Jordparametere ved jordskjelvdimensjonering

Sammenstilt av Jörgen Johansson,

Bidrag fra mange: Steven Kramer, Brian Carlton, Jean-Sebastian L'Heureux, mfl. og litteratur

Innhold

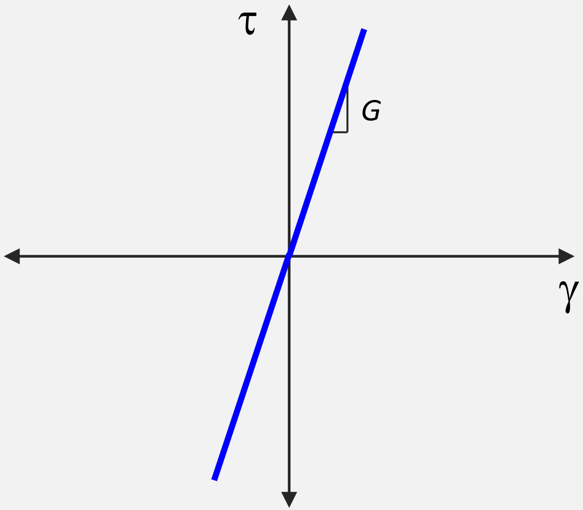
- Grunnleggende materialoppførsel for jordskjelvanalyser
- Labforsøksapparater
- Feltmålinger av Vs og korrelasjon mot CPT
- Eksempel på empiriske ligninger for ikkelinær oppførsel
- Eksempel på empiriske korrelasjoner og egenskaper for forskjellig material, leire, kvikkleire, sand/silt, kalksement, grovere material og knust berg

Parameter for jordskjelvanalyser og vurderinger

- Skjærmodul, Gmax/G0 eller skjærbølgehastighet, vs
- Stivhet og Demping variasjon med skjærtøyning
- Syklisk styrke (ikke så mye)
- Tverrkontraksjonstall

Soil stress strain behaviour (simplified!)

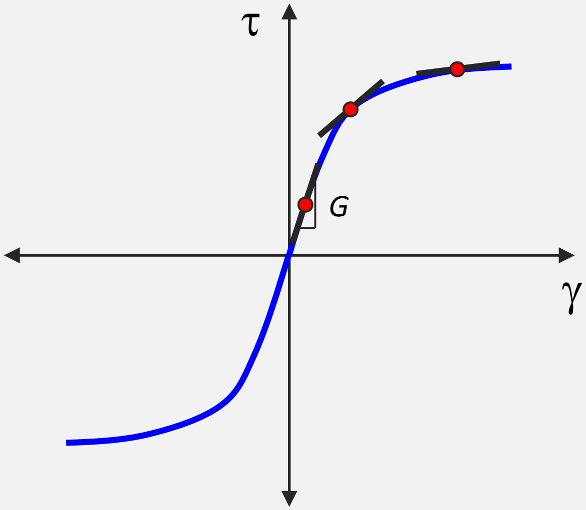
Shear strain is not proportional to shear stress



Linear, elastic behavior

Constant stiffness

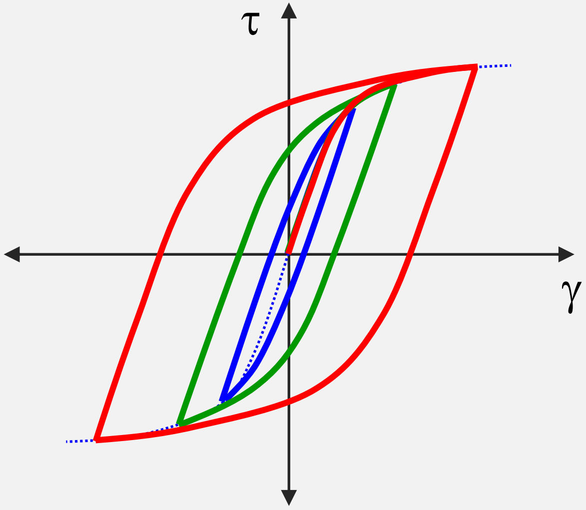
Infinite strength



Nonlinear, elastic behavior

Variable stiffness

Unloads along loading path



Nonlinear, plastic behavior

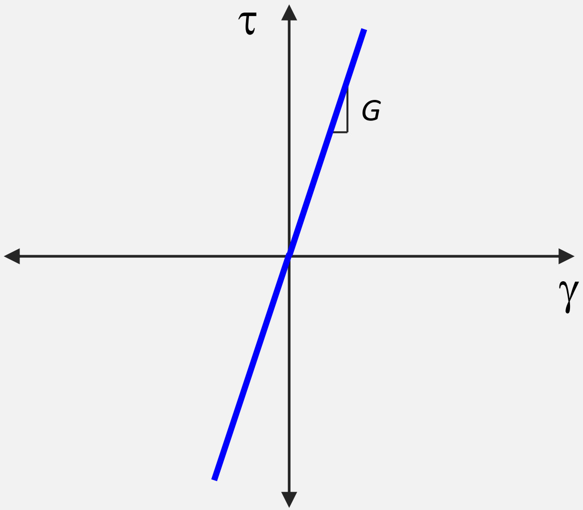
Variable stiffness

Unloads inelastically - damping

Fra Kramer 2011

Large Strain Behaviour

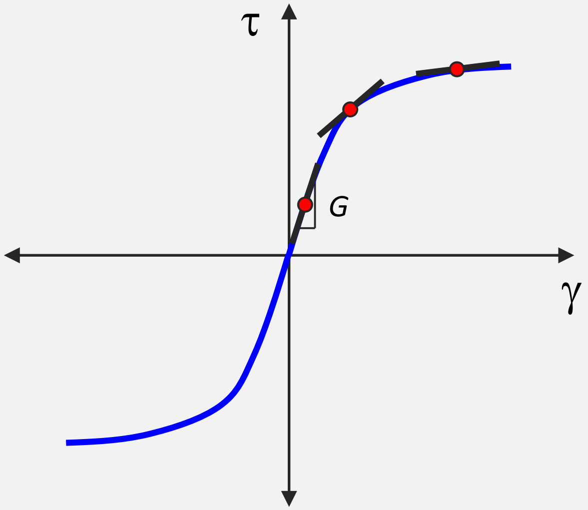
Shear strain is not proportional to shear stress



<u>Linear, elastic behavior</u>

Constant stiffness

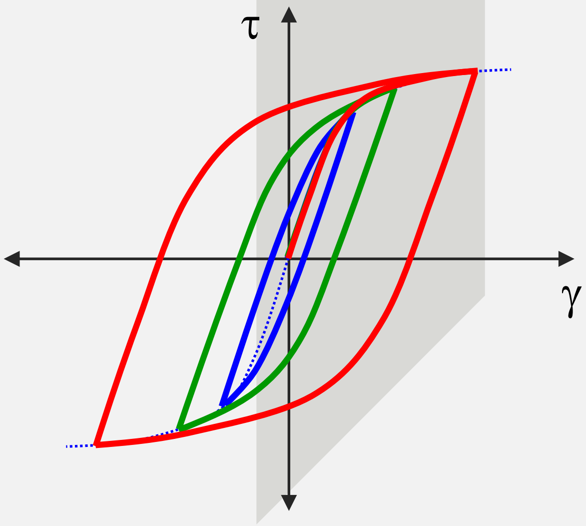
Infinite strength



<u>Nonlinear, elastic behavior</u>

Variable stiffness

Unloads along loading path



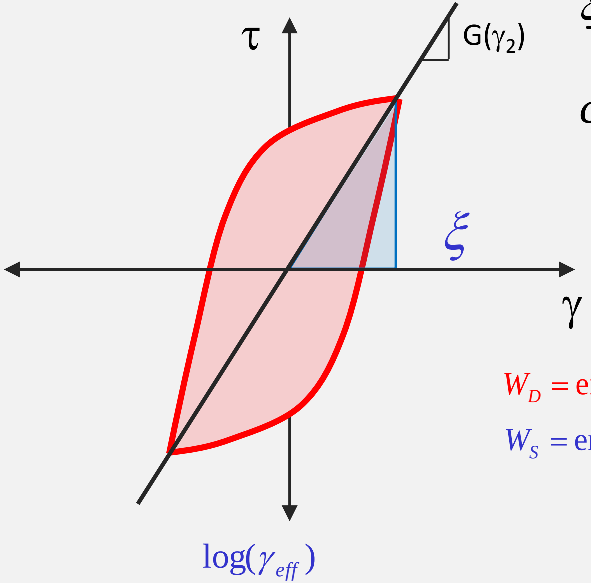
<u>Nonlinear, plastic behavior</u>

Variable stiffness

Unloads inelastically - damping

Kramer 2011

Large Strain Behaviour

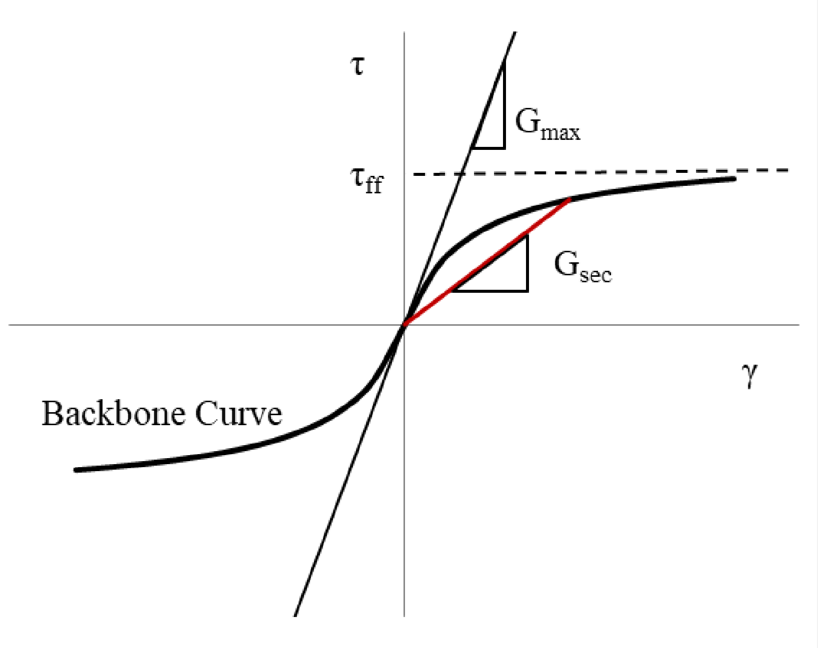


$$\xi = \frac{c\omega_0}{2G} = \frac{W_D}{4\pi W_S}$$

c = viscous damping

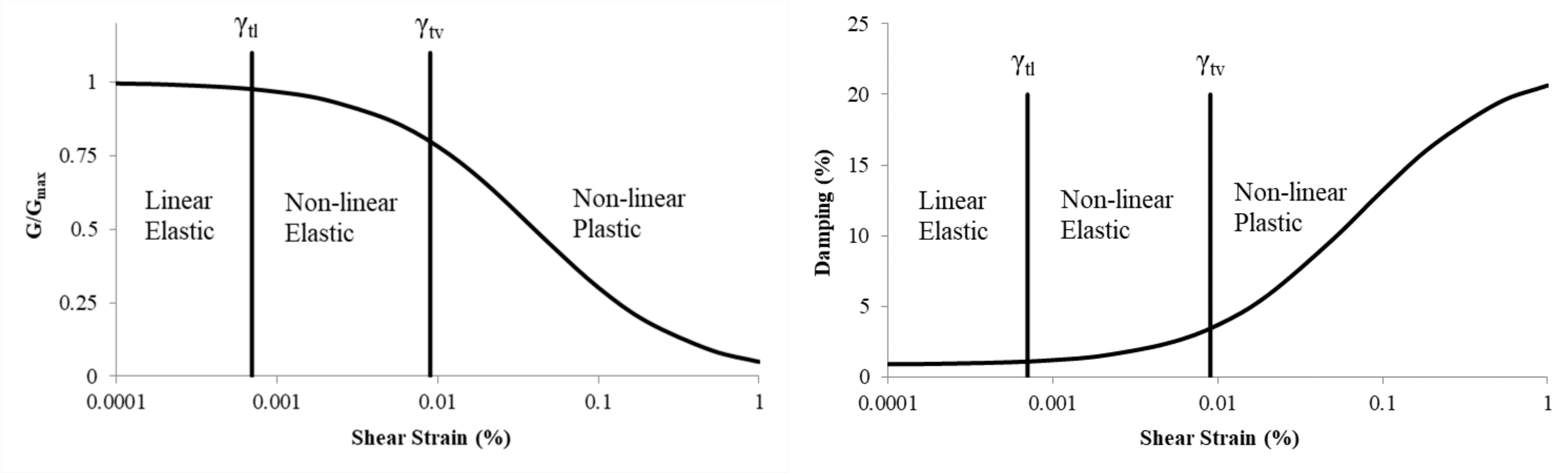
W_D = energy dissipated in one cycle

W_S = energy stored in one cycle



Equivalent Linear Models

- The actual nonlinear hysteretic stress-strain behaviour of cyclically loaded soils can be approximated by equivalent linear properties called shear modulus reduction and damping curves



An **improved method** for determining material soil damping from DSS and Triaxial laboratory tests

General nature of loading – combined cyclic and offset load (e.g. average + variable wind load)

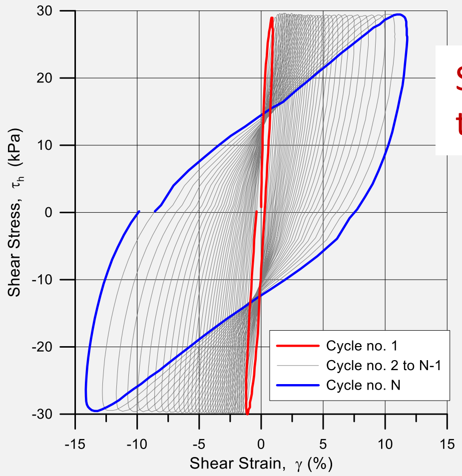
Most previous damping values are derived from symmetric cyclic strain-controlled tests

Offset load component influencing the damping must be corrected for when the offset is large

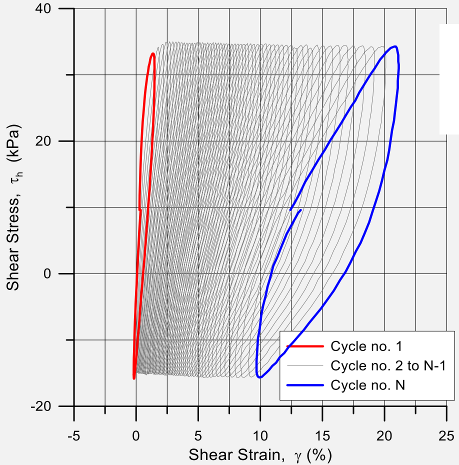
The **improved method** closes the cycles where strain accumulation is present

