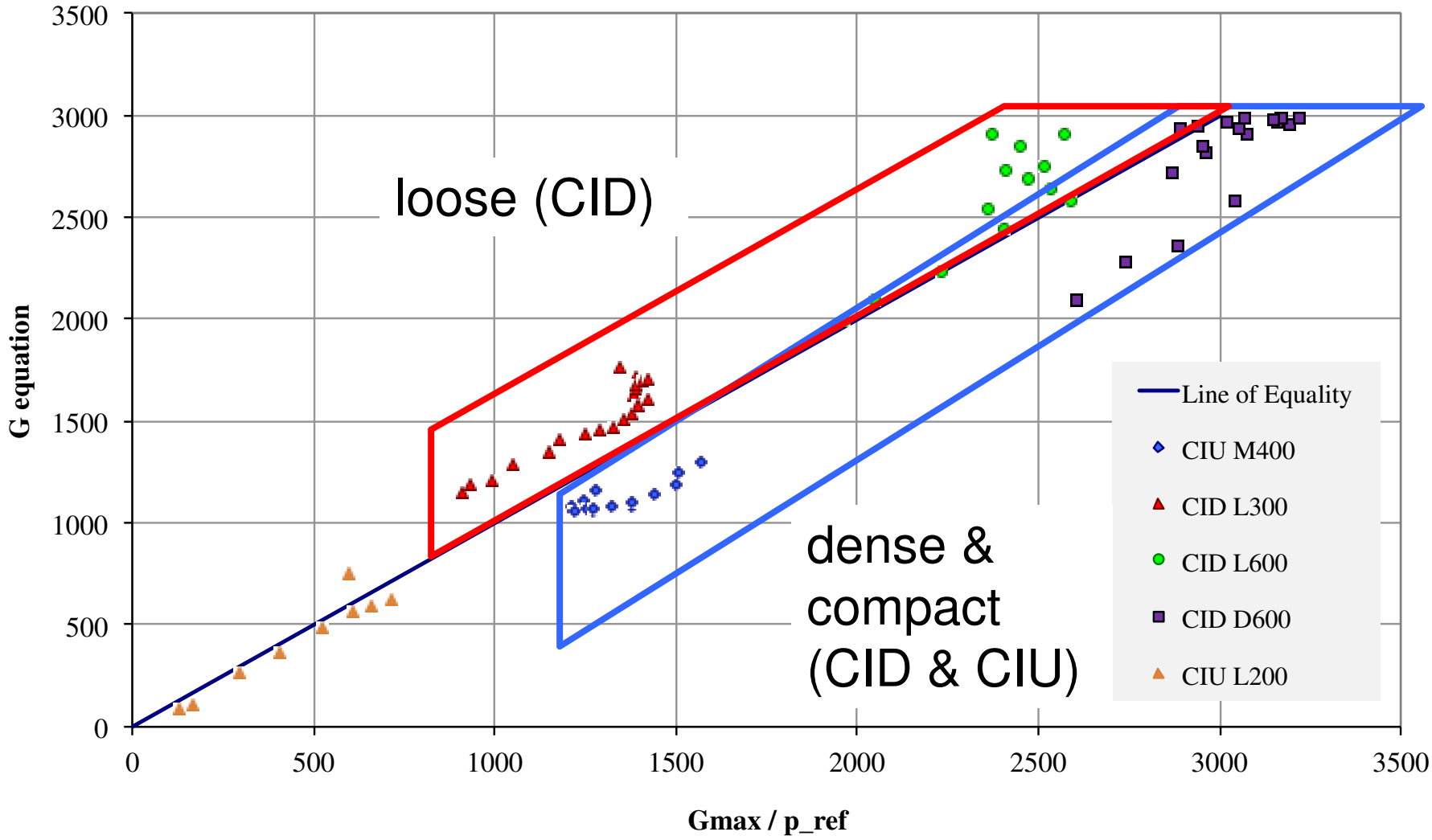
…where a and b are fitted parameters, p_{ref} = 100 kPa.

Elasticity – simpler equation for workshop

$$G(in\,MPa) = 50\left(\frac{p'}{p_{ref}}\right)^{0.72}$$



Elasticity – simpler equation for workshop



Elasticity – end notes

- Elasticity is easy to measure – especially as part of a CPT testing program.
- For calibration measuring elasticity is important because both elasticity (G_{max}) and hardening (H_0, H_ψ) have a similar effect on the measured q-ε_1 and ε_v –ε_1 response.
- Finally – although NorSandM_txl_FRS uses the simple equation:

$$G = a\left(\frac{p'}{p_{ref}}\right)^b$$

…it is not difficult to modify the spreadsheet to use the more accurate equation for future use if you have laboratory bender tests including void ratio measurement.

NorSand Calibration - Purpose

- Purpose of the calibration ?
  - Engineering 'hand' calculations (e.g. M_{tc} for stability)
  - FE / FD analysis
  - CPT interpretation, etc, etc, etc
- What's NOT the purpose of the calibration ?
  - Getting a fantastic match between the experimental and theoretical curves for a single test (although it is tempting to use the best fit for technical articles….)

NorSand Calibration - Purpose

- A SINGLE SET of material properties is required
- It should fit all of the tests reasonably well
- Where necessary bias your “best” fits to in situ conditions
- If you want to make an exception you must be able to recognize the relevant condition in situ
- This requires ENGINEERING JUDGMENT…….
  and while you’ll find silly fits exist, there is no unique “correct” fit.

NorSand Calibration – "data summary" sheet

Fraser River Sand index properties reported in Ghafghazi (2011)

Index Properties		
D50	0.271	microns
fines =	0.8	%
emin =	0.827	
SG =	2.72	

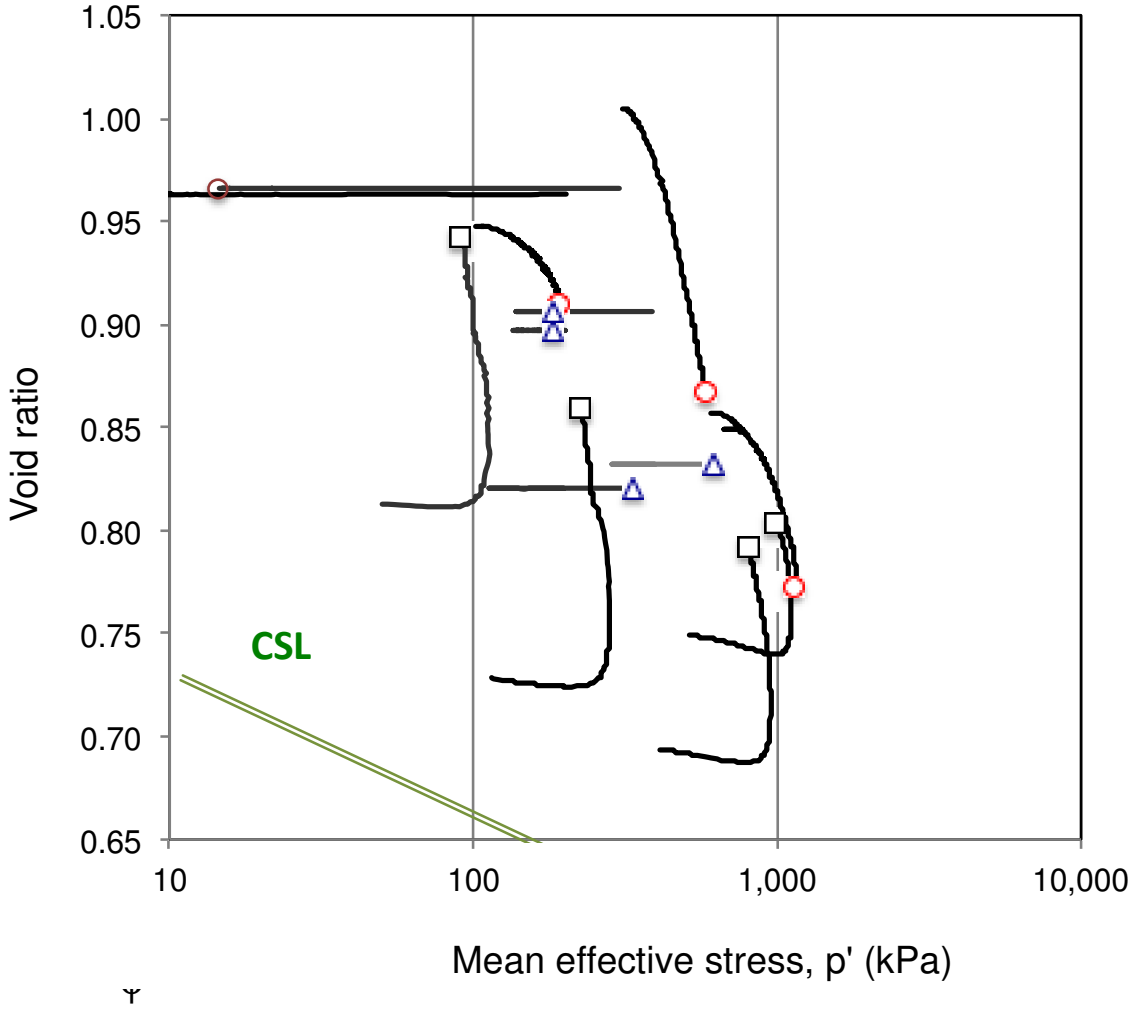
Soil Properties	
Gamma =	**0.8**
lambda10 =	**0.069**
Mtc =	**1.20**
Ntc =	**0.30**
chi_tc =	**3.50**
H_0 =	**200**
H_ψ =	**0**

