UChile - LMMG 2015

Shear Wave Velocity (V_S): Measurement, Uncertainty, and Utility in Seismic Hazard Analysis

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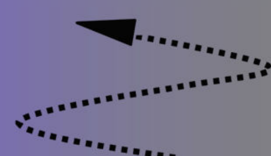
DEFINITIONS ▪ APPLICATIONS ▪ MEASUREMENTS

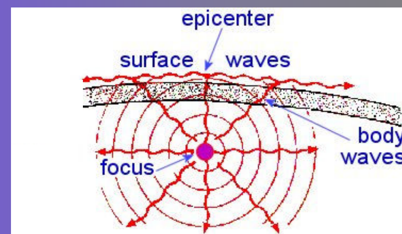
DEFINITIONS:
What is V_S and why is it of interest in earthquake engineering.

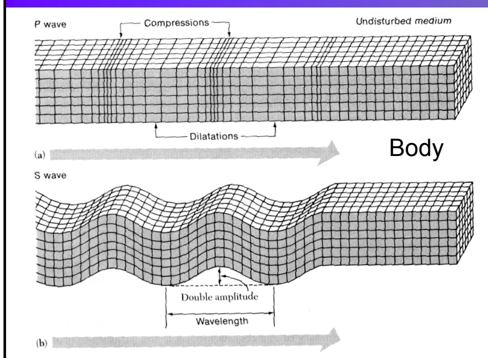
APPLICATIONS:
How V_S is used in earthquake engineering for:
•Site Response
•Liquefaction
•Dynamic Slope Stability
•Fault Rupture
•Other

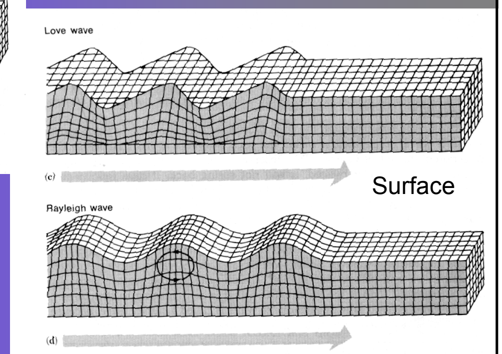


MEASUREMENTS:
How VS is measured in the lab and in the field.
•Field methods: invasive and noninvasive
•What uncertainty exist in the various measurements
•How this uncertainty propagates in earthquake engineering

DEFINITIONS ▪ APPLICATIONS ▪ MEASUREMENTS



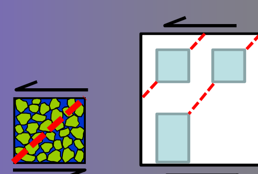




DEFINITIONS ▪ APPLICATIONS ▪ MEASUREMENTS

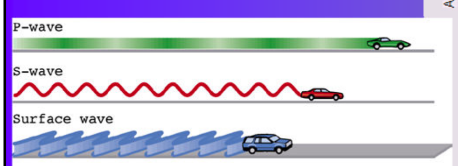
Why Shear Waves? and not Compression?

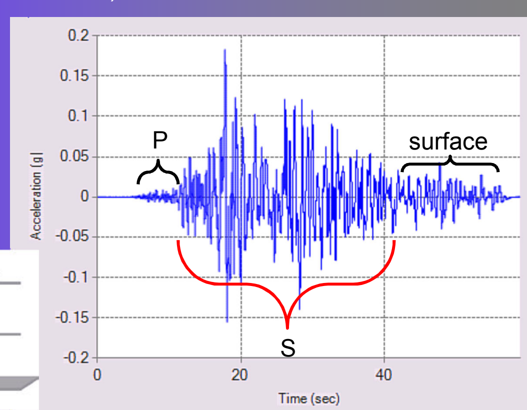
A) Soils and Structures fail in Shear



B) The bulk of seismic energy in Shear Waves
(because seismogenic rock fails in Shear)

V_S/V_P~2/3 in rock





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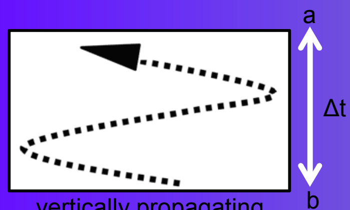
Wave Velocity (m/s) = 1 / Slowness (s/m)

= Distance (m) / Travel time (s)



vertically propagating horizontal shear wave

Geomaterial	V_S (m/s)
Peaty/Organic	20-80
Loose Sands – Soft Clays	100-200
Dense Sands –Stiff Clays	200-400
Soft Rock	450-800
Intact Shallow Rock	800-2000
Crustal Rock	2500-3500