→ Revised damping characteristics

→ Incorporated in the NGI in-house DLP program



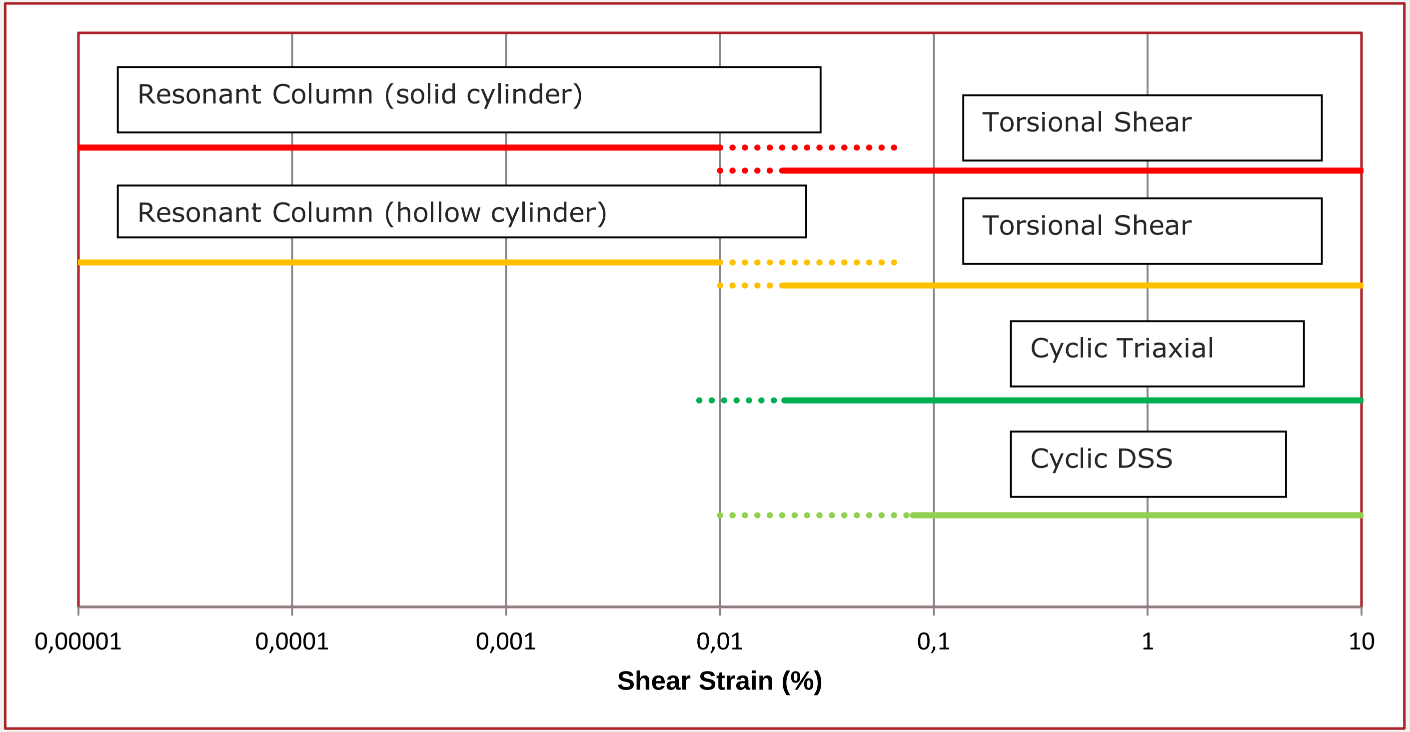
Symmetric test



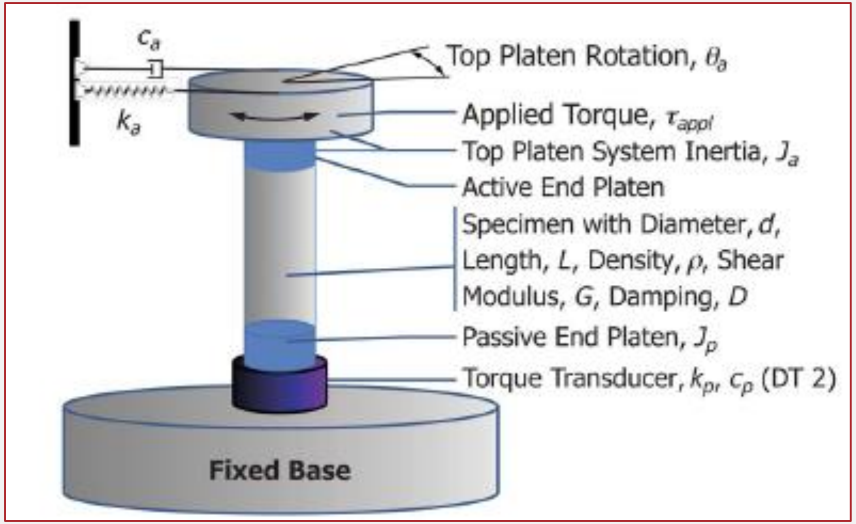
Cyclic test with offset

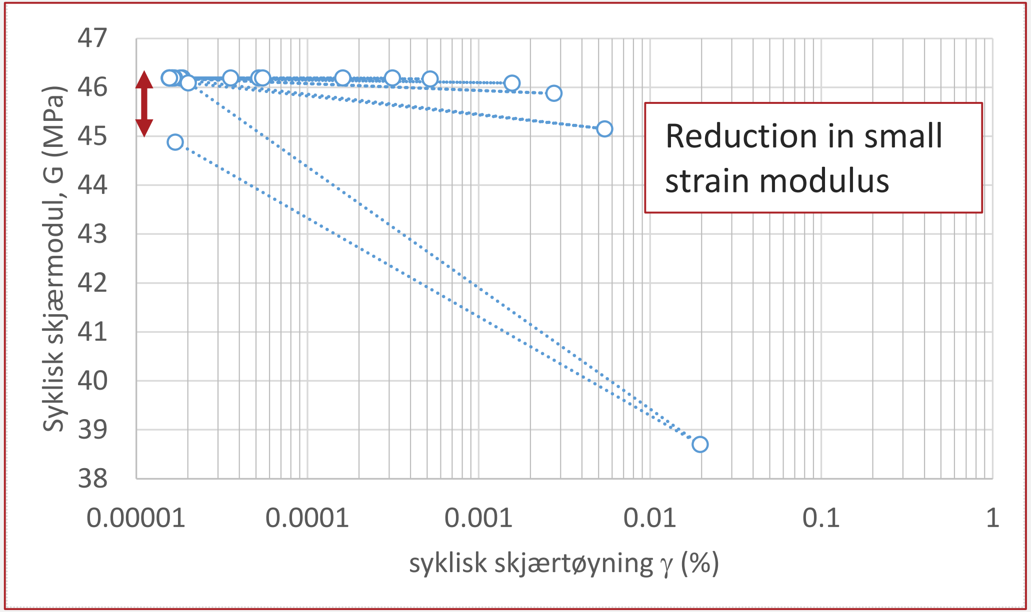
Labforsøk - apparater

Lab test for different strain levels



Resonant Column test
Evaluating (small) pore pressures from

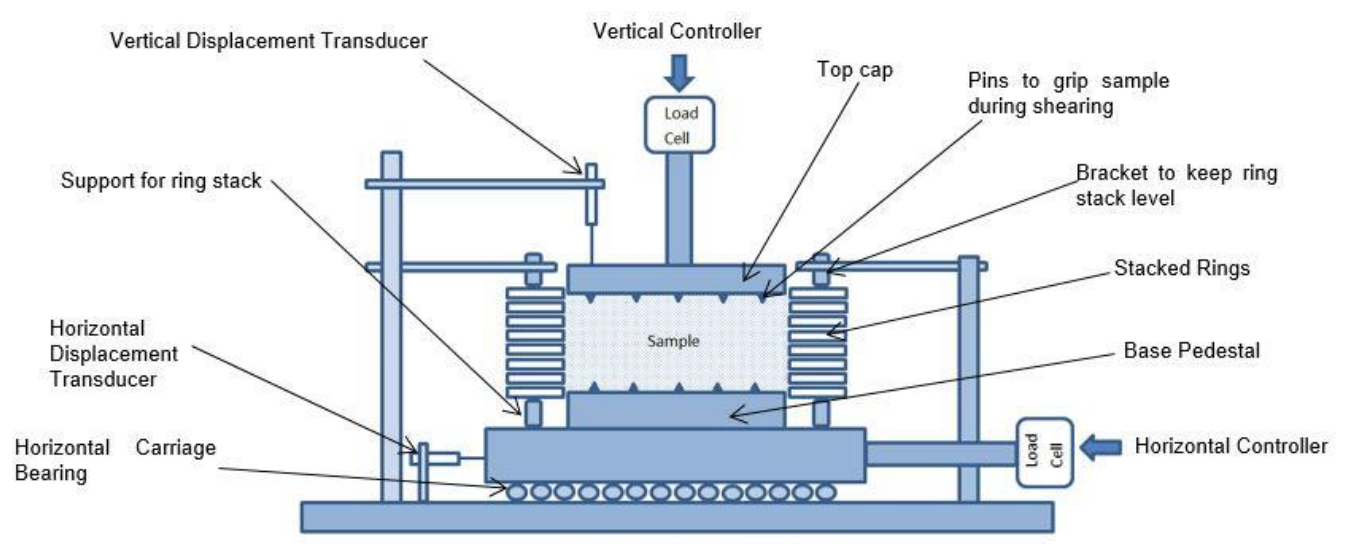




Reduction in small strain modulus

Measurement of Large Strain G and D: Direct Simple Shear

- Can reproduce earthquake stress conditions more accurately than triaxial test (similar to vertically propagating horizontal shear wave)
- Typical strain range 0.1 % to 20 %
- Can use stacked metal rings or wire reinforced membrane



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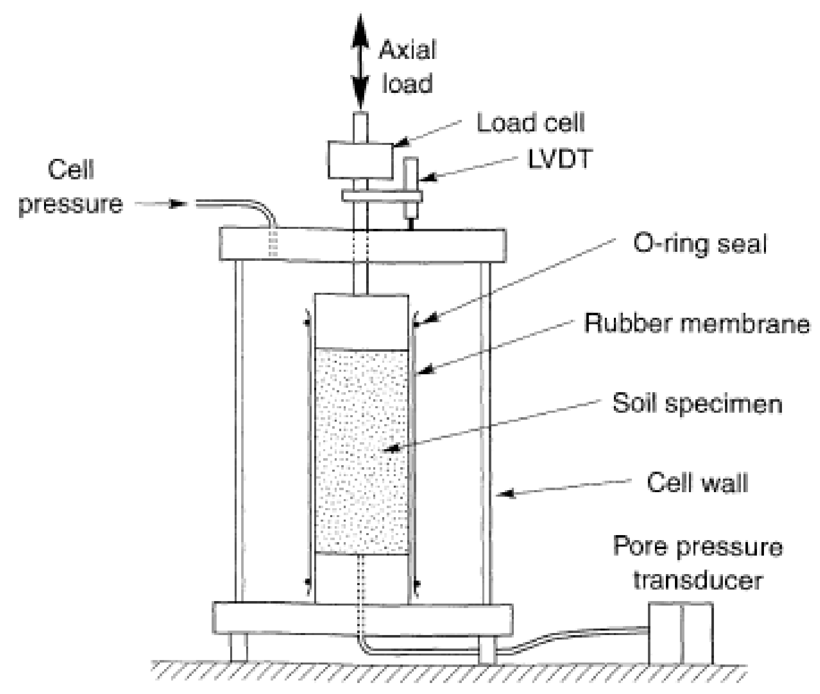
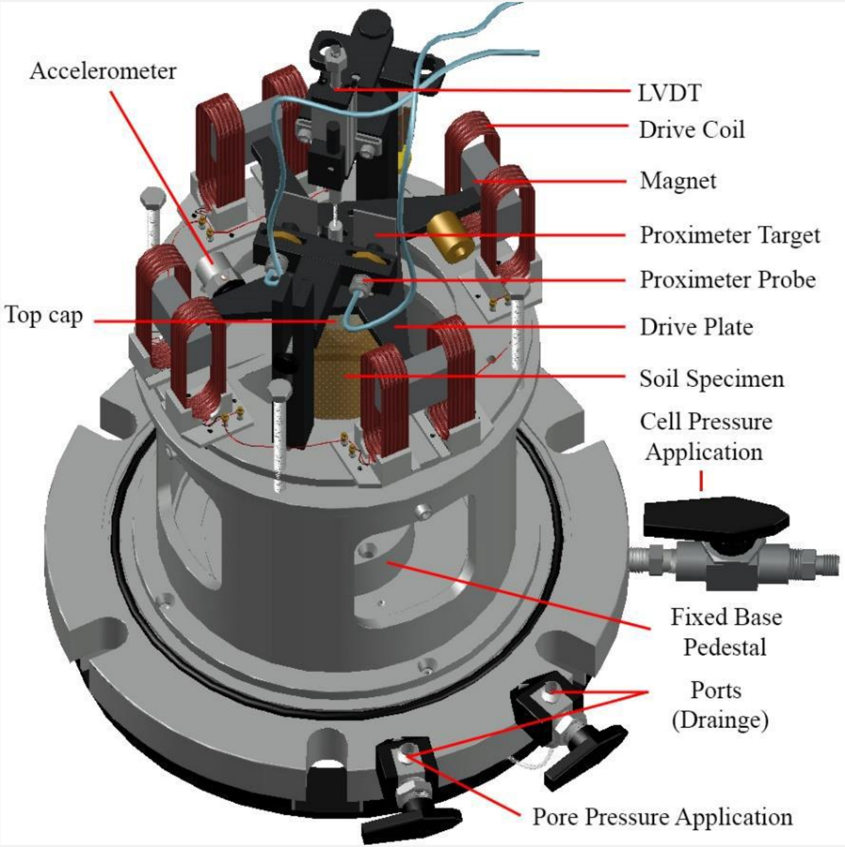
Measurement of Large Strain G and D: Triaxial

- Can be isotropic (level ground) or anisotropic (sloping ground)
- Cycle vertically (compression and extension)
- Strain range of 10^{-2} % to 10 %
- Typically conducted at 1 hz
- Can lead to stress reversals depending on if the deviator stress is larger than the confining stress



Measurement of Large Strain G and D: RCTS

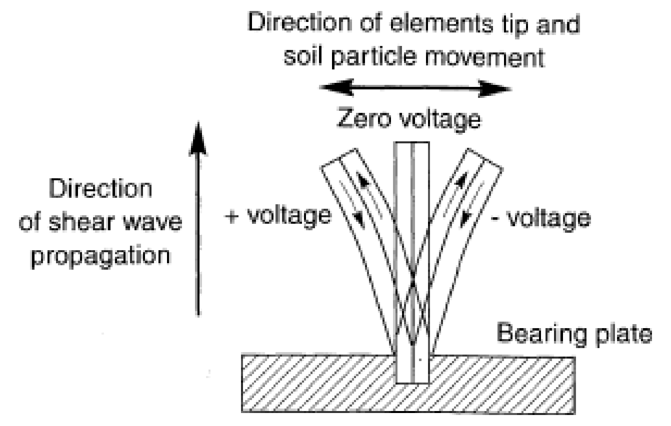
- Resonant Column Torsional Shear test
- Torques soil back and forth
- Resonant Column
  - Performs test at 100 Hz
  - uses accelerometers to measure strain
  - G calculated from resonant frequency
  - Strain range 10^{-5} % to 10^{-2} %
- Torsional Shear
  - Performs test at 1 Hz
  - uses displacement transducers
  - G measured directly
  - Strain range 10^{-2} % to 10 %
  - Hollow soil specimen often used to get uniform measurement of G

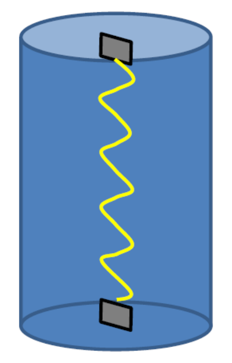


Fra Richard Coffman

Measurement of Vs: Bender Element Test

- Bender elements embedded in top and bottom of sample
- Pulse induced at source element
- Pulse recorded at receiver element
- Velocity calculated from travel time and known height of specimen
- Can be performed during other tests

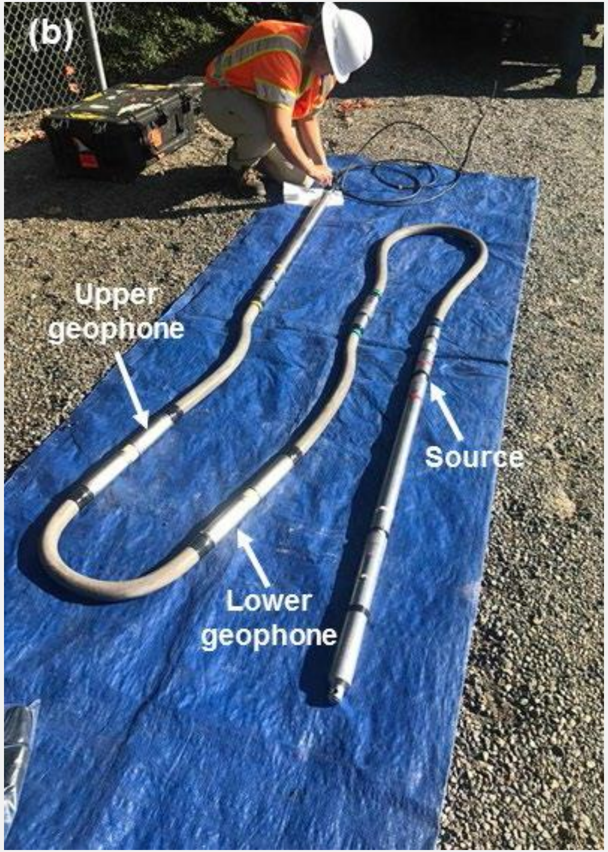




Feltmålinger

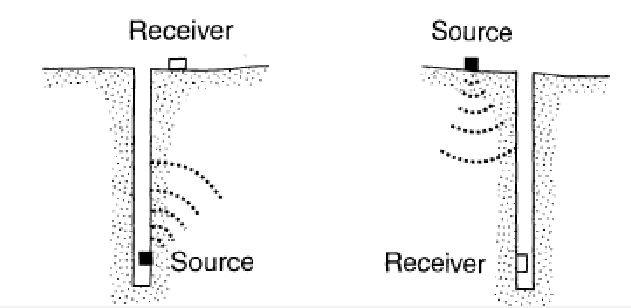
Measurement of Vs

- Direct field measurements
  - Seismic downhole, uphole
  - Seismic CPT
  - Seismic cross-hole
  - Suspension logger
  - SASW
  - MASW
- Laboratory measurements
  - Resonant column
  - Bender elements
- Indirect measurements
  - Correlation to CPT
  - Empirical models

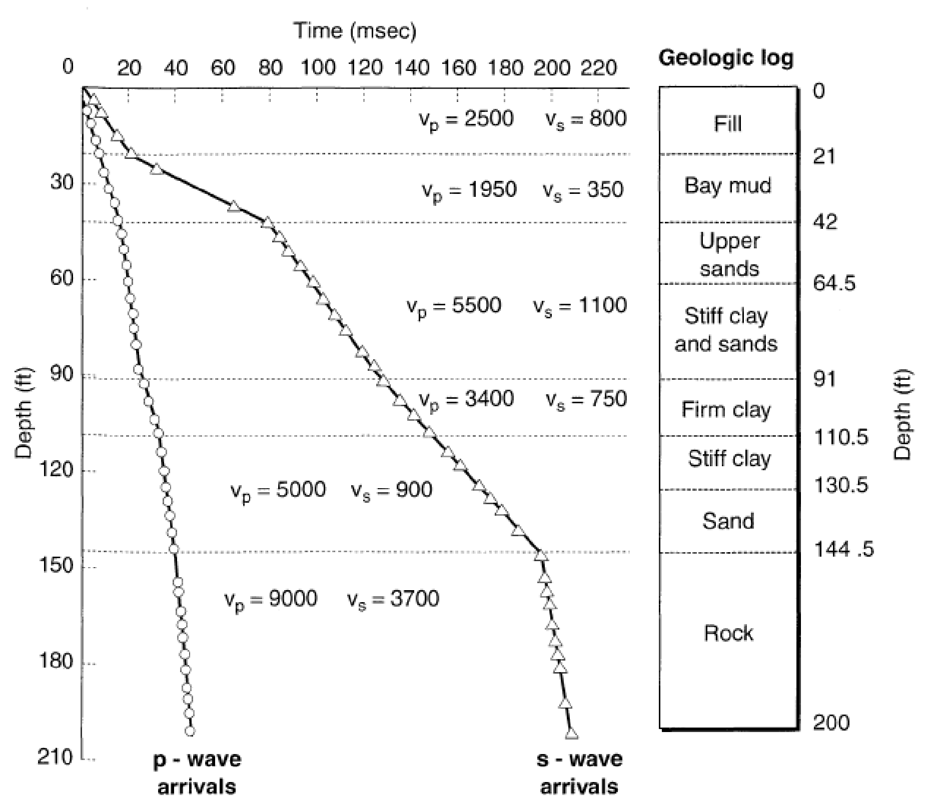


Measurement of Vs: Uphole / Downhole

- Source sends out seismic waves which are then recorded at a receiver
- Vs = distance / time
- Material and geometric spreading limit practical depths to 30-60 m

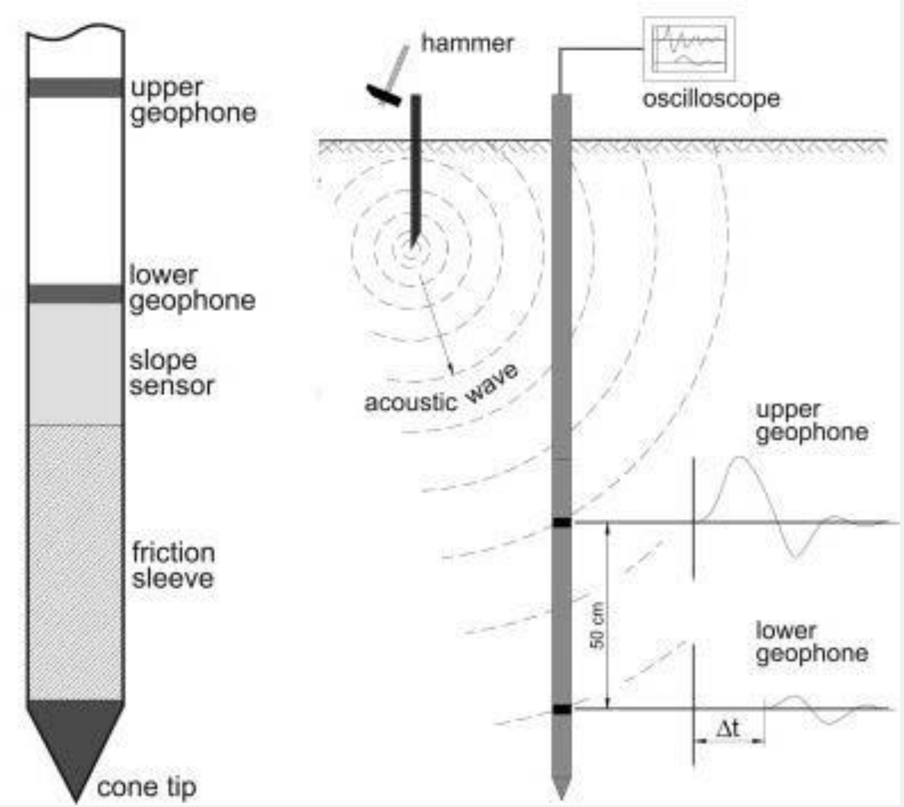


uphole downhole



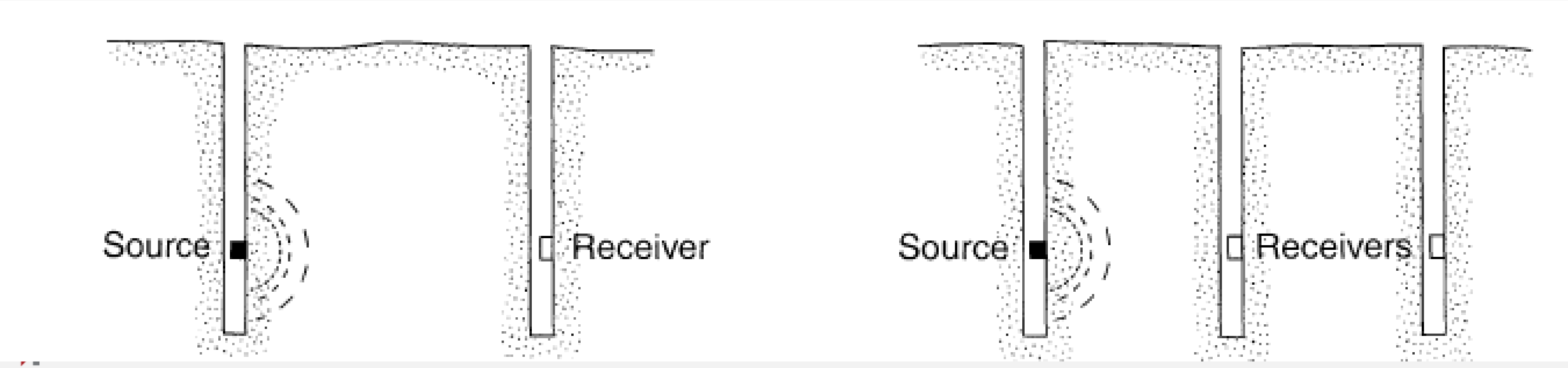
Measurement of Vs: Seismic CPT

- Similar to downhole
- Geophone (receiver) mounted on cone
- With two geophones, we can obtain time interval and more precise Vs measurement



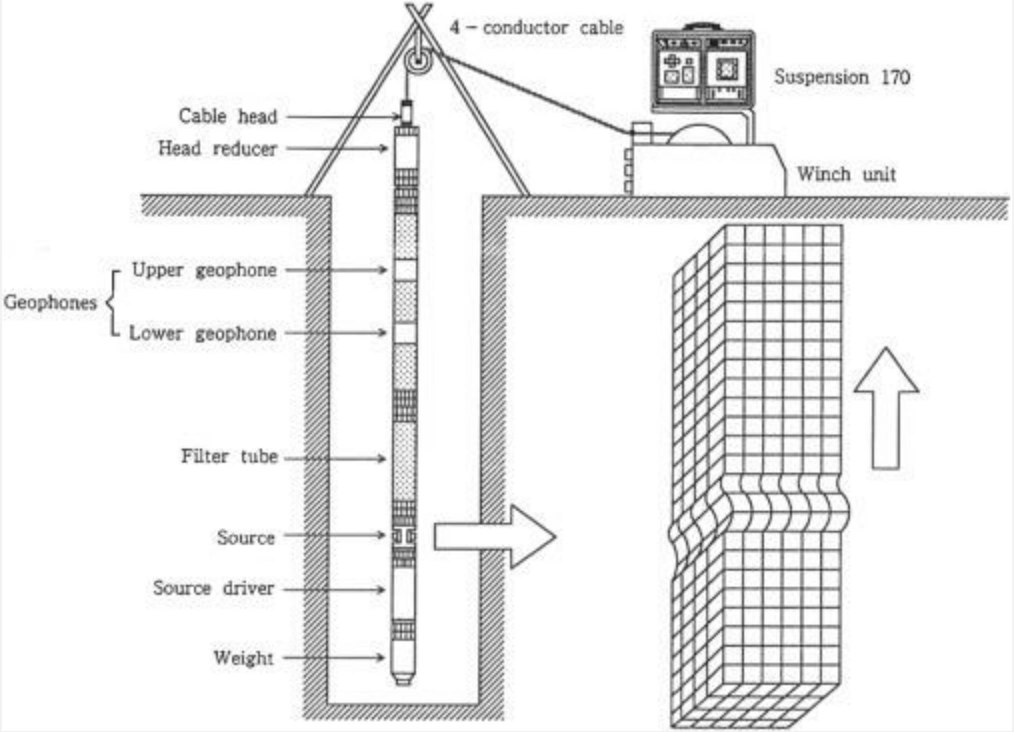
Measurement of Vs: Cross-hole

- Both the source and receiver located in boreholes
- Easier to measure Vs of individual layers
- More expensive than downhole
- Multiple receivers can be used to estimate material damping