NorSand Calibration – "data summary" sheet

	As tested initia			At max dilation (= D_{min})			At end of test	
Test	p0	e0	psi0	Dmin	eta_max	psi	p	e
CID_D_50kPa	50.3	0.813	0.130					
CID_D_115kPa	113.9	0.728	0.070					
CID_D_410kPa	409.6	0.694	0.074					
CID_D_515kPa	514.5	0.749	0.136					
CID_L_100kPa	102.1	0.948	0.286					
CID_L_300kPa	302.9	1.005	0.377					
CID_L_600kPa	603.3	0.857	0.249					

	As tested initia			At critical state (if reached		At end of test (not at CS)	
	p0	e0	psi0	p_c	e_c	p	e
CIU_L_200kPa	201.9	0.963	0.322				
CIU_M_200kPa	200.2	0.897	0.256				
CIU_D_200kPa	196.4	0.820	0.178				
CIU_L_300kPa	301.0	0.966	0.337				
CIU_L_390kPa	388.4	0.906	0.285				
CIU_M_400kPa	393.3	0.832	0.211				

NorSand Calibration – Γ and λ_{10}



NorSand Calibration – "Data Summary" sheet

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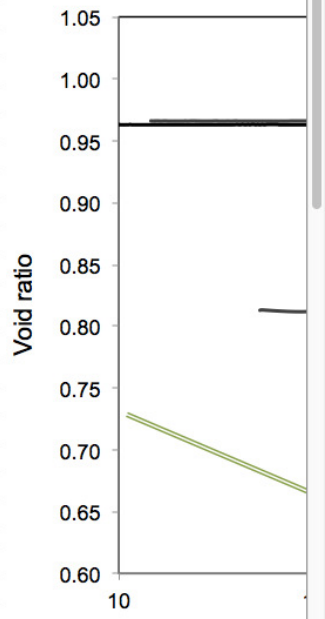
		D50	0.271	microns	Gamma =	0.8				
		fines =	0.8	%	lambda10 =	0.069				
		emin =	0.827		Mtc =	1.2				
		SG =	2.72		Ntc =	0.3				
					chi_tc =	3.5				
					H_0 =	200				
					H_v =	0				
		As tested initial			At max dilation (= D_{min})			At end of test		
	Test	p0	e0	psi0	Dmin	eta_max	psi	p	e	
	CID_D_50kPa	50.3410866	0.81289597	0.13032863						
	CID_D_115kPa	113.886756	0.72789879	0.06979544						
	CID_D_410kPa	409.63169	0.69385172	0.07410688						
	CID_D_515kPa	514.508955	0.74915547	0.13624158						
	CID_L_100kPa	102.070875	0.94782889	0.28644312						
	CID_L_300kPa	302.902237	1.00535849	0.37656836						
	CID_L_600kPa	603.254945	0.85680685	0.24866141						
		As tested initial			At critical state (if reached		At end of test (not at CS)			
		p0	e0	psi0	p_c	e_c	p	e		
	CIU_L_200kPa	201.885733	0.963	0.32205229						
	CIU_M_200kPa	200.210032	0.897	0.25580252						
	CIU_D_200kPa	196.409314	0.82000003	0.17822822						
	CIU_L_300kPa	300.992171	0.966	0.33702031						
	CIU_L_390kPa	388.40034	0.9062	0.28486029						
	CIU_M_400kPa	393.317095	0.83197792	0.21101517						



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CID_L_600kPa	603.3	0.857	0.249					

Fill in blanks by reviewing supplied test data

	As tested initial			At critical state (if reached		At end of test (not at CS)	
	p0	e0	psi0	p_c	e_c	p	e
CIU_L_200kPa	201.9	0.963	0.322				
CIU_M_200kPa	200.2	0.897	0.256				
CIU_D_200kPa	196.4	0.820	0.178				
CIU_L_300kPa	301.0	0.966	0.337				
CIU_L_390kPa	388.4	0.906	0.285				
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NorSand Calibration – "data summary" sheet

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use cell references

	As tested initial			At critical state (if reached		At end of test (not at CS)	
	p0	e0	psi0	p_c	e_c	p	e
CIU_L_200kPa	201.9	0.963	0.322				
CIU_M_200kPa	200.2	0.897	0.256				
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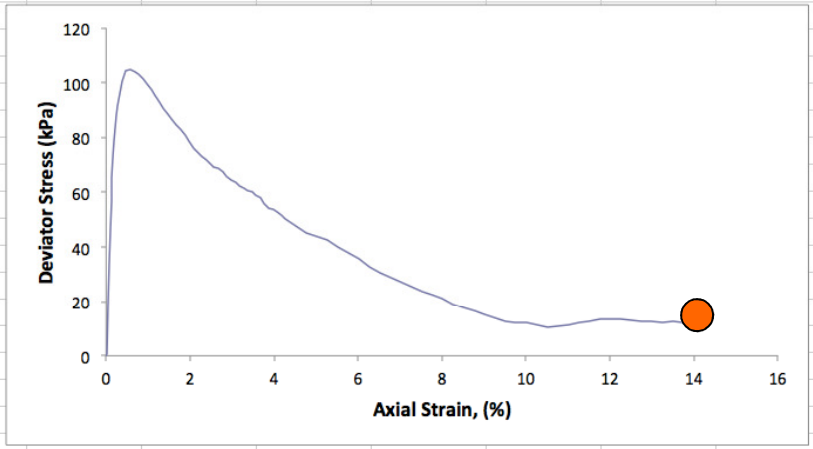
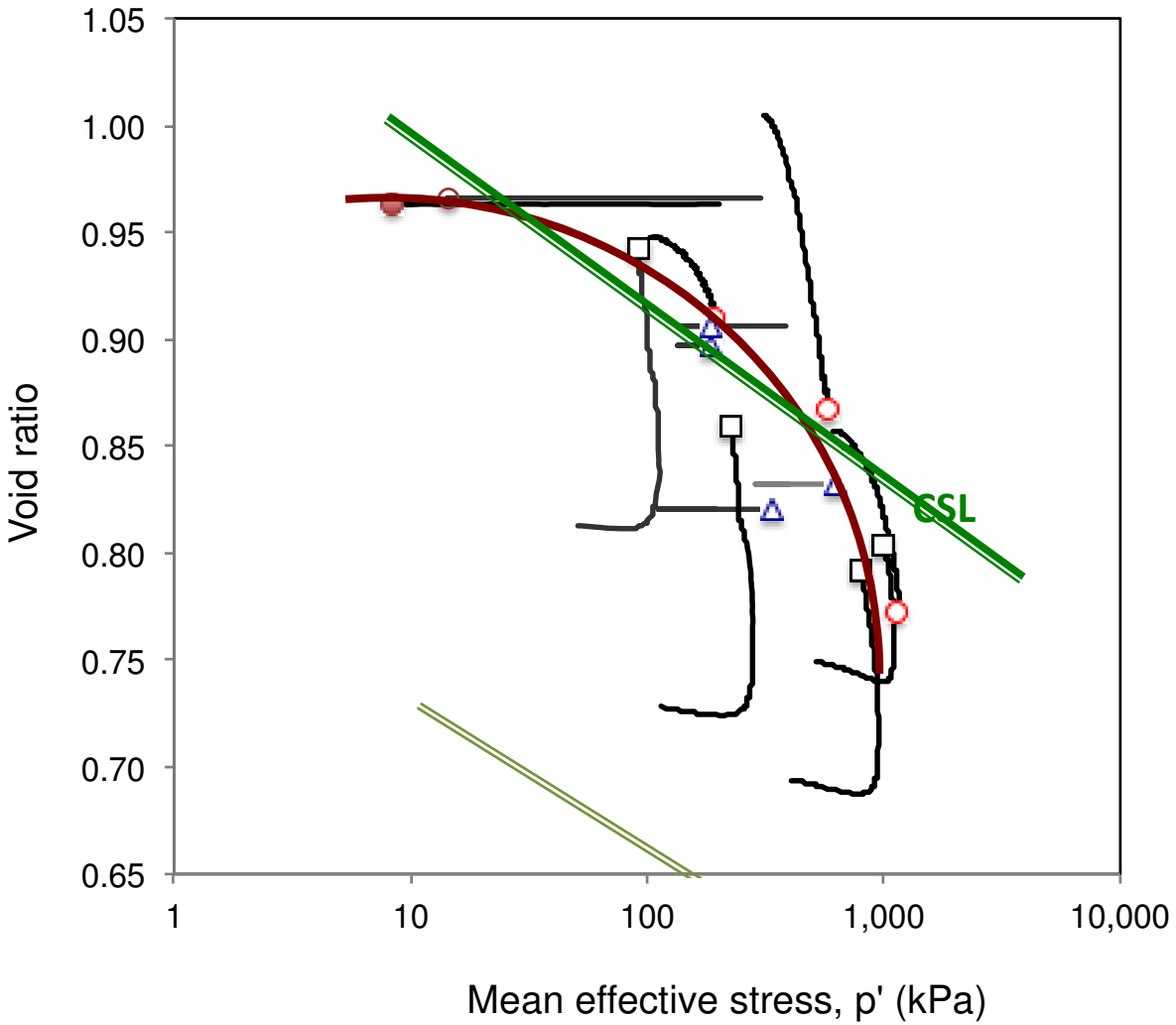
use cell references