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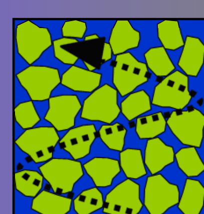
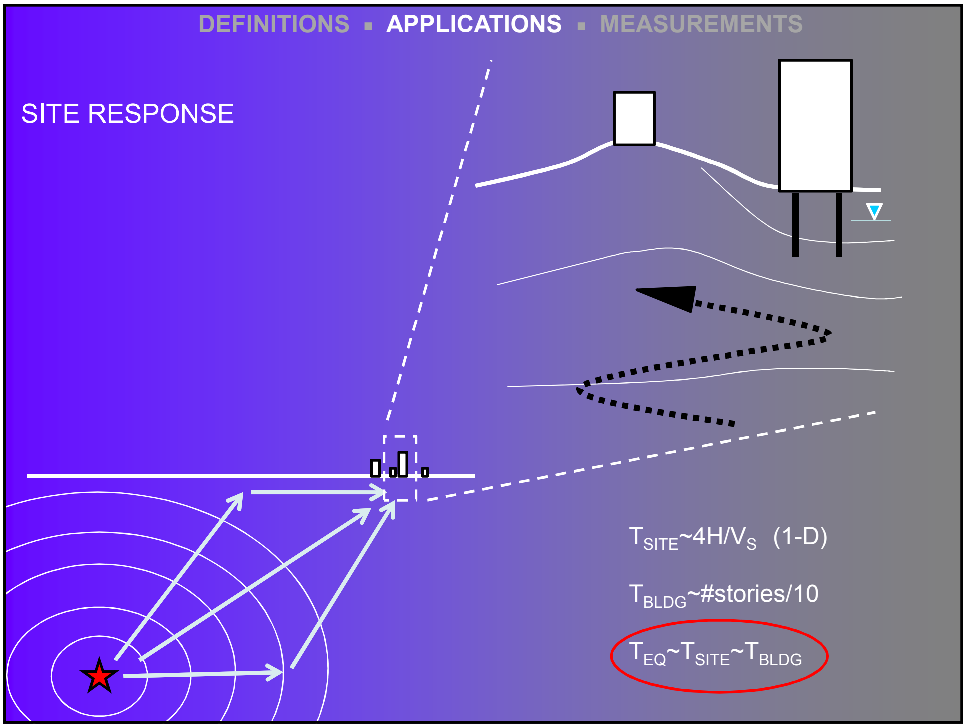
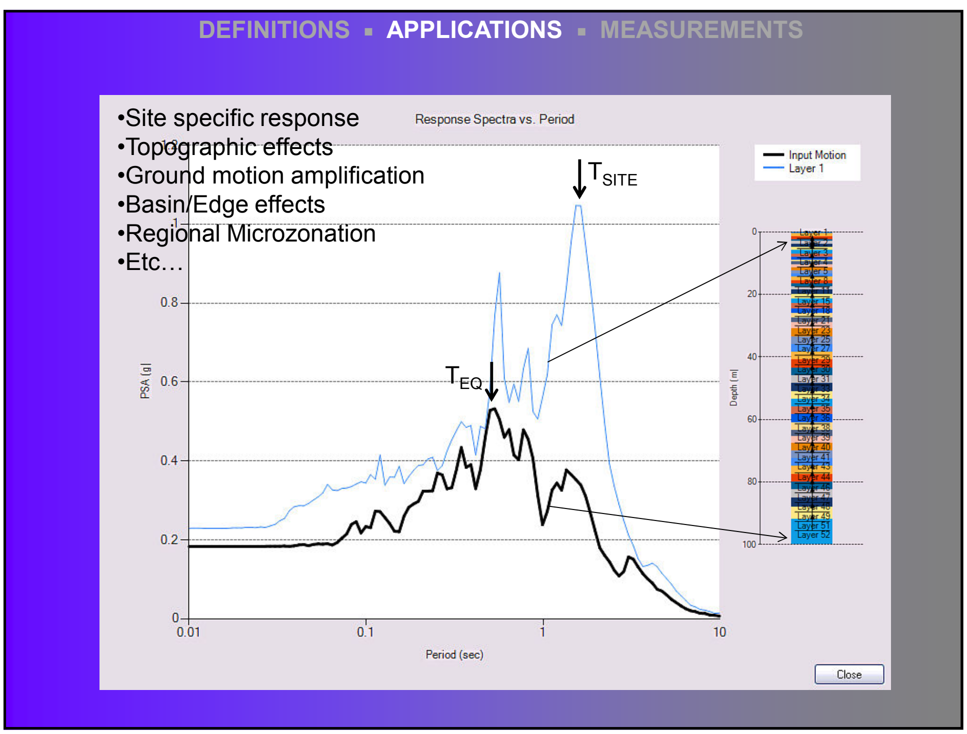
$$G_o = \frac{\tau}{\gamma} = \rho \cdot V_S^2$$

The small strain shear stiffness is the ratio of the initial shear stress to the shear strain, equivalent to the product of the density of the soil and the squared shear wave velocity.

V_S in soil is a function of:
- individual particle stiffness
- bulk matrix stiffness
- particle packing/arrangement
- bonding or cementation agents
- viscosity of the pore fluid
- other properties




DEFINITIONS ▪ APPLICATIONS ▪ MEASUREMENTS
SITE RESPONSE
T_{SITE}~4H/V_S (1-D)
T_{BLDG}~#stories/10
T_{EQ}~T_{SITE}~T_{BLDG}


DEFINITIONS ▪ APPLICATIONS ▪ MEASUREMENTS
•Site specific response
•Topographic effects
•Ground motion amplification
•Basin/Edge effects
•Regional Microzonation
•Etc…
Response Spectra vs. Period
Input Motion
Layer 1
T_{SITE}
T_{EQ}
PSA [g]
0
0.2
0.4
0.6
0.8
1
0.01
0.1
1
10
Period (sec)
Depth [m]
0
20
40
60
80
100
Close

DEFINITIONS ▪ **APPLICATIONS** ▪ MEASUREMENTS

V_S used as a single index parameter for estimating site response

Code-based

NEHRP Category	Description
A	Hard rock; V_{S30} > 1500 m/s
B	Rock; 760 m/s < V_{S30} ≤ 1500 m/s
C	Very dense soil and soft rock; 360 m/s < V_{S30} ≤ 760 m/s
D	Stiff soil; 180 m/s ≤ V_{S30} ≤ 360 m/s
E	A soil profile with V_{S30} < 180 m/s, or any profile with more than 3 m of soft clay defined as soil with *PI* > 20, *w* ≥ 40 percent, and average undrained shear strength in top 30m < 25 kPa
F	1. Soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils. 2. Peat and/or highly organic clays with a thickness > 3 m, 3. Very high plasticity clays (Thickness > 8 m with Plasticity Index > 75) 4. Very thick, soft/medium stiff clays (Thickness > 36 m with average undrained shear strength in top 30 m < 50 kPa.)