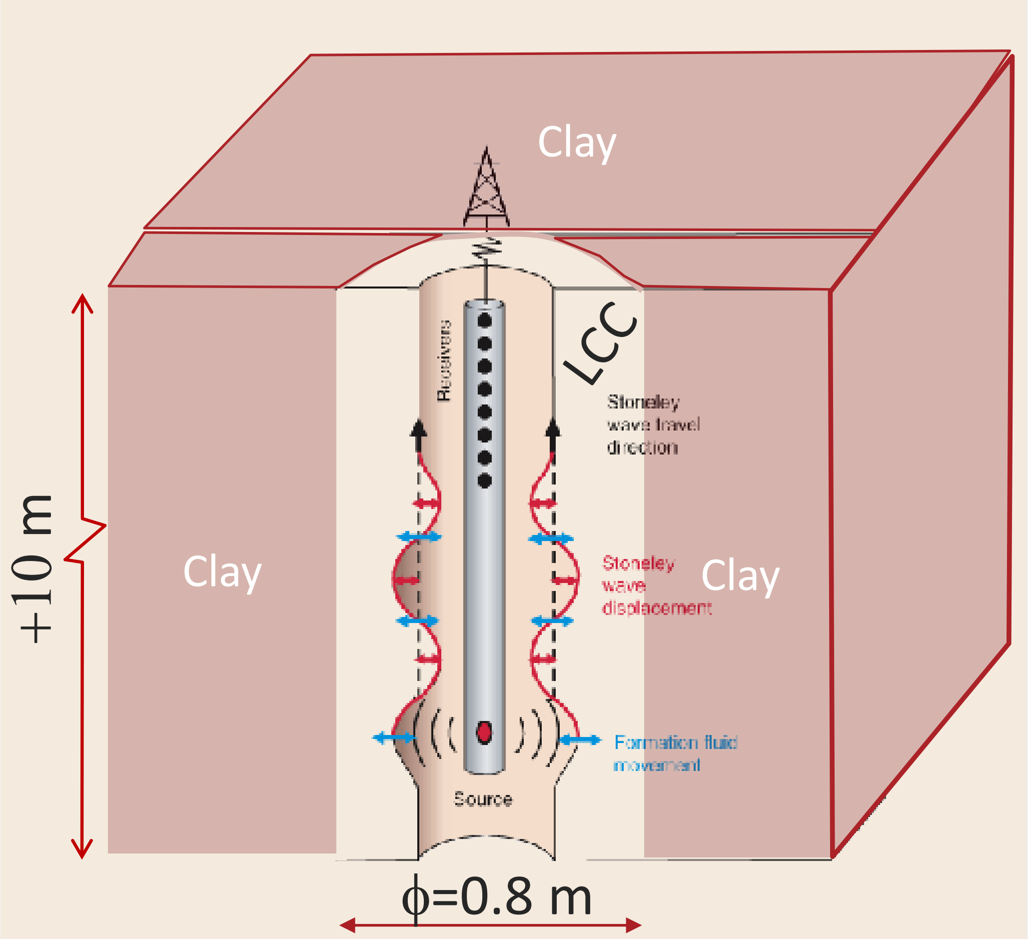
Measurement of Vs: Suspension Logger

- Source and receivers lowered into fluid filled borehole
- Impulse from source travels through fluid to soil
- Seismic wave travels through soil emitting energy back into the fluid and receivers
- Difference in travel time to receivers used to calculate Vs



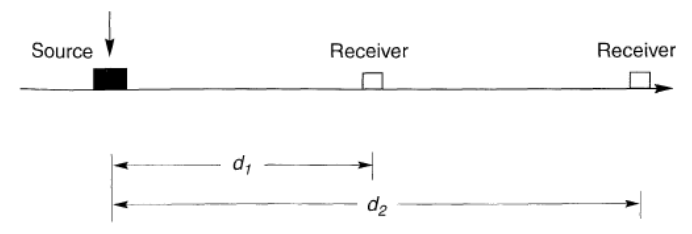
Stonely wave

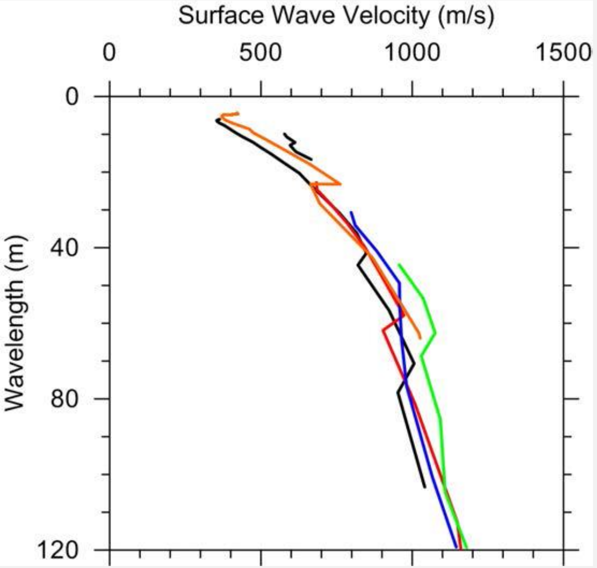
- Eksempel test i Kalksementpeler
- Mange forskjellige type bølger
- Trenger å skjønne frekvensinnhold
- Numerisk modell nødvendig for tolkning



Measurement of Vs: SASW

- Spectral Analysis of Surface Waves
- The travel time between the receivers at each frequency is calculated using the phase difference
- The Rayleigh wave phase velocity and wavelength are then calculated for each frequency to get a dispersion curve
- Theoretical layering and Vs matched to the measured dispersion curve until a fit is found (inversion)



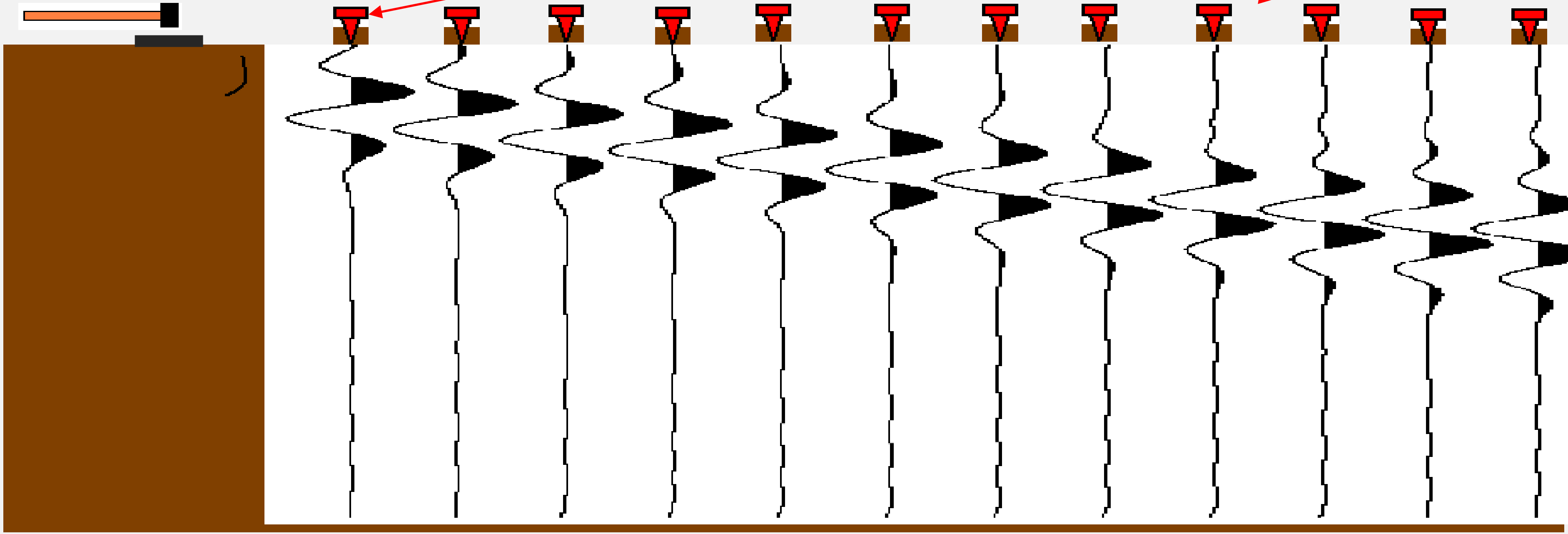


Dispersion curve

MASW procedure

(1) Generation of surface wave

(2) Measure & (3) Record surface wave


Low Frequency Geophones (4.5Hz)

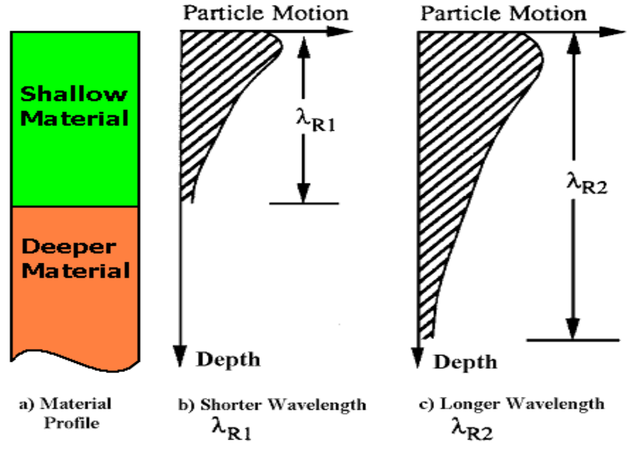
MASW analysis

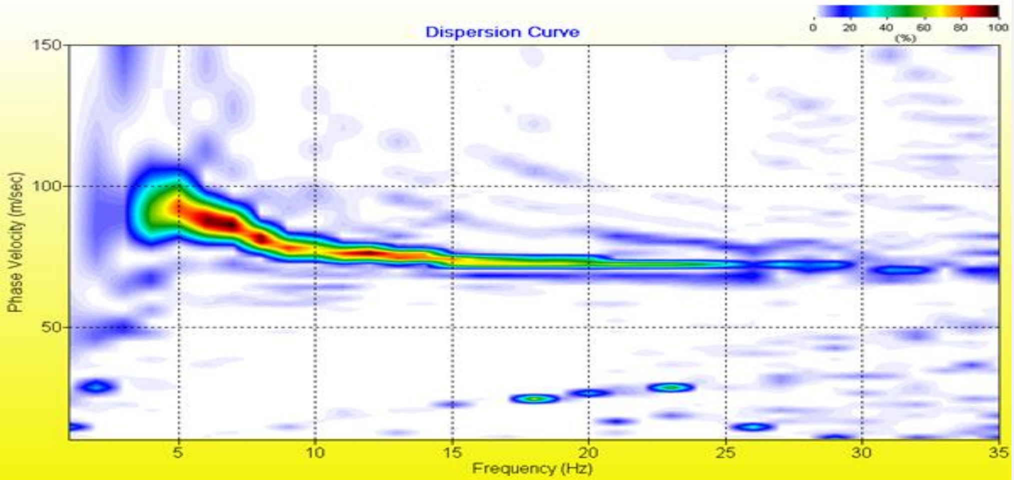
- Use dispersive properties of soil – velocity of propagation depends on frequency.

⇨ High frequency near surface

⇨ Low frequency affects deeper layers

- Dispersion curve (Careful!)



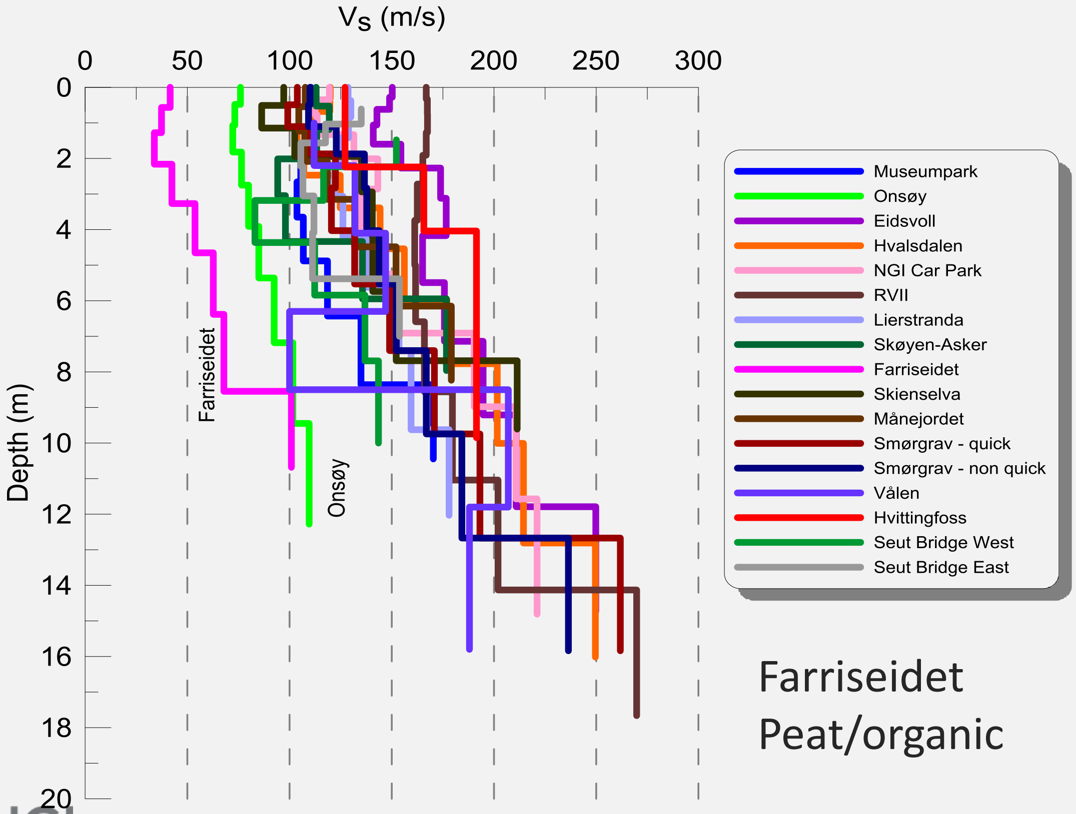


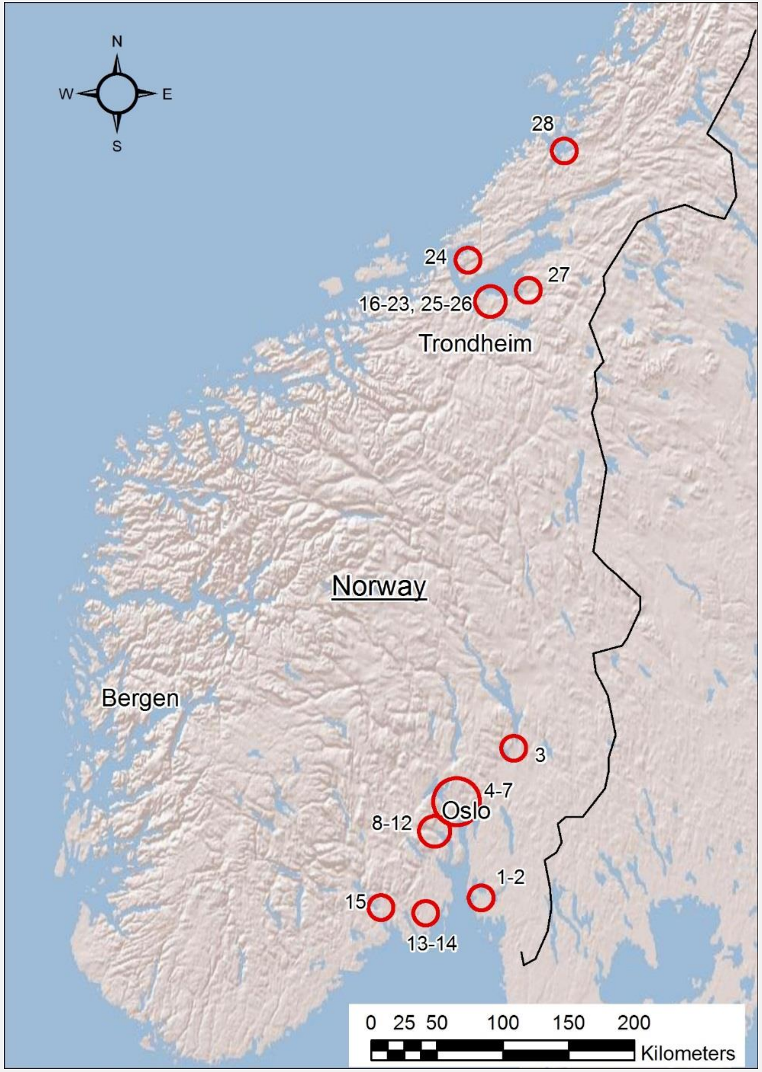
Typiske bølgehastigheter

Soil Type	P-Wave Speed (m/s)	S-Wave Speed (m/s)
Water	1,450	0
Glacial till	600 - 1,800	200 - 600
Dry gravel	500 - 1,000	250 - 400
Saturated gravel	1,450	300 - 400
Dry sand	300 - 600	150 - 200
Saturated sand	1,450	150 - 250
Silts and stiff clays	1,450	100 - 200
Plastic clay	1,450	50 - 100
Organic soils	1,450	30 - 50