Example of data (CIU_L_200kPa)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Test type :			CIU										
2	Lab :			GOLDER(V)										
3	Job number :													
4	Test date :													
5	Material tested :			FRASER RIVER SAND										
6	Preparation method :			MOIST TAMPED										
7	Specific gravity of solids :			2.72										
8														
9	Post consolidation void ratio :			0.963										
10	K0 :			1.00										
11														
12														
13														
14														
15														
16														
17														
18														
19	AXIAL STRAIN	VOL STRAIN	SIGMAA'	SIGMAR'		p	q	e						
20	(%)	(%)	(kPa)	(kPa)		(kPa)	(kPa)	(-)						
21	0.001	0.000	201.844	201.906		201.886	-0.062	0.963						
22	0.024	0.000	202.060	201.550		201.720	0.511	0.963						
23	0.056	0.000	215.006	195.521		202.016	19.485	0.963						
24	0.081	0.000	223.300	188.719		200.246	34.581	0.963						
25	0.108	0.000	228.131	181.523		197.059	46.608	0.963						
26	0.128	0.000	231.127	174.238		193.201	56.889	0.963						
27	0.143	0.000	232.389	166.870		188.709	65.519	0.963						
28	0.167	0.000	232.151	159.525		183.734	72.625	0.963						
29	0.196	0.000	231.578	153.037		179.218	78.541	0.963						
30	0.212	0.000	230.345	146.834		174.671	83.512	0.963						



NorSand Calibration – Γ and λ_{10}



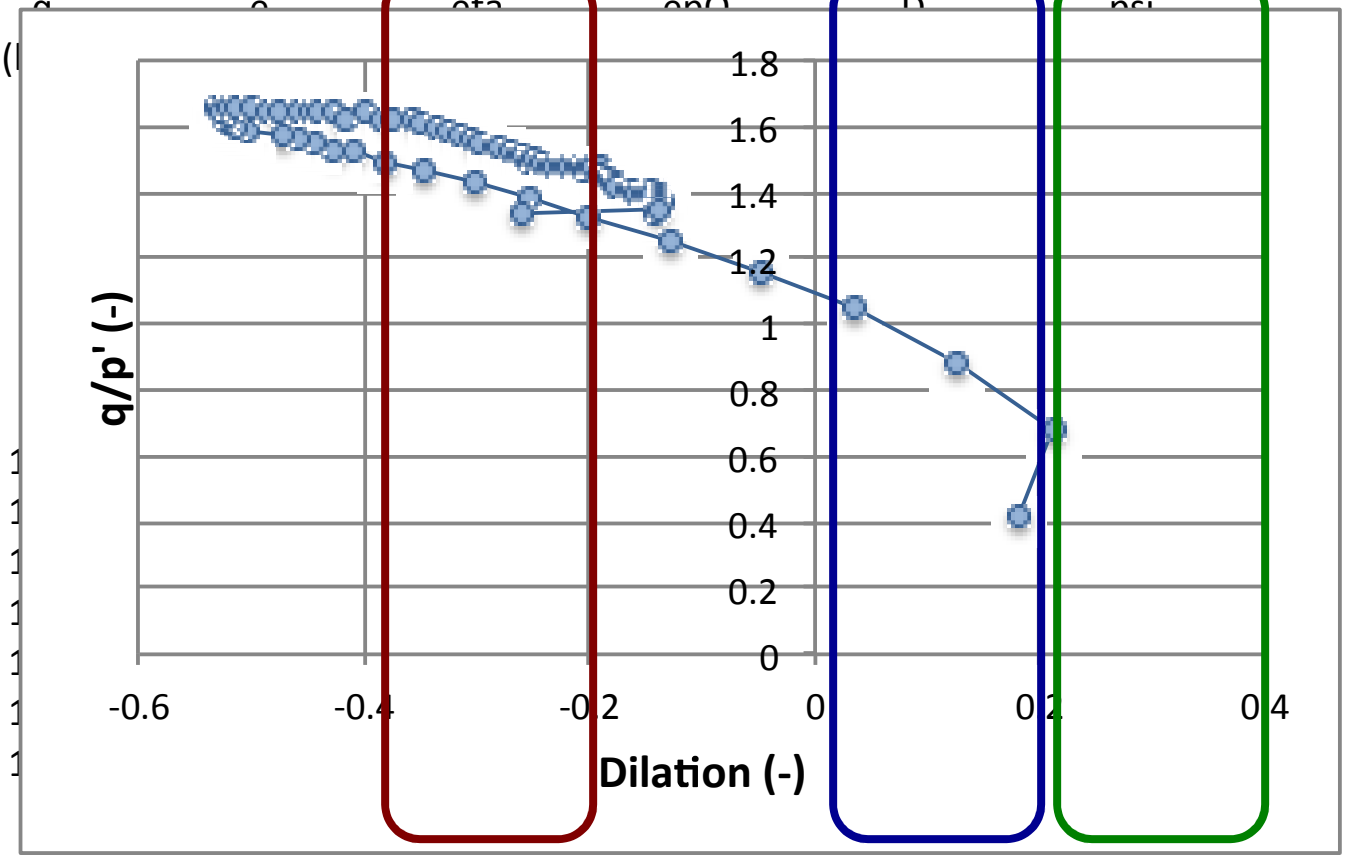
Now you estimate Γ and λ

NorSand Calibration – stress-dilatancy

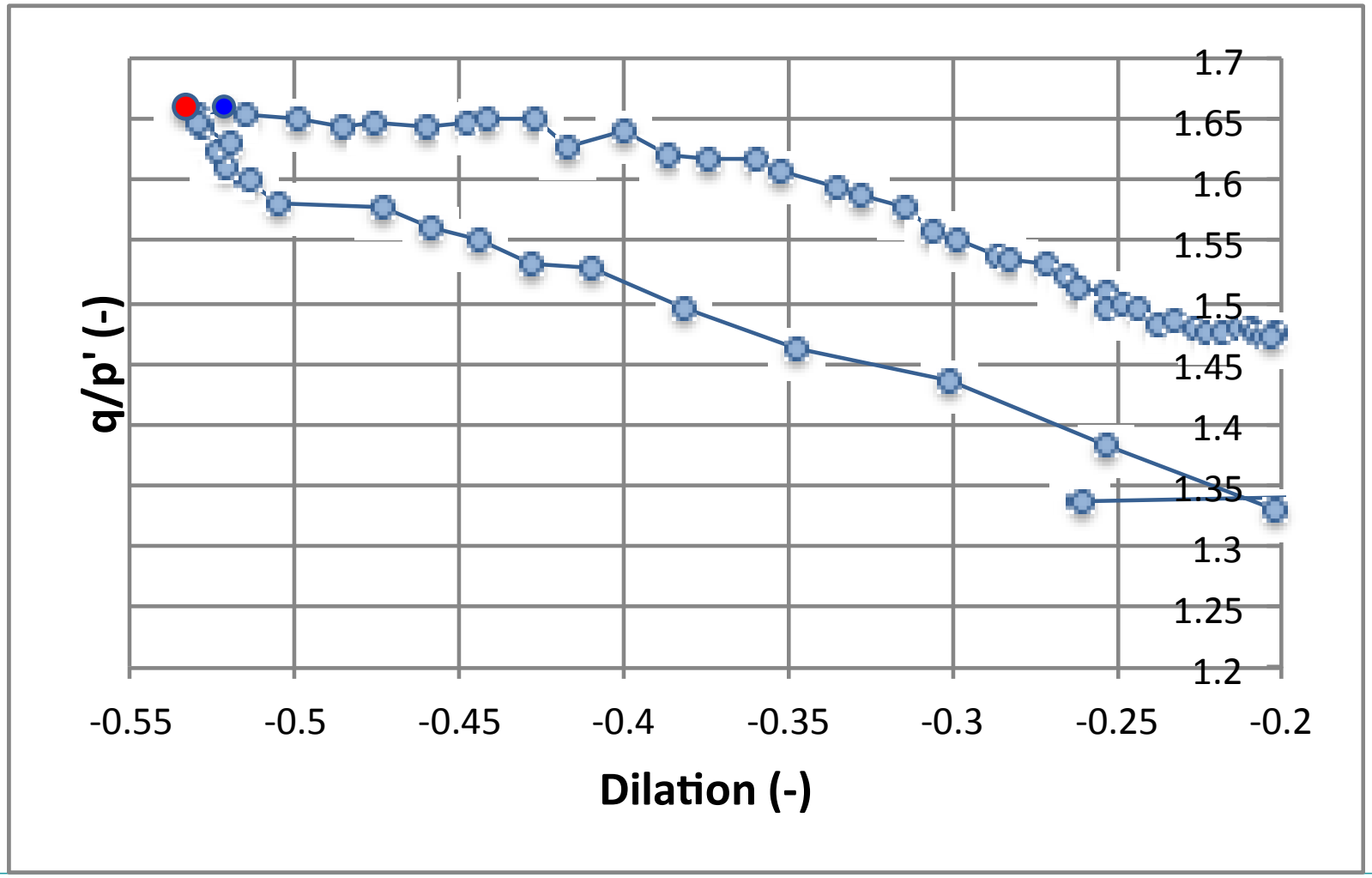
eta_max	1.6614826	Dmin =	-0.5330172	…@ psi=	0.17652153