Regression-based

$$\ln(Y)=f(M_w,R,\mathbf{V_{S30}},\ldots)+\sigma_{inter}+\sigma_{intra}$$

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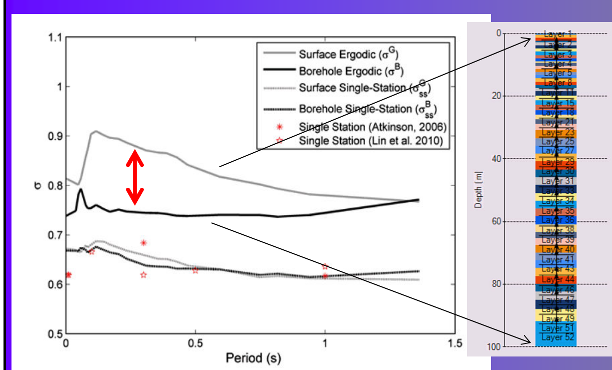

V_S as a proxy for site response
-good in concept

V_{S30} as a single parameter
-incomplete at best

When forecasting ground motions for design the magnitude of the standard deviation can make a big difference in hazard and cost.

"…the large difference in standard deviations between surface and borehole data when using the ergodic assumption can be attributed to a poor parameterization of site response."

Rodriguez-Marek, Montalva, Cotton, & Bonilla (2011) BSSA

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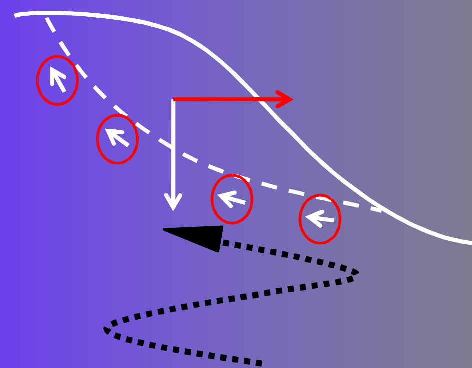
DYNAMIC SLOPE STABILITY



Primary Variables:

a) Period of slide mass
b) Period of earthquake } resonance
c) Earthquake Duration
d) Shear Strength

$T_{SLIDE} \sim T_{EQ}$

$T_{SLIDE} \sim 4H/V_S$ (1-D)

DEFINITIONS ▪ **APPLICATIONS** ▪ MEASUREMENTS

$T_{SLIDE} \sim T_{EQ}$

Resonance or First-Mode response results in "Newmark" (aka Ambraseys) type deformations.

Rigid-block /ductile deformation analysis is a function of V_S of slide mass.

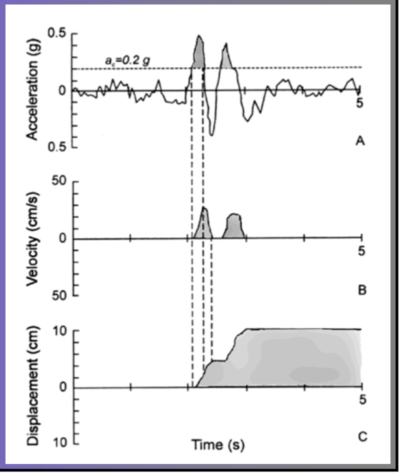
Makdisi & Seed (1978) JGE

Bray et al. (1998) JGGE

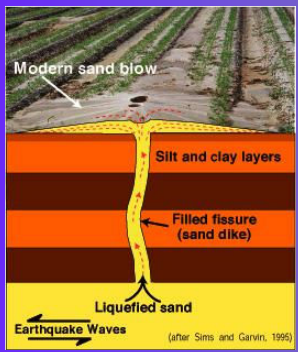
Bray and Travasarou (2007) JGGE

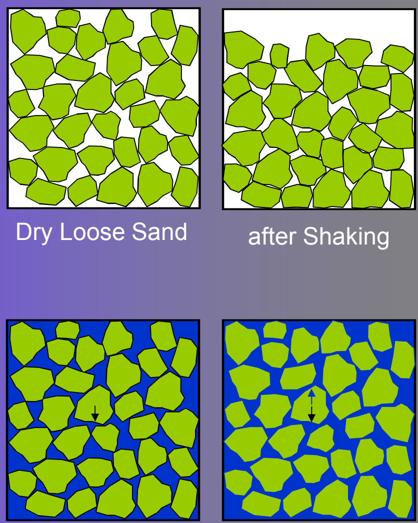
Jibson & Jibson (2003) USGS

Jibson et al. (2013) USGS



LIQUEFACTION





Dry Loose Sand

after Shaking

Saturated Loose Sand

after Shaking

$$\tau_{ff} = c + \sigma_n' tan\varphi'$$

0 0

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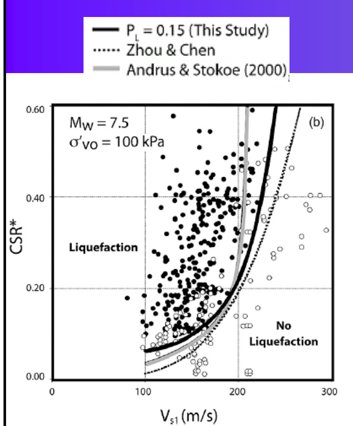
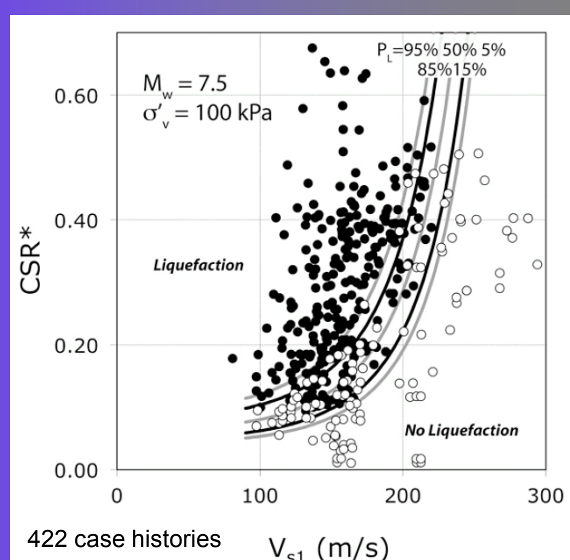
Forecast of liquefaction likelihood with V_S