Modifisert fra Massarsch og Fellenius 2008

Sør-Østlandet

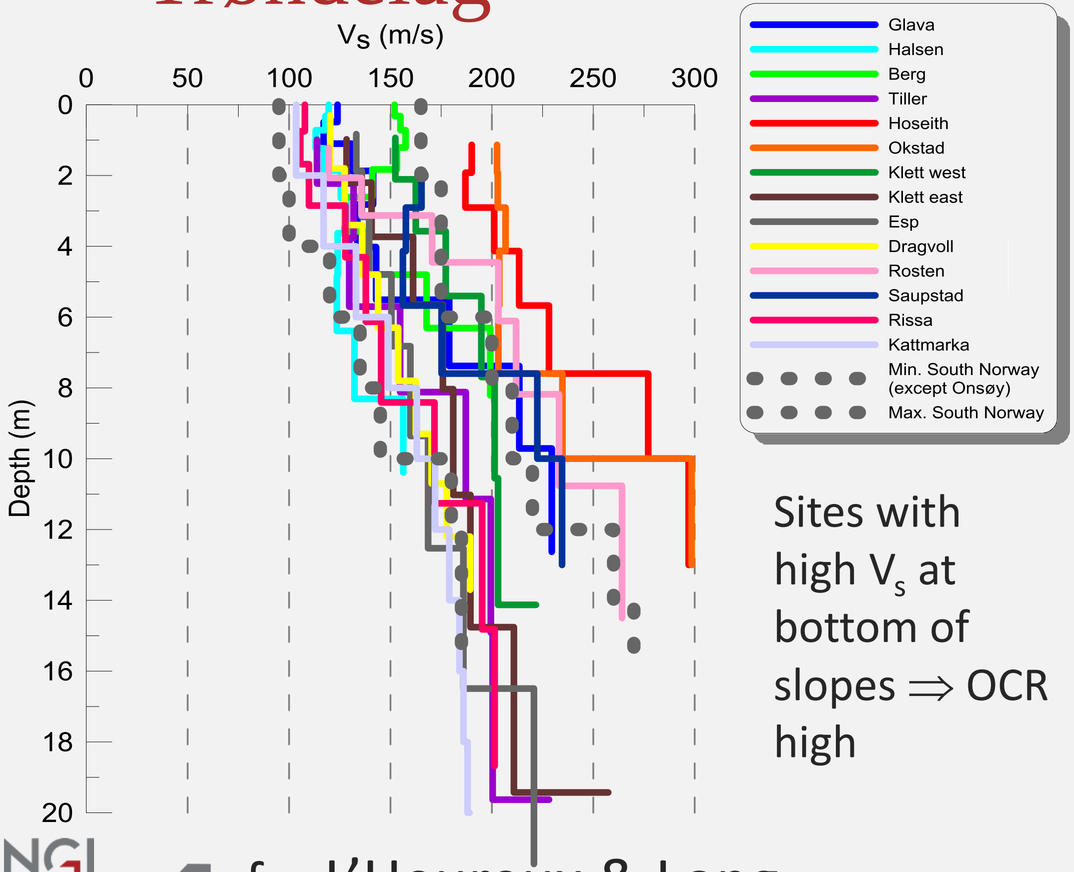




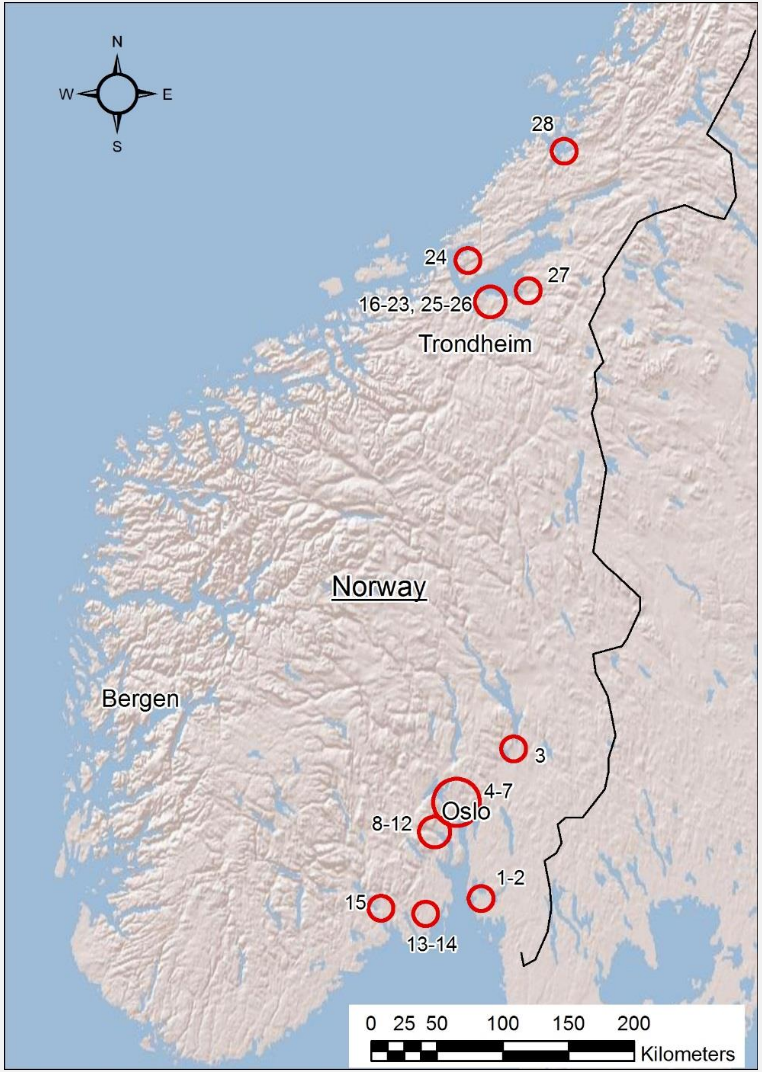
Farriseidet
Peat/organic

fra L'Heureux & Long

Trøndelag

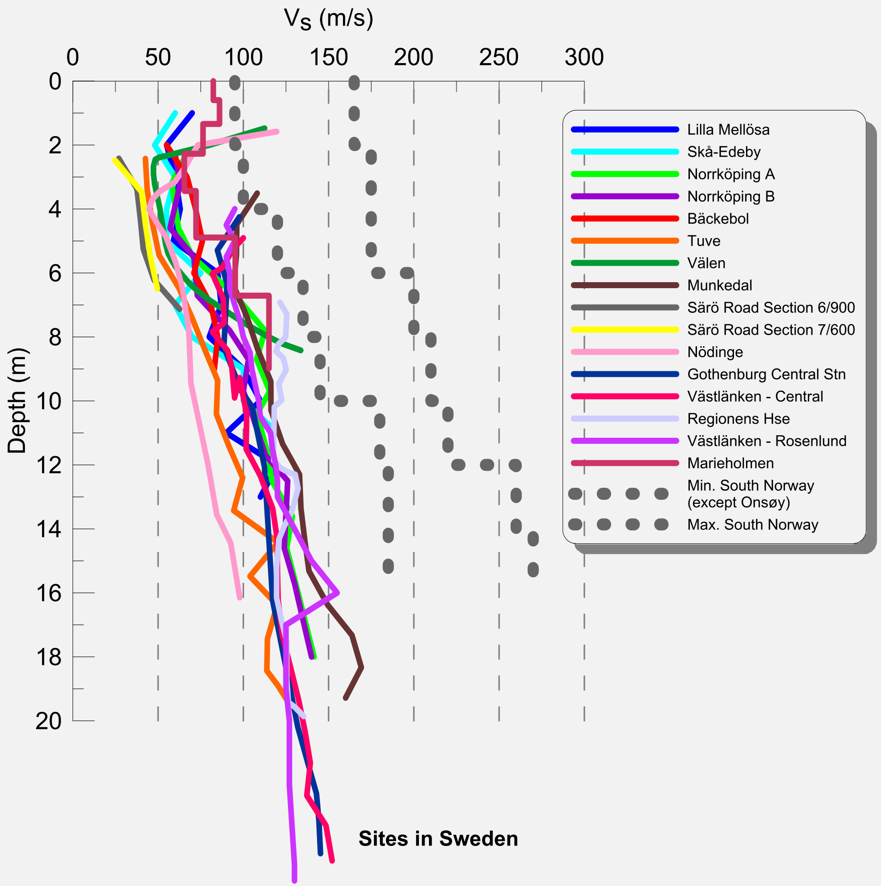


Sites with high V_s at bottom of slopes ⇒ OCR high



fra L'Heureux & Long

Swedish clays



- fra L’Heureux & Long

Refs. SGI Report 40, Varia 508, Andréasson, 1979, Wood 2015
Same scale as in previous plots

Material egenskaper i basert på labforsøk

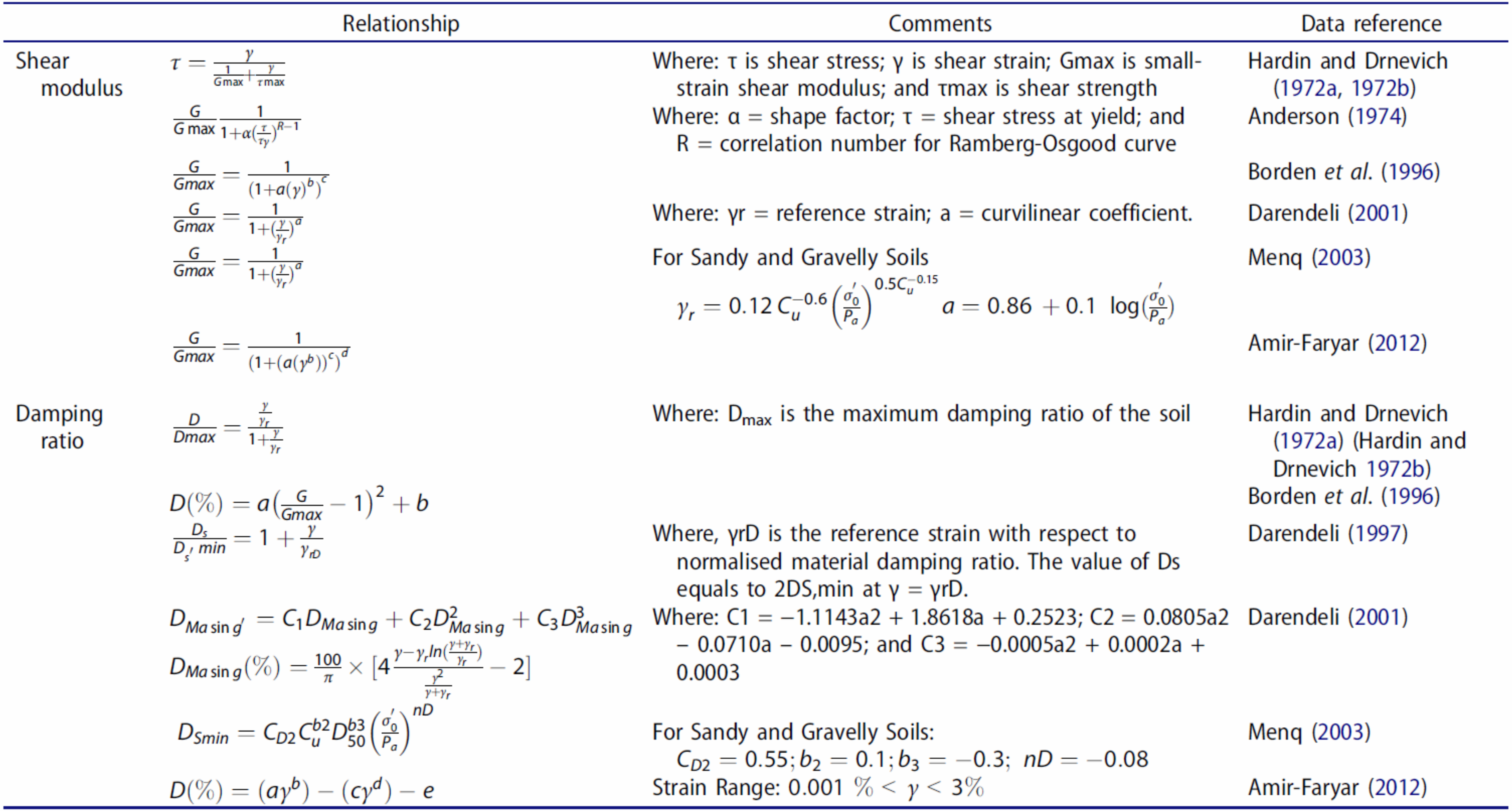
Modulus reduction /damping curves

- Dynamic Soil Properties and factors that affect them
  - Seed and Idriss 1970, Hardin and Drnevich 1972a, 1972b, Kokusho et al. 1982, Sun et al. 1988; Drnevich et al. 1989, Vucetic and Dobry 1991; Kagawa 1992, Ishibashi and Zhang 1993, Lanzo et al. 1997, Vucetic et al. 1998, Darendeli 2001, Menq 2003, Stokoe et al. 2004, Zhang et. al. 2005, Aggour and Zhang 2006, Kallioglou et al. 2008, Nie 2008, Amir-Faryar 2012, Biglari 2012, Amir-Faryar and Aggour 2012b, 2015.
- Analytical models to predict the nonlinear behaviour of soils
  - Kondner and Zelasko 1963, Hardin and Drnevich 1972a, 1972b, Anderson 1974, Borden et al. 1996, Darendeli 1997, 2001, Menq 2003, Amir-Faryar 2012, Groholski et. al. 2016

Partially from Amir-Faryar et. al. 2017
Universal model forms for predicting the shear modulus and material damping of soils

fra Amir-Faryar et. al. 2017

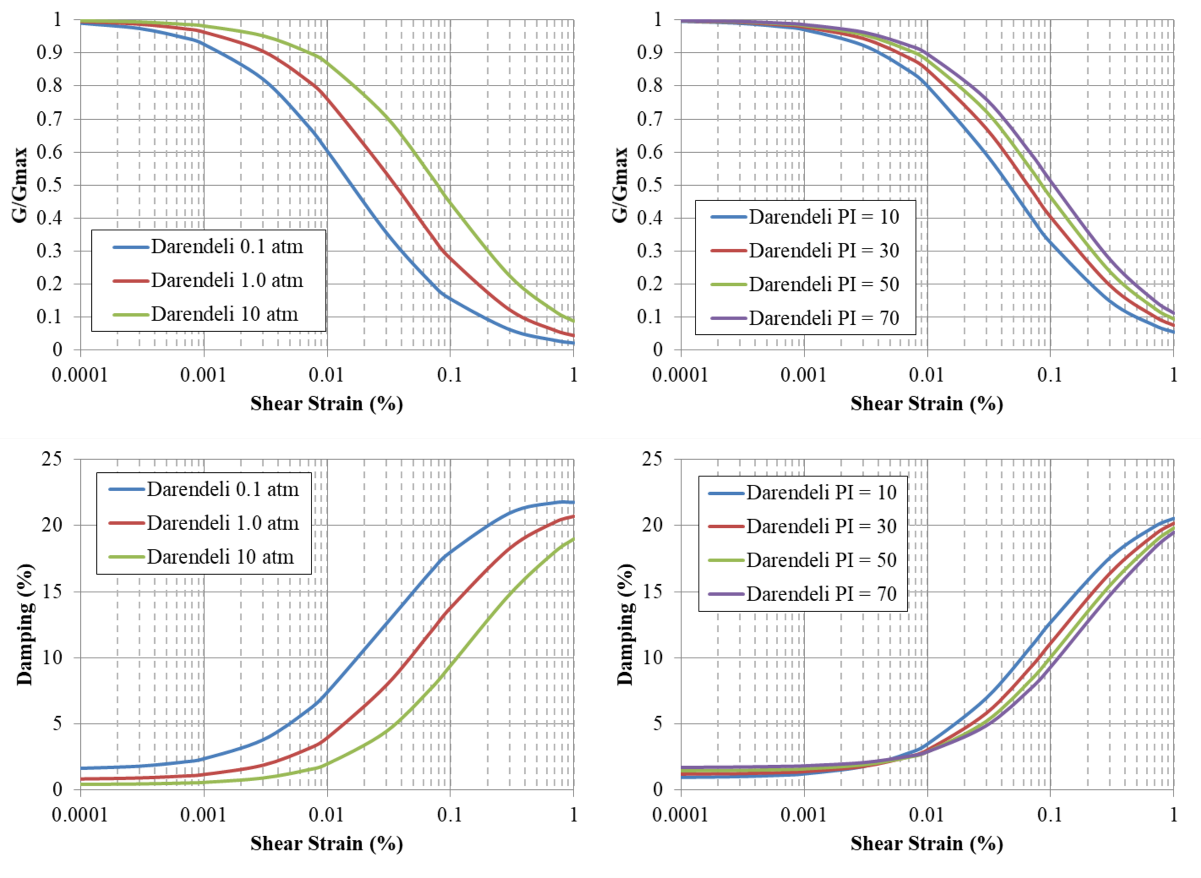
Table 1. Summary of the available model functions.



	Relationship	Comments	Data reference
Shear modulus	$\tau = \frac{\gamma}{\frac{1}{\text{Gmax}}+\frac{\gamma}{\tau\text{max}}}$	Where: τ is shear stress; γ is shear strain; Gmax is small-strain shear modulus; and τmax is shear strength	Hardin and Drnevich (1972a, 1972b)
	$\frac{G}{G\max}\frac{1}{1+\alpha(\frac{\tau}{\tau\gamma})^{R-1}}$	Where: α = shape factor; τ = shear stress at yield; and R = correlation number for Ramberg-Osgood curve	Anderson (1974)
	$\frac{G}{Gmax} = \frac{1}{(1+a(\gamma)^b)^c}$		Borden *et al.* (1996)
	$\frac{G}{Gmax} = \frac{1}{1+(\frac{\gamma}{\gamma_r})^a}$	Where: γr = reference strain; a = curvilinear coefficient.	Darendeli (2001)
	$\frac{G}{Gmax} = \frac{1}{1+(\frac{\gamma}{\gamma_r})^a}$	For Sandy and Gravelly Soils $\gamma_r = 0.12\,C_u^{-0.6}\left(\frac{\sigma_0'}{P_a}\right)^{0.5C_u^{-0.15}}$ $a = 0.86 + 0.1\ \log(\frac{\sigma_0'}{P_a})$	Menq (2003)
	$\frac{G}{Gmax} = \frac{1}{(1+(a(\gamma^b))^c)^d}$		Amir-Faryar (2012)
Damping ratio	$\frac{D}{Dmax} = \frac{\frac{\gamma}{\gamma_r}}{1+\frac{\gamma}{\gamma_r}}$	Where: D_{max} is the maximum damping ratio of the soil	Hardin and Drnevich (1972a) (Hardin and Drnevich 1972b)
	$D(\%) = a\left(\frac{G}{Gmax} - 1\right)^2 + b$		Borden *et al.* (1996)
	$\frac{D_s}{D_{s'}\ min} = 1 + \frac{\gamma}{\gamma_{rD}}$	Where, γrD is the reference strain with respect to normalised material damping ratio. The value of Ds equals to 2DS,min at γ = γrD.	Darendeli (1997)
	$D_{Ma\sin g'} = C_1 D_{Ma\sin g} + C_2 D^2_{Ma\sin g} + C_3 D^3_{Ma\sin g}$ $D_{Ma\sin g}(\%) = \frac{100}{\pi} \times [4\frac{\gamma-\gamma_r ln(\frac{\gamma+\gamma_r}{\gamma_r})}{\frac{\gamma^2}{\gamma+\gamma_r}} - 2]$	Where: C1 = −1.1143a2 + 1.8618a + 0.2523; C2 = 0.0805a2 – 0.0710a – 0.0095; and C3 = −0.0005a2 + 0.0002a + 0.0003	Darendeli (2001)
	$D_{Smin} = C_{D2}C_u^{b2}D_{50}^{b3}\left(\frac{\sigma_0'}{P_a}\right)^{nD}$	For Sandy and Gravelly Soils: $C_{D2} = 0.55; b_2 = 0.1; b_3 = -0.3;\ nD = -0.08$	Menq (2003)
	$D(\%) = (a\gamma^b) - (c\gamma^d) - e$	Strain Range: 0.001 $\% < \gamma < 3\%$	Amir-Faryar (2012)

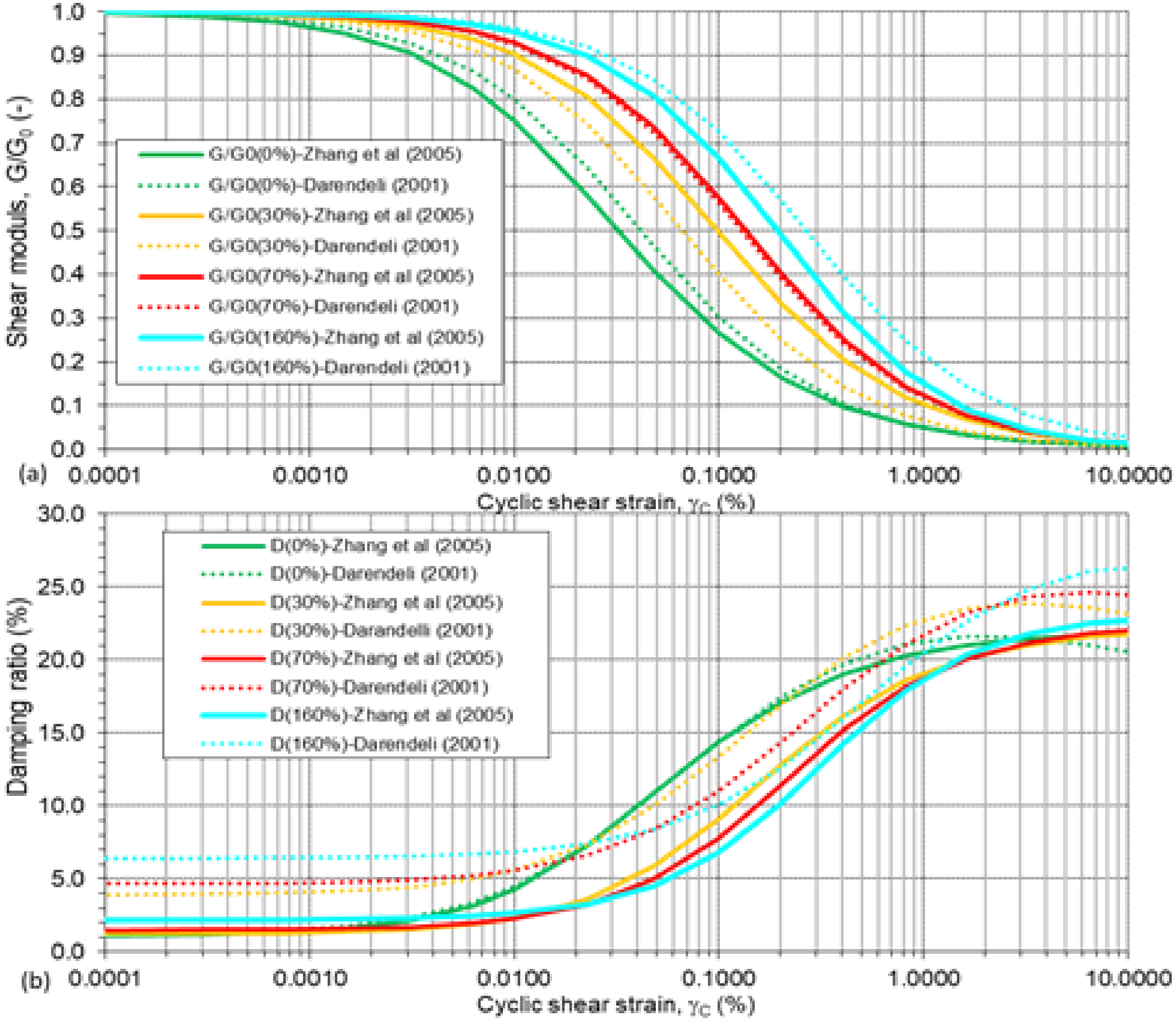
Equivalent Linear Models: Darendeli (2001)