PROCESSED

p (kPa)	q	e	eta	epQ	D	psi
50.341	1					
51.747	1					
58.270	1					
64.849	1					
70.589	1					
77.245	1					
82.996	1					
86.978	1					
90.241	1					
93.139	1					
95.719	1					
97.880	1					
99.822	1					
101.037	1					



NorSand Calibration – M_{tc}, N_{tc} and χ



NorSand Calibration – M_{tc}, N_{tc} and χ

CID_D_50kPa

eta_max	1.6614826	Dmin =	-0.5330172	…@ psi=	-0.1019257

PROCESSED

p (kPa)	q (kPa)	e (-)	eta (-)	epQ (%)	D (-)	psi (-)
50.341	0.000	0.813	0.000	0.000		-0.172
51.747	7.291	0.813	0.141	0.113		-0.171
58.270	24.401	0.812	0.419	0.200	0.181	-0.164
64.849	44.525	0.812	0.687	0.298	0.211	-0.158
70.589	62.099	0.812	0.880	0.384	0.125	-0.153
77.245	81.166	0.811	1.051	0.477	0.036	-0.148
82.996	96.370	0.811	1.161	0.574	-0.048	-0.144
86.978	109.282	0.812	1.256	0.673	-0.129	-0.141
90.241	119.996	0.812	1.330	0.778	-0.202	-0.138
93.139	128.661	0.812	1.381	0.882	-0.253	-0.136
95.719	137.435	0.813	1.436	0.998	-0.301	-0.134
97.880	143.149	0.814	1.462	1.119	-0.348	-0.132
99.822	149.264	0.814	1.495	1.223	-0.382	-0.130
101.037	154.343	0.815	1.528	1.328	-0.410	-0.128
102.584	156.971	0.816	1.530	1.446	-0.428	-0.126
103.976	161.312	0.817	1.551	1.566	-0.444	-0.125
104.899	163.899	0.818	1.562	1.691	-0.459	-0.123
105.466	166.303	0.819	1.577	1.801	-0.474	-0.122
105.971	167.500	0.820	1.581	1.926	-0.505	-0.120
106.797	170.828	0.821	1.600	2.050	-0.515	-0.119
107.643	172.172	0.822	1.599	2.157	-0.514	-0.117
108.063	174.027	0.823	1.610	2.272	-0.521	-0.116
108.771	176.579	0.826	1.623	2.587	-0.523	-0.113
109.800	179.183	0.829	1.632	2.890	-0.520	-0.109
111.431	183.132	0.832	1.643	3.183	-0.528	-0.105
112.587	186.958	0.835	1.661	3.493	-0.533	-0.102
113.247	187.150	0.838	1.653	3.793	-0.530	-0.099
111.999	184.466	0.841	1.647	4.101	-0.530	-0.096
111.798	185.750	0.844	1.661	4.400	-0.521	-0.094
111.549	184.503	0.847	1.654	4.710	-0.515	-0.091

psi must be chosen by hand

NorSand Calibration – M_{tc}, N_{tc} and χ

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Test	p0	e0	psi0	Dmin	eta_max	psi	p	e
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From top line of "data review"

	As tested initial			At critical state (if reached		At end of test (not at CS)	
	p0	e0	psi0	p_c	e_c	p	e
CIU_L_200kPa	201.9	0.963	0.322				
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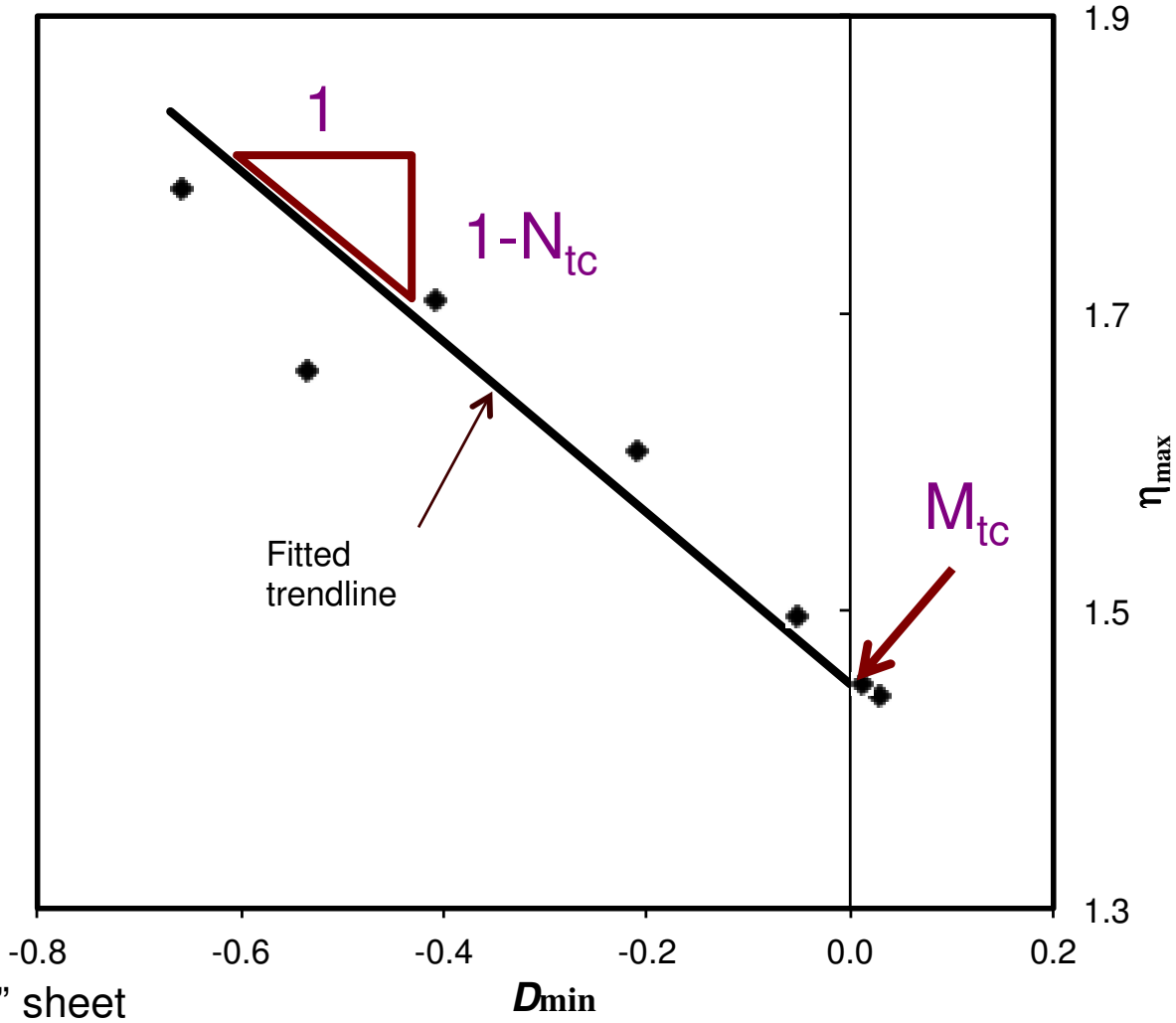
NorSand Calibration – M_{tc} and N_{tc}