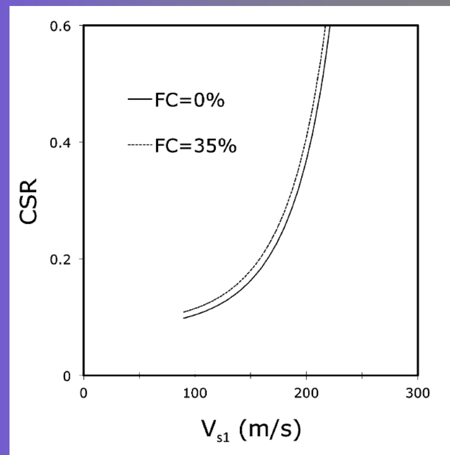




Kayen, Moss, Thompson, Seed, Cetin, Der Kiureghian, Tanaka, & Tokimatsu (2013) JGGE

Comments on V_S and Liquefaction Triggering

- Not good for assessing the influence of fines content (FC)
- Very good for assessing ageing (Holocene vs Pleistocene)
- Often very complimentary to CPT and/or SPT triggering analysis



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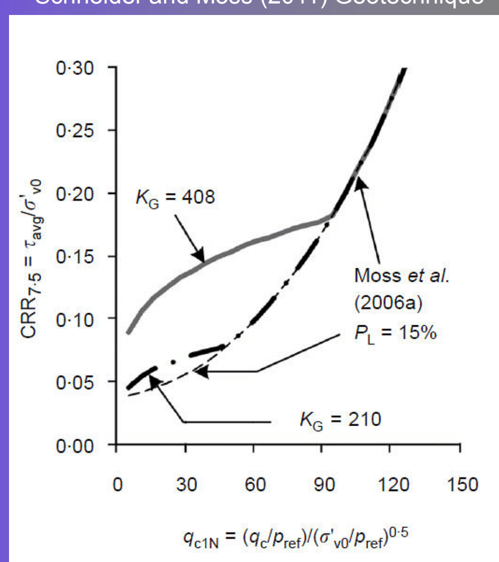
Ageing and Liquefaction

$$K_G = \frac{G_0/q_c}{\left[(q_c/p_{ref})/(\sigma'_{v0}/p_{ref})^{0.5}\right]^{-m}} = \frac{G_0/q_c}{q_{c1N}{}^{-m}}$$

Older Soil = Higher V_S
= Higher G_o
= Higher CRR

Schneider and Moss (2011) Geotechnique



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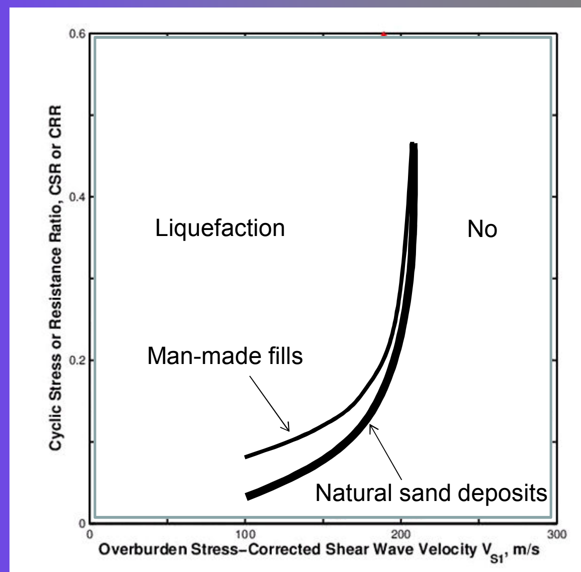
Dobry et al. (2014) JGGE

Ageing and Liquefaction



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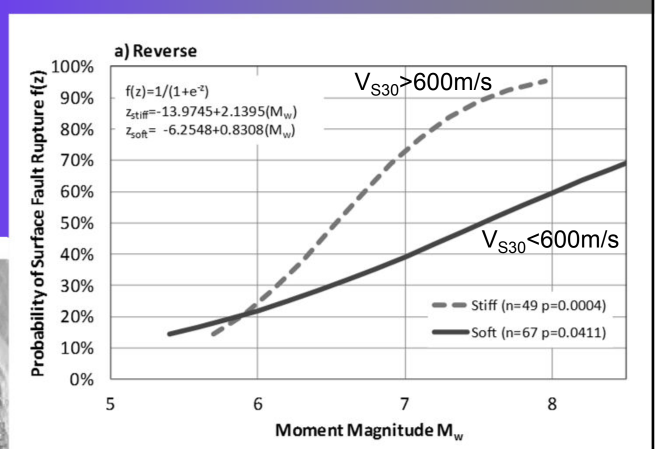
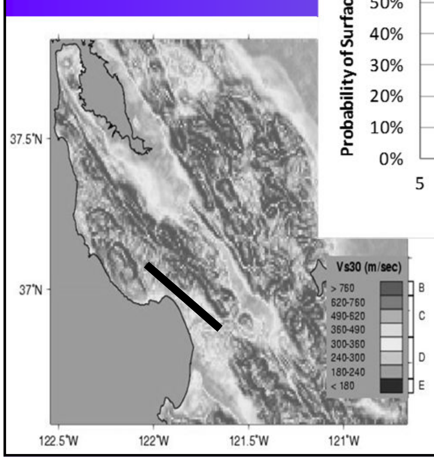
SURFACE FAULT RUPTURE