- Silts, clays, and silt/clay/sand mixtures
- 110 resonant column tests on samples from 20 sites
- Input parameters: PI, σ’m, OCR, f, N
- Not very sensitive to f or N



Eksempel

- Zhang 2005
- Darendeli 2001



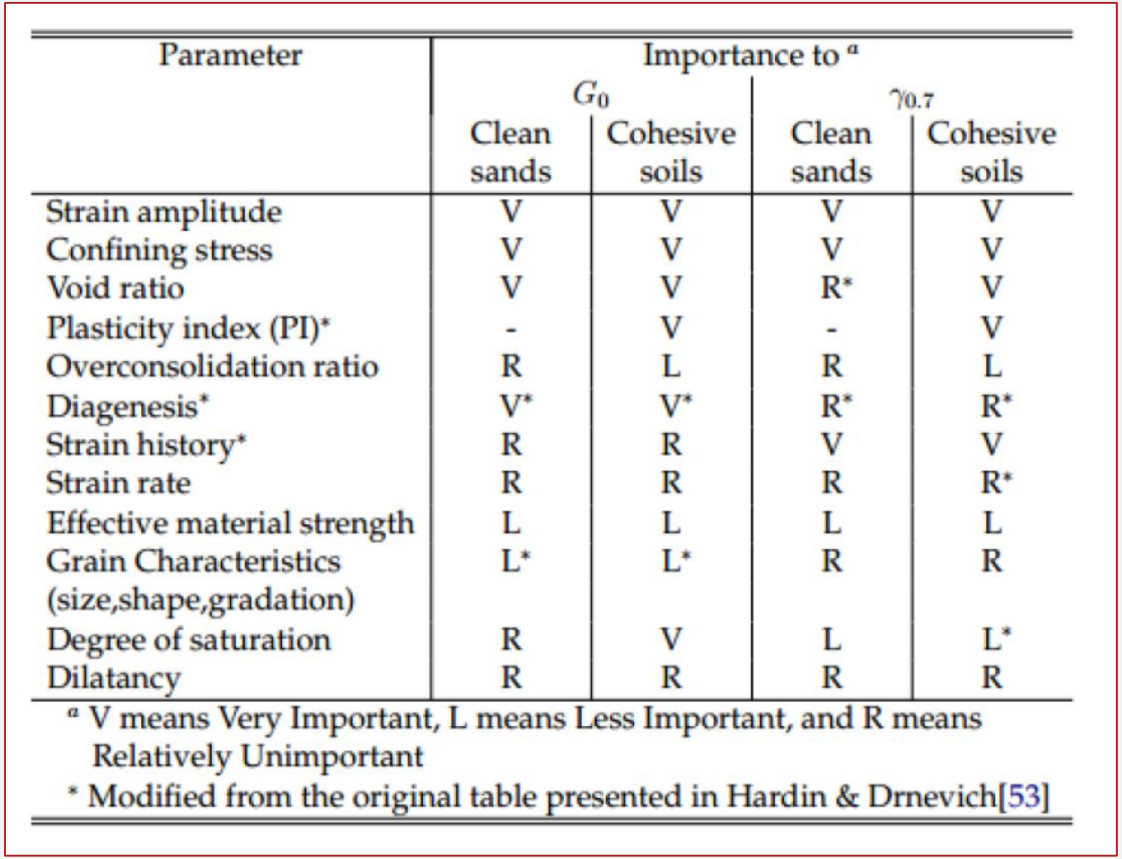
Small Strain Properties of Soils: Trends

Increasing Parameter	G_{max} Clay	G_{max} Sand	D_{min} Clay	D_{min} Sand
σ'_m	↑	↑	↓	↓
e	↓	↓	↓	↓
Time	↑	↑	↓	↓
OCR	↑	negligible	↓	negligible
Frequency	negligible	negligible	↑	↑
Number of Cycles	negligible	negligible	negligible	negligible
PI	↓		↑	
FC	↓	↓		
D_{50}		↑		↓
Cu		↓		↑

Large Strain Behaviour: Trends

Increasing Parameter	**G/G_{max} Clay**	**G/G_{max} Sand**	***D* Clay**	***D* Sand**
σ'_m	↑	↑	↓	↓
e	↑		↓	
Time	↑		negligible	negligible
OCR	negligible	negligible	negligible	negligible
Frequency	negligible	negligible	↓	negligible
Number of Cycles	↓	↑	↓	↓
PI	↑		↓	
FC				
D_{50}		↑		↑
Cu		↓		

Viktige parametere for Gmax og tøyning for 30% reduksjon av G



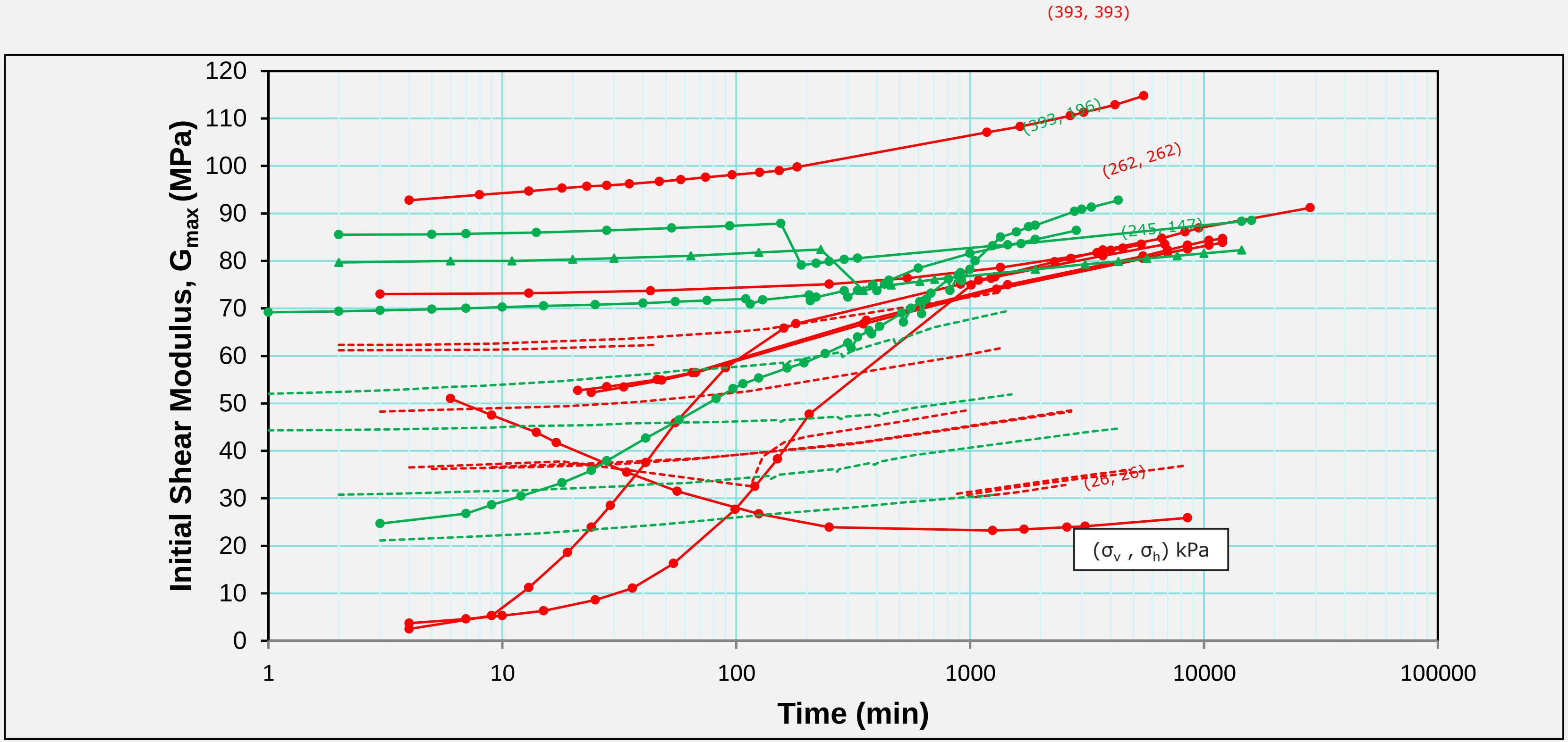
Parameter	Importance to[a]			
	G_0		$\gamma_{0.7}$	
	Clean sands	Cohesive soils	Clean sands	Cohesive soils
Strain amplitude	V	V	V	V
Confining stress	V	V	V	V
Void ratio	V	V	R*	V
Plasticity index (PI)*	-	V	-	V
Overconsolidation ratio	R	L	R	L
Diagenesis*	V*	V*	R*	R*
Strain history*	R	R	V	V
Strain rate	R	R	R	R*
Effective material strength	L	L	L	L
Grain Characteristics (size,shape,gradation)	L*	L*	R	R
Degree of saturation	R	V	L	L*
Dilatancy	R	R	R	R

[a] V means Very Important, L means Less Important, and R means Relatively Unimportant

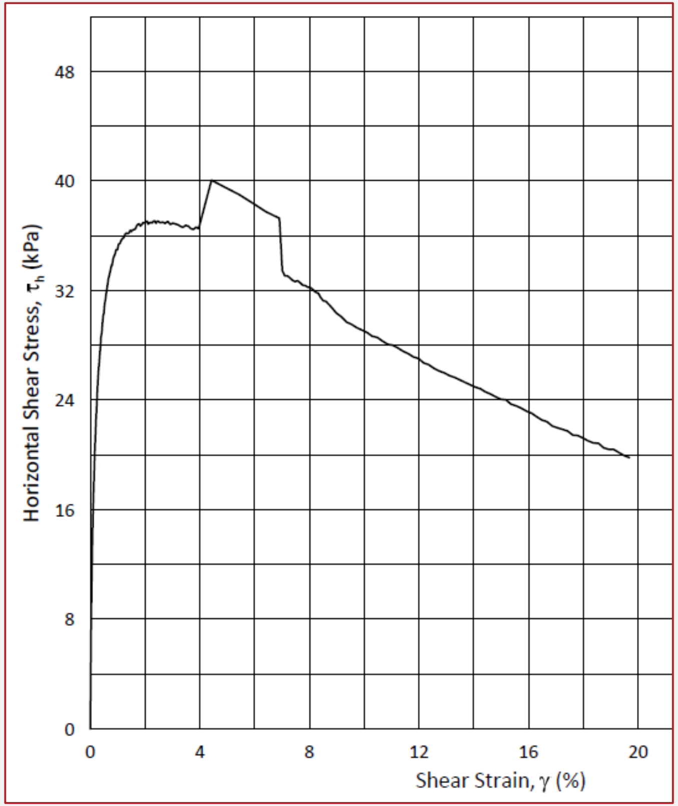
* Modified from the original table presented in Hardin & Drnevich[53]

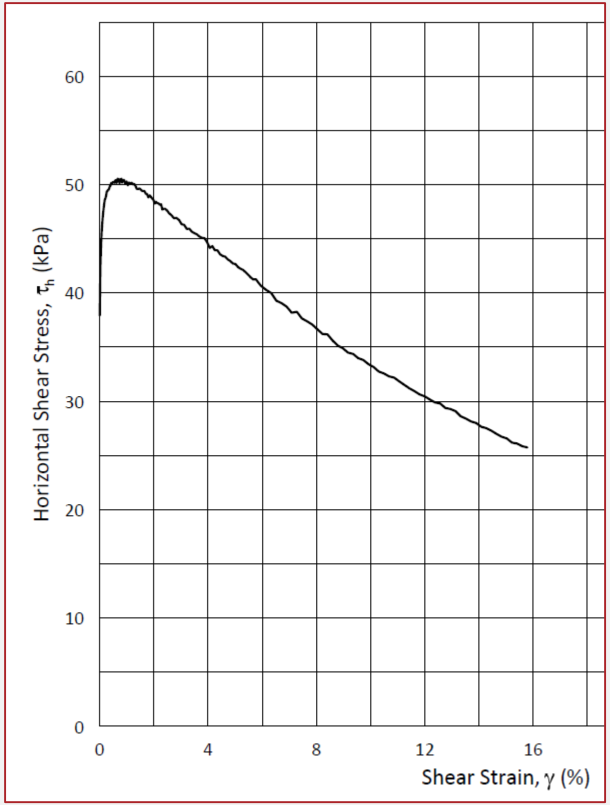
Fra Benz 2007

Gmax versus Time in the Lab



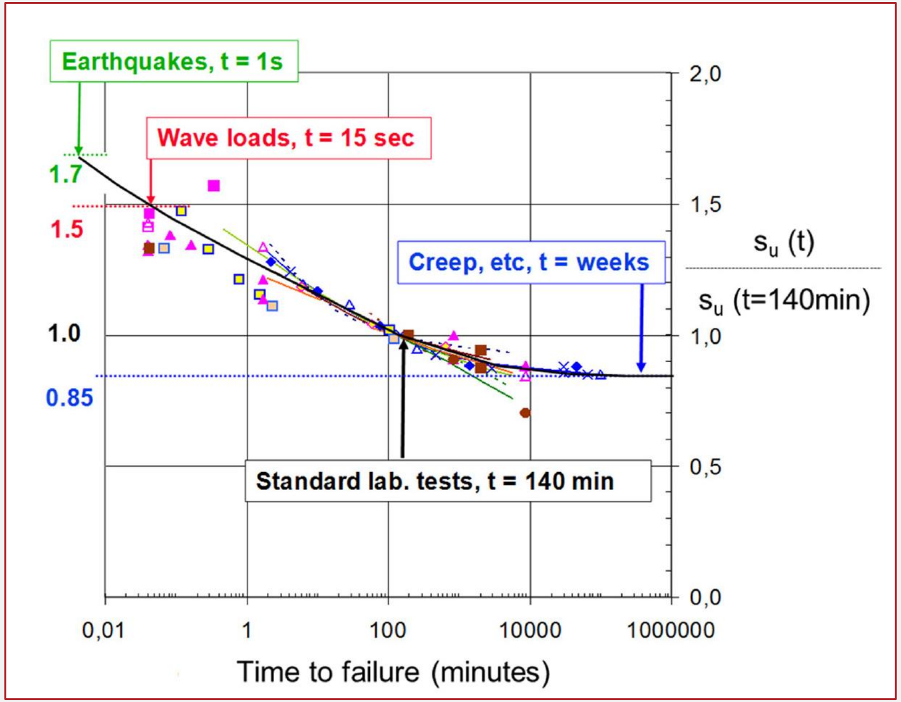
Effekt av lastrate, gjennomsnittlig skjærspenning



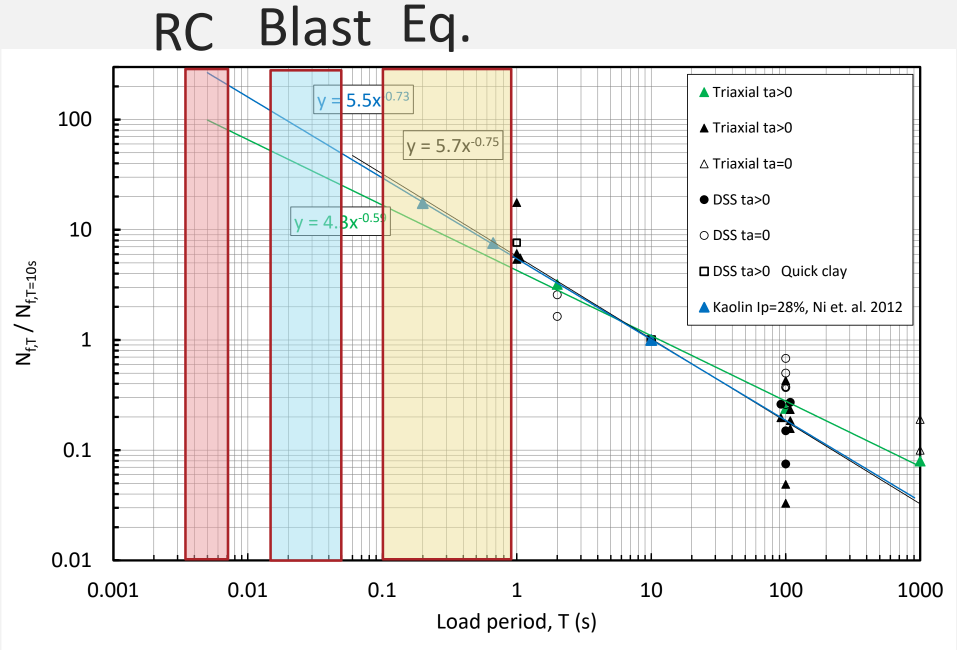


Se f.eks. Andersen 2015

Effekt av lastrate på statisk styrke og på antall sykler til brudd



Modifisert Andersen 2015, fra Lunne & Andersen 2007



Modifisert fra Andersen 2015 med data fra Ni et. al. 2012

Leire

Gmax i Leire

- Empiriske ligninger fra lab og/eller feltmålinger.
  - Inndata kvalitet og stedspesifikke
- Gmax/su, Gmax/σ_{vc}',

$$G_{max} = A\, f(e)\, OCR^{k} \left(\frac{p'}{p_{ref}}\right)^{n}$$

Hardin & Black 1968, Hardin 1978

$$\frac{G_{\mathrm{max}}}{c_{\mathrm{u}}^{\mathrm{DSS}}} = 325 + 55/(\frac{I_{\mathrm{p}}}{100})^{2}$$?

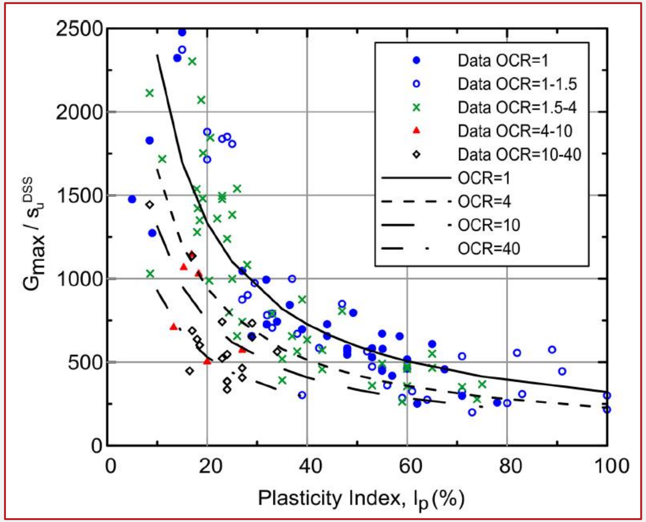
$G_{max}/s_u^{DSS} = (30+300/(I_p/100+0.03))\cdot OCR^{-0.25}$ and

$G_{max}/\sigma_{ref}' = (30+75/(I_p/100+0.03))\cdot OCR^{0.5}$

Inkluderer OCR

Reflekterer øvre jordlag bedre?

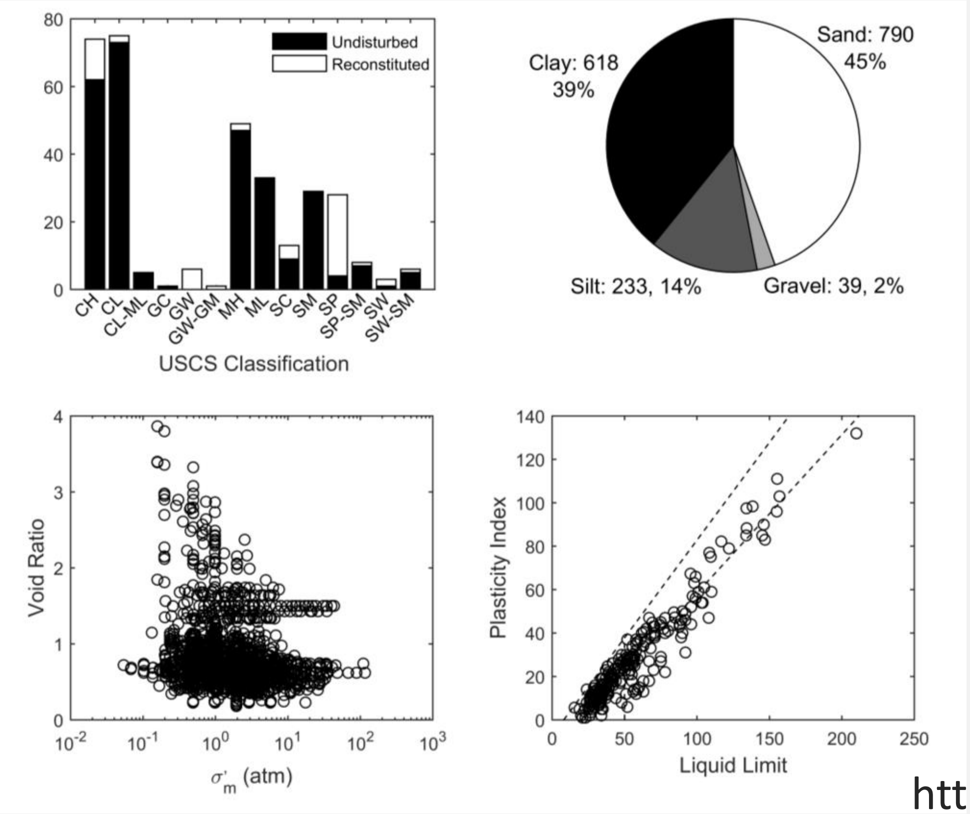
Obs -+ fremfor OCR



fra K. H. Andersen, «Cyclic soil parameters for offshore foundation design. The 3rd ISSMGE McClelland Lecture,» 2015, ISFOG III. Tilgjengelig på nett.