"Data Summary" sheet

NorSand Calibration – "Data Summary" sheet

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2		**Index Properties**			**Soil Properties**									
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5		emin =	0.827		Mtc =	1.2								
6		SG =	2.72		Ntc =	0.3								
7					chi_tc =	3.5								
8					H_0 =	200								
9					H_y =	0								
10														
11		As tested initial			At max dilation (= D_{min})			At end of test						
12	Test	p0	e0	psi0	Dmin	eta_max	psi	p	e					
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22		p0	e0	psi0	p_c	e_c	p	e						
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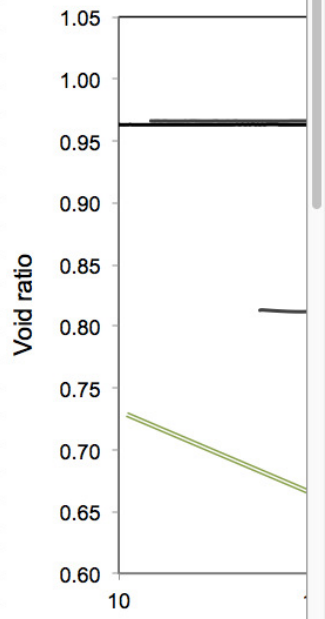
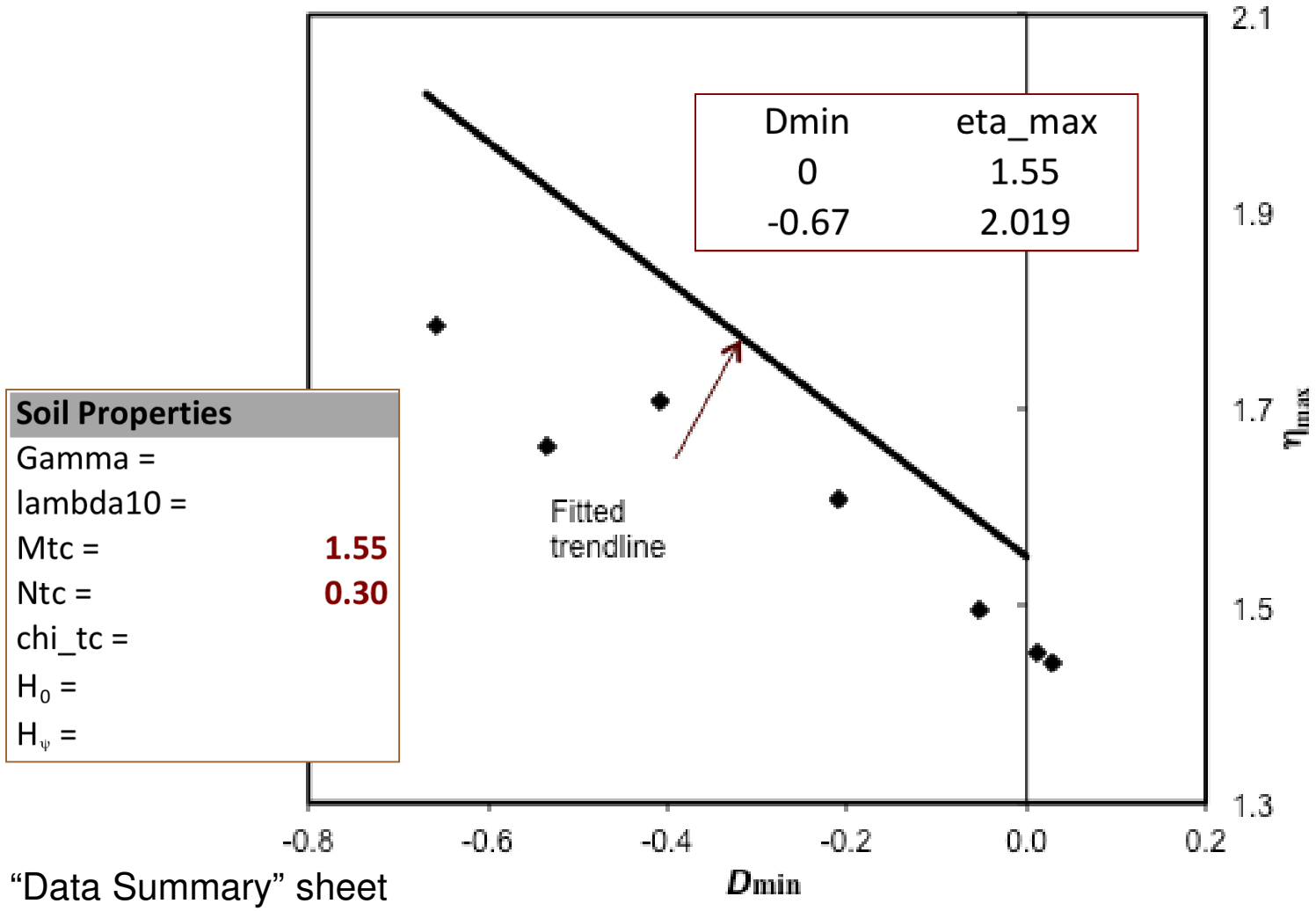
30														