Moss et al. (2013) SRL

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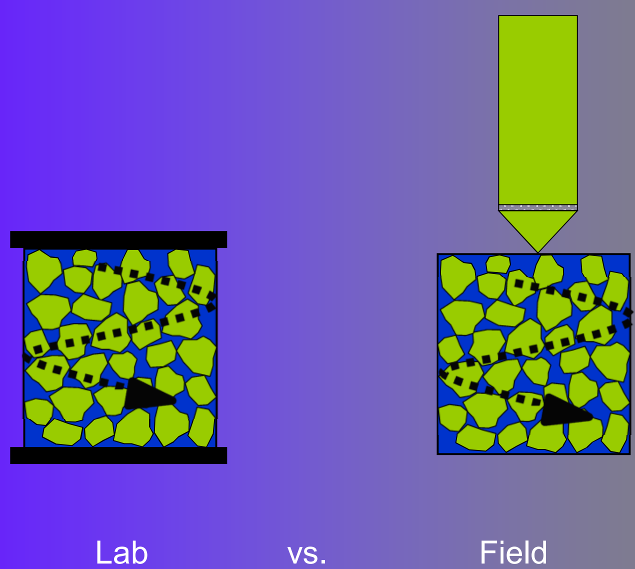
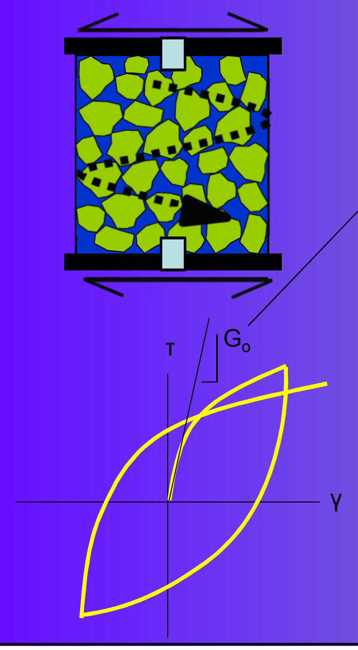
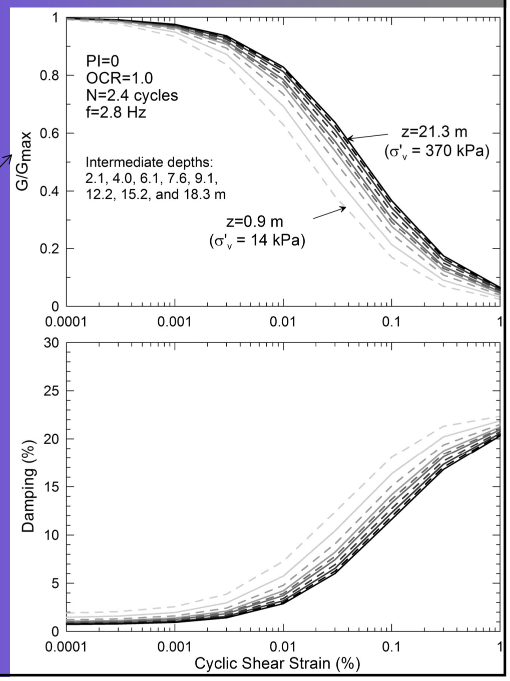
DEFINITIONS ▪ APPLICATIONS ▪ **MEASUREMENTS**



DEFINITIONS ■ APPLICATIONS ■ MEASUREMENTS

LAB: SMALL SCALE





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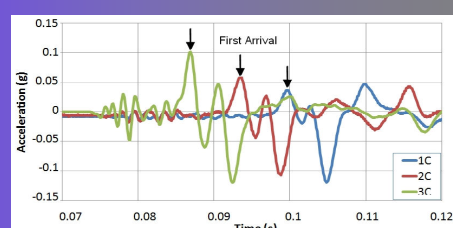
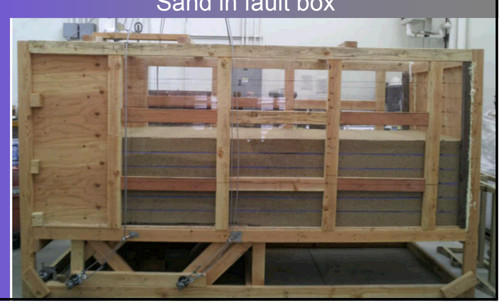
LAB: LARGE SCALE