Indirect Measurement of G_{max} (Vs): Carlton and Pestana (2016)

$$G_{max,in-situ}/p_{at} = 0.78 \times [c_1 \times e^{c_2} \times (\sigma'_m/p_{at})^n \times OCR^k \times (FC+1)^{c_7} \times [1 + B({C_u}^{c_8} - 1)]\,]^{1.10}$$



$$n = c_3 \times {C_u}^{B \times c_4}$$

$$k = c_5 \times \left(\frac{PI}{100}\right)^{c_6} \leq 0.5$$

$$B = \begin{cases} 1 & for\ FC < 30\% \\ 0 & for\ FC \geq 30\% \end{cases}$$

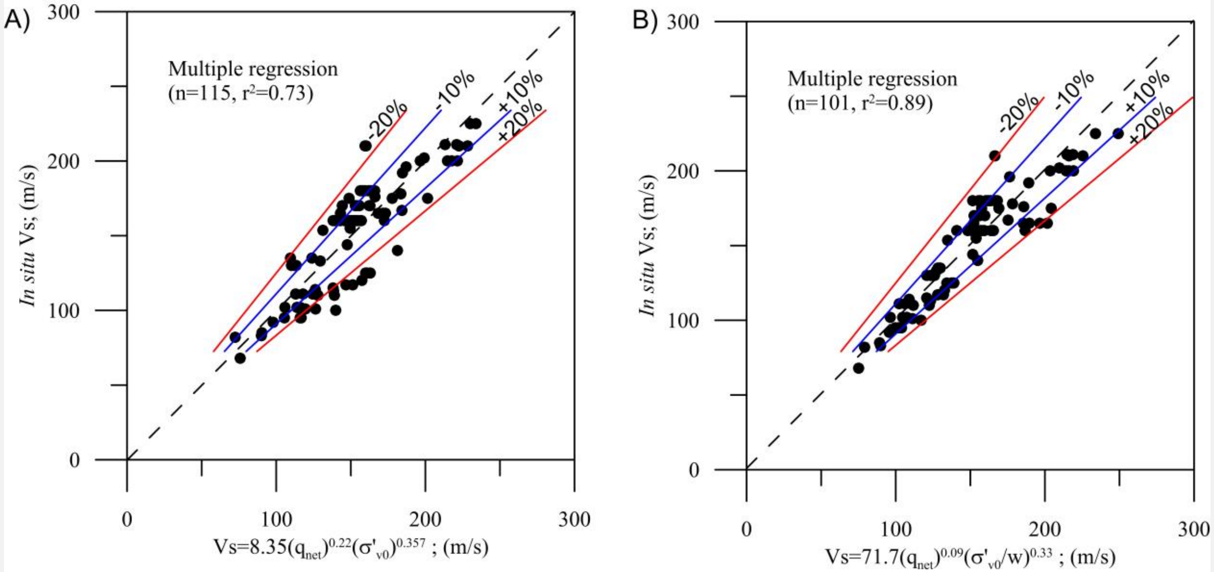
where e is void ratio, σ'_m is mean confining pressure, p_{at} is atmospheric pressure, OCR is overconsolidation ratio, FC is fines content, C_u is coefficient of uniformity and PI is plasticity index.

http://dx.doi.org/10.1016/j.soildyn.2016.01.019

Korrelasjoner med CPTU data

$$V_s = 8.35 \cdot (q_{net})^{0.22} \cdot (\sigma'_{v0})^{0.357} \quad V_s = 71.7 \cdot (q_{net})^{0.09} \cdot \left(\frac{\sigma'_{v0}}{w}\right)^{0.33}$$

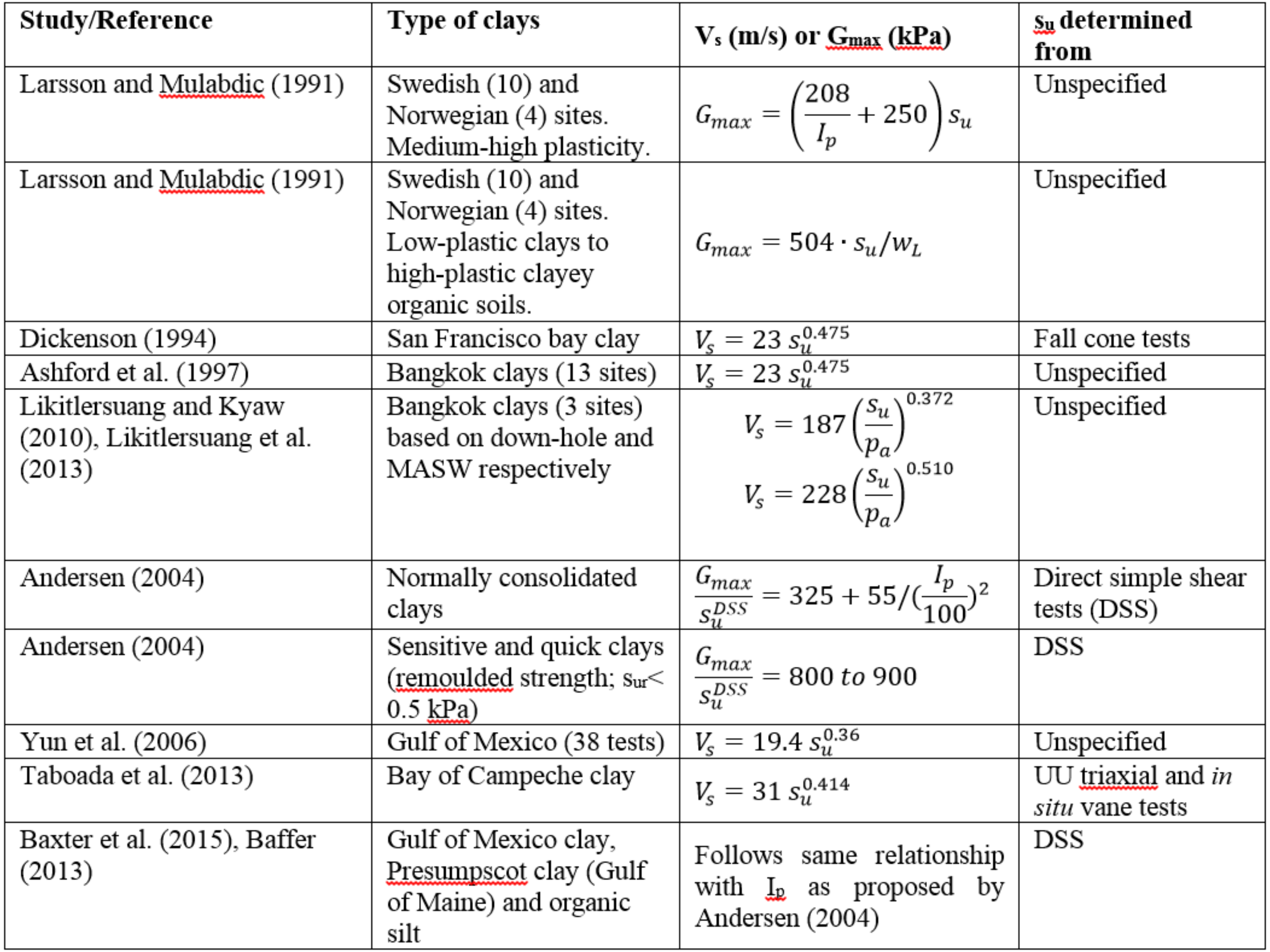
- Spissmotstand, ~styrke ved stor tøyning
- Vs, Gmax små tøyninger, målt med SCPT, MASW, SDMT



fra L'Heureux & Long

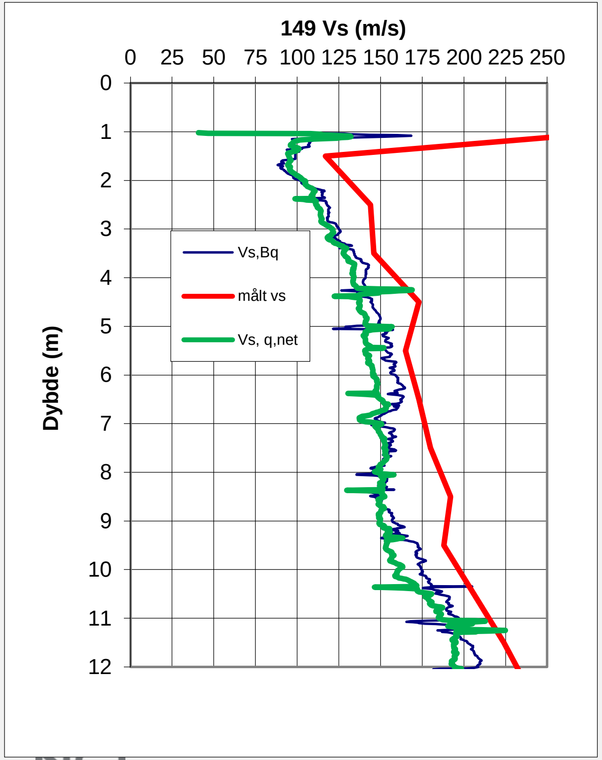
Korrelasjoner med udrenert skjærstyrke

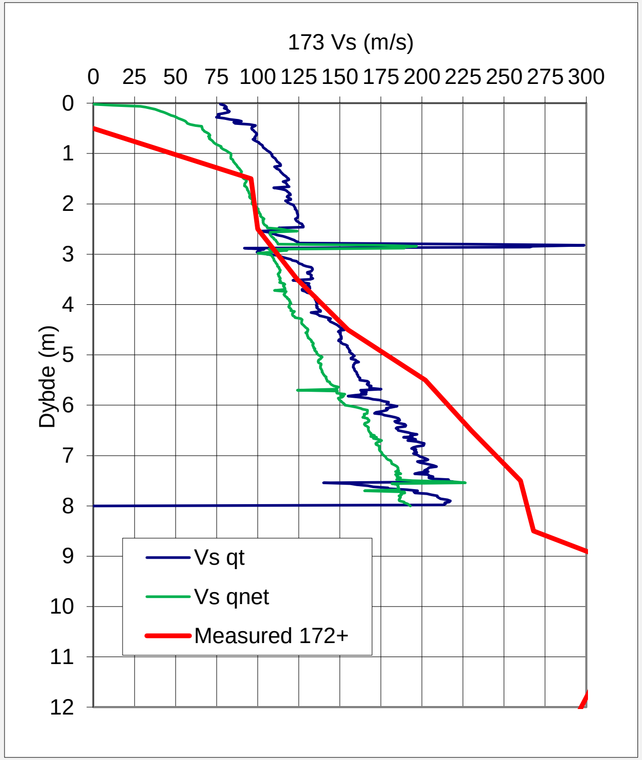
- Stedspesifikke
- Basert på forskjellige type felt/labmålinger
- Sjekk antakelser og grunnlag i ursprungsreferansen!
- Oppdateres ofte når nye data blir tilgjengelige

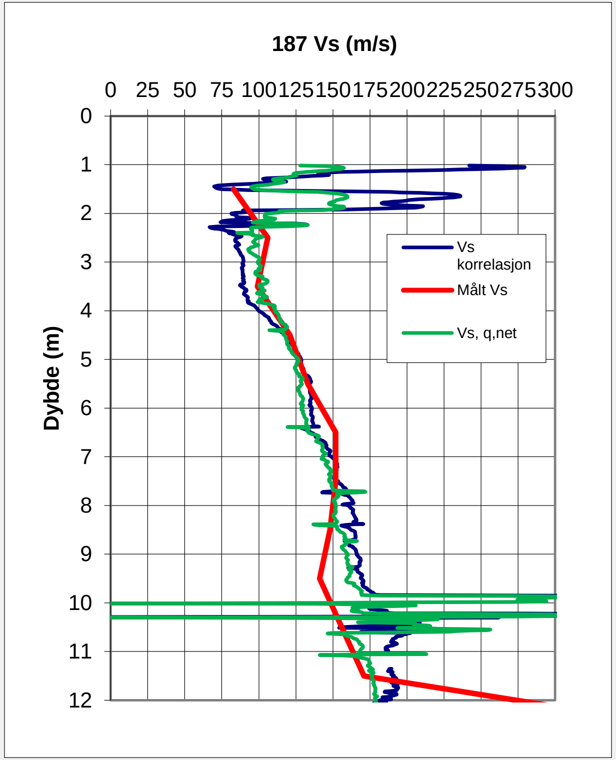


Study/Reference	**Type of clays**	**V_s (m/s) or G_{max} (kPa)**	**s_u determined from**
Larsson and Mulabdic (1991)	Swedish (10) and Norwegian (4) sites. Medium-high plasticity.	$G_{max} = \left(\frac{208}{I_p} + 250\right) s_u$	Unspecified
Larsson and Mulabdic (1991)	Swedish (10) and Norwegian (4) sites. Low-plastic clays to high-plastic clayey organic soils.	$G_{max} = 504 \cdot s_u / w_L$	Unspecified
Dickenson (1994)	San Francisco bay clay	$V_s = 23\ s_u^{0.475}$	Fall cone tests
Ashford et al. (1997)	Bangkok clays (13 sites)	$V_s = 23\ s_u^{0.475}$	Unspecified
Likitlersuang and Kyaw (2010), Likitlersuang et al. (2013)	Bangkok clays (3 sites) based on down-hole and MASW respectively	$V_s = 187\left(\frac{s_u}{p_a}\right)^{0.372}$ $V_s = 228\left(\frac{s_u}{p_a}\right)^{0.510}$	Unspecified
Andersen (2004)	Normally consolidated clays	$\frac{G_{max}}{s_u^{DSS}} = 325 + 55/(\frac{I_p}{100})^2$	Direct simple shear tests (DSS)
Andersen (2004)	Sensitive and quick clays (remoulded strength; s_{ur}< 0.5 kPa)	$\frac{G_{max}}{s_u^{DSS}} = 800\ to\ 900$	DSS
Yun et al. (2006)	Gulf of Mexico (38 tests)	$V_s = 19.4\ s_u^{0.36}$	Unspecified
Taboada et al. (2013)	Bay of Campeche clay	$V_s = 31\ s_u^{0.414}$	UU triaxial and *in situ* vane tests
Baxter et al. (2015), Baffer (2013)	Gulf of Mexico clay, Presumpscot clay (Gulf of Maine) and organic silt	Follows same relationship with I_p as proposed by Andersen (2004)	DSS

Usikkerheter i ligninger

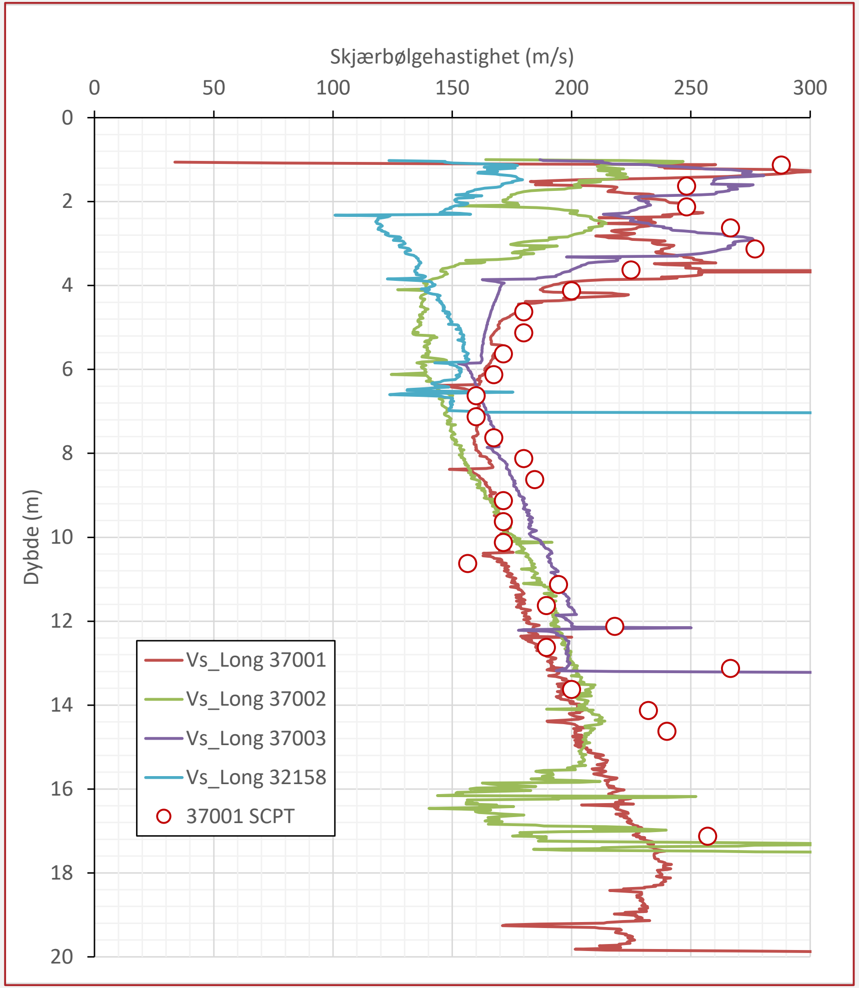






Usikkerheter i ligninger

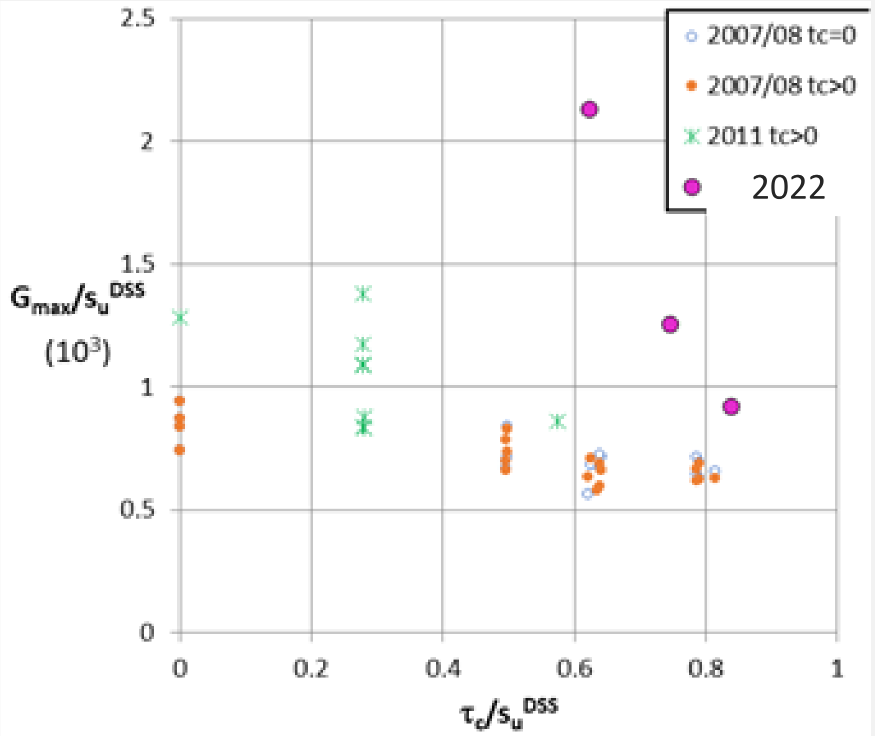
- Måle i felt og lab på noen få steder og benytt ligninger til å skjønne variasjon