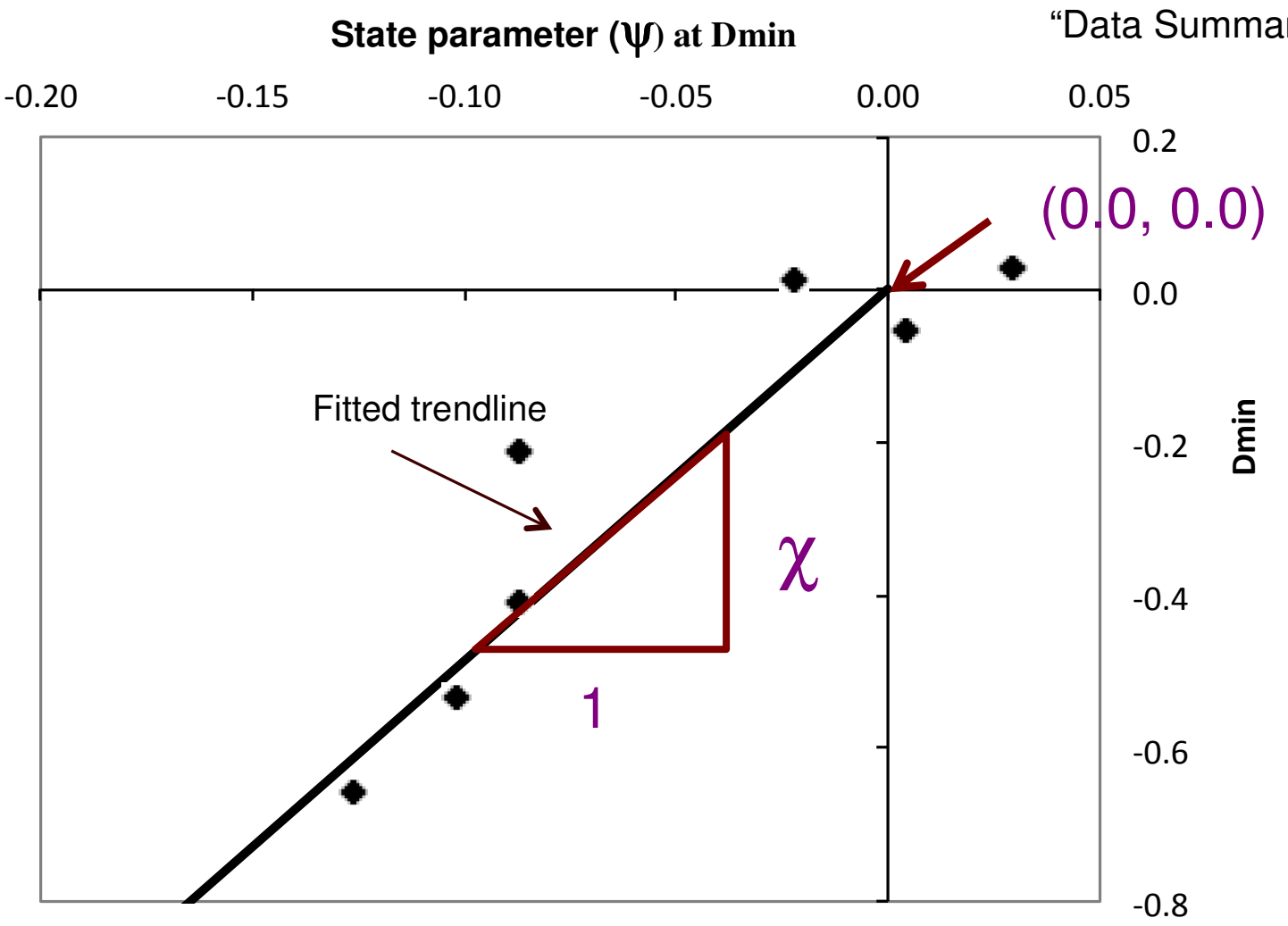
NorSand Calibration – M_{tc} and N_{tc}



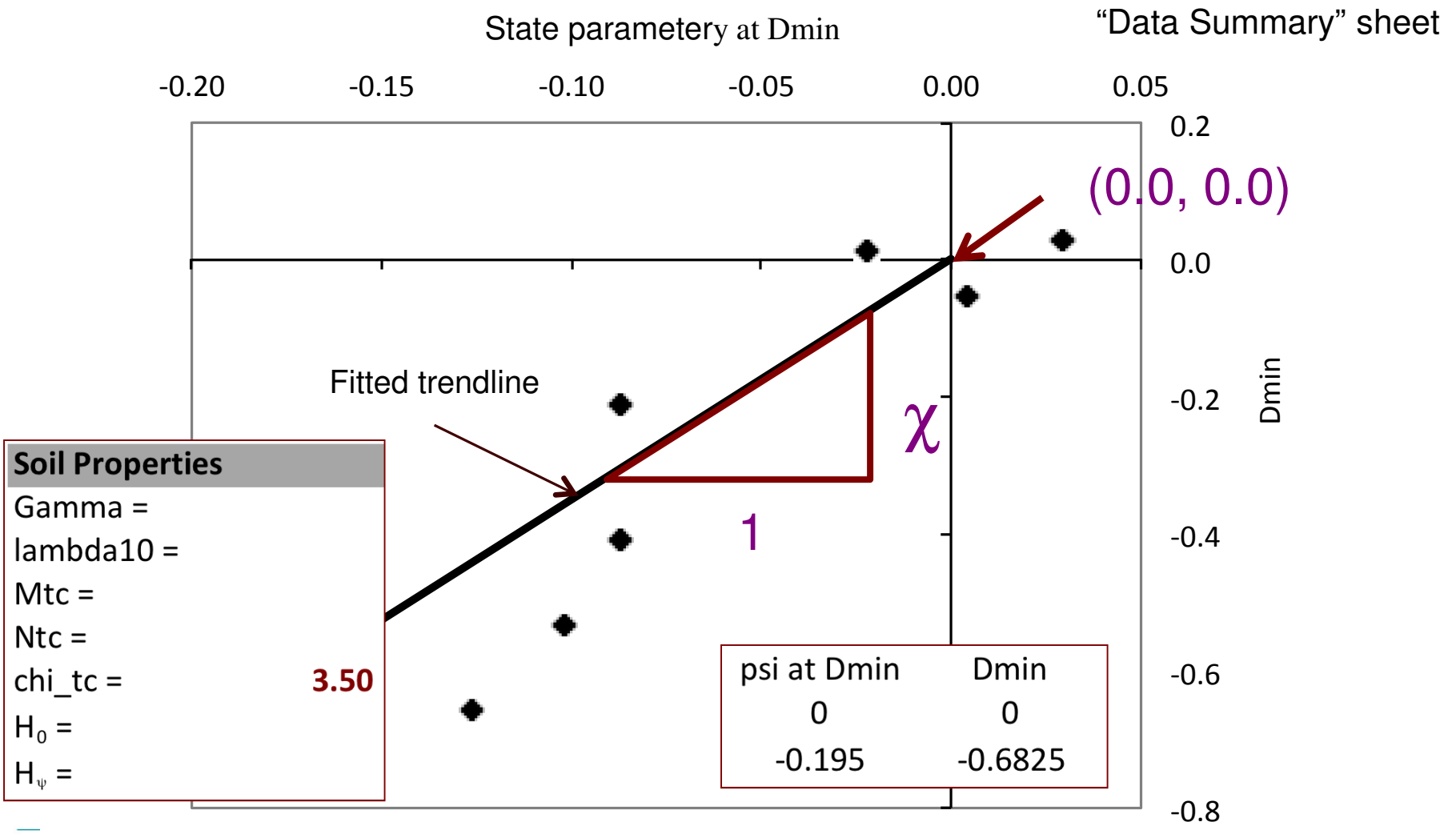
Soil Properties	
Gamma =	
lambda10 =	
Mtc =	**1.55**
Ntc =	**0.30**
chi_tc =	
H_0 =	
H_ψ =	

"Data Summary" sheet

NorSand Calibration – χ



NorSand Calibration – χ



Now you estimate M, N and χ

NorSand Calibration – finally to H……

for first pass set $H_\psi = 0$

Soil properties….

CSL parameters

Γ =	0.8	---
λ =	0.030	*on base e*
λ_{10} =	*0.069*	

Plasticity

M_{tc} =	1.2	
N =	0.3	*(typ 0.2 - 0.3)*
χ_{tc} =	3.5	*often taken as 4*
H_0 =	200	*> H_c = 30*
H_ψ =	0	
(H = H_0 - H_ψ.ψ…)	*200*	*(typ 60 - 400)*

Elasticity

G_{max} @ p_0 =	50	MPa	50.0
G_exp =	0.72	*elastic exponent*	
ν =	0.2		
(Ir …)	*500*	---	
κ=	*0.00249*	---	

Initial soil state…

ψ_0 =	0	
=> e_0 =	*0.662*	
p_0 =	100	*kPa*
K_0 =	1	---
(sig1…)	*100*	
OCR ("R") =	1	---

NorSand Calibration – finally to H……

Soil properties….

CSL parameters

Γ =	0.8	---
λ =	0.030	*on base e*
λ_{10} =	*0.069*	

Plasticity

M_{tc} =	1.2	
N =	0.3	*(typ 0.2 - 0.3)*
χ_{tc} =	3.5	*often taken as 4*
H_0 =	200	*> H_c = 30*
H_ψ =	0	
($H = H_0 - H_\psi . \psi ...$)	*200*	*(typ 60 - 400)*

Elasticity

G_{max} @ p_0 =	50	MPa	50.0
G_exp =	0.72	*elastic exponent*	
ν =	0.2		
(Ir …)	*500*	---	
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Initial soil state…

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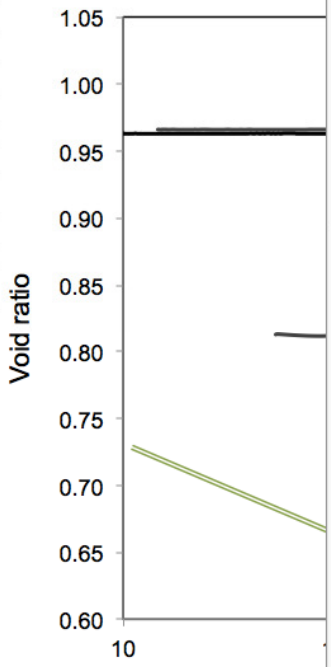
=> e_0 =	*0.662*	
p_0 =	100	*kPa*
K_0 =	1	---
(sig1…)	*100*	
OCR ("R") =	1	---

NorSand Calibration – finally to H……

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Fraser River Sand index properties reported in Ghafghazi (2011)													
2		**Index Properties**			**Soil Properties**									
3		D50	0.271	microns	Gamma =	0.8								
4		fines =	0.8	%	lambda10 =	0.069								
5		emin =	0.827		Mtc =	1.2								
6		SG =	2.72		Ntc =	0.3								
7					chi_tc =	3.5								
8					H_0 =	200								
9					H_y =	0								
10														
11		As tested initial			At max dilation (= D_{min})			At end of test						
12	Test	p0	e0	psi0	Dmin	eta_max	psi	p	e					
13	CID_D_50kPa	50.3410866	0.81289597	0.13032863										
14	CID_D_115kPa	113.886756	0.72789879	0.06979544										
15	CID_D_410kPa	409.63169	0.69385172	0.07410688										
16	CID_D_515kPa	514.508955	0.74915547	0.13624158										
17	CID_L_100kPa	102.070875	0.94782889	0.28644312										
18	CID_L_300kPa	302.902237	1.00535849	0.37656836										
19	CID_L_600kPa	603.254945	0.85680685	0.24866141										
20														
21		As tested initial			At critical state (if reached			At end of test (not at CS)						
22		p0	e0	psi0	p_c	e_c	p	e						
23	CIU_L_200kPa	201.885733	0.963	0.32205229										
24	CIU_M_200kPa	200.210032	0.897	0.25580252										
25	CIU_D_200kPa	196.409314	0.82000003	0.17822822										
26	CIU_L_300kPa	300.992171	0.966	0.33702031										
27	CIU_L_390kPa	388.40034	0.9062	0.28486029										
28	CIU_M_400kPa	393.317095	0.83197792	0.21101517										
29														
30														



NorSand Calibration – finally to H……

Soil properties….