Clay on shake table



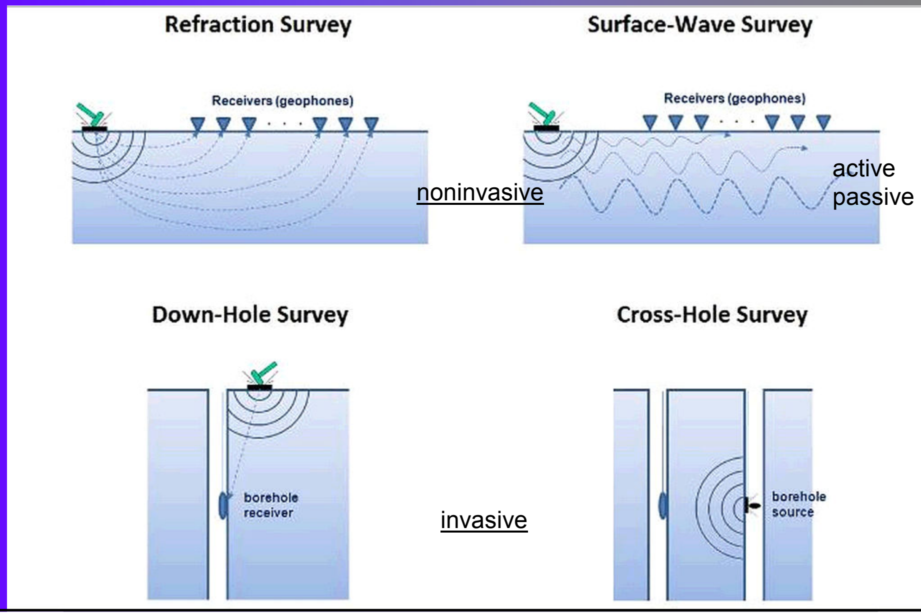
Sand in fault box



DEFINITIONS ■ APPLICATIONS ▪ **MEASUREMENTS**

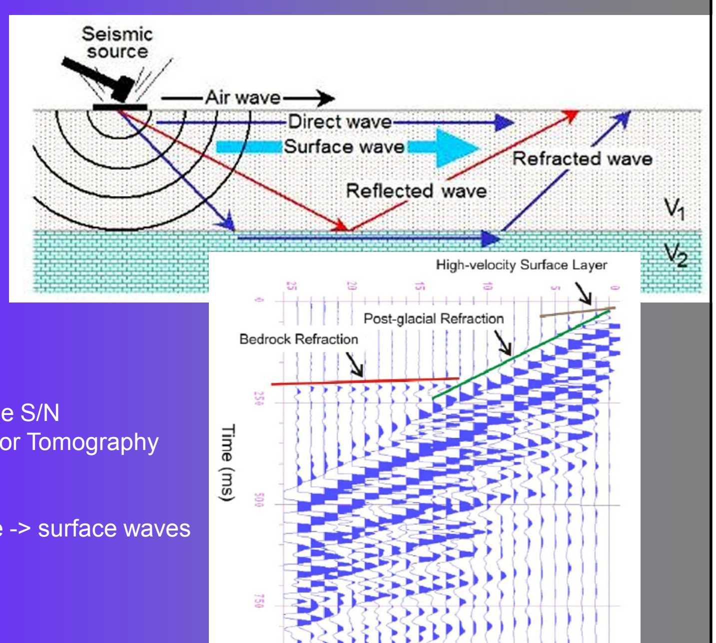
FIELD

Typical Near Surface Field Measurement Approaches



DEFINITIONS ■ APPLICATIONS ▪ **MEASUREMENTS**

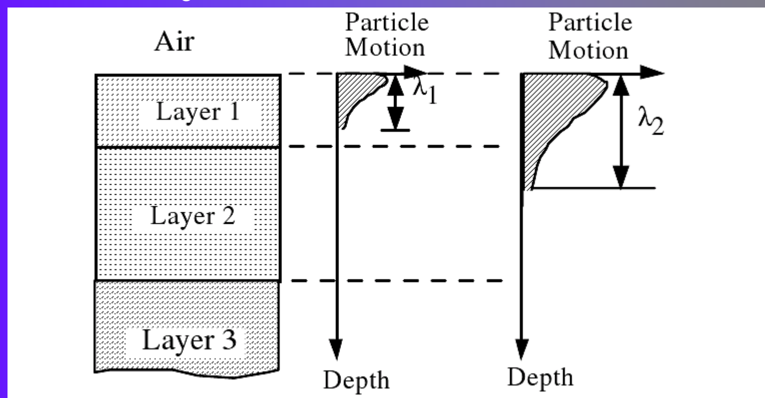
Refraction/Reflection



- Timing
- Filtering
- Source amplitude S/N
- Layer-modeling or Tomography
- “Hidden Layers”
- Long Arrays
- Up to 2/3 source -> surface waves

DEFINITIONS ■ APPLICATIONS ▪ **MEASUREMENTS**

Surface Wave Testing



- Rayleigh and Love waves are **dispersive**; different wavelengths travel at different velocities based on the velocity of the materials they encounter (Aki and Richards, 2003).
- Longer wavelengths travel through deeper layers (depth~$3\lambda_R$).
- $V_R = 0.95(V_S)$ for poisson = 0.5
  $= 0.85(V_S)$ = 0.0

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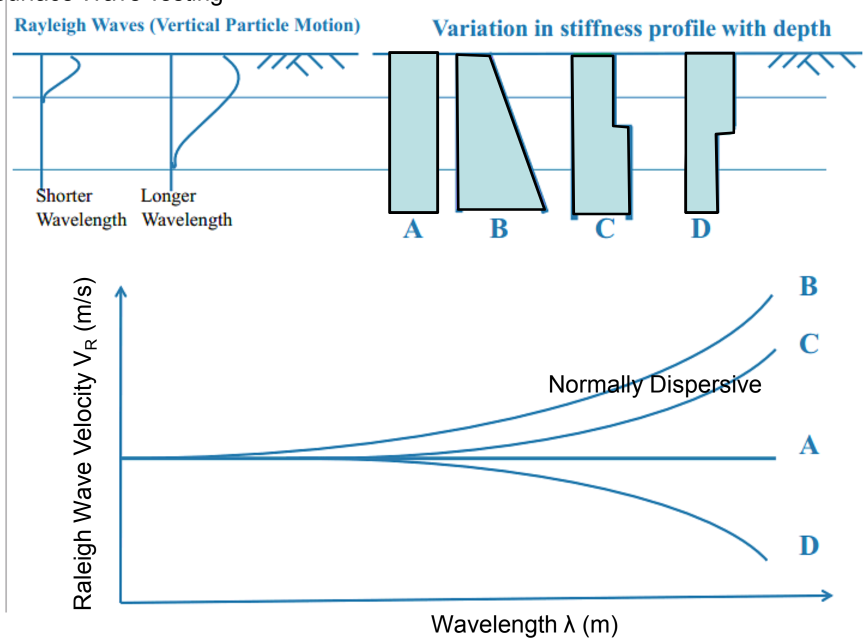
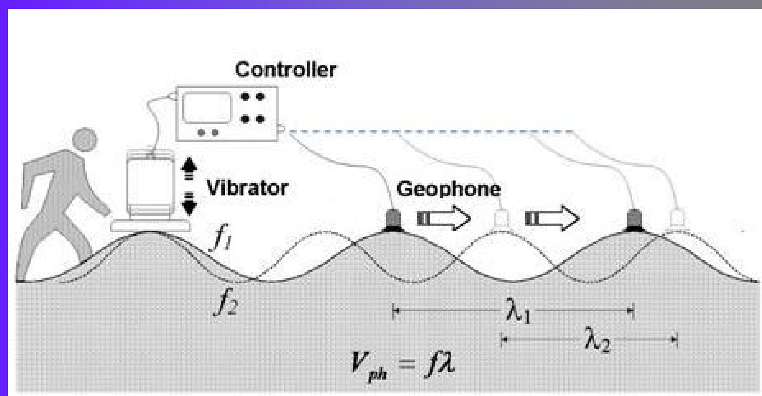
Surface Wave Testing



Surface Wave Testing

Steady State Method

Van der Pol (1951), Jones (1955)



CSW Method (Matthews et al., 1996)

Surface Wave Testing

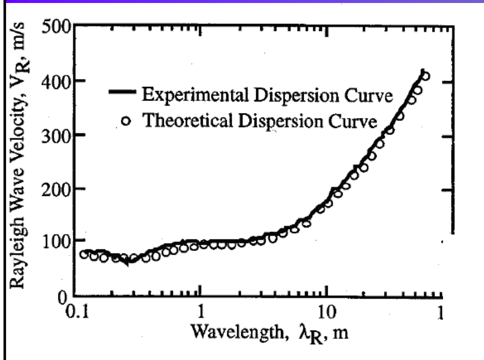
SASW, Stokoe and Nazarian 1985
MASW, Park et al., 1994