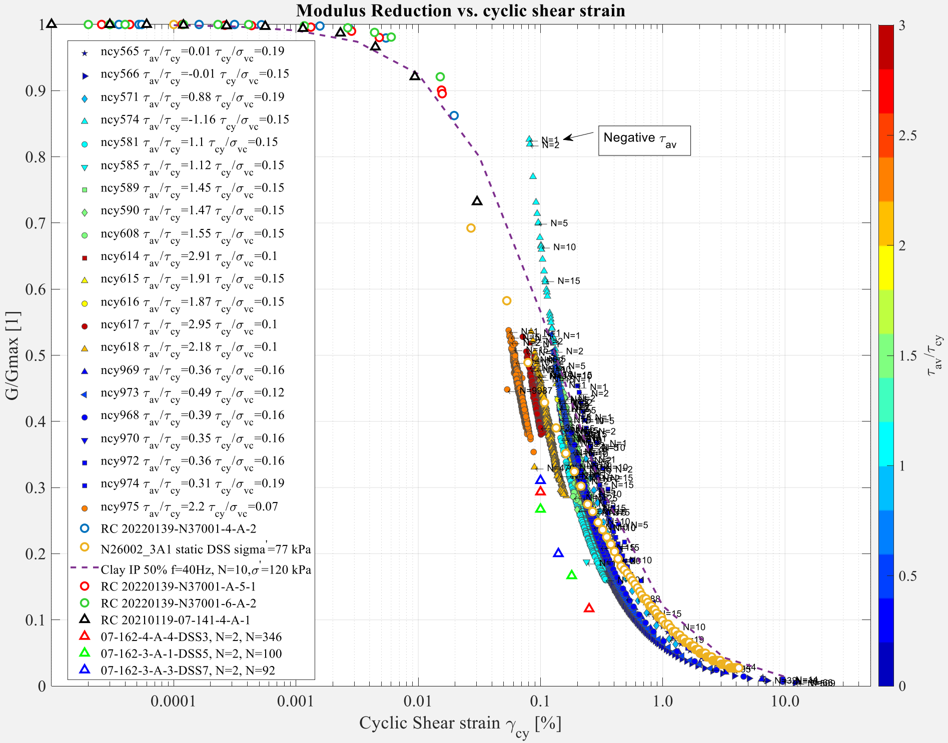


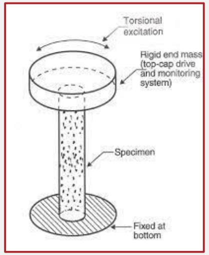
Kvikkleire

Kvikkleire

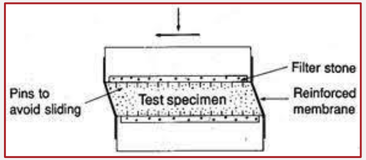
- Gmax/su old and new data



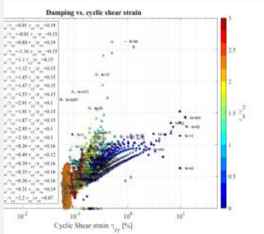




$$\gamma_{cy}=\tau/G$$

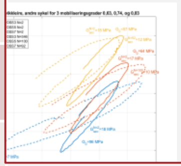


Kvikkleire demping



Sykliske Dss forsøk på kvikkleire for skråningsstabilitet

Parameter	Dss 3	Dss 5	Dss 7
$s_{u,\tau C}$ (kPa) (statisk styrke)	45	51	62
$\tau_C/s_{u,\tau C}$	0,63	0,74	0,83
τ_{cy} (kPa) syklisk spenning	18		
G_{max} (MPa)	96	64	57
G_{sec} N=2, (MPa)	17 (@γ_{cy}=0,1%)		
Poretrykk, u_p/σ_{vc}', N=10 (%)	3,5	7	9
v_s (m/s) skjærbølgehastighet	220?	180	170
$v_{s,sec}$ (m/s)	95		
Vibration (mm/s) @ 1 Hz	97 (=$v_{s,sec}$ *γ_{cy})		
Acceleration (m/s^2)	0,6 (sammenlignes 0,2-0,6, a_{gr}, PGA)		
NS 1998-5 sier ved αS=0,1	G/Gmax=0,8 (+-0,1)		



Sand/Silt

Gmax i sand

- K. Ishihara, Soil behaviour in earthquake geotechnics, American Library Association, 1996
- Wichman & Triantafyllidis 2009 (RC-test på tørr sand)
  - Effekt av Coefficient of uniformity.
- SVV 604

$$G_{\mathrm{max}} = A\,\frac{(a-e)^2}{1+e}\,p^n$$

$$G_{\mathrm{max}} = 625\,\frac{1}{0{,}3 + 0{,}7e^2}\sqrt{p_{\mathrm{a}}\sigma'_{\mathrm{m}}}$$

K. Ishihara, Soil behaviour in earthquake geotechnics, American Library Association, 1996

Sand/Gravel material laboratory based Gmax, G/Gmax and D

$$G_{\text{max}} = A\frac{(a-e)^2}{1+e}\left(\frac{p}{p_{\text{atm}}}\right)^n p_{\text{atm}}$$

Wichtmann et. al. (2009, 2013, 2015)

$$A = 1563 + 3.13C_u^{2.98}$$

$$a = 1.94\exp(-0.066C_u)$$

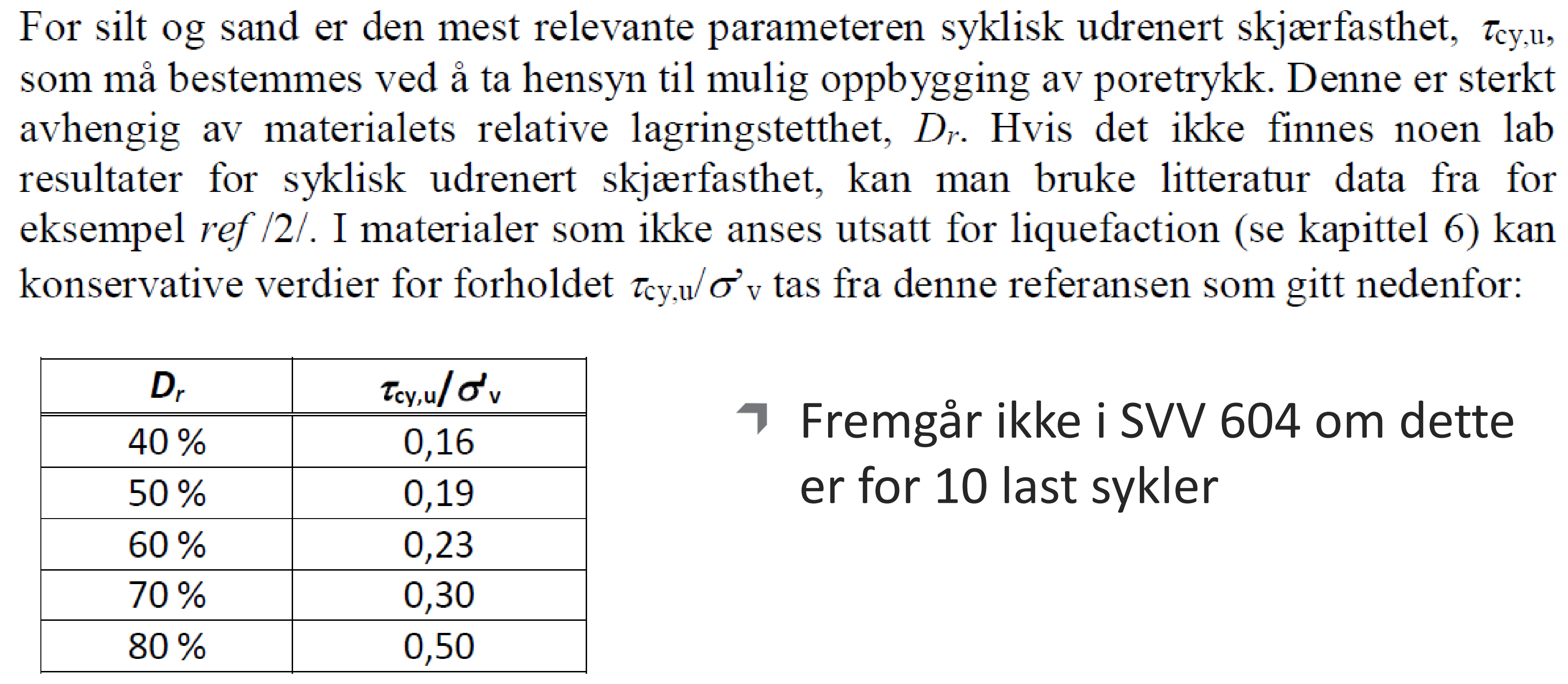
$$n = 0.40C_u^{0.18}$$

- Resonant column tests on a large set of materials with different grain size distribution. Only dry material.
- e Voidratio, skeleton
  - For void ratio up to 1.0
  - «Arbitrary limit» of Fines content FC

$$e_{\text{skel}} = (e + FC[\%]/100)/(1 - FC[\%]/100)$$

- p Average effective normal pressure, p_{atm}=100 kPa
- n Pressure exponent

Sand/Silt

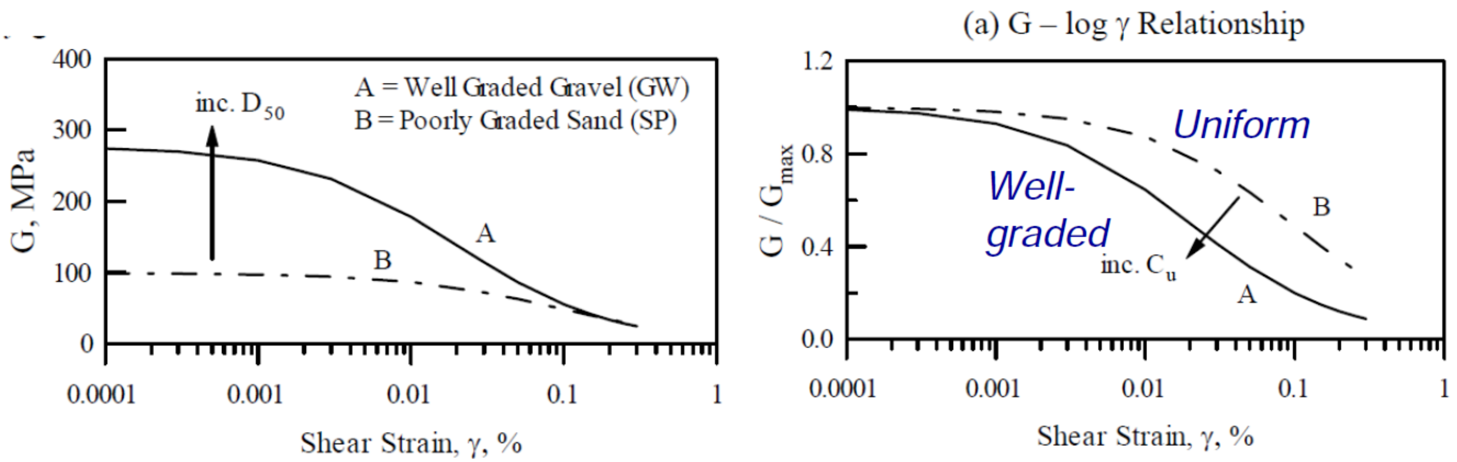


For silt og sand er den mest relevante parameteren syklisk udrenert skjærfasthet, $\tau_{cy,u}$, som må bestemmes ved å ta hensyn til mulig oppbygging av poretrykk. Denne er sterkt avhengig av materialets relative lagringstetthet, D_r. Hvis det ikke finnes noen lab resultater for syklisk udrenert skjærfasthet, kan man bruke litteratur data fra for eksempel *ref* /2/. I materialer som ikke anses utsatt for liquefaction (se kapittel 6) kan konservative verdier for forholdet $\tau_{cy,u}/\sigma'_v$ tas fra denne referansen som gitt nedenfor:

D_r	$\tau_{cy,u}/\sigma'_v$
40 %	0,16
50 %	0,19
60 %	0,23
70 %	0,30
80 %	0,50

- Fremgår ikke i SVV 604 om dette er for 10 last sykler

Equivalent Linear Models: Menq (2003)



- Non-plastic silts and sands
- Similar methodology as Darendeli (2001)

$$\gamma_r = 0.12 \times C_u^{-0.6} \times \left(\frac{\sigma_o'}{P_a}\right)^{0.5\times C_u^{-0.15}}$$

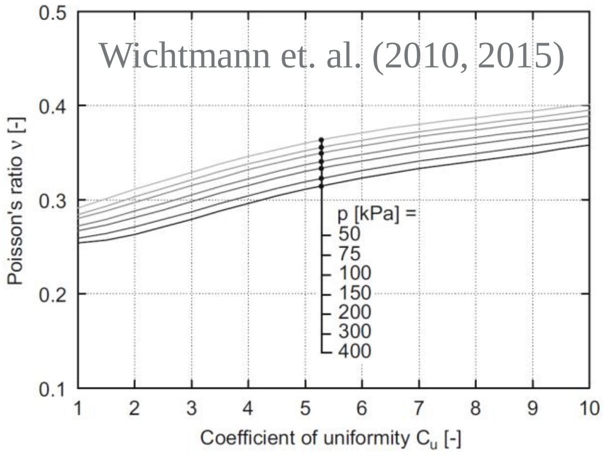
$$a = 0.86 + 0.1 \times \log(\sigma_o'/P_a).$$

Well-graded soils tend to be more nonlinear than uniformly graded soils

Kramer 2021

Poisson’s ratio

- Drained and dry material, use a Poisson’s ratio of 0,3
- Saturated clay 0,5 (or close 0,48-0,49). Numerical issues with incompressibility
- Decreases with depth (confinging pressure), (Hamilton 1979)
- Organic materal (mud etc.) gas -> non-saturated thus a lower poisson value than saturated clay.
- Ballast and crushed rock ~0,25



Wichtmann et. al. (2010, 2015)

Fig. 14. Poisson's ratio ν for a constant void ratio $e=0.55$ as a function of the coefficient of uniformity C_u, ν-values calculated with Eqs. (1)–(8).

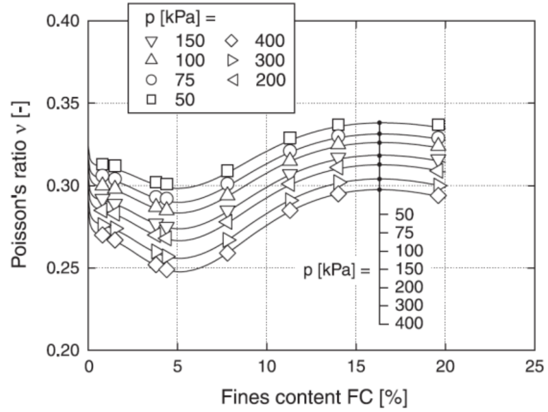
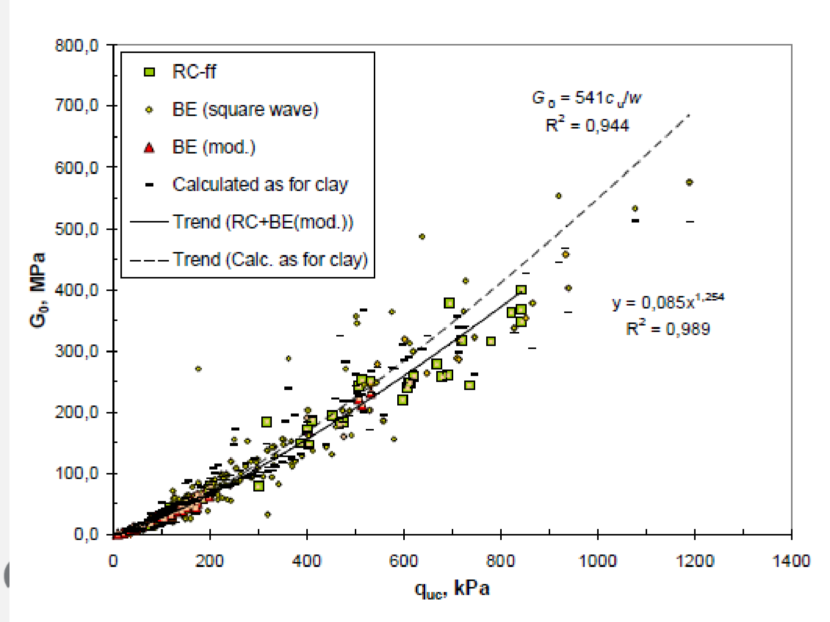


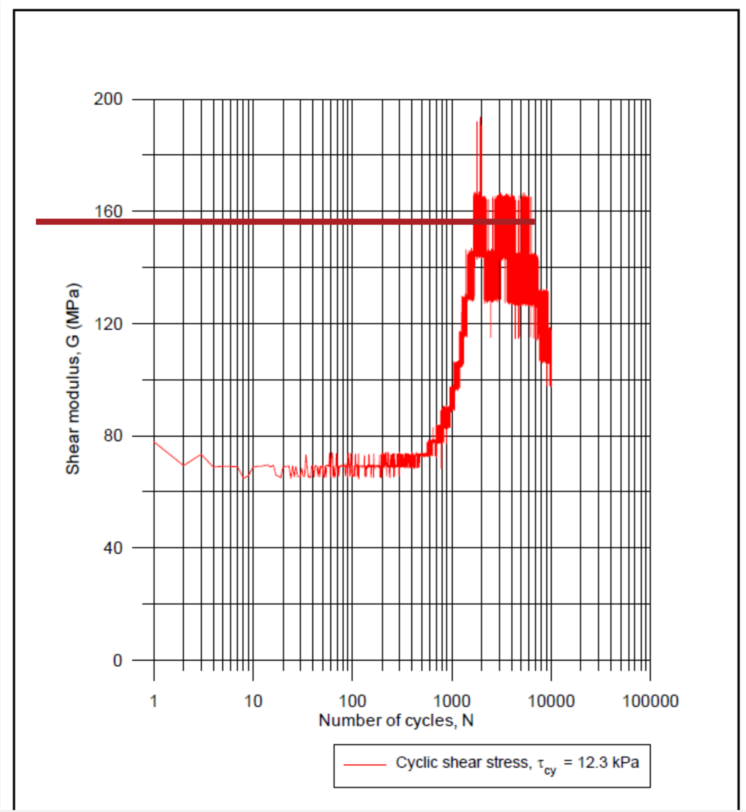
Fig. 13. Poisson's ratio ν for a constant void ratio $e=0.825$ as a function of fines content FC, calculated from Eq. (1) with the correlations (23)–(25) and from Eq. (6) with the correlations (28)–(30).