CSL parameters

Γ =	0.8	---
λ =	0.030	*on base e*
λ_{10} =	*0.069*	

Plasticity

M_{tc} =	1.2	
N =	0.3	*(typ 0.2 - 0.3)*
χ_{tc} =	3.5	*often taken as 4*
H_0 =	200	*> H_c = 30*
H_ψ =	0	
($H = H_0 - H_\psi . \psi$...)	*200*	*(typ 60 - 400)*

Elasticity

G_{max} @ p_0 =	50	MPa	50.0
G_exp =	0.72	*elastic exponent*	
ν =	0.2		
(Ir …)	*500*	---	
κ=	*0.00249*	---	

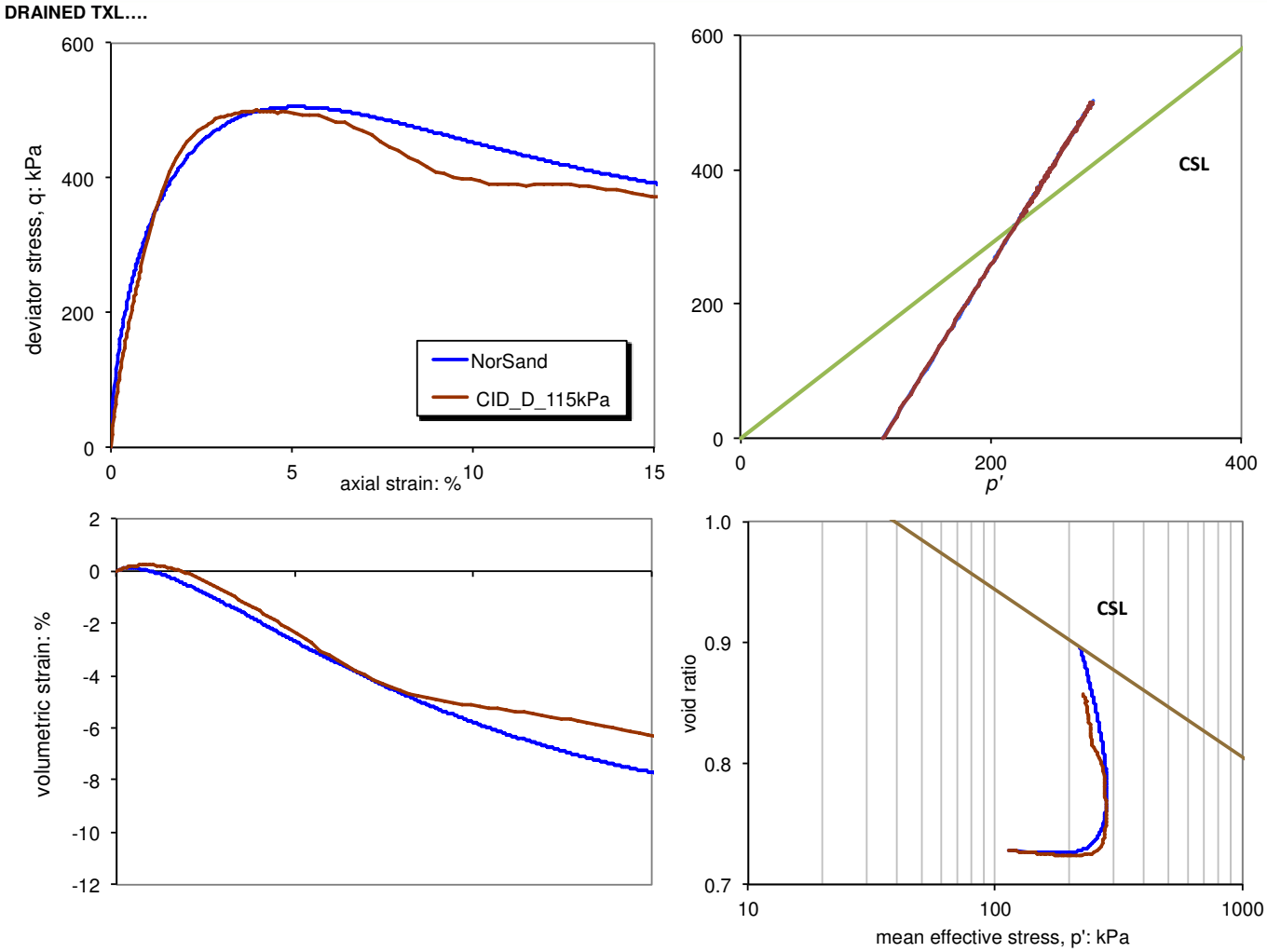
Initial soil state…

ψ_0 =	0	
=> e_0 =	*0.662*	
p_0 =	100	*kPa*
K_0 =	1	---
(sig1…)	*100*	
OCR ("R") =	1	

small changes to ψ_0 allowed

$K_0 = 1$ apart from CIU. M 200 may increase for CIU if needed

NorSand Calibration – H



NorSand Calibration – finally to H……

Soil properties….

CSL parameters

Γ =	0.8	---	
λ =	0.030	*on base e*	
λ_{10} =	*0.069*		

Plasticity

M_{tc} =	1.2		
N =	0.3	*(typ 0.2 - 0.3)*	
χ_{tc} =	3.5	*often taken as 4*	
H_0 =	200	*> H =*	*30*
H_ψ =	0		
(H = H_0 - H_ψ.ψ...)	*200*	*(typ 60 - 400)*	

Elasticity

G_{max} @ p_0 =	50	MPa	50.0
G_exp =	0.72	*elastic exponent*	
ν =	0.2		
(Ir …)	*500*	---	
κ=	*0.00249*	---	

Initial soil state…

ψ_0 =	0		
=> e_0 =	*0.662*		
p_0 =	100	*kPa*	
K_0 =	1	---	
(sig1…)	*100*		
OCR ("R") =	1	---	