} automated steady state

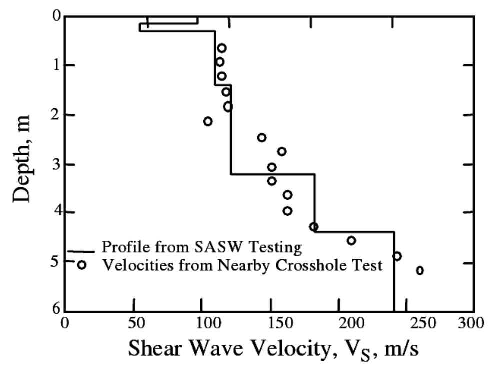
GEER 2011 Tohoku

DEFINITIONS ■ APPLICATIONS ■ **MEASUREMENTS**

Surface Wave Testing



Stokoe et al., 1994



- •S/N
- •Velocity reversals
- •Higher mode identification
- •Depth resolution
- •Horizontal layering
- •Indirect measure of V_S

DEFINITIONS ■ APPLICATIONS ■ **MEASUREMENTS**

Surface Wave Testing

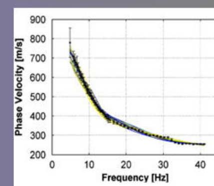
Passive Methods – SPAC, f-k, HVSR (H/V), ReMi, etc…

Passive surface wave application had come under study a half-century ago in Japan under the name of Microtremor Survey Method (MSM) by Aki (1957)

DEFINITIONS ■ APPLICATIONS ■ **MEASUREMENTS**

Surface Wave Testing

Passive -> same caveats as SASW/MASW and….

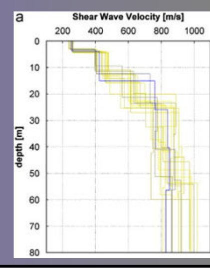


H/V
•Assumes that S is influenced by site conditions but P is not
•Need more info to estimate V_S profile

SPAC
•Azimuthal coverage needed (circular array or similar)

f-k
•Generally requires higher ambient energy with particular orientation

ReMi
•Linear array orientation with respect to ambient noise



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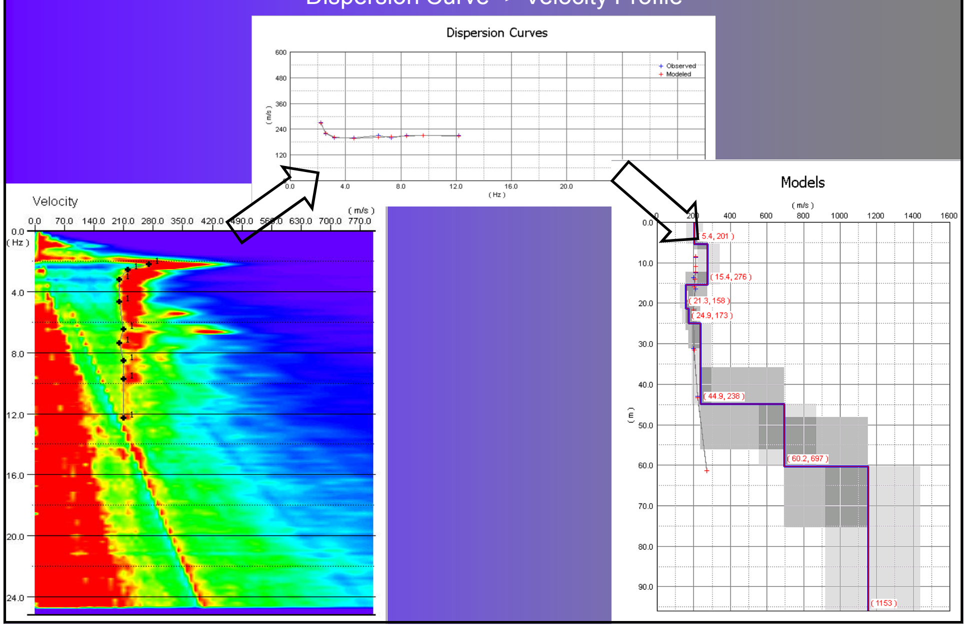
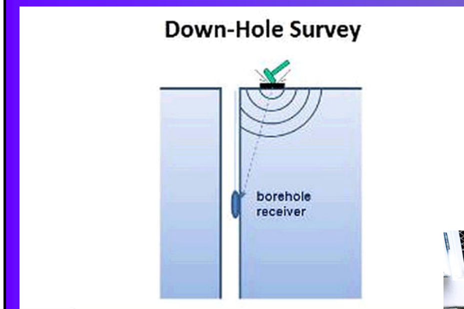
Surface Wave Testing

Dispersion Curve -> Velocity Profile



DEFINITIONS ■ APPLICATIONS ■ **MEASUREMENTS**

Invasive Methods

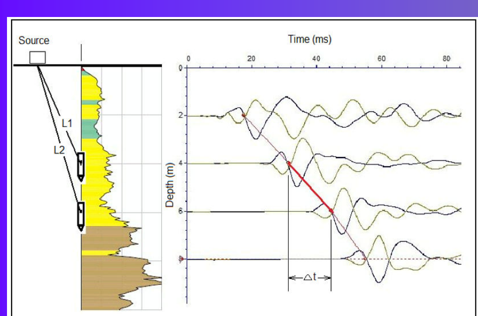


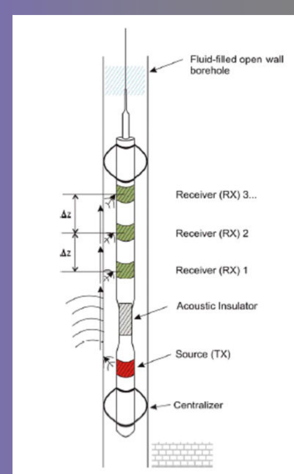
- Standard Downhole
- Seismic CPT
- Suspension Logging
- Cross-Hole
- Other….