Kalksement

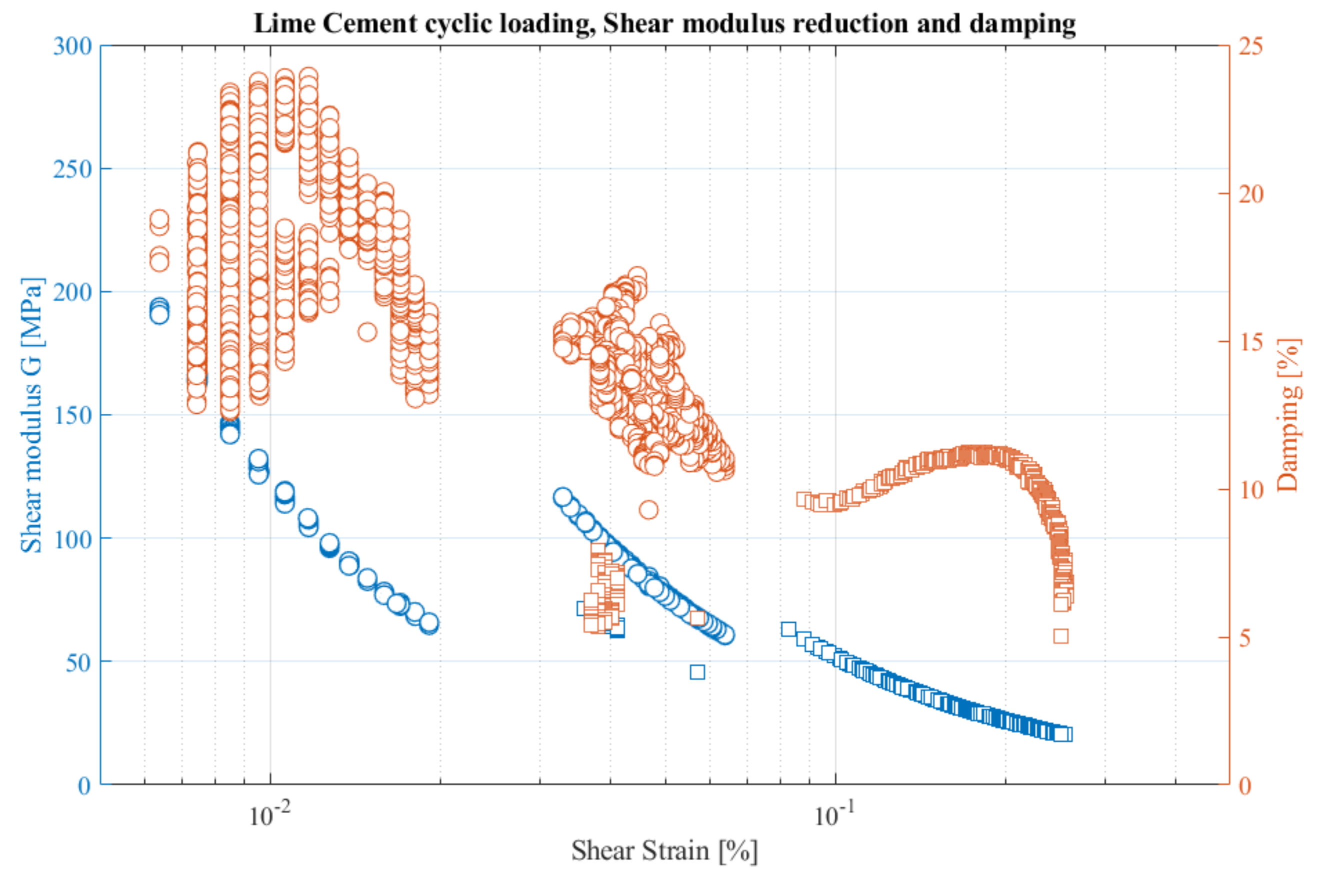
NGI test shear modulus

- $G_0=541*C_u/w_n$
- 540*160/.65 =130 MPa

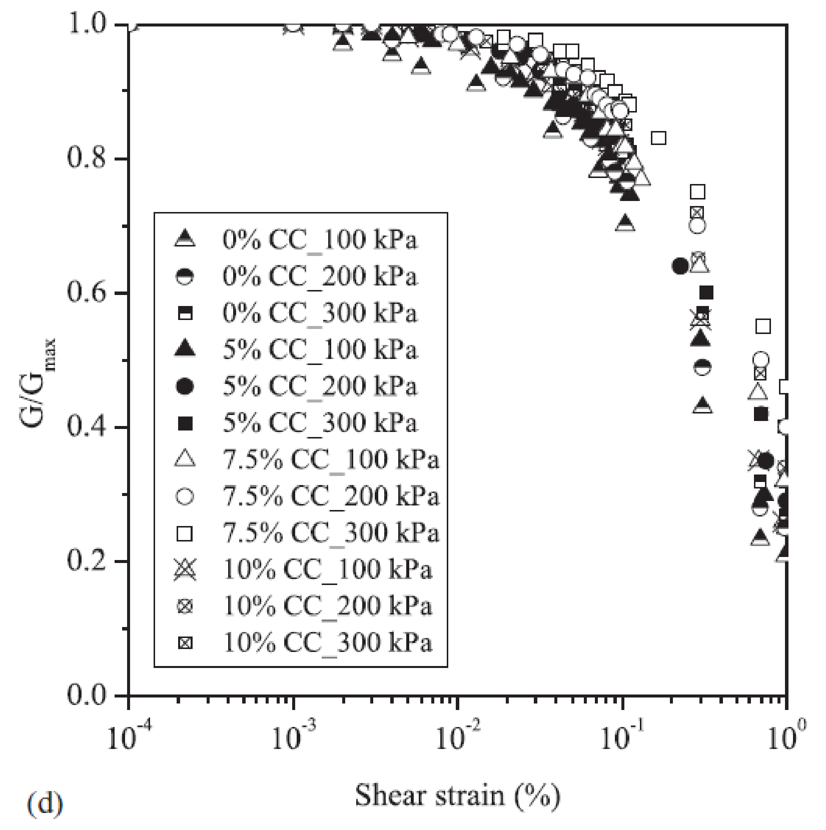


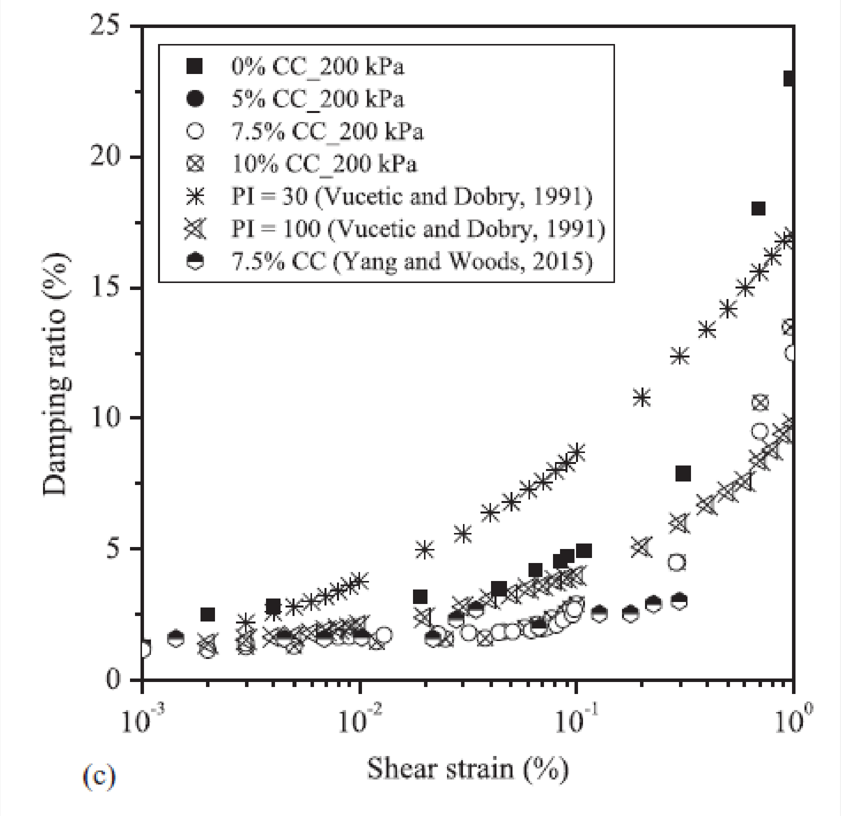


Skjærmodul og demping for kalksement Ledsgård



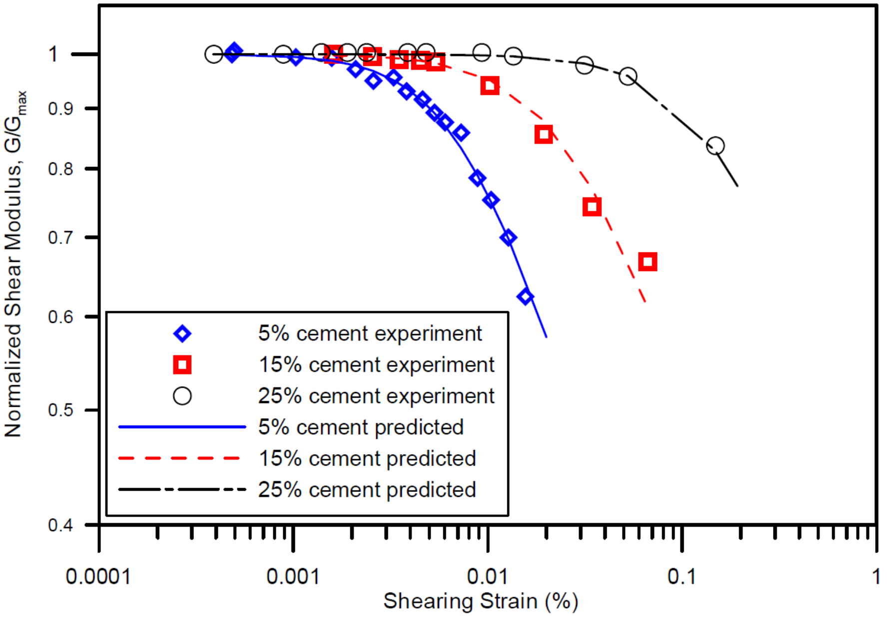
India cement treated clay result of RCTS





from Subramaniam 2020

LCC Taipei clay



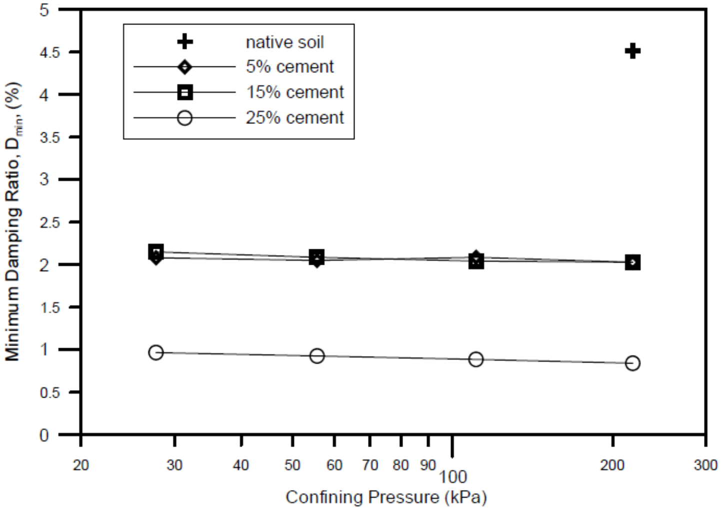


Figure 4. Influence of cement content on D_{min}

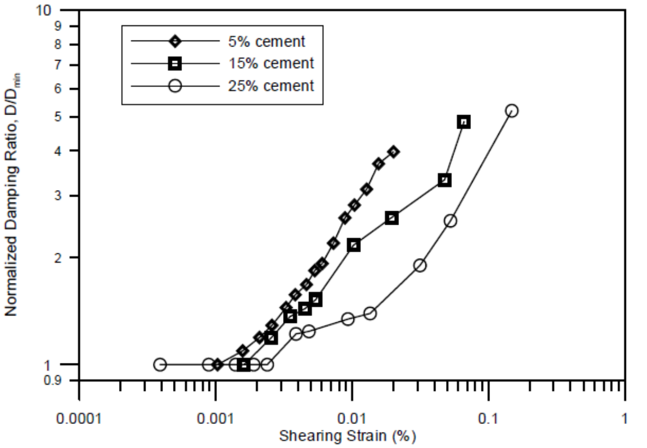


Figure 9. Influence of cement content on D/D_{min} versus γ curve

After Tsai & Ni 2012

Knust berg, grovere materialer, komprimert fyllmaterial

Knust Berg NGIs database skjærmodul

$$G(p) = G_a\left({}^{p}/_{p_a}\right)^n$$

$$p_a = 100\ kPa$$

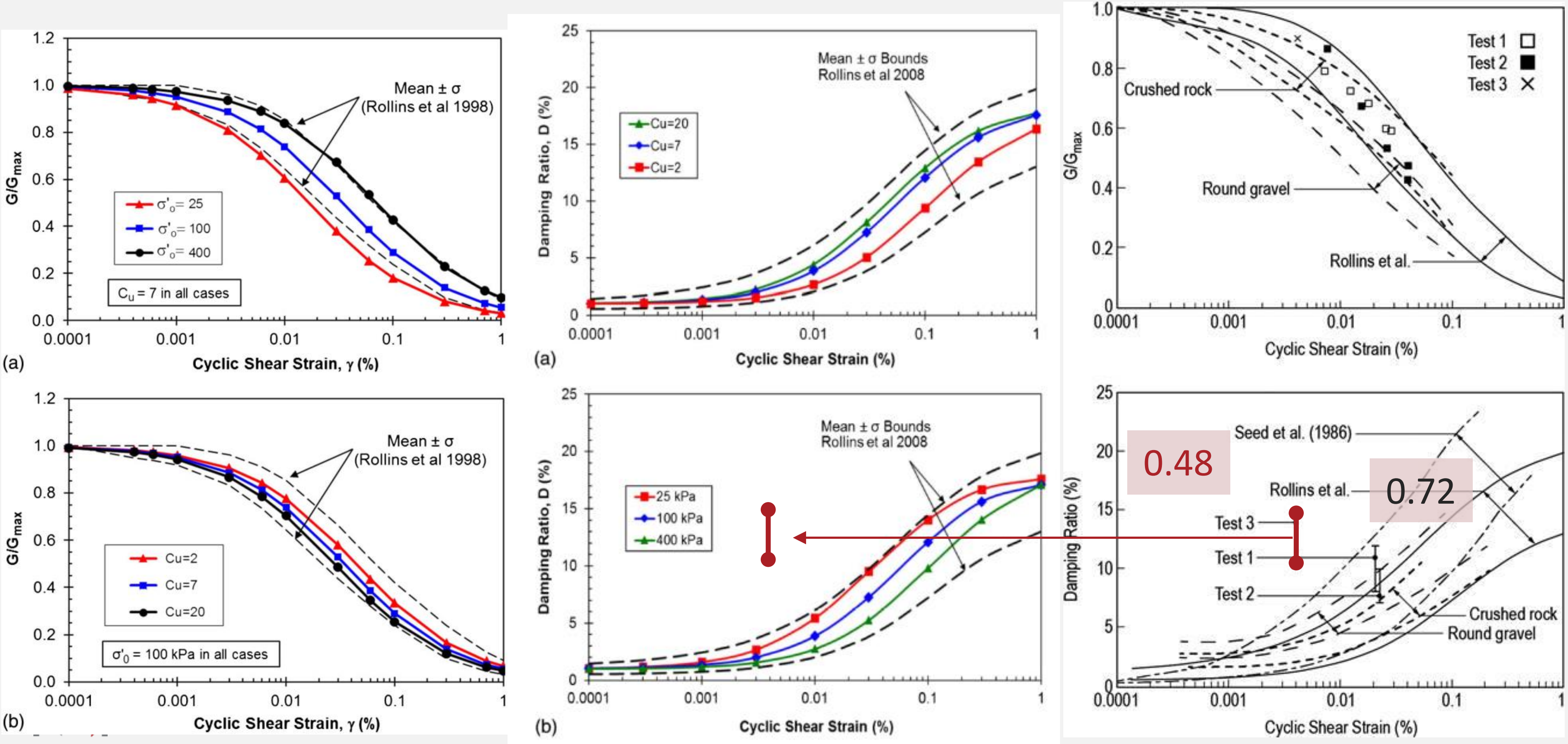
(Dawson et. al., 1994)

- Vakuum Triax försök, naturlig vattenkvot.
- Stort antall cykler, ingen ändring i cyklisk skjuvmodul. Flera olika faser med 1000 cykler i varje. Totalt antall cykler per försök upp till 90 000.
- Mycket information som inte är publicerat/rapporterat

Type materiale	Partikkel størrelse mm	Sted	G_a (Mpa)	n	Tilpassning
Grus med sandpukkel (A)	0-32	Hovinmoen grustak	116	0,83	Nokså god
Grus uten sandpukkel (D)	0-32	Hovinmoen grustak	98	0.59	Meget god
Knust stein Pukk (B)	25-50	Åndalen pukkverk, god stein (klasse 2)	99	0.0	Nokså god
Knust stein (E)	20-120	Åndalen pukkverk, god stein (klasse 2)	159	0.3	Meget god
Knust stein (F)	0-120 m noe finstoff	Åndalen pukkverk, god stein (klasse 2)	141	0.25	Svært god
Knust stein (C)	0-120 mm	Garderfjell, mindre god stein (klasse 3-4)	99	0.0	Nokså god

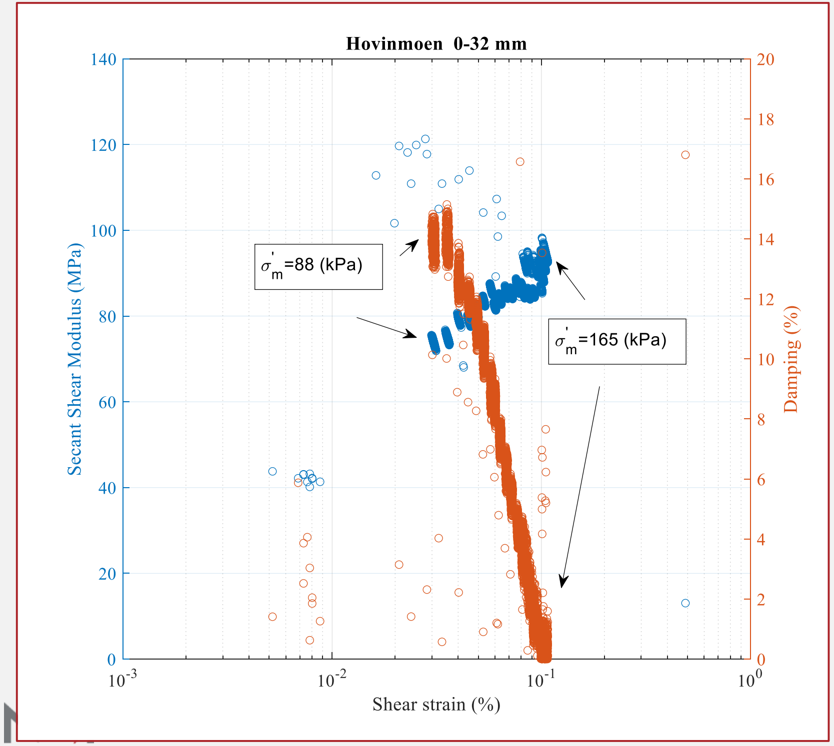
Rollins et. al. 2020 and NGI tests

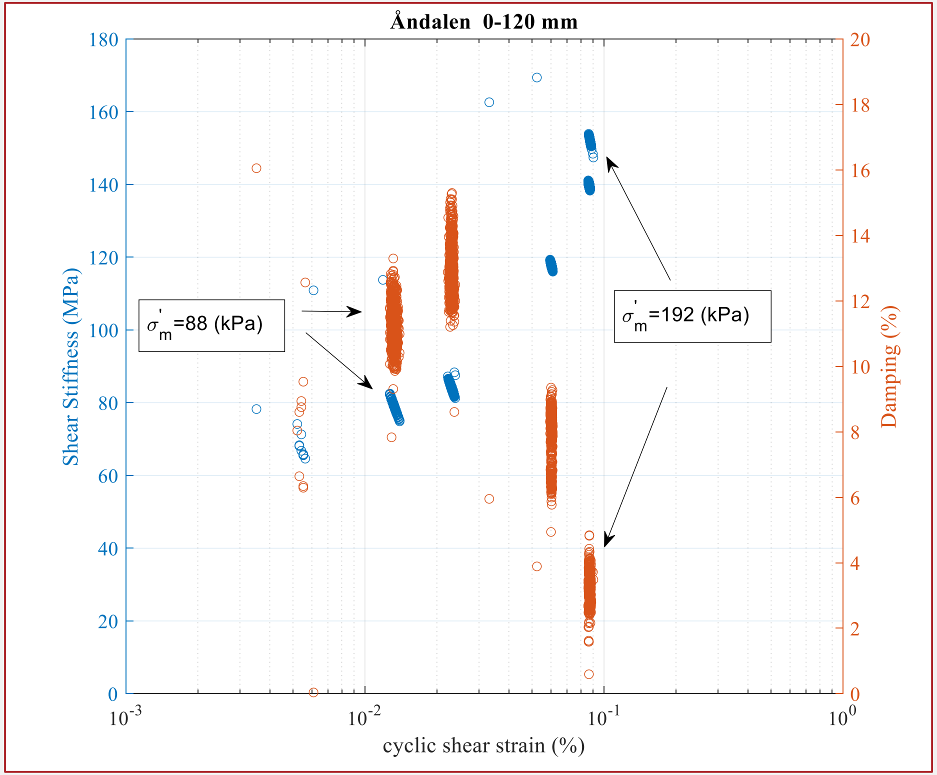
τ_{cy}/τ_{av}

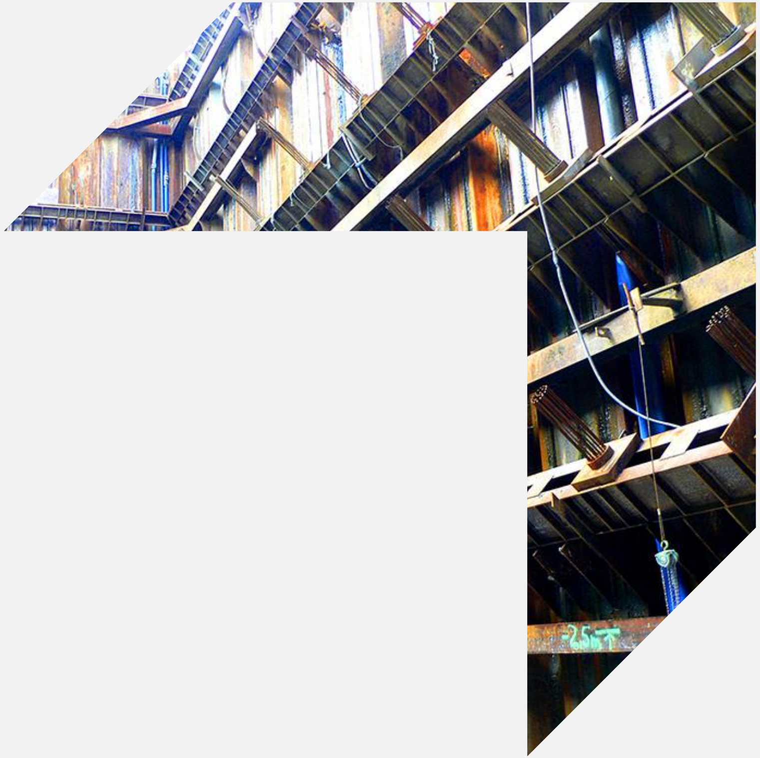


Fra Dyvik & Kaynia 2018

Eksempel på effekt av overlagringstrykk på skjærmodulens og dempingens variasjon med tøyning forknust berg







Slutt

#påsikkergrunn

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