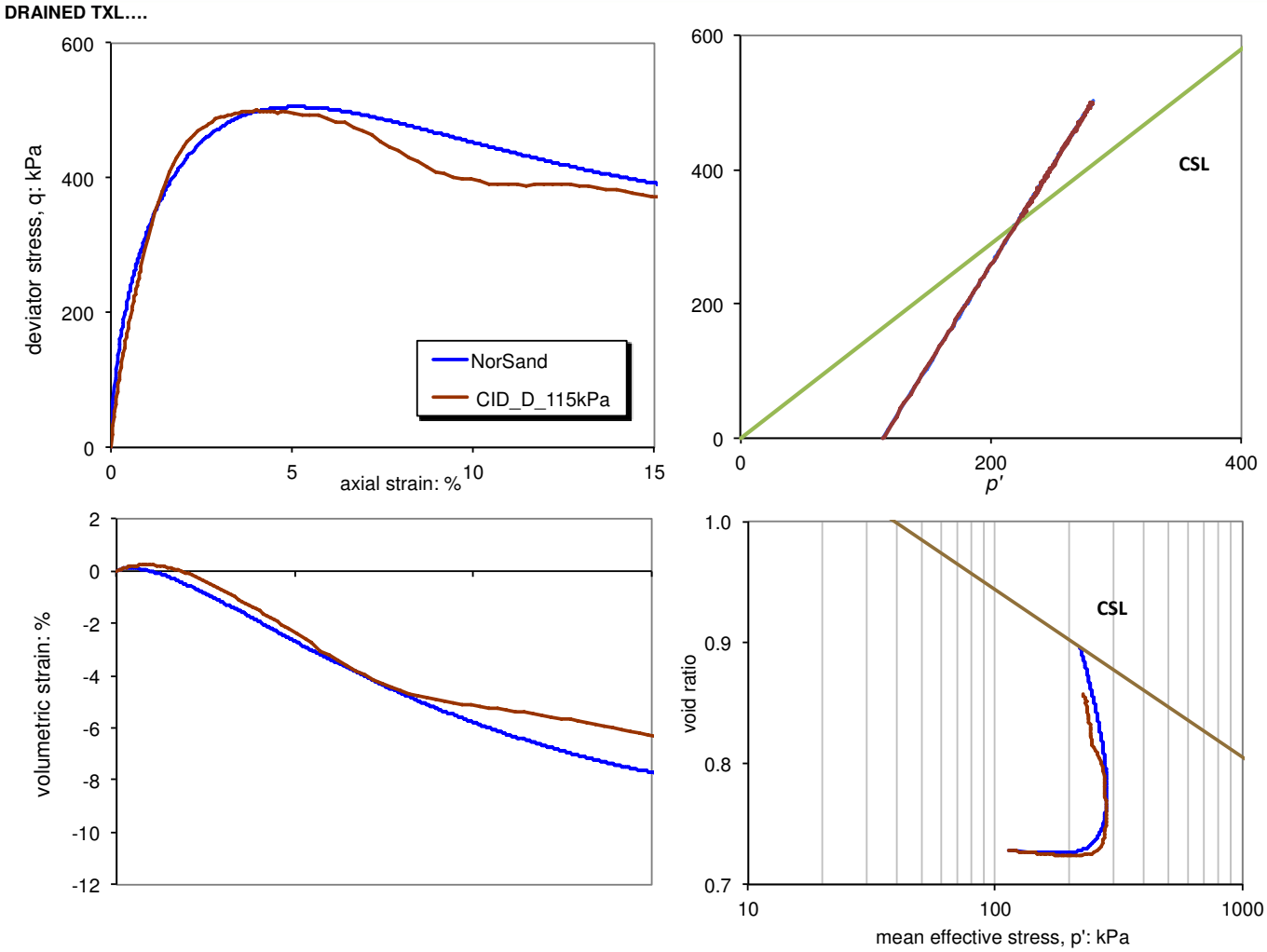
NorSand Calibration – H

Parameter sets used in sims

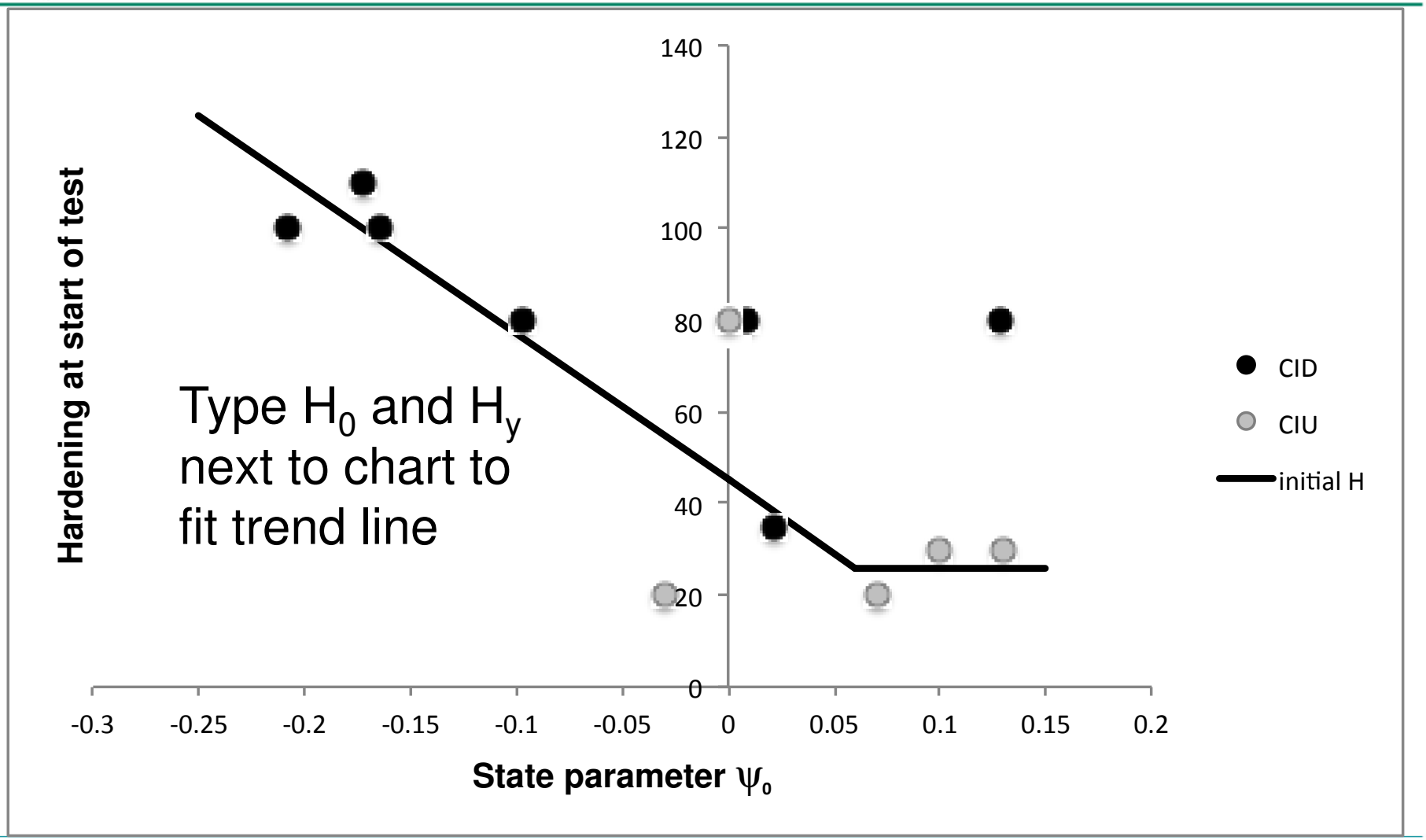
	DRAINED							UNDRAINED					
Data set:	1	2	3	4	5	6	7	8	9	10	11	12	13
	CID_D_50	**CID_D_115**	**CID_D_410**	**CID_D_515**	**CID_L_100**	**CID_L_300**	**CID_L_600**	**CIU_L_200**	**CIU_M_200**	**CIU_D_200**	**CIU_L_300**	**CIU_L_390**	**CIU_M_400**
M_{tc} =													
N =													
χ_{tc} =													
H_0 =													
H_ψ =													
($H = H_0 - H_\psi . \psi$...)													
G_{max} @ p_0=													
G_exp =													
ν =													
(Ir …)													
κ=													
ψ_0 =													
=> e_0 =													
p_0 =													
K_0 =													
(sigV…)													
OCR ("R") =													

On “data summary” sheet

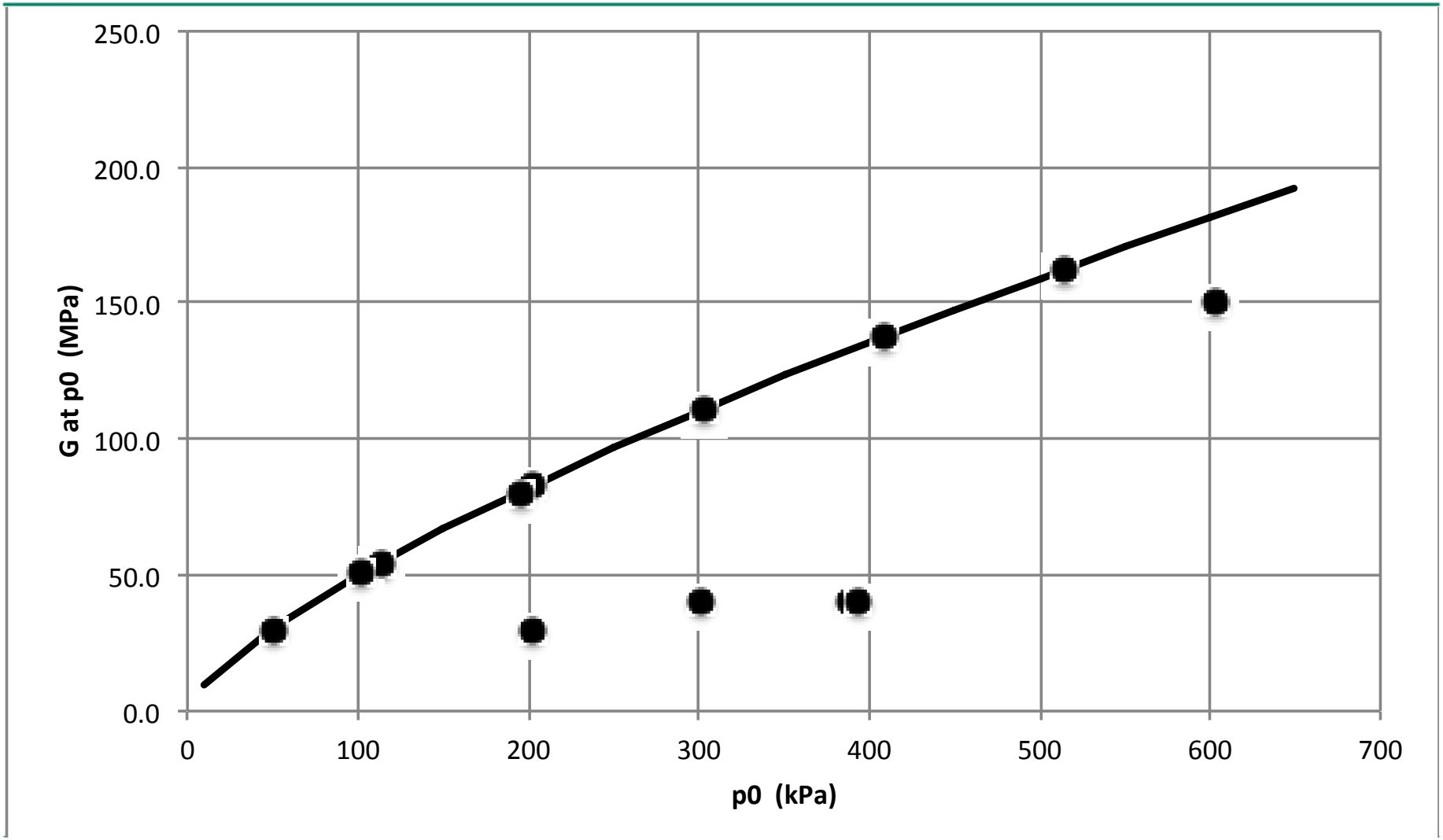
NorSand Calibration – H



NorSand Calibration – H



NorSand Calibration – check on elasticity



NorSand Calibration – final pass

- If time – run through calibration using trend line for Hardening….
- Tweak if necessary……

- CALIBRATION COMPLETE !

NorSand Calibration – Γ and λ_{10}