DEFINITIONS ■ APPLICATIONS ■ **MEASUREMENTS**

Invasive Methods

- Use interval travel time and other methods of analysis for direct V_S measure of layering ++
- For cased holes the bonding is critical
- Underground structures/foundations can act as wave guides
- Often expensive to drill and case





DEFINITIONS ■ APPLICATIONS ■ **MEASUREMENTS**

PRECISION AND ACCURACY

What methods work best? Under what conditions?

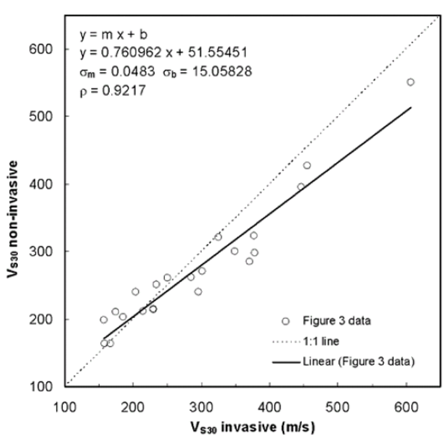
Variables that influence Precision :
- Equipment
- Methods
- Site-conditions
- Operator experience
- other

Method	**COV=stdev/mean**
Invasive (DH, SCPT, P-S Log, CH)	1-3% (?)
SASW and MASW	5-6%
ReMi	5-15%
f-k and SPAC	?
Inferred (Geology or Topography)	10-50%

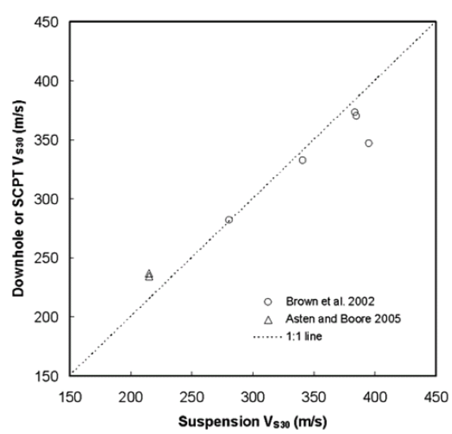
Moss (2008) BSSA

DEFINITIONS ■ APPLICATIONS ■ **MEASUREMENTS**

PRECISION AND ACCURACY



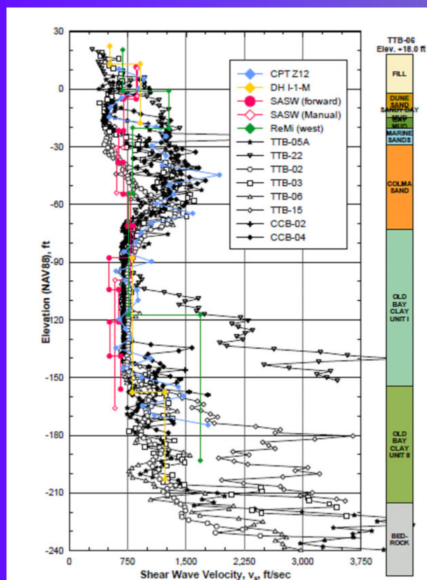
Moss (2008) BSSA



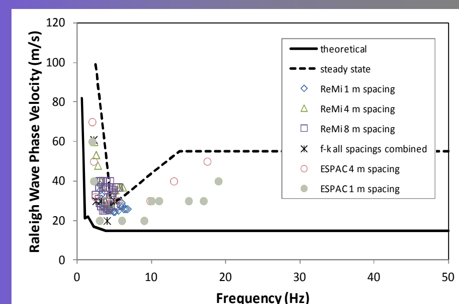
Accuracy of invasive a function of soil disturbance…
Accuracy of noninvasive a function of resolution /fidelity of surface waves…

DEFINITIONS ■ APPLICATIONS ■ **MEASUREMENTS**

PRECISION AND ACCURACY



Blind Studies; e.g.,
- Asten and Boore (2005)
- Brown, Boore, & Stokoe (2002),
- Xia et al., (2002)
- Other…
- more needed!



DEFINITIONS ■ APPLICATIONS ■ **MEASUREMENTS**

PRECISION AND ACCURACY

How accurate is accurate enough? Depends…

Site Response
-need resonant period of entire soil column
~Δ10% does not influence results appreciable
-rough estimate excludes period lengthening
and structural softening

Not-Important

Important

Liquefaction
-need V_S of specific layer
~Δ10% does influence results
-uncertainty could results in large cost difference:
Mitigation vs. non-Mitigation

Future Work:

- Need more blind study sites with as many methods as possible
- Focus on difficult sites: dense urban, stiff-over-soft, shallow rock,…
- Establish specific minimum requirements for different methods
- Consensus best-practices because there is no single best-method
- Measure V_S at every site, for every project:
  Small strain stiffness is the easiest engineering property to directly measure
- Better measure of V_S = more accurate seismic hazard analysis

Thank You

DEFINITIONS ▪ APPLICATIONS ▪ MEASUREMENTS

Shear Wave Velocity (V_S): Measurement, Uncertainty, and Utility in Seismic Hazard Analysis

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Shear wave velocity (V_S) is a primary input variable in many seismic hazard analyses. It is essential for performing seismic site response analysis, used as an index for liquefaction triggering analysis, important for identifying the modal resonance of seismic slopes and embankments, and has many other seismic hazard uses. Shear wave velocity can be measured both in the lab and in the field providing a crucial bridge between table-top and field scales. The measurement and determination of V_S can be accomplished with many methods, which range from conceptually straightforward using invasive methods to often conceptually and computationally complex using non-invasive methods. This presentation will cover the use of V_S in geotechnical earthquake engineering, discuss the uncertainty in the measurement of this property, and provide an overview of current research into quantifying the uncertainty, improving the methods, and applying the knowledge gained to reduce seismic hazards.